

SYMBIOTIC BACKSCATTER COMMUNICATION

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By

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10 December 2024

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LIST OF SYMBOLS

$ \cdot $	: Cardinality of a Set
$(\cdot)^T$	: Transpose
θ_A	: Phase of Antenna Impedance
θ_L	: Phase of Load Impedance
θ_b	: Phase of Backscatter Signal
Φ	: Characteristic Function
Γ_b	: Reflection Coefficient
ζ	: Frequency Index
$*$	: Convolution Operation
γ	: Complex Channel Path Gain
Π	: Product of Sequence of Terms
$\sigma_{(\cdot)}^2$	: Noise Variance
Δ	: Matrix of the Complex Channel Path Gains
∇	: Power Allocation Coefficient
$\hat{\phi}_\varrho$	: Pre-Defined Spatial Directions
ϕ_R	: Angle of Arrival
ϕ_T	: Angle of Arrival
Θ	: Photodiode's Field of View
μ	: Wavelength
Υ	: Normalization Factor
α	: Power of Sub-Channel Block
ρ	: Power of Sub-Channel Block
β	: Bit-Energy-to-Noise-Ratio
ψ	: Angle of Irradiance
Ψ	: Angle of Incidence
Λ	: Area of Photodiode
ω	: Lambertian Emission Order
η_0	: Noise Power Spectral Density
η	: Threshold
ξ	: Energy Efficient Constant
ϱ	: Index of Transmit Antennas
λ	: Rate Parameter of the Exponential Distribution
$\mathbf{a}_{Tx}$	: Array Steering Vector of the Transmitter
$\mathbf{a}_{Rx}$	: Array Steering Vector of the Receiver
$\mathbf{A}_{Tx}$	: Array Response Matrix of the Transmitter
$\mathbf{A}_{Rx}$	: Array Response Matrix of the Receiver
$\mathbb{A}_D$	: Average User Data Rate
$\mathbb{B}$	: Transmission Bandwidth of the Signal
$\mathbf{c}$	: Backscatter Switch States
$\mathbf{D}$	: Data Rate of User
$\mathbf{E}$	: Expected Value
$\mathbf{E}_b$	: Bit Energy
f_c	: Carrier Frequency
f_ζ	: Frequency Shift in Backscatter Signal
F_r	: Cumulative Distribution Function
g	: Optical Concentration Gain
$\mathbb{G}$	: Optical Filter Gain

$\mathbf{G}$	: Precoding Matrix
$\mathbf{h}_b$	: Bob's Channel Impulse Response
$\mathbf{h}_{bd}$	: Channel Impulse Response on the Backward Link
$\mathbf{h}_d$	: Channel Impulse Response on the Direct Link
$\mathbf{h}_e$	: Eve's Channel Impulse Response
$\mathbf{h}_f$	: Channel Impulse Response on the Forward Link
$\mathbf{H}$	: Beamspace Channel Matrix with Selected Beams
$\tilde{\mathbf{H}}$	: Beamspace Channel Matrix
$\mathcal{H}_0$	: Hypothesis Testing for Information Bit 0
$\mathcal{H}_1$	: Hypothesis Testing for Information Bit 1
$\mathbf{H}_B$	: Bob's Channel Frequency Response
$\tilde{\mathbf{H}}_B$	: Estimated Bob's Channel Frequency Response
$\mathbf{H}_{bd}$	: Channel Frequency Response on the Backward Link
$\mathbf{H}_d$	: Channel Frequency Response on the Direct Link
$\mathbf{H}_E$	: Eve's Channel Frequency Response
$\tilde{\mathbf{H}}_E$	: Estimated Eve's Channel Frequency Response
$\mathbf{H}_f$	: Channel Frequency Response on the Forward Link
i	: Imaginary Unit
$\mathbf{I}$	: Sub-Channel Block
$\hat{\mathbf{I}}$	: Interleaved Sub-Channel Block Vector
K	: Total Active Subcarriers
$\mathcal{K}_b$	: Index of Subcarriers Containing Data of Backscatter Device
$\mathcal{K}_d$	: Index of Subcarriers Containing Data of The Base Station
K_{usr}	: Total Number of Users
$\mathbb{L}$	: Height of Users
L_b	: Maximum Excess Delay of Bob's Channel
L_e	: Maximum Excess Delay of Eve's Channel
$\mathbb{L}_h$	: LED Height from Ground
$\mathcal{M}_c$	: Mask for Selection of Dominant Beams
n	: Time Domain Sample Index
$\mathcal{N}(\cdot)$	: Gaussian Distribution
$\mathbb{N}$	: Total Number User Pairs
N	: Inverse Discrete Fourier Transform Size
N_0	: Noise-Ratio
N_b	: Number of Subcarriers Containing Backscatter Device's Data
N_{bd}	: Number of Backscatter Devices
N_c	: Total Subcarriers Within a Sub-Channel Block
N_{cp}	: Cyclic Prefix Length
N_d	: Number of Subcarriers Containing Primary Users' Data
N_l	: Number of Ordinary Scatterers
N_p	: Number of Channel Paths
N_s	: Total Number of Data Streams
N_{Tx}	: Total Number of Transmit Antenna Elements
N_{Rx}	: Total Number of Receive Antenna Elements
N_u	: Total Sub-Channel Blocks
$\mathcal{O}(\cdot)$	: Big O Notation
p	: Probability Density Function
P_e	: Probability of Error
P_{FA}	: Probability of False Alarm

$\mathbf{P}_{\text{ler}}$	: Probability of Erroneous Pilot Detection
$\mathbf{P}_{\text{MD}}$	: Probability of Miss Detection
$\mathbf{Pr}$	: Probability
$\mathbf{P}_t$	: Transmit Power
$\mathbf{q}_b$	: Backscatter Device's Signal
$\mathbf{r}$	: Test Statistic
$\mathbb{R}$	: Refractive Index
$\mathbf{R}_s$	: Room Size
$\mathbf{S}$	: Primary Data Symbol
$\mathbb{S}$	: Signal-to-Noise-Ratio
$\mathbf{s}_c$	: Set of Beams
$\boldsymbol{\tau}$	: Channel Delay
$\boldsymbol{\tau}_b$	: Channel Delay of the Channel on the Backward Link
$\boldsymbol{\tau}_f$	: Channel Delay of the Channel on the Forward Link
$\boldsymbol{\tau}_{\text{max}}$	: Maximum Excess of the Channel on the Backward Link
$\mathbf{v}$	: Probability Density Function of the Backward Channel
$\mathbf{u}$	: Sub-Channel Block's Index
$\mathbf{U}$	: Unitary Matrix
$\mathbf{w}$	: Additive White Gaussian Noise
$\mathbf{x}$	: Time Domain Passband Primary Signal
$\mathbf{x}_{bb}$	: Time Domain Baseband Primary Signal
$\mathbf{x}_{out}$	: Signal at Output of Backscatter Device
$\mathbf{X}$	: Frequency Domain Primary Signal
$\mathbf{X}_\rho$	: Pilot Symbols
$\mathbf{X}_d$	: Data Symbols
$\mathbf{y}$	: Time Domain Signal at the Receiver
$\mathbf{y}_d$	: Time Domain Signal Received from the Direct Link
$\mathbf{y}_b$	: Time Domain Signal Received from the Backscatter Link
$\mathbf{Y}$	: Frequency Domain Signal at the Receiver
$\mathbf{Y}_d$	: Frequency Domain Signal Received from the Direct Link
$\mathbf{Y}_{\text{Bd}}$	: Frequency Domain Signal Received from the Backscatter Link
$\mathbf{Y}_b$	: Frequency Domain Signal Received at the Bob
$\mathbf{Y}_e$	: Frequency Domain Signal Received at the Eve
$\mathbb{Z}^+$	: Set of Real Numbers
$\mathbf{Z}_b$	: AWGN Noise at the Bob
$\mathbf{Z}_e$	: AWGN Noise at the Eve
$\mathbf{Z}_A$	: Antenna Impedance
$\mathbf{Z}_L$	: Load Impedance

ABBREVIATIONS

1G	: First-Generation
3GPP	: 3rd Generation Partnership Project
5G	: Fifth-Generation
6G	: Sixth Generation
AASC	: Active-Active Systems Coexistence
AmBackCom	: Ambient Backscatter Communication
ABCmS	: Ambient Backscatter Communication System
ACS	: Active Communication System
ADC	: Analogue-to-Digital Converter
AI	: Artificial Intelligence
AoA	: Angle-of-Arrival
AoD	: Angle-of-Departure
AP	: Access Point
APSC	: Active-Passive Systems Coexistence
APwA	: Adaptive Power Allocation
ARQ	: Automatic Repeat Requests
ARDS	: Active Radar System
ARS	: Active Radio System
ASK	: Amplitude-Shift Keying
AT	: Active Transmitter
AWGN	: Additive White Gaussian Noise
BackCom	: Backscatter Communication
BBC	: British Broadcasting Corporation
BBCmS	: Bistatic Backscatter Communication System
BC	: Backscatter Communications
BCmS	: Backscatter Communication System
BD	: Backscatter Device
BER	: Bit-Error-Rate
BS	: Base Station
BPSK	: Binary Phase Shift Keying
CDRL	: Centralized Deep Reinforcement Learning
CDF	: Cumulative Distribution Function
CFO	: Carrier Frequency Offset
COVID-19	: Coronavirus Disease-2019
CP	: Cyclic Prefix
CRC	: Cyclic Redundancy Check
CR	: Cognitive Radio
CSI	: Channel-State-Information
CSCG	: Circularly Symmetric Complex Gaussian
DDRL	: Distributed Deep Reinforcement Learning
DFRC	: Dual Function Radar and Communication
DFT	: Discrete Fourier Transform
DSA	: Dynamic Spectrum Access
ELPC	: Extremely Low-Power Communication
ERLLC	: Extremely Reliable and Low-Latency Communication
ETSI	: European Telecommunications Standards Institute
FCC	: Federal Communication Commission
FD	: Full-Duplex
FFT	: Fast Fourier Transform

FMCW	: Frequency Modulated Continuous Wave
FM	: Frequency Modulation
FSK	: Frequency-Shift Keying
GPS	: Global Positioning System
ICI	: Inter-Carrier Interference
IDFT	: Inverse Discrete Fourier Transform
IFFT	: Inverse Fast Fourier Transform
IoE	: Internet-of-Everything
IOMT	: Internet of Medical Things
IoT	: Internet-of-Things
ISAC	: Integrated Sensing and Communication
ISBC	: Integrated Sensing and Backscatter Communication
ISM	: Industrial Scientific and Medical
ITS	: Intelligent Transportation System
LAA-LTE	: Licensed Assisted Access Long-Term Evolution
LDHMC	: Long-Distance and High-Mobility Communication
LED	: Light-Emitting Diode
LIS	: Large-Intelligent Surface
LoS	: Line-of-Sight
LSE	: Least Square Estimator
LTE	: Long-Term-Evolution
MBCmS	: Monostatic Backscatter Communication System
MCS	: Monostatic Communication System
MCU	: Microcontroller Unit
MIMO	: Multiple-Input Multiple-Output
ML	: Machine Learning
MM	: Maximum Magnitude
mmWave	: Millimeter Wave
MRS	: Mono-Static Radar System
MSE	: Mean Square Error
NOMA	: Non-Orthogonal Multiple Access
OFDM	: Orthogonal Frequency Division Multiplexing
OOK	: On-Off Keying
PCS	: Passive Communication System
PD	: Photodiode
PDF	: Probability Density Function
PFA	: Probability of False Alarm
PIoT	: Passive IoT
PLER	: Pilot Location Error Rate
PMD	: Probability of Miss Detection
PoD	: Probability of Detection
PRDS	: Passive Radar System
PRS	: Passive Radio System
PU	: Primary User
P2RC	: Passive-Reconfigurable-Reflective Communication
RADAR	: Radio Detection and Ranging
RF	: Radio Frequency
RFID	: Radio Frequency Identification
RIS	: Reconfigurable Intelligent Surfaces
ROC	: Receiver Operating Characteristic

RX	: Receiver
SNR	: Signal-to-Noise-Ratio
SINR	: Signal-to-Interference-Plus-Noise-Ratio
SR	: Symbiotic Radio
SRD	: Symbiotic Radar
SCm	: Symbiotic Communication
SCaS	: Symbiotic Communication and Sensing
SSA	: Static Spectrum Access
SSaC	: Symbiotic Sensing and Communication
SU	: Secondary User
TDD	: Time Division Duplexing
THz	: Terahertz
TV	: Television
TVWS	: TV White Space
Tx	: Transmitter
UAV	: Unmanned Aerial Vehicle
UE	: User Equipment
UGV	: Unmanned Ground Vehicles
ULA	: Uniform Linear Array
V2X	: Vehicle-to-Everything
VLC	: Visible Light Communication
WiFi	: Wireless Fidelity
uRLLC	: Ultra-Reliable Low Latency Communication
umMTC	: Ultra-Massive Machine-Type Communication

SİMBİYOTİK GERİ SAÇILMA İLETİŞİMİ

ÖZET

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Altıncı nesil (6G) ve ötesi kablosuz ağlar, çevresel olarak sürdürülebilir ve küresel olarak birbirine bağlı sistemleri teşvik ederek kritik zorlukları ele almayı amaçlamaktadır. 6G'yi mümkün kılan temel bir teknoloji, simbiyotik ilişkiler yoluyla çeşitli radyo sistemleri arasında kaynakların paylaşımını teşvik eden simbiyotik radyodur (SRad). Özellikle, bu düşünülen radyo sistemleri, geri saçılım iletişimine (BC) dayanan mevcut kablosuz sistemler ve pasif Nesnelerin İnterneti (IoT) cihazlarıdır. Bu tez, temel ilkelerini, son teknoloji metodolojilerini ve potansiyel uygulamalarını keşfederek simbiyotik BC için SRad teknolojisinin kapsamlı bir araştırmasını sunmaktadır. Araştırma, farklı radyo sistemleri arasında bir arada yaşamayı ve verimli kaynak yönetimini mümkün kılan çeşitli simbiyotik ilişki türleri de dahil olmak üzere radyo simbiyozunun temel kavramlarını inceleyerek başlar. Bu temel anlayışa dayanarak, SRad etkinleştirilmiş BC sistemlerindeki belirli zorlukları ele almak için yeni teknikler önerilmektedir. İlk araştırma, simbiyotik bir radyo sistemi içinde parazitsiz BC elde etmek için tasarlanmış ortogonal frekans bölmeli çoğullama (OFDM) tabanlı bir şema sunmaktadır. Özellikle, birincil sinyali (yani bir baz istasyonundan (BS) iletilen OFDM sembollerini) bilgi iletimini kolaylaştırmak için frekans alanında kaydıran üç frekans kaydırmalı anahtarlama (FSK) tabanlı geri saçılma modülasyon şemaları önerilmiştir. Geri saçılma aygıtından gelen frekans kaydırılmış sinyaller ile birincil sinyal arasındaki ortogonaliteyi korumak için, BS bant içindeki belirli alt taşıyıcıları boşaltır. İlk şema, açık-kapalı anahtarlama (OOK) FSK modülasyonu ile bütünleştirirken, diğer ikisi değişen bant içi boş alt taşıyıcı tahsisleriyle geleneksel FSK modülasyonuna dayanmaktadır. Bu stratejiler, alıcıda tutarsız algılamayı mümkün kılarak, geri saçılma aygıtından gelen sinyaller için kanal tahmini zorluğunu etkili bir şekilde ele alır. Teorik analiz ve kapsamlı simülasyonlar, önerilen yaklaşımın doğrudan bağlantı girişimini ortadan kaldırarak BC için 30 dB'de 10^{-4} kadar düşük bir bit hata oranına ulaştığını ortaya koymaktadır. Daha ileri araştırmalar, yüksek veri hızları ve düşük güç iletişimi elde etmeyi amaçlayan ortam BC için milimetre dalgası (mmWave) sinyallerinin kullanımını araştırır. Ancak, kanal seyrekliği nedeniyle mmWave frekanslarında sinyallerinin geri saçılma cihazlarına (BD'ler) düzensiz olarak erişebilmesi önemli bir zorluk oluşturmaktadır. Bunu aşmak için, bir ışın alanı mmWave simbiyotik radyo sistemi için verimli bir ışın seçimi yöntemi geliştirilmiştir. Bu yaklaşım, BD'lere tutarlı sinyal erişilebilirliğini sağlarken genel toplam oranı performansını %30'a kadar önemli ölçüde artırır. Bu katkılara ek olarak, tez,

ortaya çıkan 6G teknolojilerine odaklanan iki çalışmayı sunmaktadır: entegre algılama ve iletişim (ISAC) ve görünür ışık iletişimiyle ortogonal olmayan çoklu erişim (NOMA-VLC). ISAC çalışması, kötü amaçlı düğümlerden pilot konum bilgilerini gizleyerek iletişim ve algılama verilerini korumak için güvenli bir pilot tahsis yöntemi sunmaktadır. Alıcının pilot konum tespiti sırasında performans sorunlarını azaltmak için uyarlanabilir bir güç tahsis stratejisi de önerilmiştir. Bu algoritmaların etkinliği, içgörülü sonuçlara yol açan performans değerlendirmeleri aracılığıyla gösterilir. Son olarak, NOMA-VLC araştırması, farklı yüksekliklerdeki kullanıcıları dikkate alarak ve dinamik güç tahsis stratejilerini dahil ederek 3D NOMA-VLC sistemleri için iki yenilikçi kullanıcı eşleştirme şeması önermektedir. Önerilen şemalar, kullanıcı eşleştirmesi ve ortogonal çoklu erişim (OMA) olmadan NOMA'ya kıyasla önemli performans kazanımları göstermektedir. Temel sistem parametreleri analiz edilir ve genel performans üzerindeki etkileri ayrıntılı olarak tartışılır. Bu tez, 6G kablosuz ağların ve daha geniş SRad teknolojisi alanının ilerlemesine katkıda bulunan kapsamlı içgörüler ve yenilikçi çözümler sunar. Bu katkılar, daha sürdürülebilir, verimli ve güvenli kablosuz iletişim sistemleri için yolu açmaktadır.

Anahtar Kelimeler: 6G, simbiyotik radyo, geri saçılım iletişimi, OFDM, FSK, alt taşıyıcı tahsisi, ortam geri saçılım iletişimi, mmWave simbiyotik radyo, ışın seçimi, ışın alanı MIMO, girişim yönetimi, entegre algılama ve iletişim (ISAC), fiziksel katman güvenliği, CSI tabanlı algılama, yerleştirme, 3D VLC-NOMA, kullanıcı eşleştirme, güç tahsisi.

SYMBIOTIC BACKSCATTER COMMUNICATION

ABSTRACT

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The sixth generation (6G) and beyond wireless networks aim to address critical challenges by fostering environmentally sustainable and globally interconnected systems. A key technology enabling 6G is symbiotic radio (SRad), which promotes the sharing of resources among diverse radio systems through symbiotic relationships. Specifically, these considered radio systems are existing wireless systems and passive Internet-of-Things (IoT) devices which rely on backscatter communication (BC). This dissertation provides a comprehensive investigation of SRad technology for symbiotic BC, exploring its fundamental principles, state-of-the-art methodologies, and potential applications. The research begins by examining the core concepts of radio symbiosis, including various types of symbiotic relationships that enable coexistence and efficient resource management among different radio systems. Building upon this foundational understanding, novel techniques are proposed to tackle specific challenges in SRad-enabled BC systems. The initial investigation introduces an orthogonal frequency division multiplexing (OFDM)-based scheme designed to achieve interference-free BC within a symbiotic radio system. Specifically, three frequency shift keying (FSK)-based backscatter modulation schemes are proposed, which shift the primary signal—i.e., the OFDM symbols transmitted from a base station (BS)—in the frequency domain to facilitate information transmission. To maintain orthogonality between the frequency-shifted signals from the backscatter device and the primary signal, the BS empties specific subcarriers within the band. The first scheme integrates on-off keying (OOK) with FSK modulation, while the other two are based on conventional FSK modulation with varying in-band null-subcarrier allocations. These strategies enable non-coherent detection at the receiver, effectively addressing the challenge of channel estimation for signals from a backscatter device. Theoretical analysis and comprehensive simulations reveal that the proposed approach achieves a bit-error rate as low as 10^{-4} at 30 dB for BC by eliminating direct link interference. Further exploration delves into the utilization of incident millimeter-wave (mmWave) signals for ambient BC aimed at achieving high data rates and low-power communication. However, the erratic availability of incident signals to backscatter devices (BDs) at mmWave frequencies, due to channel sparsity, poses a significant challenge. To overcome this, an efficient beam selection method is developed for a beamspace mmWave symbiotic radio system. This approach significantly enhances the overall sum-rate performance by up to 30% while ensuring consistent signal accessibility to BDs. In addition to these contributions, the dissertation presents two studies focused on emerging 6G technologies: integrated sensing and communication (ISAC) and non-orthogonal multiple access with visible light communication (NOMA-

VLC). The ISAC study introduces a secure pilot allocation method to protect communication and sensing data by concealing pilot location information from malicious nodes. An adaptive power allocation strategy is also proposed to mitigate performance issues during the receiver's pilot location detection. The efficacy of these algorithms is demonstrated through performance evaluations, leading to insightful conclusions. Lastly, the NOMA-VLC research proposes two innovative user pairing schemes for 3D NOMA-VLC systems, considering users at different heights and incorporating dynamic power allocation strategies. The proposed schemes show significant performance gains compared to NOMA without user pairing and orthogonal multiple access (OMA). Key system parameters are analyzed, and their impacts on overall performance are discussed in detail. This dissertation offers comprehensive insights and innovative solutions, contributing to the advancement of 6G wireless networks and the broader field of SRad technology. These contributions pave the way for more sustainable, efficient, and secure wireless communication systems.



Keywords: 6G, Symbiotic radio, backscatter communication, OFDM, FSK, subcarrier allocation, ambient backscatter communication, mmWave symbiotic radio, beam selection, beamspace MIMO, interference management, integrated sensing and communication (ISAC), physical layer security, CSI-based sensing, localization, 3D VLC-NOMA, user pairing, power allocation.

CHAPTER 1

1. INTRODUCTION

Nowadays, sixth generation (6G) networks and their application scenarios are under discussion. One key motivation is to develop communication from a societal and humanitarian perspective i.e., designing the communication technologies to improve the quality of life in all aspects [3]–[6]. In this regard, many services and technologies are being proposed under the 6G vision in the literature, such as holographic telepresence, tactile internet, autonomous and teleoperated vehicles, aerial networks, uncoordinated networks and co-existence of radio frequency (RF), and visible light communication (VLC) [7]. These technologies would help in developing a strong communication infrastructure for the smart healthcare system in terms of extreme reliability, ultra-massive connectivity, connection continuity, network scalability, and flexibility for rapid response, allowing monitoring and taking preventive actions in pandemic situations. Physical layer security is another significant technology especially for e-health applications, which is expected to be offered in 6G for making the communication link secure [8]. Moreover, in case of natural disasters, information on population activities, such as mobility, can give insight into the scale and location of the damage.

The fifth-generation (5G) networks are going to offer better services with significant advancement compared to earlier generations. However, there is a need to fill the gaps in security, intelligence, wireless connectivity, energy efficiency, etc., which require the development of new wireless generation networks. Therefore, 6G vision is to utilize communication technologies with intelligence for transforming the world into a secure and fully connected digital society. Aggressive research regarding 6G vision categorizes into (i) large spectrum bandwidth (ii) integrated terrestrial-aerial networks (iii) energy-efficient and communication environment intelligence (iv) holistic security paradigm.

Due to the spectrum scarcity in lower frequency bands, higher frequency bands are proposed to provide communication with very high bandwidth of 6G networks. Additionally, other spectrum resources such as VLC are expected to be used as potential candidates to support the RF spectrum that utilizes commodity lighting infrastructure for high data rate wireless communication, positioning, and localization, especially in the indoor environment. Future wireless networks will not be limited to terrestrial networks, rather they will be expanding to cover the space. Energy efficiency is critical for the Internet-of-Things (IoT) devices; thus, ambient backscatter communication (AmBackCom) provides ultra-low power communication using ambient signals generated from conventional RF systems i.e., FM, TV, WiFi, etc [9]. reconfigurable intelligent surfaces (RIS) is a passive or semi-passive surface, containing antenna elements to provide an intelligent communication environment, along with improved coverage and capacity via customizing radio signals intelligently before reflection [7]. Apart from cryptography-based security, 6G will provide a new solution to the security paradigm with the inclusion of physical layer security (PLS) and quantum cryptography. In addition to security, the privacy of the confidential data can be maintained using backscatter communications (BC) algorithms. These techniques will solve communication security and users' privacy challenges of the future systems [10]–[12].

- Capacity enhancement: Increasing number of users and high data rate demands are pushing the network operators to focus on the planning and development of network infrastructure that can meet high capacity enhancement demands. For example, a network operator in Turkey has recorded an increase in data usage up to 35% since the beginning of coronavirus disease-2019 (COVID-19) [13]. To meet the high capacity needs, current RF communication infrastructure based on low-frequency bands is insufficient. Therefore, the utilization of high-frequency bands and ultra-massive multiple-input multiple-output (MIMO) should be implemented to improve the overall capacity of the network. Alternatively, indoor capacity enhancement can be realized through VLC [14]. Cognitive radio with AmBackCom technology also known as symbiotic radio can support a large number of low-power IoT devices, which means the IoT devices can take advantage of both the cognitive radios and AmBackCom for spectrum sharing and ultra-low power communication, respectively. In this way, connectivity enhancement and energy efficiency can be

achieved, simultaneously.

- Coverage enhancement: Seamless coverage and connectivity is required is another 6G enabler that has not been met by the earlier generations of wireless networks. Network coverage in RF sensitive areas such as hospitals is limited because of complex physical structure. Currently, Wi-Fi networks are deployed for communication within the hospital. However, severe electromagnetic interference issues restrict coverage in sensitive areas. To provide coverage in such areas, AmBackCom with RIS is expected to be deployed at certain places i.e., walls, ceiling, etc., in the hospitals for enhancing coverage as well as protecting RF restricted areas [15], [16].
- Accurate positioning and localization: Indoor and outdoor positioning is expected in the 6G wireless networks for industrial revolution and autonomous driving. Outdoor positioning and localization can be achieved through the global positioning system (GPS). However, GPS cannot provide accurate indoor positioning due to the complex electromagnetic propagation environment [4]. Indoor positioning and localization cannot be achieved through GPS due to signal loss in indoor environments. Some critical applications of indoor positioning and localization include automated guided vehicles, elderly people activities, and remote surgery. Particularly in remote surgery, highly precise localization and positioning are crucial. To achieve a high level of precision, 6G systems are expected to support integrated sensing and communication (ISAC), where the sensing capabilities will be integrated into the existing wireless systems.
- Ensuring extreme security and privacy: Security and privacy are also among the top 6G requirements. For instance, end-to-end link security is mandatory, during remote surgery because any attack can alter the information going to the robotic apparatus and threaten the patient's life. Cryptography-based techniques are currently being used for security and privacy concerns of the healthcare system. However, these algorithms have high complexity. Aside from cryptography based techniques, physical layer security has been developed to make the communication link secure from jamming, spoofing, and eavesdropping. PLS techniques, including channel-based adaptation and key generation, cross-layer security, etc., can be applied to

improve communication security [11], [17]. Channel and hardware-based authentication techniques can also be used to avoid unauthorized access to the patient's critical information [18]. RIS and meta-surfaces-based solutions can be developed for securing the communication data, which can filter and manipulate the signals against jamming and spoofing attacks [19], [20].

Considering the rapid deployment of the IoT, energy efficiency is critical for 6G technologies, especially for low-power and low-cost devices. The efficient energy harvesting and utilization protocols are highly desired to support the longevity of low-power sensors and devices particularly in industry, healthcare, and disaster scenarios where the energy resources are limited.

1.1. Symbiotic Backscatter Communication

6G technology has the potential to revolutionize communication networks by connecting the world through sustainable means, to improve quality of life [4]. The rapid advancement of IoT is driving this change, as it is projected that by 2030 the number of connected devices will reach 125 billion [21], exacerbating the issue of spectrum scarcity. In addition, the majority of IoT devices are energy-constrained and designed to have a long lifespan. One of the major power-consuming components of these devices is the communication radio, which requires energy-intensive components such as amplifiers and oscillators. To address the challenges of spectrum scarcity and power consumption in IoT devices, a new class of IoT known as passive IoT has been proposed in 3rd generation partnership project (3GPP) technical studies [22]. The goal of this new class of IoT is to design and implement ultra-low power passive communication technologies to enhance spectrum efficiency and support the deployment of large numbers of IoT devices and sensors, using the existing wireless infrastructure.

Backscatter communication (BC) is an emerging candidate for ultra-low power wireless communication, in which backscatter technology is used to modulate and reflect incident signals transmitted by RF source for information transfer [23]. This approach eliminates the need for energy-intensive and costly electronic components for RF signal generation at the device, thus congruent with the objective of passive IoT to reduce power consumption and enhance the longevity of IoT devices. The signal required for BC can be sourced

from a dedicated signal generator or an ambient RF source such as the base station of cellular, television (TV), or radio broadcast systems. While the use of a dedicated signal generator has been widely adopted in radio frequency identification (RFID) technology due to its low power and low-cost advantages at the device level, the deployment costs of such systems can be a major limitation to scalability. As the network grows, more dedicated signal sources are required, leading to increased costs [24].

The utilization of ambient RF signals for BC has been the subject of extensive investigation as a means of surmounting the limitations of RFID and establishing an alternative technology that is known as AmBackCom [9]. Interestingly, it eliminates the need for dedicated RF source deployment by enabling BC to use the signals from wireless systems in the surrounding environment. This approach not only reduces the cost and complexity of deployment but also allows for greater scalability and flexibility regarding the available signal sources, which can be sourced from existing infrastructure, rather than requiring dedicated RF sources [25]. For instance, in [26], researchers have demonstrated information transfer between two backscatter devices (BDs) by re-modulating and backscattering the incident signals emitted by a nearby TV station. While AmBackCom has the potential to enhance overall radio resource utilization and spectral efficiency, its performance is often hindered by interference from strong direct-path signals at the receiver [27]. To address this issue, various approaches have been proposed, such as shifting the incident signal to a different frequency band [28]–[31], exploiting the cyclical features of the source signal [1], [32]–[34], and utilizing multiple antenna receivers for interference suppression [35]–[37]. However, it should be noted that these methods tend to come with a trade-off, such as increased spectrum utilization or receiver complexity, which can limit the practical applications of AmBackCom. To overcome these challenges, one potential solution is to enable cooperative coexistence between passive devices and existing wireless systems, through radio resource sharing. This approach can help to mitigate the impact of increased spectrum utilization and receiver complexity, while also enabling more efficient use of available resources and increasing the scalability of the system.

In traditional coexistence methods, devices from different systems independently share radio resources by transmitting their own RF signals. However, in the case of AmBackCom-assisted passive IoT, devices depend on the signals emitted by other devices and RF

sources in the environment. This type of resource sharing is similar to symbiotic relationships in biology, where different species form associations to share resources such as food, shelter, and protection. These associations, known as symbiosis, can be either obligatory or facultative, depending on the degree of mutual dependence between the organisms [38]. In facultative symbiosis, two organisms can survive independently but also choose to share resources. In contrast, in obligatory symbiosis, one organism is dependent on the other and cannot survive independently. In both cases, the resource sharing between the organisms can range from mutualism, where both organisms benefit, to competition, where each organism primarily benefits itself [39]. The concept of symbiosis can also be applied to the coexistence of passive devices and existing wireless systems. In this scenario, a symbiotic radio (SR) paradigm has been introduced, where the wireless systems are designed to support the passive devices with their radio resources for communication while still performing their primary functions. This allows for a mutually beneficial relationship, where both the passive devices and the existing wireless systems can thrive [40].

This work contributes to the literature with the following contributions

- This work provides a comprehensive overview of SR systems for coexistence and resource sharing of passive and active radio systems.
- The study covers fundamental concepts and state-of-the-art methodologies and examines the integration of advanced technologies such as MIMO, RIS, full-duplex communication, and active load.
- It also presents the potential applications of SR in 6G wireless networks for various industries, including healthcare, transportation, agriculture, manufacturing, and logistics.
- The work also identifies the important challenges in developing and implementing SR for passive IoT and highlights key areas for future research in this field.

1.1.1. Study I: Interference-free backscatter communications for OFDM-based symbiotic radio

Next-generation wireless networks are expected to be energy-efficient and sustainable by supporting use cases that involve IoT devices with very low power consumption [41]. In this direction, passive and ambient IoT devices were studied in the 5G New Radio Release 18 and Release 19 [42]. The ambient devices can be battery-less or have a battery and operate with the harvested energy from radio waves or other sources [43]. Under such limitations, modulation techniques relying on active components may not be feasible for communication due to their high power consumption, leading to the BC paradigm that is widely used in RFID systems for low-power information transfer [25], [44]–[47]. With BC, the data is transmitted by modulating the response of the antenna to the incoming RF signals. In the RFID systems, a dedicated RF signal exciter is deployed to transmit unmodulated carrier signals for BC. As the coverage area and the number of tags (i.e., BD) increases, more carrier exciters are needed to serve all the BDs in the environment. Considering the limitations of RFID systems, an ambient BC is developed in which a BD utilizes the signals transmitted by existing wireless systems as a carrier for data transmission [26]. The ambient BC eliminates the need for a dedicated device for carrier signal transmission and opens a new era of BC. However, the reliability of ambient BC is very low due to the interference between the unknown strong RF and weak backscatter signal at the intended receiver (Rx). In this study, we address this interference challenge with the concept of SR by designing the incoming RF signals.

The idea of SR for BC in passive IoT was first thoroughly investigated in [48], where the BD was considered a parasitic entity in a primary system, e.g., an existing wireless system. In contrast to ambient BC, BD is regarded as a component of the primary system in SR and shares radio resources with the primary user, with the primary transmitter being designed to support its requirements. In [49], the authors show that SR can exploit the benefits of both ambient BC and cognitive radio since SR can have spectrum sharing between primary users and BD. Also, it can provide highly reliable BC through a joint decoder at the receiver. The authors in [50] and [51] analyze the mutualistic relationship between BD and a primary system in SR, where both systems benefit each other by sharing the radio resource. Some other SR-based relationships between low-power IoT devices and existing

wireless systems are explored in [52]–[56]. These earlier studies suggest that by cooperative resource sharing and system design, SR can avoid the need for new infrastructure to support BC and may allow the network to overcome the coexistence issues. Also, SR can mitigate interference issues between the primary and backscatter signals. Since most wireless systems, including cellular and Wi-Fi networks, utilize orthogonal frequency division multiplexing (OFDM) as their standard waveform, an opportunity arises to design the OFDM signal in SR to address the interference issue in BC concerning ambient IoT devices.

In this work, we propose an OFDM-based scheme in the context of SR. Our contributions can be listed as follows:

- We design the OFDM signal transmitted from a base station (BS) such that it is always orthogonal to the backscatter signal within the band. To this end, we utilize frequency-shift keying (FSK) modulations at the BD and shift the data symbols to the subcarriers dedicated to BD in the frequency domain. As a result, the primary user's and BD's data are received on separate subcarriers within the received OFDM signal, and the interference originating from the direct link is circumvented.
- By extending our preliminary work in [57], we analyze and compare the on-off keying (OOK) modulation with FSK modulation schemes for BC. The proposed OOK waveform shifts the data symbols to the subcarriers dedicated to BD during on period. We provide the theoretical derivation for error-rate based on **Lemma 3.1.1**. We evaluate the retransmission probability of the proposed schemes based on the RFID Gen2 standard 5-bit cyclic redundancy check (CRC) encoder/decoder.
- We show the efficacy of the non-coherent detector in receiving BD's data at Rx. We analyze the error-rate performance of the non-coherent detector analytically and assess the scheme via comprehensive simulations. We also demonstrate the impact of hardware impairments, specifically carrier frequency offset (CFO), on the efficiency of FSK-based BC schemes.

1.1.2. Study II: The mmWave SRad system

We are witnessing great technological strides in the widespread adoption of IoT. As a result, more and more devices are going online, and the demand for the electromagnetic

spectrum is now more than ever. In recent years, we have witnessed the inclusion of IoT in various systems such as healthcare, education, industry, agriculture, transportation, and so on [58]. Until now, IoT devices are supposed to have low data rates and energy efficiency requirements. However, with the development of extended reality, a high data rate has become another critical requirement, particularly in the case of wearable devices, e.g., XR glasses [59].

AmBackCom is considered a revolutionary energy-efficient technology for sixth-generation (6G) and beyond wireless systems [7]. Unlike conventional radio systems, AmBackCom system uses ambient RF signals of existing wireless systems as a carrier for communication. Although AmBackCom system can substantially enhance energy efficiency, its dependency on ambient signals poses a great question regarding its reliability. Recently, a SR is proposed to enhance the reliability of AmBackCom through a cooperative resource sharing with existing wireless systems [56].

A beamspace MIMO system has been proposed to exploit the channel sparsity at millimeter wave (mmWave) frequency. In addition, different beam-selection methods are applied to select the beams with high path gains to reduce the number of RF chains and enhance the energy efficiency gains [60], [61]. For instance, a maximum magnitude (MM) beam-selection method captures the maximum fraction of power from the channel by selecting dominant beams and leaving the weak ones. However, the conventional beam selection schemes are not suitable in the case of the mmWave AmBackCom system since BDs may exist in beams with low path gains and be out of coverage.

In this work, our main contributions to the literature for the development of mmWave SR are as follows,

- To the best of the authors' knowledge, this is the first study that addresses the RF signal inaccessibility issue for AmBackCom in the sparse mmWave system. In particular, we develop a SR to enable cooperation among AmBackCom and existing mmWave systems to ensure signal accessibility to BDs.
- This work leverages the beamspace MIMO and proposes a beam selection scheme considering BDs as a part of the mmWave system to enhance the sum-rate performance of SR.

- Assuming perfect channel-state-information (CSI), the performance of the proposed scheme is compared with the conventional MM based beam selection scheme, showing up to 30% sum-rate enhancement with the beam-selection and the selection of the paths with BDs and ordinary scatterers.

In addition to the contributions mentioned above, our results can be used as a benchmark for future studies.

1.2. Emerging Technologies for Beyond 5G

1.2.1. Study III: Secure pilot allocation for integrated sensing and communication

6G wireless networks are anticipated to have significantly more pronounced sensing needs compared to earlier generations [62]. This is realizable for applications such as remote healthcare, the Internet of Things (IoT), and autonomous driving. To facilitate such applications, ISAC is being explored as a potential candidate, where connected nodes may intelligently sense and image the surrounding environment using communication radio frequency signals. The rapid development of ISAC-based algorithms and technologies has been witnessed in the past few years, especially for environment sensing and monitoring human activities [63].

Although there are many ways to monitor human activities, the common and easy method based on ISAC is the CSI based sensing [64]. Therein CSI acquired from the pilots (i.e., pilot symbols known to receiver) transmitted in the communication signal is used for sensing [65]. Anyone can perform CSI-based sensing with pilot symbols and location information. Even a malicious node can use it to sense the surroundings and extract information about a specific target [66]. Since the proliferation of ISAC will raise severe security and privacy concerns, developing a new security mechanism for securing ISAC is highly desired.

One way to secure ISAC is to make the signal useless for malicious nodes at the physical layer [67]. Different physical channel characteristics such as channel randomization, interference, fading, noise, and dispersion have been widely explored to enhance physical layer security [11]. Most of these techniques aim to secure the data symbols, for example, through channel coding, channel-based adaptation, and artificial signal injection [66]. A

system can provide physical layer security for sensing and communication information if the pilot symbols are secured instead of data symbols. A few studies in the literature have endeavored to secure the pilot information to enhance physical layer security [68]–[70].

The work in [68] proposes a mechanism for the random pilot allocation based on the codebook to hide the pilot location from the malicious node. Initially, the random pilot codebook is generated from the compressive channel sensing measurement matrix (i.e., partial Fourier transform matrix). Additionally, the authors in [68] propose an instantaneous CSI-based key generation mechanism to encrypt the random pilot codebook. However, this scheme requires random pilot codebook generation and sharing among legitimate nodes at the beginning of pilot allocation. Besides, the random pilot codebook has a limited number of patterns that a malicious node can estimate through extensive simulations. In [69], the amplitude and phase of the pilot symbol are manipulated based on the shared CSI between the legitimate nodes to provide data security. The drawback of this strategy is that since everyone knows the pilots' locations, the illegitimate node can identify them through correlation. In [70], an anti-eavesdropping optimal pilot design is proposed based on the pilot signal's mutual information observed by users and mean square error (MSE) of channels estimation for each user. To obtain the optimal pilot design and prevent eavesdropping, users must have full-duplex capabilities, and they are required to measure CSI constantly, which limits the proposed approach's applicability.

Although the approaches mentioned above may provide security at the physical layer manipulating the data and pilot symbols information, none of these studies considered securing the pilot location. Furthermore, in earlier research, the receiver must have access to CSI. In this study, we propose a method to secure pilot locations with an adaptive pilot allocation based on the instantaneous channel between the legitimate nodes to provide security instead of generating a random pilot codebook, manipulating pilot symbols, or proposing the optimal pilot design. Unlike the studies in the literature, the proposed scheme does not require the availability of CSI at the receiver. Our main contributions to the development of secure ISAC are as follows:

- A secure pilot allocation mechanism in OFDM system for ISAC.
- An adaptive power allocation (APwA) mechanism to overcome the system's performance degradation occurs due to the erroneous pilot detection at the receiver.

- Extensive simulations are done to analyze the performance of the proposed method in terms of pilot location error rate (PLER) and bit-error-rate (BER) for adaptive pilot allocation, and MSE for channel estimation considering least square estimator (LSE).
- Simulation results validate that the adaptive pilot allocation with APwA enhances the physical layer security for ISAC by significantly degrading the malicious node's pilot location detection and channel estimation capabilities compared to the legitimate node.

1.2.2. Study IV: User pairing and power allocation strategies for 3D VLC-NOMA systems

Visible light communication (VLC) is envisaged as a complementary technology to radio frequency (RF) communication in providing high-speed wireless communication to indoor users [71]. VLC not only uses the unlicensed spectrum but also provides unlimited utilization factor with high security, ultra-high bandwidth, and low energy consumption. Although in visible light spectrum huge bandwidth is available, light-emitting diodes (LED) can support only tens of Mega-Hertz (MHz) of modulation bandwidth, which constrains the VLC system to low capacity [72].

Multiple access schemes play an important role in increasing the capacity and spectral efficiency of the system. Non-orthogonal multiple access (NOMA), a dominating multiple access scheme for next-generation wireless networks, is being considered for deployment in terrestrial and unmanned aerial vehicles (UAV) with the aim to guarantee massive connectivity with spectral efficiency and ultra-reliable low latency communication (uRLLC) [73]. Furthermore, NOMA is also considered as a potential candidate for VLC to offer high spectral efficiency and capacity gains [74]. These gains can be achieved by allowing multiple users to share the same time and frequency resources in the power or code domain. Particularly, in power-domain NOMA (PD-NOMA), signals of different users are superimposed with different power levels and successive interference cancellation (SIC) is applied at the receiver to recover the data from the received signal. If the channel gain difference between superposed signals is low, the decoding performance of SIC decreases. Therefore, in order to get better SIC performance, users with high channel gain differences are paired together, which requires smart user pairing schemes [75].

PD-NOMA faces several challenges in RF communication due to the following reasons: a large number of users, imperfect channel state information (CSI), and low signal-to-noise ratio (SNR). However, NOMA can offer better gains in the VLC scenario due to small cell size, availability of perfect CSI at the transmitter, and high SNR values [76].

Performance of NOMA in VLC systems has been investigated under various aspects [76]–[78]. Performance comparison of orthogonal multiple access (OMA) and NOMA in the VLC system is given in [77] to ensure higher throughput and fairness gains. As power allocation and interference cancellation are critical in NOMA, a comparison of gain ratio power allocation (GRPA) versus static power allocation is investigated for the VLC-NOMA system in [76] and it is shown that bit error rate (BER) can be improved from the combination of NOMA and VLC. Likewise, in [78] VLC-NOMA is investigated in terms of error rate assuming both perfect and imperfect CSI availability. Furthermore, it is shown in [77], [79] that an efficient user pairing can significantly improve the ergodic capacity and user sum rate in NOMA systems. Different user grouping approaches are proposed in [80] for VLC-NOMA systems. However, the study on 3D VLC-NOMA scenarios considering the users' deployment at different heights has not been studied so far. Specifically, the aforementioned works consider the unrealistic case of all users being located at the same height, which is not the most practical case. Therefore, considering the 3D deployment of users is more appealing from a practical perspective and provides new insights for VLC-NOMA system performance in realistic scenarios.

In this work, our main contributions to the literature for the development of VLC systems are as follows:

- To the best of the authors' knowledge, this is the first study considering user pairing schemes for 3D VLC-NOMA systems.
- This work leverages fractional transmit power allocation (FTPA) and improved power-law strategy (IPLS) methodologies to enhance the user pairing performance.
- Performance of the proposed schemes is compared with the conventional OMA and NOMA without pairing (NOMA-WP) schemes, showing 17 % improvement in the average user data rate (AUDR) compared to the latter.

In addition to the above-mentioned contributions, our results can be used as a benchmark.

CHAPTER 2

2. THEORETICAL PART

2.1. Background of Symbiotic Radio

The 6G technology has the potential to revolutionize communication networks by connecting the world through sustainable means, to improve quality of life [4]. The rapid advancement of IoT is driving this change, as it is projected that by 2030 the number of connected devices will reach 125 billion [21], exacerbating the issue of spectrum scarcity. In addition, the majority of IoT devices are energy-constrained and designed to have a long lifespan. One of the major power-consuming components of these devices is the communication radio, which requires energy-intensive components such as amplifiers and oscillators. To address the challenges of spectrum scarcity and power consumption in IoT devices, a new class of IoT known as passive IoT has been proposed in 3GPP technical studies [22]. The goal of this new class of IoT is to design and implement ultra-low power passive communication technologies to enhance spectrum efficiency and support the deployment of large numbers of IoT devices and sensors, using the existing wireless infrastructure.

BC is an emerging candidate for ultra-low power wireless communication, in which backscatter technology is used to modulate and reflect incident signals transmitted by RF source for information transfer [23]. This approach eliminates the need for energy-intensive and costly electronic components for RF signal generation at the device, thus congruent with the objective of passive IoT to reduce power consumption and enhance the longevity of IoT devices. The signal required for BC can be sourced from a dedicated signal generator or an ambient RF source such as the base station of cellular, TV, or radio broadcast systems. While the use of a dedicated signal generator has been widely adopted in RFID technology due to its low power and low-cost advantages at the device level, the

deployment costs of such systems can be a major limitation to scalability. This is because as the network grows, more dedicated signal sources are required, leading to increased costs [24].

The utilization of ambient RF signals for BC has been the subject of extensive investigation as a means of surmounting the limitations of RFID and establishing an alternative technology that is known as AmBackCom [9]. Interestingly, it eliminates the need for dedicated RF source deployment by enabling BC to use the signals from wireless systems in the surrounding environment. This approach not only reduces the cost and complexity of deployment but also allows for greater scalability and flexibility in terms of the available signal sources, which can be sourced from existing infrastructure, rather than requiring dedicated RF sources [25]. For instance, in [26], researchers have demonstrated information transfer between two BDs by re-modulating and backscattering the incident signals emitted by a nearby TV station. While AmBackCom has the potential to enhance overall radio resource utilization and spectral efficiency, its performance is often hindered by interference from strong direct-path signals at the receiver [27]. To address this issue, various approaches have been proposed, such as shifting the incident signal to a different frequency band [28]–[31], exploiting the cyclical features of the source signal [1], [32]–[34], and utilizing multiple antenna receivers for interference suppression [35]–[37]. However, it should be noted that these methods tend to come with a trade-off, such as increased spectrum utilization or receiver complexity, which can limit the practical applications of AmBackCom. To overcome these challenges, one potential solution is to enable cooperative coexistence between passive devices and existing wireless systems, through radio resource sharing. This approach can help to mitigate the impact of increased spectrum utilization and receiver complexity, while also enabling more efficient use of available resources and increasing the scalability of the system.

In traditional coexistence methods, devices from different systems independently share radio resources by transmitting their own RF signals. However, in the case of AmBackCom-assisted passive IoT, devices depend on the signals emitted by other devices and RF sources in the environment. This type of resource sharing is similar to symbiotic relationships in biology, where different species form associations to share resources such as food, shelter, and protection. These associations, known as symbiosis, can be either obligatory or facultative, depending on the degree of mutual dependence between the or-

ganisms [38]. In facultative symbiosis, two organisms can survive independently but also choose to share resources. In contrast, in obligatory symbiosis, one organism is dependent on the other and cannot survive independently. In both cases, the resource sharing between the organisms can range from mutualism, where both organisms benefit, to competition, where each organism primarily benefits itself [39]. The concept of symbiosis can also be applied to the coexistence of passive devices and existing wireless systems. In this scenario, a SR paradigm has been introduced, where the wireless systems are designed to support the passive devices with their radio resources for communication while still performing their primary functions. This allows for a mutually beneficial relationship, where both the passive devices and the existing wireless systems can thrive [48]. To the best of the author's knowledge, no previous survey has presented a systematic summary of SR systems. In this work, we provide a comprehensive overview of SR systems for coexistence and resource sharing of passive and active radio systems. We cover fundamental concepts and state-of-the-art methodologies and examines the integration of advanced technologies such as MIMO, RIS, full-duplex communication, and active load. We also presents the potential applications of SR in 6G wireless networks for various industries, including healthcare, transportation, agriculture, manufacturing, and logistics. The work also highlights the important challenges in developing and implementing SR for passive IoT and highlights key areas for future research in this field.

2.1.1. Basics of symbiotic radio paradigm

In this section, we present a general classification of radio systems and revisit the traditional resource-sharing methods with their limitations. We then describe the origination of radio symbiosis and its two variants. Lastly, we discuss the resource-sharing methods based on symbiotic relationships in the SR system.

2.1.1.1. Classification of radio systems

The radio systems can be categorized into active and passive types based on the RF signal generation requirement at the device. Active radio systems generate an RF signal at the device for information transfer and extract the information from the transmitted signal at the receiver. In a passive radio system, there is no need for active RF signal generation at the device. Instead, external signals are reflected/backscattered for information transfer.

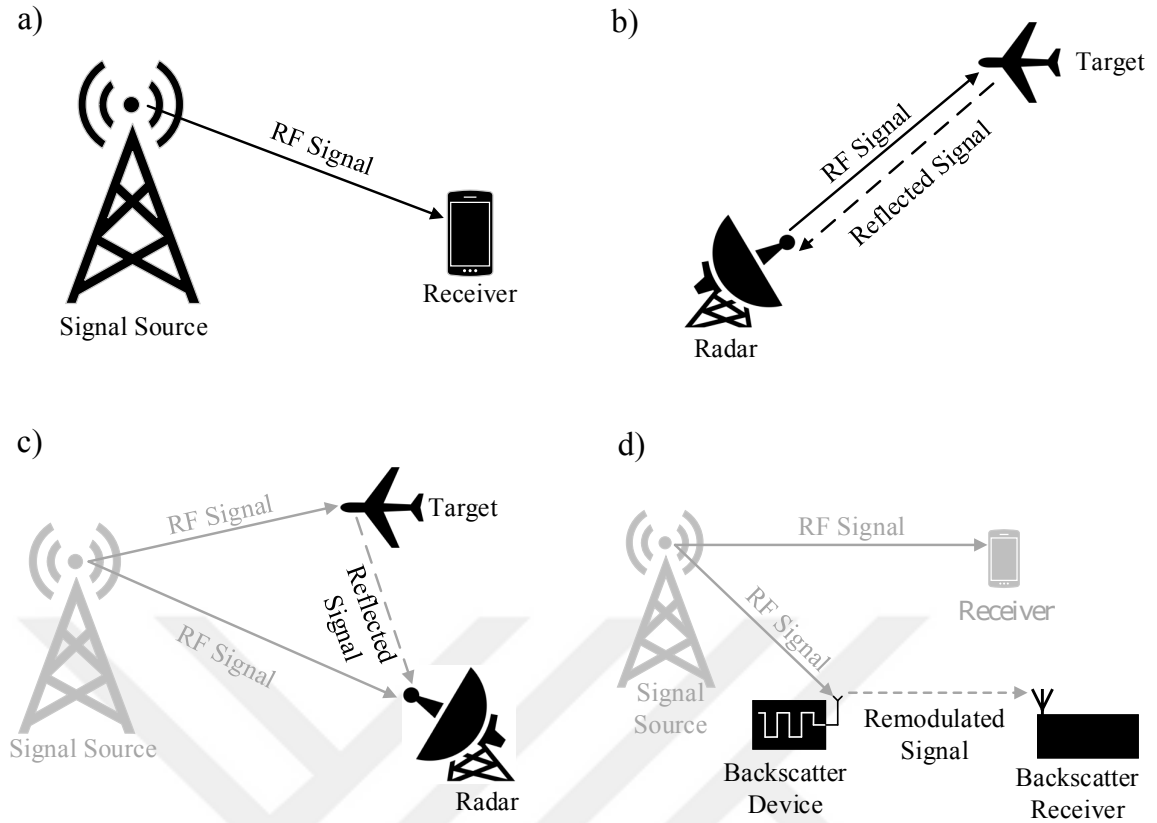


Figure 2.1: Classification of radio systems: **a)** active communication system, **b)** active Radar/Sensing system, **c)** passive Radar system, and **d)** passive communication system.

The receiver processes the reflected/backscattered signals for information extraction.

A simple active radio system consists of two parts; a transmitter equipped with a dedicated signal source and a receiver. The transmitter sends the information by transmitting a radio signal in the air, where the receiver detects the signal and extracts the information. The radio signal can be an information-modulated signal or a continuous wave signal depending on whether the system is for communication or radio detection and ranging (RADAR).

Figure 2.1a shows an active communication system with a transmitter sending a signal to the receiver for information transfer. On the other hand, **Figure 2.1b** shows an active RADAR system, which contains a transceiver that radiates the radio wave in the air to detect the presence of the target and its related information. The common examples of active communication systems are TV, cellular, Bluetooth, and wireless fidelity (WiFi) while active RADAR systems are mapping, earth monitoring, and navigation.

The use of passive radios based on the backscattering principle can be dated back to the development of passive RADAR technology used in World War II. A passive radio reflector was mounted on the allied aircraft to backscatter the signal transmitted by the home

RADAR with better illumination than enemy aircraft [81]. Afterward, Harry Stockman proposed the idea of reflected power communication in 1948, which contributed to the development of RFID technologies [82]. However, a completely passive RFID system that is operated and controlled by the illuminated signals was demonstrated by Alfred Koelle in 1975 [83]. Since then, RFID technology has been widely used in various fields such as medical, business, logistics, and so on [84]. Passive radio systems are used for communication in simple low-power devices and sensors and for RADAR in military applications. A passive RADAR system is shown in **Figure 2.1c**, where the receiver utilizes the radio waves radiated by ambient radio systems for target detection instead of generating a signal [85]. On the other hand, in a passive communication such as BC, a BD or tag re-modulates the ambient RF signals to send the information to a receiver as shown in **Figure 2.1d**. The ambient RF signal source can be any wireless system including a tiny Bluetooth device, a large satellite base station placed in space, and every system in between [52], [86]–[88].

2.1.1.2. Radio spectrum utilization

Spectrum scarcity has been an issue since the advent of radio transmissions since the time of Guglielmo Marconi when his transatlantic transmission occupied the entire radio spectrum. This problem became more pronounced with more people/companies trying to send their transmissions, resulting in debilitating interference [89]. This problem can be looked at from two perspectives: policy for spectrum allocation/accessing and secondly from the technological perspective, aimed at improving spectrum utilization. Different mechanisms for existing radio spectrum utilization are shown in **Figure 2.2**.

In general, two approaches are considered for spectrum access, i.e., static spectrum access (SSA) and dynamic spectrum access (DSA). The SSA is categorized into licensed, rule-based, or unlicensed access. The exclusive licensing strategy has served cellular networks until the recent development of IoT and the proliferation of wireless devices, which needs the spectrum in abundance more than ever before [90]. In rule-based access, certain conditions must be satisfied for accessing the radio spectrum, such as fee payment, transmit power levels, and unoccupied channels. Lastly, the license-exempt or unlicensed access is initiated by the United States Federal Communication Commission (FCC) in the Industrial Scientific and Medical (ISM) bands, which allows every technology to access

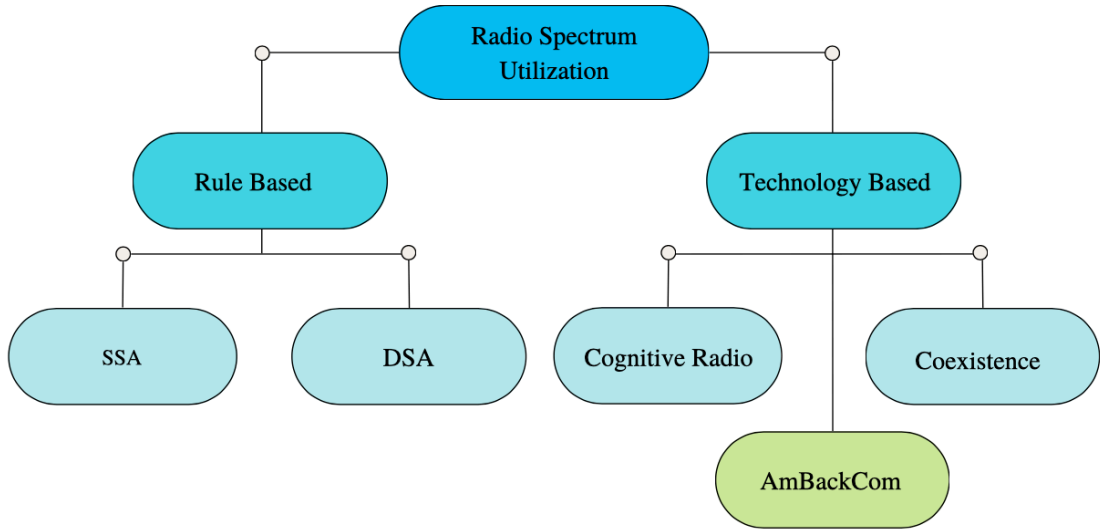


Figure 2.2: Conventional methods for radio spectrum utilization.

the spectrum with equal rights under some basic regulations [91]. On the other hand, DSA provides more flexible spectrum usage methods than SSA to improve spectrum efficiency. It preserves the rights of exclusive use for licensees and permits them to trade and sell spectrum. Besides, dynamic spectrum allocation can be performed to assign spectrum based on the traffic statistics of a particular service to enhance spectrum efficiency [92]. These regulations and allocations may vary between countries according to their legislative bodies, geo-locations, operating conditions, and technological developments; however, the common objective is to achieve the optimum utilization and to overcome the shortfall of spectrum resources [93].

From a technological perspective, different approaches have been considered to accommodate the upcoming surge of IoT devices and high spectrum demands, including allocation of new bands (i.e., mmWave and terahertz (THz)) [94], re-allocation of legacy licensed spectrum bands [95], cognitive radio (CR) [96]–[99], and the coexistence of wireless technologies [100]–[102]. The first two approaches require either innovations, technological enhancements, transfer of property rights, or clearing the existing users, which are exorbitant and time-consuming [95]. CR is a more convenient approach than the former ones in terms of cost, complexity, and enhancing the spectrum efficiency of under-utilized bands, where the number of users using the spectrum is less than the available resources [103]. In this case, CR users share the under-utilized part of the spectrum as secondary users

and enhance the spectrum utilization [104]. However, CR systems can create unavoidable interference to the primary systems if not operated under defined regulations. Due to the interference concerns of CRs, their adoption in real-time applications is limited so far [39]. Besides the CR approach, the coexistence of technologies is considered another vital solution to overcome the spectrum scarcity issue, where different wireless systems can share and access the resources with minimal interference. Several spectrum-sharing approaches have been proposed in the literature for the coexistence of systems such as WiFi and TV in TV white space (TVWS) [104]–[106], integrated non-terrestrial and satellite [107], WiFi and long-term-evolution (LTE) in the unlicensed 5-GHz band [108], narrow band IoT and LTE [58], and communication and RADAR [109]. The coexistence of different wireless systems has been a successful approach for efficient spectrum utilization; however, resource sharing among different wireless systems brings major interference issues.

To support low-power devices, AmBackCom has become popular due to its ability to improve overall spectral efficiency without additional energy or infrastructure costs, in which the communication device utilizes the resources of existing wireless systems in a passive manner [26]. Unlike earlier co-existing systems, dedicated infrastructure and resource allocation are not required for AmBackCom systems [25]. One of the main advantages of this technology lies in its passive way of spectrum sharing without causing significant interference, which can enhance the spectral efficiency of the existing wireless system. Furthermore, it can work with the current spectrum-sharing approaches. For instance, authors in [49] proposed a technique named cognitive backscattering to improve spectrum utilization together with energy efficiency by combining the advantages of CR and AmBackCom. Different from the conventional coexistence of wireless systems where two systems independently share the spectrum, in this technique, backscattering systems can share both the unlicensed spectrum and licensed spectrum without creating significant interference. However, the backscattering system faces strong interference because of the absence of coordination with the existing wireless systems. As a result, the performance of AmBackCom is limited by interference [27]. Although coexistence mechanisms have been mentioned sporadically in the literature [49], [58], [91], [104]–[112], we need a general framework that can define other possible means of coexistence and coordination between active and passive radio systems.

2.1.1.3. Radio symbiosis

A natural ecosystem consists of two components, namely biotic and abiotic. Biotic components include all living organisms such as animals, plants, bacteria, etc., and abiotic components refer to non-living physical resources that affect the ecosystem, such as water, soil, minerals, etc. Multiple biotic components live together in a biological ecosystem and have different associations while sharing physical resources for survival or facultative. In 1879, a pathologist named Anton de Bary coined the term symbiosis, which means living together for interspecific associations or interactions among dissimilar organisms [113]. He defines symbiosis as “interspecific associations, or symbioses, a phenomenon in which two different species of organisms depend on each other for food, shelter, or protection.” The organism that takes part in the symbiosis is called a symbiont. Symbiotic relationships define how two or more symbionts interact for resource sharing. The symbiosis can be facultative and obligatory as per the dependence of the symbionts on each other. If one or two symbionts depend entirely on each other and cannot survive without symbiosis, this type is called obligatory symbiosis. On the other hand, if both symbionts can survive independently and engage in symbiosis, this type of symbiosis is termed facultative or optional symbiosis. Symbionts can have different symbiotic relationships to achieve common or individual objectives. The possible symbiotic relationships include but are not limited to mutualism, commensalism, parasitism, and competition [114].

The radio ecosystem is somehow not different than the biological ecosystem. The radio resources and systems are similar to the abiotic and biotic components. The radio systems utilize the radio resources such as time, frequency, and space, to perform their functionalities, e.g., communication, and RADAR. The radio ecosystem evolves rapidly with the proliferation of wireless applications. Yet, the radio resources, particularly the frequency spectrum, are limited and insufficient to accommodate the needs of radio systems. Different radio systems can engage in symbiosis to meet the radio resource requirements for intelligent radio resource sharing. Radio symbiosis is analogous to biological symbiosis, where two or more radio systems have inter-specific associations and interactions for sharing resources. The radio system that is developed from symbiosis is known as an SR system. In addition, radio symbiosis can be obligatory or facultative according to the dependencies of radio systems. In facultative symbiosis, both systems are active and share

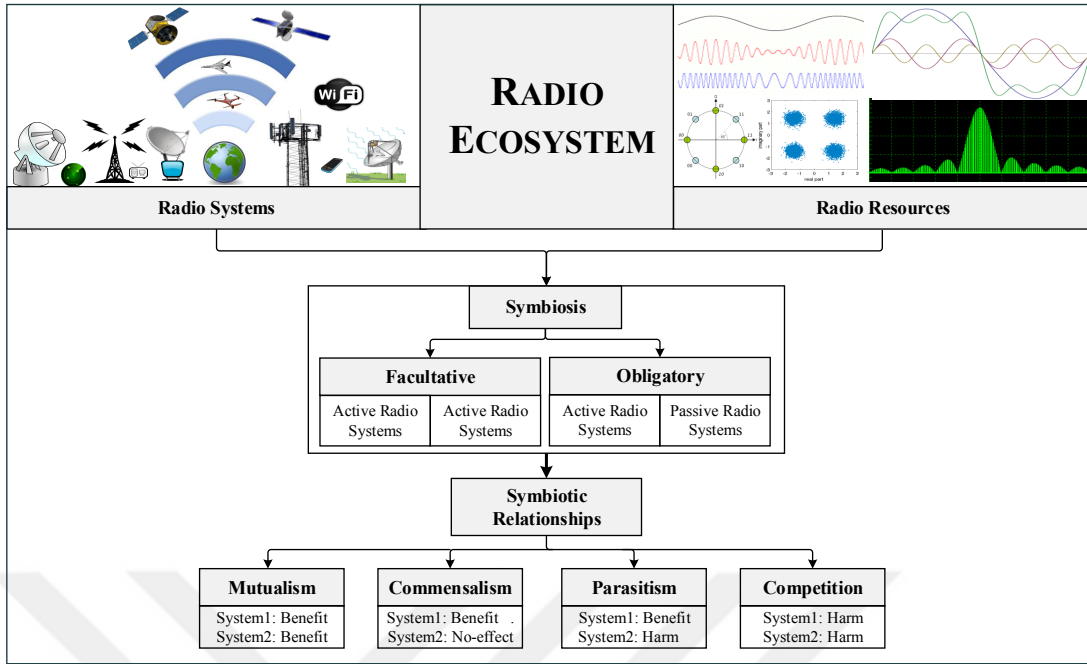


Figure 2.3: Symbiosis in the radio ecosystem.

the resources, even though they do not depend on each other e.g., LTE and WiFi. On the other hand, in obligatory symbiosis, one radio system is passive and the other is active and both share the same resources, where the passive radio system depends on the resources of the active radio system e.g., passive IoT and WiFi [9], [88]. The radio symbiosis enables the coordination among the radio systems for intelligent resource utilization and to achieve common or individual objectives from symbiosis in an SR system [49]. There are several types of symbiotic relationships that can be developed between the different radio systems and users for sharing resources [39], [49]. **Figure 2.3** illustrates a flow diagram of SR system from radio symbiosis to symbiotic relationships in the radio ecosystem. The possible symbiotic relationships include:

- **Mutualism relationship:** In this type of relationship, both systems work together to improve the overall performance of the network, resulting in a positive impact on both systems.
- **Commensal relationship:** In this type of relationship, one system maximizes its data rate without considering the performance of the other.
- **Parasitic relationship:** In this type of relationship, one system transmits at the same

rate as the other to achieve maximum data rate, but at the expense of the transmission rate of the other system.

- **Competition relationship:** In this type of relationship, both systems try to gain the maximum transmission rate by competing for resources, which can lead to a reduction in performance for both systems.

Interestingly, in each symbiotic relationship, one radio system receives the benefit from symbiosis but the other system either gets benefit or harm. Nonetheless, the overall resource utilization efficiency is increased. As the radio systems provide a wide range of functionalities, the SRs systems can be designed from radio systems that provide the same radio service e.g., communication only, or radio systems that provide different services e.g, RADAR and communication. An example of former SRs is symbiotic communication (SCm), while symbiotic RADAR is an example of the latter. In SCm, different radio systems share the radio resources to perform communication tasks [39]. However, radio systems share the radio resources to perform RADAR/sensing and communication functions in symbiotic RADAR [115]–[117]. In this survey, we will focus on SCm in SR with obligatory symbiosis.

2.1.2. State-of-the-art methodologies in symbiotic radio

2.1.2.1. Symbiotic communication

In SCm, relevant radio systems establish symbiotic relationships to enable communication. Unlike the conventional communication methods, SCm allows the radio systems to cooperate and share the resources intelligently in an SR system. **Figure 2.4** shows the SR system for enabling SCm between active and passive radio systems. The active radio system comprises an active transmitter (AT) and an active user (AU) that engages in conventional active radio communication. Meanwhile, a passive radio system with a BD sends data through BC over the signals transmitted by AT. These two systems communicate through SCm in obligatory symbiosis, characterized by efficient resource and service exchange. In this way, the BD performs energy harvesting and information transfer tasks without requiring additional infrastructure, energy, and spectrum [48]. In return, the BD can provide services such as data relaying depending on the different symbiotic relationships.

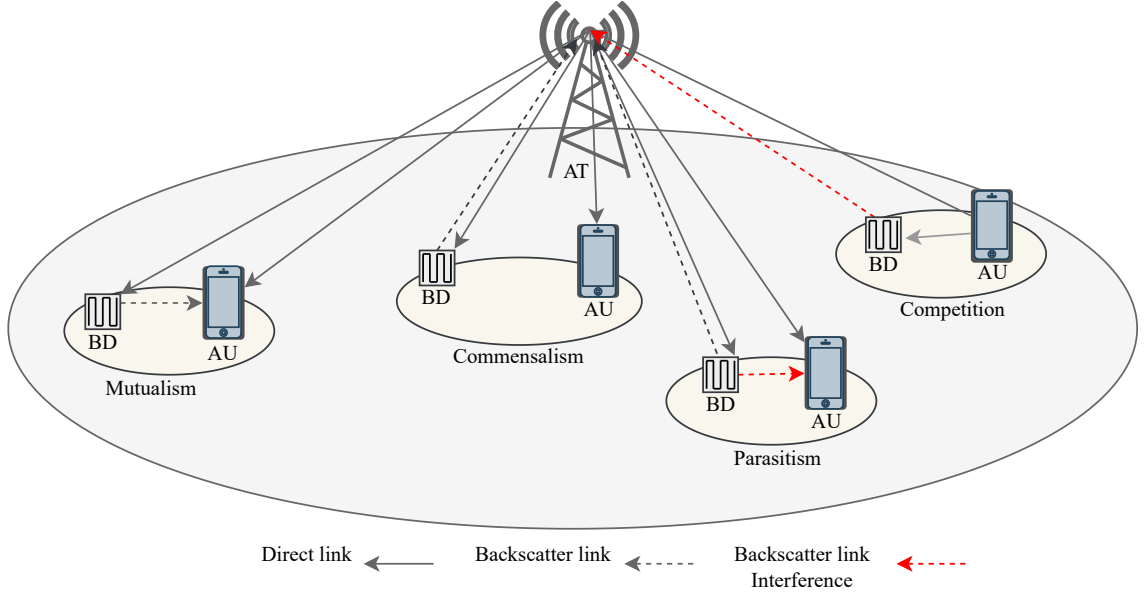


Figure 2.4: SR system with different symbiotic relationships between BD and AU for resource sharing.

In a mutualistic relationship, the transmission rate of the backscattered signal is selected to be significantly lower than the active signal, thus avoiding interference to the AU while providing additional multi-path gain [50]. Even in a commensal relationship, the BD modulation rate is low, but the backscattered signal is weak and does not add multi-path gain or interference to the AU. Here, the BD benefits from utilizing the signal of the AU without providing any benefit or harm. On the other hand, in a parasitic relationship, the BD backscatters the signal at a high data rate, creating interference to the AU and thereby improving its data rate while degrading the performance of the AU. Furthermore, the BD and AU compete for radio resources in competition symbiotic relationship. For example, when the AU transmits a signal, the BD backscatters a signal with a maximum reflection coefficient and causes interference. In response, the AU transmits at high power to improve its performance and suppress the weak BD signal. Through this relationship, both devices aim to improve their performance by harming each other. Despite these differences, the ultimate goal is to create a flexible SR design for efficient resource sharing. In [118], the authors evaluate the commensal, parasitic, and competition relationships to increase the data rate of active and passive radio systems. In a commensal relationship, the AU endeavors to maximize its data rate without considering the performance of the passive radio system. Conversely, in a parasitic relationship, the BD transmits with a maximum reflection coefficient and at the same rate as the active user to achieve the maximum data

rate, while sacrificing the transmission rate of the active radio system. Both systems strive to attain the maximum transmission rate by competing for resources, thus harming each other in the competition. Besides, in commensal and parasitic symbiotic relations, the spectrum growth problem occurs because BD transmits at different data rates compared to an AU. This problem is solved by jointly optimizing the reflection coefficient and transmit power of BD and AU [119]. In [48], the authors apply optimal beamforming at the AT to find the optimal achievable rates of each system in both symbiotic relationships.

Combining the benefits of BC and CR in an SR system can improve spectrum sharing and energy efficiency through SCm. In this approach, the secondary transmitter acts as a BD and reflects signals from the primary transmitter to send messages to the secondary receiver. This allows the secondary system to share not only the radio spectrum but also power and infrastructure with the primary system. Additionally, the secondary transmission provides multipath diversity to the primary system. The authors in [49] explore mutualistic spectrum sharing in an SR system with CR-based AmBackCom and utilize joint decoding at the secondary receiver to achieve highly reliable BC. To further enhance performance, a full-duplex function is added to the primary transmitter and an RIS is placed in the environment to benefit both primary and secondary systems. In [120], the authors study the power resource optimization problem under hardware impairments constraints in SR system with CR based active radio system and full-duplex BD. The problem is solved by maximizing both active radio system link rates subject to the CR link and sum rate.

2.1.2.2. Resource allocation and multiple access

In an SR system, radio systems may consist of multiple transmitters and receivers sharing the resources in a symbiotic manner. Interference between the users and resource allocation such as spectrum, time, and power are critical issues in the concurrent communication of multiple users. The energy-efficient power allocation for cooperative and non-cooperative SR systems is studied in [121]. In particular, finite blocklength channel codes are exploited under different transmission rates and symbol periods of BD to minimize the transmission power of AT and maximize the energy efficiency of BD. The authors in [122] propose a scheduling system called timing SR to minimize energy consumption and increase energy efficiency while ensuring a minimum required throughput

for BDs. This scheme allows BDs to harvest energy from ambient signals and simultaneously send their information without interfering with each other by using the carrier of AU signal. The authors use mathematical methods called conic quadratic representation and sequential quadratic techniques to solve the non-convex optimization problem.

In a symbiotic radio network, multiple access refers to the capability of several AUs and BDs to simultaneously use the communication resources. It is crucial to ensure the effective use of communication resources and prevent interference between active and passive users by separating them in time, frequency, space, code, and power. In [123] authors investigate the interference issues in a multi-BD BC based SR system, in which multiple BDs transmit simultaneously to the AU. The authors designed the coding algorithms with orthogonal code chips to enable interference-free communication. A distributive multiple BD access scheme is proposed in [124] to overcome the frequent inter-system and inter-BD coordination. Precoding is performed at each BD by multiplying the data with random spreading code. Furthermore, an iterative algorithm is proposed to optimize the signal-to-interference plus noise ratio at BD and minimize the transmission power of the active radio transmitter. A stochastic transceiver design is proposed in [125] to solve interference issues such as inter-BD and interference in the downlink transmission. A batch stochastic parallel decomposition algorithm is proposed to solve stochastic multiple ratios fractional non-convex problems such as coverage analysis and acquiring the real-time tag's symbol information with minimum feedback signaling. The authors in [126] try to improve the energy efficiency of an active radio system in a multiple BDs SR system. The resource to BDs are allocated based on a time-domain multiple access approach, and it is analyzed that the maximum energy efficiency is achieved when the maximum time is allocated to the BD with maximum throughput. In [51], the authors demonstrate a full mutualism relationship with a massive number of BDs by separating them in the power domain to enhance the sum rate of the SR system.

The non-orthogonal spectrum sharing between active and passive radio systems is also investigated in SR system, in which two users share the same spectrum with separability in power, code, or space domains [127]. Different from the conventional non-orthogonal multiple access (NOMA) schemes, the spectrum sharing between active and passive radio systems is inherently supported by SR because the power of the backscattered signal is very low compared to that of the AU. Some studies have exploited NOMA to enhance

the spectral efficiency and security of both active and passive radio systems [127]–[130]. In [127], an SR system is proposed to enhance the ergodic rates of NOMA assisted BC system. Active radio system employs power domain NOMA between the near and far users while BD backscatters its signal to the near AU. To extract the data, the near AU applies successive interference cancellation and the far AU treats the BD signal as noise. A NOMA enhanced dynamic time division multiple access scheme is proposed in [128] to increase the spectral efficiency in an SR system. Full-duplex functionalities are also adopted at the active radio transmitter to send the signals to the receiver while receiving backscatter signals from BDs. An SR with cellular-NOMA is proposed in [129], and the system performance is analyzed in terms of the outage and ergodic rates of cellular users and BDs. A NOMA based decode and forward relay assisted SR is investigated in [130]. The relay is considered to transmit information and power simultaneously. By employing the power domain NOMA, the relay assists in forwarding the information of an AU and parasite BD to their destinations. While observing the performance of both systems, it is concluded that this relaying mechanism achieves better throughput than the conventional one at the cost of minor throughput degradation of AUs.

2.1.2.3. MIMO and beamforming

MIMO technology allows the use of multiple antennas to simultaneously transmit and receive multiple data streams, increasing network capacity and reliability. This reduces vulnerability to fading and other channel impairments and mitigates interference through beamforming techniques [131]. MIMO improves energy efficiency by reducing power consumption, leading to a more efficient and reliable SR system with higher capacity, better coverage, and improved energy efficiency. Different studies have been conducted to exploit the benefits of MIMO and beamforming in SR systems, [132]–[136]. An end-to-end MIMO SR system is proposed in [132], where each component of the system is equipped with multiple antennas as shown in **Figure 2.5a**. An optimal beamforming design problem is investigated to maximize the transmission rate of BD subject to the constraints of AT transmission rates. To solve this problem, a locally optimal solution is proposed based on an exact penalty to obtain the capacity upper bound. An SR system with cell-free massive MIMO is investigated in [133]. Firstly, a two-step uplink training algorithm is proposed to estimate the CSI of the backscattered and direct links, wherein

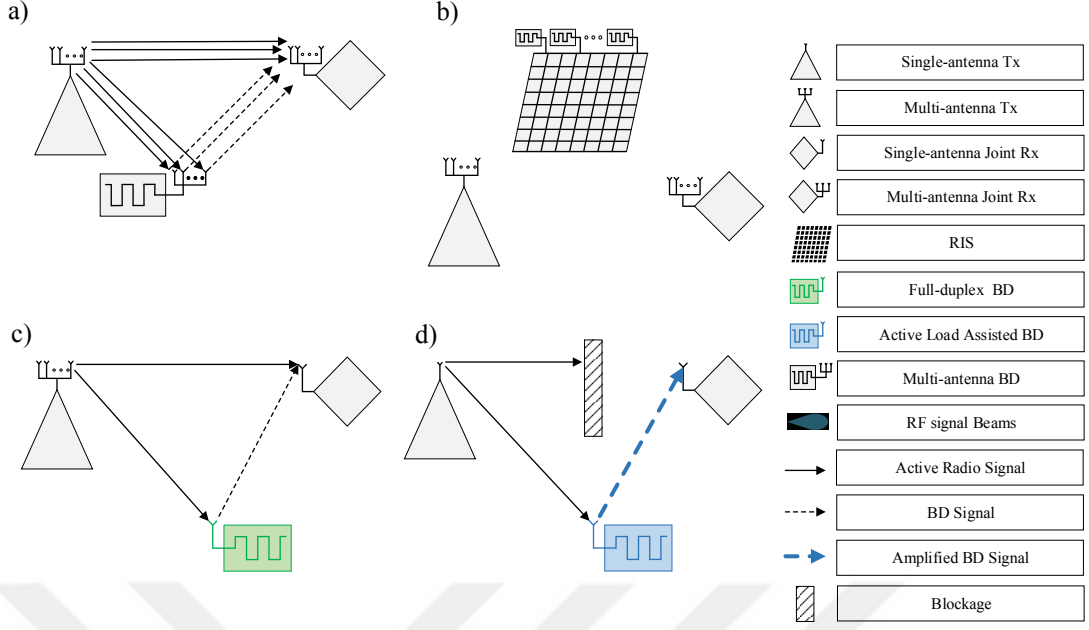


Figure 2.5: Scenarios of SR with integration of advanced technologies: **a)** MIMO **b)** RIS **c)** full-duplex BD, and **d)** active-load assisted BD.

the first step is to estimate the direct link from the pilots received from AT without the involvement of BD while in the second step, both BD and ATs transmit for estimation of backscattered link. Secondly, low complex beamforming is exploited to derive the achievable transmission rates of both systems. The authors in [134] focus on the limitations of active radio link enhancement by single BD, and how the full mutualism of symbiotic radio can be achieved by using MIMO SR systems with massive BDs. They derive the achievable rates of primary active and secondary passive communication and consider the asymptotic regime as the number of BDs increases. They also study the precoding optimization problem to maximize the AU rate while ensuring that the BD communication rate is no lower than a certain threshold. Moreover, the authors in [135] propose a beam selection scheme to improve access of BDs to RF signals in a millimeter wave SR system. As the millimeter-wave channel is sparse, it is possible that some of the BDs lack RF signals. The scheme selects beams based on channel measurement and dominant paths between AT and AU, ensuring signal accessibility to BDs, and leading to an improvement in the overall system's sum rate.

On the other hand, beamforming can help in securing the SR systems from eavesdropping at the physical layer. The authors in [136], propose a secure beamforming approach to

enhance the secrecy of BD in a multiple input-single-output NOMA-based SR system. They assume the presence of a potential eavesdropper in the network and maximize the secrecy rate with a constrained concave-convex procedure-based algorithm from the BD to the central AU while considering the achievable secrecy rate constraints from the AT to the central and cell-edge AUs. Moreover, beamforming can be used to create the null in the direction of the eavesdropper to prevent her from listening to the SCm and ensuring the privacy of users. Although MIMO and beamforming techniques are applied to maximize the transmission, and secrecy rate of SR systems, there are major challenges to overcome such as accurate channel estimation, synchronization, and efficient spatial resource allocation. Besides, the use of multiple antennas and beamforming techniques at BD leads to high computational cost and power consumption, which can be a problem for passive IoT devices. To address this, new techniques are needed to reduce the complexity of the MIMO for SR system and improve energy efficiency.

2.1.2.4. Reconfigurable intelligent surface assistance

Large-intelligent surface (LIS) or RIS is a two-dimensional metasurface that consists of a large number of low-power scattering components. It is capable of reflecting the incident signals into desired directions through passive beamforming [137]. Recently, due to its low power consumption and passive beamforming feature, it has been considered a promising solution to minimize the transmit power active radio system while enhancing the achievable rate of BD in a SR system [138]–[142]. A simple RIS assisted SR is shown in **Figure 2.5b**, where multiple BDs are integrated to the RIS and passive beamforming is approach is used to improve the communication link of AU and to backscatter the information of BD to the BC receiver.

RIS is also deployed in a downlink SR system to enhance the performance of active radio system and multi-BDs BC system in [138]. The transmission power of the active radio system is minimized by jointly designing the beamforming at AT and RIS considering the signal-to-noise ratio and transmission rates of both systems as optimization constraints. A cooperative beamforming approach is proposed in [139] for a simple BC based SR system. RIS transmits the data of BD (i.e., connected to it through a wire) to a joint receiver by modulating the incident signals while configuring those signals to enhance the performance of AU. RIS can also transmit the data of multiple BDs connected to it via wired

links to the BC receiver while improving the wireless channel of the AU. A joint optimization approach for active beamforming at radio transmitter and passive beamforming at LIS is studied in [140]. The aim is to enhance the transmission rate of the passive radio system without affecting the rate of the active radio system. Other works on RIS assisted SR system with multiple AUs and a single BD are also investigated in the literature [141], [142]. As RIS reflects the signals to an AU, it simultaneously modulates the data of BDs. This study focuses on the power minimization problem under the rate constraints of AUs and BD. The problem is solved by jointly optimizing active and passive beamforming at AT and RIS, respectively. Implementation of RIS in SR can provide several benefits, such as improving the performance of an active radio system while enabling multi-BD communication. Readers interested in RIS assisted enhancement in SR for spectral efficiency and energy efficiency are referred to [143].

2.1.2.5. Full-duplex techniques

Full-duplex technology is critical for spectral efficiency and reducing the system's latency. Full-duplexing at AT and BD can improve the data rate and resource utilization in SR system. For instance, an SR system with full-duplex BD is shown in **Figure 2.5c** which is capable of simultaneously transmitting to AU while receiving data from AT in the incident signal. In particular, the BD divides the incident signal into two parts, one for decoding the signal and the other for backscattering its data. To analyze the potential of this technology in SR, a low complex full-duplex BD design is proposed in [144]. The authors optimize transmit power at an AT while optimizing the power splitting factor at BD. The performance of the system is measured in terms of transmission rates of BD. The research on full-duplex communication is still in its infancy, and new studies are needed to understand its limits in SR for enhancing spectral and energy efficiency.

2.1.2.6. Active-load assistance

One of the main reasons for the short range of BD transmission is double-fading attenuation. The backscatter signal suffers from strong interference due to the high power of direct path active radio signal [40]. One way to solve this problem is to use multiple antennas at BD similar to RIS and increase the signal power through passive beamforming [140]. However, this is not possible in all cases, especially when the BD is a small IoT device

Table 2.1: Overview of SR system developments

Ref.	Design objective	System	Symbiotic Relationships			
			Mutualistic	Commensal	Parasitic	Competitive
[48]	Rate maximization of BD and power minimization at active transmitter	Single BD	✓	–	–	–
[49]	Rate maximization of passive and active radio system	Single BD	✓	–	–	–
[118]	Rate maximization of passive and active radio system	Single BD	–	✓	✓	✓
[51]	Sum rate maximization of active users with massive number of BDs	Multi-BDs	–	✓	✓	–
[119]	Resource allocation under fading channels	Single BD	–	✓	✓	–
[120]	Power optimization of CR based active radio system under hardware impairments	Single BD	✓	✓	–	–
[121]	Resource allocation with cooperative and non-cooperative active radio system	Single BD	–	✓	✓	–
[122]	Optimal resource allocation by scheduling BDs in time	Multi-BDs	–	✓	–	–
[123]	Random access with orthogonal interference	Multi-BDs	–	✓	–	–
[124]	Power optimization in random code based multiple access	Multi-BDs	–	–	✓	–
[125]	Stochastic transceiver design for performance improvement under downlink and inter-BD interference	Multi-BDs	–	–	✓	–
[126]	Resource allocation to maximize energy efficiency of active radio system	Multi-BDs	✓	–	–	–
[127]	Outage probability and ergodic rate analysis of backscatter NOMA	Single BD	–	✓	–	–
[128]	Throughput maximization of BD in NOMA-DTDM system	Multi-BDs	–	–	✓	–
[129]	Outage analysis under signal interference of cellular-NOMA AU and BDs	Multi-BDs	–	✓	–	–
[130]	Performance analysis of decode and forward relay network	Multi-BDs	–	–	✓	–
[132]	BD transmission rate optimization	Multi-BDs	–	–	✓	–
[134]	AU link enhancement with massive BDs deployment and MIMO receiver	Multi-BDs	✓	–	–	–
[136]	Secure beamforming and secrecy rate analysis of BD	Single BD	–	✓	–	–
[135]	Signal accessibility to BDs in millimeter wave beamspace channel through beam selection	Multi-BDs	–	✓	–	–
[138]	Joint transmit beamforming for power minimization of active radio system	Multi-BDs	✓	–	–	–
[139]	Transmit power minimization of active radio system	Single BD	–	✓	–	–
[140]	Beamforming for BDs rate enhancement	Multi-BDs	✓	–	–	–

or sensor. In this case, an active load can be used at BD to amplify and backscatter the incident signal through negative resistance [145]. In [40], authors investigate an active load assisted SR to increase the range of BC in CR network. Specifically, an active load is used in BD to amplify the backscattered signal using negative resistances, increasing the transmission range. Besides, the dynamic range between the backscatter and direct link signal powers is also reduced and the probability of correct signal detection is increased. However, BD with active load may create severe interference to the primary signal in a parasitic relationship. Therefore, a beamforming vector is designed to minimize the interference while maximizing the rate of BD. This approach requires additional power but still has a lower power consumption than an active radio or RF chains for beamforming. Additionally, it reduces the dynamic range between the direct-link signal power and the backscatter-link signal power, making it easier to recover the BD signal [146]. BD with active load can also act as a relay while backscattering its data in case of direct signal blockage at the AU [147]. An SR system with active-load assisted BD is shown in **Figure 2.5d**, where the AU does not have a direct signal from an active radio transmitter due to blockage, but it can receive the signal from the BD. To assist AU, the BD amplifies the incident signal while modulating its data over the signal. Further research is needed to fully understand the potential of active load-assisted BD in enhancing the performance of passive radio systems. An exciting avenue for future investigation could be the integration of active load-assisted BDs with full-duplex technology and RIS in various symbiotic relationships. **Table 2.1** provides a summary of the developments in SR along with the classification in terms of symbiotic relationships.

2.1.3. Applications for 6G and beyond

The SR can enable a wide range of applications in 6G and beyond. The existing and future wireless networks could aid power-constrained devices with symbiotic communication, particularly in locations with extensive passive sensors deployment. This section will go through some of the potential application areas of SR that are shown in **Figure 2.6**.

2.1.3.1. Healthcare and living

6G technology is foreseen to bring advancements in the healthcare field through robot-assisted surgery, telemedicine, and deep body implants with interconnected devices.

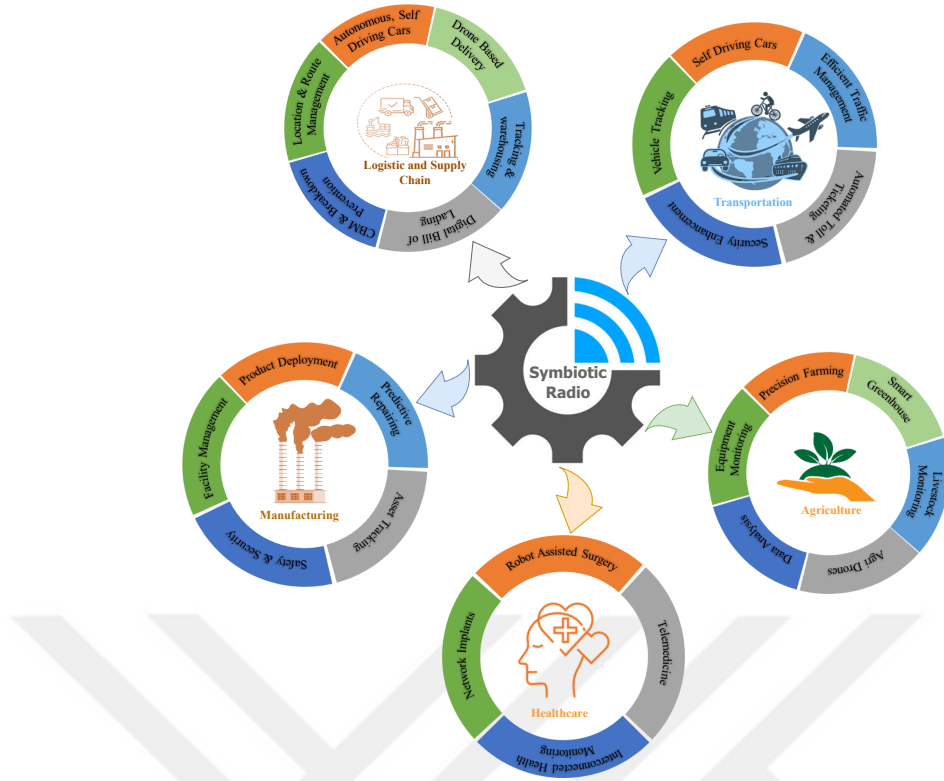


Figure 2.6: Applications of symbiotic radio.

These medical facilities require continuous health data collection and transfer through wireless devices and sensors, primarily low-power, and battery-operated [14]. Active radios for wireless data transfer in medical devices significantly reduce battery life. Also, complex RF circuits and signal processing techniques limit their use in wearables and tiny deep implants [148], [149]. Implementing BC in medical devices can permanently overcome power issues and enhance battery life. However, traditional BC methods need the signal from dedicated or ambient RF sources, resulting in high system costs and limited connectivity. Through SR, medical devices can reliably use the signal of existing wireless systems. For instance, WiFi access points available in hospitals or homes can support these while serving their users. In return, WiFi users can benefit from the backscattered signals as multipath under mutualistic relationships for performance enhancement. Moreover, medical devices frequently transfer their information to a centralized or a cloud server that needs a gateway in the localized network. In SR, medical devices could be able to transfer their information online through WiFi. Furthermore, outdoor medical devices can connect to a cellular base station for SCm via commensal or mutual relationship and get the required radio resources.

The elderly population is increasing rapidly, and older people prefer to stay at home. Due

to old age, people suffer from loneliness and diseases such as dementia, which creates difficulty for them to locate their daily use things, e.g., medicine kits. SR based passive IoT devices can assist the older person in their daily activities at home or outside by locating personal belongings and providing environmental information. The household devices equipped with passive sensors can send their data to the cell phone with SCm utilizing WiFi network resources in the uplink/downlink [150]. WiFi nodes, in return, can get some helpful information from the passive devices about the environment to improve its quality of service working in different symbiotic relationships.

2.1.3.2. Agriculture

Collecting information about the environment and utilizing it to support agriculture is realized through an IoT-based ecosystem. IoT devices and sensors are placed on plants for precision farming and data gathering, particularly in smart greenhouses. These devices should be small and power efficient for ultra-dense deployment and must operate for a long time. Existing communication technologies for wireless sensor networks, e.g., Zigbee and Bluetooth, consume high power and are large. SR can overcome these challenges by SCm while operating in a commensal relationship with TV and radio base stations. Moreover, the application of nano unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) in agriculture for online surveillance of fruit trees/crops and soil measurements has gained popularity [151]. These tiny unmanned devices communicate with other UAVs and UGV through power-consuming radios that reduce their active duration. Implementing SR in these vehicles can greatly enhance their energy efficiency and operating time. Instead of communicating via active radios, they can leverage SCm with backscatter radios. Additionally, they can develop a symbiotic relationship with the available cellular or satellite network to attain an RF carrier.

2.1.3.3. Transportation

Intelligent transportation system (ITS) is evolving with the advancements in information and communication technologies. Autonomous driving, active collision protection, driver assistance, and mobility management systems are being developed to reduce road fatalities. These systems collect data from the environment through sensors and process it to take necessary actions. The collected data is also shared with nearby vehicles and the

infrastructure using IEEE 802.11p and cellular vehicle-to-everything (V2X) communication technologies. IoT sensors and devices in vehicular networks are battery-operated and must send active radio signals for information transfer. With the rapid expansion of transportation systems, a massive sensor deployment is expected globally, requiring more frequent data transfer. As a result, future ITS needs communication radios that are power-efficient and sophisticated in their utilization of radio resources. Strong research efforts are being conducted to replace active radios with backscatter radios. For instance, to improve driver's awareness, information on pedestrians crossing the road was supplied to the car with a passive sensor utilizing a BC radio in [152]. SR can enhance ITS with SCm in symbiosis with cellular V2X and IEEE 802.11p networks to encourage spectrum and energy-efficient communication.

2.1.3.4. Manufacturing

SR technology holds the potential to revolutionize the manufacturing industry by improving the efficiency, productivity, and scalability of processes. The deployment of industrial IoT devices enabled by SR technology can allow for real-time monitoring and control of manufacturing operations [153]. This includes the ability to perform predictive maintenance to detect equipment failures early, automation for improved efficiency and reduced labor costs, and smart factory implementation for real-time communication between machines. Additionally, SR technology can be used for asset tracking to improve inventory management and supply chain efficiency. The symbiotic relationships between different radio systems with SR technology enable the integration of different manufacturing processes into a cohesive system, leading to improved efficiency and scalability. Furthermore, SRad technology can be utilized for monitoring and control of safety-critical systems, ensuring the safety of employees in the manufacturing facility. Overall, SR technology has the potential to play a key role in the digitalization and automation of the manufacturing industry, enabling efficient, smart, and sustainable manufacturing.

2.1.3.5. Logistic and supply chain

SR technology can be used in logistics and supply chain management to improve communication and efficiency. Usually, RFID tags are connected to the products for tracking and management [154]. Manual scanning of a large number of tags is a time-consuming

task and requires human effort. SR can be used for real-time asset location tracking and inventory management in a warehouse, by using available WiFi access points to locate and manage inventory. RFID tags can be replaced with passive IoT devices that modulate the signals of WiFi, and it gets their information and location from the received signal, reducing the need for manual scanning. Additionally, SR can be used for real-time shipment tracking outdoors by using the cellular network. By intelligently allocating and adapting the available spectrum, SR can enable real-time communication and coordination, reducing delays and costs and improving the overall performance of logistics and supply chain operations. This can provide better visibility and control over the supply chain, reducing delays and increasing efficiency. Additionally, it can improve RFID tagging by minimizing interference and optimizing communication range, resulting in improved accuracy and reliability of RFID data. Fleet management can also be improved by enabling real-time tracking and coordination, reducing delays, and increasing efficiency. Furthermore, warehouse management can be improved by enabling real-time tracking of inventory, optimizing communication, and reducing the time required to locate and retrieve items.

2.2. Study I: Interference-Free Backscatter Communications for OFDM-Based Symbiotic Radio

Exploiting the OFDM signal for BC is critical for low-power passive IoT devices as they coexist with the existing wireless systems. Within this context, multiple studies consider OFDM-based BC [1], [2], [33], [34], [155]–[157]. These studies explore the cyclostationary features of OFDM signal generated by an ambient wireless system for BC. In [1], a backscatter modulation scheme is designed for BC over OFDM signal in the time domain. The uncorrupted part of the cyclic prefix (CP) is processed at the receiver for direct link interference cancellation and BD signal detection. Still, the receiver must be aware of the channel's lengths for this scheme to work in practical scenarios. Also, the waveform designed for BC causes variation in the primary signal, which may lead to interference at the primary receiver. The guard bands in the OFDM signal are used for BC in [2], [155], [158]. Specifically, a BD applies FSK to shift the spectrum of the backscatter signal to the out-of-band region of the primary OFDM signal to transmit its information. This approach cannot be directly implemented in SR as the joint receiver needs to scan the adjacent channel additionally to detect the data of BD, which requires an additional filter to capture the

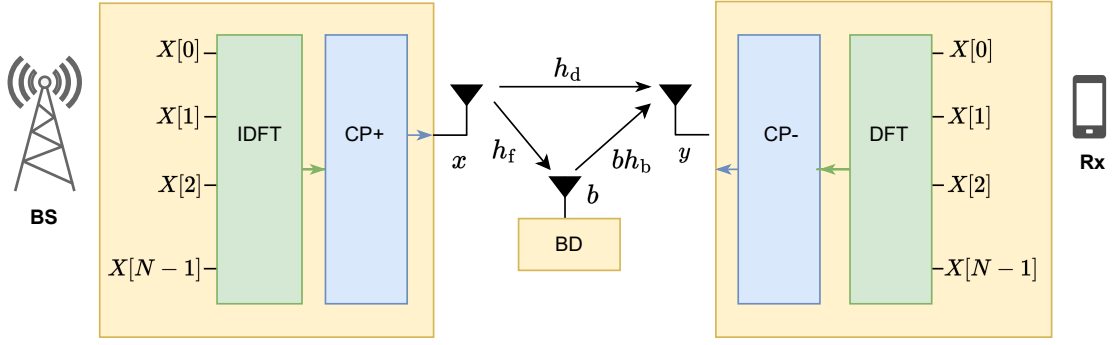


Figure 2.7: The system model with single BS, BD, and a joint RX.

backscatter signal in the guard subcarriers. Consequently, this solution adds complexity to the receiver. The authors in [156] introduce the subcarrier-wise ambient BC and propose to transmit one-bit information at each subcarrier. In this scheme, a bank of passive notch filters is required at the BD, significantly increasing its hardware complexity. The preamble and pilots in OFDM signals are used for ambient BC in [33], [34], [157], [159] but utilizing the preamble and pilots degrades the channel estimation performance at the primary receiver which reduces the reliability of the whole system. Additionally, this approach requires strict synchronization at the backscatter receiver. Besides, in [159], the authors propose to use the cell-specific reference signals in the LTE system to enable BC. In particular, the BD applies FSK to create an artificial Doppler in the incident LTE signal and shift the reference signals to another subcarrier to transmit its information. To this end, the BD and backscatter receiver need to have prior information on LTE reference signals. Nevertheless, these studies do not particularly design the OFDM symbols to achieve reliable BC for an SR system. For instance, it is possible to arrange the data, pilot, and null subcarriers at the primary system to receive the direct path and BC signals over different subcarriers if BD is capable of manipulating the signal frequency [160]. This arrangement can be achieved without changing the transceiver design of the primary system. Furthermore, such a system can support passive IoT devices and ambient power-enabled IoT devices in various wireless networks, including Wi-Fi, LTE, 5G, and beyond.

2.2.1. System model

Consider an OFDM-based SR system consisting of two primary devices, i.e., a BS, an Rx, and a BD, as shown in **Figure 2.7**, where BS and Rx are assumed to be single-antenna

active devices, and BD is a single-antenna passive device. The BD is a low-power, low-cost, and low-complexity device that belongs to a passive IoT system. The primary signal transmitted by BS is utilized as BD's carrier signal to transmit its information using BC to the Rx. Furthermore, the primary signal is a modulated signal containing the information for the Rx, and the Rx's goal is to obtain the information that is transmitted from both BD and BS.

2.2.1.1. Primary signal

The primary signal is an OFDM symbol with K active subcarriers containing data symbols for Rx. Let $X[k]$ be the k -th data symbol at BS. After an inverse discrete Fourier transform (IDFT) is applied to the data symbols, the n -th time domain sample of the corresponding OFDM symbol, denoted by $x[n]$, can be expressed as

$$x[n] = \frac{1}{N} \sum_{k=0}^{K-1} X[k] e^{j \frac{2\pi k n}{N}}, \quad n \in \{0, 1, \dots, N-1\}, \quad (2.1)$$

where N is the IDFT size. Afterward, a CP of length N_{CP} that is larger than the maximum delay spread is added to the time domain signal, and the corresponding OFDM samples are transmitted over a wireless channel. The bandpass signal transmitted by the BS can be written as

$$x(t) = x_{\text{bb}}(t) e^{j 2\pi f_c t}, \quad (2.2)$$

where $x_{\text{bb}}(t)$ is the baseband OFDM signal with CP in the time domain, and f_c denotes the carrier frequency.

2.2.1.2. BD signal

Conventionally, the load modulation is applied by switching the BD's antenna between non-reflecting and reflecting states to transmit '0' and '1', respectively [44]. The achievement of the reflecting state involves impedance matching, which is realized by connecting an antenna with an impedance of $Z_A = |Z_A| e^{j\theta_A}$ to a load with an impedance of $Z_L = |Z_L| e^{j\theta_L}$, ensuring $Z_L = Z_A$. Conversely, impedance mismatching is implemented to obtain a non-reflecting state by connecting the antenna to the load in such a way that $Z_L \neq Z_A$. Hence, the reflection coefficient Γ_b for a backscatter modulator is expressed

as [161]:

$$\Gamma_b = \frac{Z_L - Z_A^*}{Z_L + Z_A} = |\Gamma_b|e^{j\theta_b}. \quad (2.3)$$

Different values of Γ_b can be obtained by changing the values of Z_L because the value of Z_A is constant based on the antenna structure. The amplitude and phase of the backscatter signal are described by $|\Gamma_b|$ and phase θ_b , which can be defined as [162]:

$$|\Gamma_b| = \frac{|Z_A| + |Z_L| - 2|Z_A||Z_L|\cos(\theta_A - \theta_L)}{|Z_A| + |Z_L| + 2|Z_A||Z_L|\cos(\theta_A - \theta_L)}, \quad (2.4)$$

$$\theta_b = \arctan\left(\frac{2|Z_A||Z_L|\sin(\theta_A - \theta_L)}{|Z_A|^2|Z_L|^2}\right). \quad (2.5)$$

The impedance of the BD can be manipulated to attain complex values by carefully selecting appropriate inductance values. By connecting an RF switch to the loads Z_L and alternately switching between them, the BD can effectively replicate the complex signal $j2\pi f_\zeta t$ with a frequency of f_ζ [29], [163]. Here, ζ represents the frequency index used for shifting the data symbols in the primary signal. By precisely controlling the amplitude and frequency of the reflected signal, both OOK and FSK modulations can be generated to transmit the information from the BD.

Conventionally, a BD modulates the incoming signal with a rectangular pulse generated by switching between two loads [44]. Such a modulation technique is not preferable for a receiver in SR as changing load sharply requires BD to transmit in the out-of-band region of the primary communication system. One of the methods to tackle this concern is pulse-shaping, which involves continuous load variations at BD for BC [164]. A BD consists of a variable load Z_L (i.e., diode) controlled by a microcontroller unit (MCU). The MCU applies different voltage levels to the diode to perform continuous load modulations. This approach suppresses the out-of-band emissions and allows the synthesis of specific signals like a complex exponential for frequency modulation or shapes the time-frequency characteristics of the reflected signal. Besides, there are other BD hardware architectures and designs available in the literature that can generate complex signals to achieve single side-band FSK without higher order and mirror harmonics [163]. As BD design is not part of this study, interested readers are directed to the works in [165], and [166].

In this study, we consider a BD consisting of multiple loads Z_L (i.e., diode or transistors) and an MCU discussed in [163], [165], [167], which can perform single sideband FSK and

OOK modulations. We assume that the BD's MCU and other low-power operations are supported by harvesting ambient sources like RF signals or solar energy [48]. Let BD use frequency modulation to transmit information. Then, the frequency-modulated primary signal at the output of BD can be written as

$$x_{\text{out}}(t) = (h_f(t) * x(t))\Gamma_b b(t) , \quad (2.6)$$

where $b(t) = e^{j2\pi f_c t}$ is the signal generated at the BD, $h_f(t)$ represents the channel on the forward link (i.e., the link between BS and BD). Note that the implementations of single side-band FSK discussed in [163], [167] can be used to obtain $\Gamma_b b(t)$ in practice.

2.2.1.3. Received signal

The signal transmitted by the BS is received at the Rx from two links: The direct link and the backscatter link. The superposed signal in the baseband can be expressed as

$$y(t) = h_d(t) * x(t) + h_b(t) * x_{\text{out}}(t) + w(t) , \quad (2.7)$$

where $x(t)$ is the Rx data signal, $b(t)$ is the BD data signal, $*$ denotes the convolution operation, and $w(t)$ is the additive white Gaussian noise. The functions $h_d(t)$, and $h_b(t)$ represent the continuous-time channel for the direct link (between BS and Rx), and backward link (between BD and Rx), respectively. Each of the channel paths follows the multi-path Rayleigh fading, i.e., $h(\tau) = \sum_{i=0}^{L-1} \gamma_i \delta(\tau - \tau_i)$ with complex amplitude γ_i and delay τ_i of the i -th path. The maximum delay excess delay of the composite channel is $\tau_{\text{max}} = \max\{\tau_d, \tau_f + \tau_b\}$, where τ_d , τ_f , and τ_b represent the time delay corresponding to direct, forward, and backward links. After the CP is discarded, the received signal at the Rx in the discrete-time can be written as

$$y[n] = y_d[n] + y_b[n] + w[n] , \quad (2.8)$$

where $y_d[n] = h_d[n] * x[n]$ is the signal received from the BS through the direct link, $y_b[n] = h_f[n] * (h_b[n] * (x[n]\Gamma_b b[n]))$ is the signal received from the BD over the backscatter link, $h_d[n]$, $h_f[n]$, $h_b[n]$, $x[n]$, and $b[n]$ represent the direct channel, forward channel, backward channel, primary signal, and backscatter signal in discrete time domain, respectively, and $w[n] \sim \mathcal{CN}(0, \sigma_w^2)$ is the additive white Gaussian noise with zero mean and σ_w^2 variance.

We note from (2.8) that if OOK modulation is used at BD and the Rx receives the superposed y_d and y_b signals over the same frequency band, i.e., the signal y_d interferes with the signal y_b due to high channel gains. Then, the Rx must decode the primary signal and perform successive interference cancellation before detecting the BD information from y_p . The primary signal decoding is not feasible in ambient BC systems as the primary data is unknown to the Rx. In an SR system, such a decoding process degrades the performance of the BD detector significantly and negatively impacts the reliability of the BC. Moreover, successive interference cancellation increases the complexity of the Rx. On the other hand, in FSK-based approaches used in ambient BC [155], an unutilized frequency band other than the band of the primary signal is required to shift the primary signal and avoid direct link interference. To achieve a reliable BC in an OFDM-based SR system, we propose a scheme to prevent direct link interference at the Rx, discussed in the next section.

2.2.2. Proposed schemes for interference-free BC

The conventional 5G and Wi-Fi systems use OFDM as the standard waveform [168], [169], in which data symbols are placed in the frequency domain over the narrow band subcarriers. In the OFDM-based SR, BD modulates the incoming signal by changing its amplitude, phase, or frequency shift. In the case of amplitude and phase modulation BD, Rx receives the primary signal with modified amplitude or phase, but data symbols in the primary signal coming from backscatter and direct path interfere. However, one way to avoid this interference is to shift the data in the primary signal in the frequency with FSK at the BD. For instance, if subcarriers exist in the OFDM symbol, BD can shift the primary data to those subcarriers to prevent the backscatter signal from the direct path signal interference and vice versa. By exploiting this approach, we propose the placement of null subcarriers within the OFDM symbol for interference-free BC. Let N_b and N_d denote the number of subcarriers for BD and Rx, respectively. To receive the BD information with OOK, N_b must be equal to N_d ; however, N_b must be greater than N_d to receive the BD information with FSK.

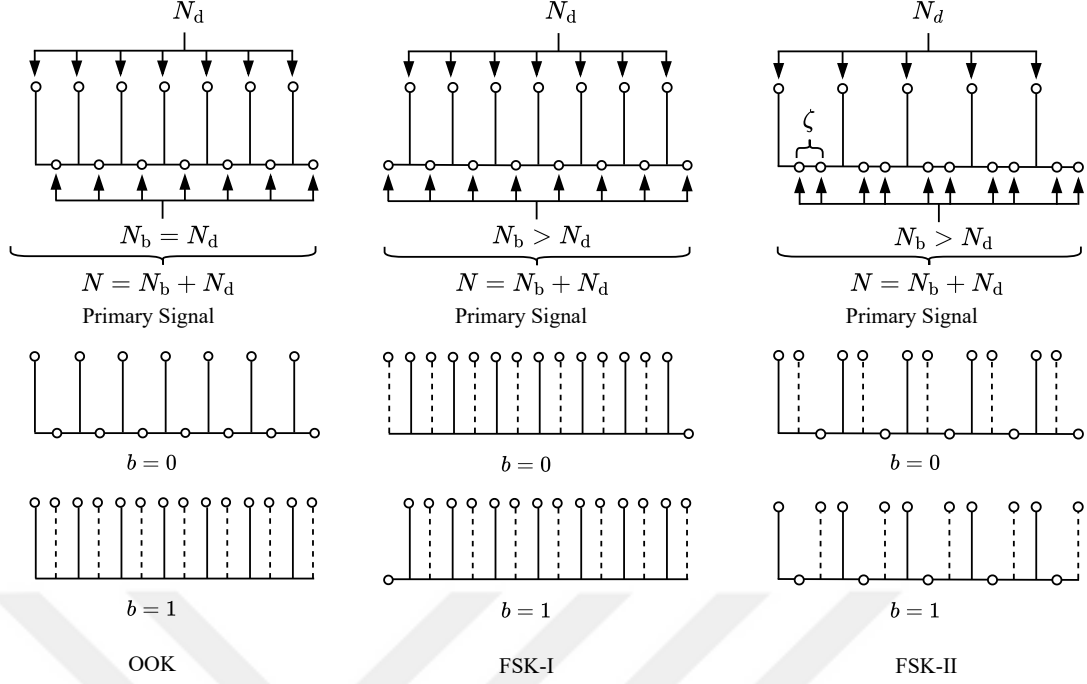


Figure 2.8: The proposed OOK, FSK-1 and FSK-2 schemes. The OOK scheme necessitates an equal amount of null and data subcarriers, and the incoming signal is selectively shifted solely to transmit the bit '1'. FSK-1 relies on the single-null subcarrier at the edges of the band, while FSK-2 utilizes a larger number of null subcarriers to improve reliability at the expense of reduced spectral efficiency.

2.2.2.1. Proposed scheme for OOK modulation

OOK is an amplitude-shift keying (ASK) modulation in which the information is represented with two amplitudes, i.e., ON and OFF. In terms of BC, OOK is performed by switching the antenna between reflecting and non-reflecting states to cause a change in the backscatter signal [170]. In the proposed system, BD also switches reflecting states at a different rate to cause a frequency shift in the backscatter signal while transmitting information bit '1'. The BD waveform can be expressed as

$$b(t) = \begin{cases} \Gamma_b, & b = 0 \\ \Gamma_b e^{j2\pi f_\zeta t}, & b = 1 \end{cases}. \quad (2.9)$$

where $f_\zeta = \zeta \Delta f$ with Δf representing the subcarrier spacing in the OFDM signal. Unlike the conventional OOK modulation, the BD shifts the data in the primary signal to transmit bit '1' and remain constant for bit '0'. The Rx detects the BD's information from the null subcarriers.

In the proposed approach for OOK-based BC without interference, null subcarriers are placed between adjacent data subcarriers, as illustrated in **Figure 2.8**. The subcarrier allocation for primary data and BC at the BS can be expressed as

$$X[k] = \begin{cases} \mathbf{S}[m], & k = 2m \\ 0, & \text{otherwise} \end{cases}, \quad (2.10)$$

where $m \in \mathbb{Z}^+$ with $m \leq \frac{N}{2} - 1$, and $\mathbf{S}[m] = [S[0], S[1], \dots, S[N_d - 1]]$ with $N_d = \frac{N}{2}$ denotes the primary data symbol. In the OOK scheme, the BD shifts the data in the incoming signal with frequency f_ζ with $\zeta = 1$ to transmit bit '1' over the null subcarrier. The Rx receives the BD bits and primary data symbols over null subcarriers and data subcarriers, respectively, as illustrated in **Figure 2.8**. Thus, the OOK scheme prevents interference from the primary signal to the BD signal at Rx. Here, we mentioned only single data and corresponding null subcarrier placement. However, different arrangements can be made to allocate more than one data subcarrier together. For instance, two data subcarriers followed by two null subcarriers can also be placed to achieve the BC without interference at the Rx. In that case, a general subcarrier allocation at the BS for OOK modulation can be expressed as

$$X[k] = \begin{cases} \mathbf{S}[m/\zeta], & k \in m \\ 0, & \text{otherwise} \end{cases}, \quad (2.11)$$

where $\zeta \in [2, 4, \dots, \frac{N}{2}]$ and subcarrier index $m = \{0, \zeta, \zeta + 2, \dots, \frac{N}{2} - \zeta\}$. Now, to prevent direct link interference when two data subcarriers are placed next to each other, the BD shifts the signal with frequency $\zeta = 2$ to transmit bit '1'.

2.2.2.2. Proposed schemes for FSK modulation

In this study, we consider two FSK strategies discussed in the following subsections.

2.2.2.3. FSK-1: dual-side single-null subcarrier-based FSK

Let one BD bit duration span one OFDM symbol duration, then the backscatter modulation in FSK-1 approach can be expressed as

$$b[n] = \begin{cases} e^{-\frac{j2\pi f_1 n}{N}}, & b = 0 \\ e^{\frac{j2\pi f_1 n}{N}}, & b = 1 \end{cases}. \quad (2.12)$$

To enable interference-free BC with FSK-1 approach, the null subcarriers are allocated between the data subcarriers such that a null subcarrier is placed before the data subcarrier so the BD can shift the signal to different frequencies and the Rx can detect both the direct link and backscatter signal information at different subcarriers allocated to each of them. According to FSK-1, the data symbols are mapped to the subcarriers as

$$X[k] = \begin{cases} S[m], & k = 2m \\ 0, & \text{otherwise} \end{cases}, \quad (2.13)$$

where $m \in \mathbb{Z}^+$ with $m \leq (N/2) - 2$. Thus, one subcarrier adjacent to each data subcarrier is left as a null subcarrier.

Upon receiving the OFDM signal with this subcarrier allocation, BD shifts the signal as follows: If the transmit information bit is '0', BD shifts the data subcarriers to the previous null subcarrier. If it transmits '1', BD shifts the data subcarriers to the next null subcarriers, as shown in **Figure 2.8**. The FSK-1 approach is applicable only for the binary FSK modulation because more null subcarriers are needed between the data subcarriers to enable a higher-order FSK without direct link interference. For instance, if the BD shifts the incident signal with a frequency equal to two subcarriers, the first data subcarrier interferes with the subsequent data subcarrier.

2.2.2.4. FSK-2: single-side multi-null subcarrier-based FSK

To improve the reliability of FSK-based BC, we introduce FSK-2 that can use multiple null subcarriers, as shown in **Figure 2.8**. With FSK-2, the data symbols are mapped to the

subcarriers as

$$X[k] = \begin{cases} S[1], & k = 1 \text{ and } m = 1 \\ S[m], & k = 2m + \zeta \text{ and } m > 1, \\ 0, & \text{otherwise} \end{cases} \quad (2.14)$$

where ζ is the number of null subcarriers between two adjacent data subcarriers and $m \leq \lfloor (N-1)/(\zeta+1) \rfloor$ for $m \in \mathbb{Z}^+$. For binary FSK, two null subcarriers are allocated between two adjacent data subcarriers (i.e., $\zeta = 2$), and the BD modulates the incident signal by shifting the data symbols to the subsequent subcarriers. For instance, to transmit the information bit '0', the data symbol is shifted by one subcarrier spacing. On the other hand, the data symbol is shifted by the twice subcarrier spacing to transmit information bit '1', as shown in **Figure 2.8**. Moreover, the value of ζ can be adjusted to achieve a higher order FSK modulation and multiple BD access. The backscatter modulation in FSK-2 approach can be expressed as

$$b[n] = \begin{cases} e^{\frac{j2\pi f_1 n}{N}}, & b = 0 \\ e^{\frac{j2\pi f_2 n}{N}}, & b = 1 \end{cases}. \quad (2.15)$$

It is worth noting that FSK-1 is spectrally efficient than FSK-2. However, it is less reliable if the detector at the RX relies on the single-null subcarrier at the band's edges. FSK-2 utilizes a larger number of null subcarriers than FSK-1. Including these additional null subcarriers significantly enhances the reliability of BC in the FSK-2 scheme.

2.2.3. Computational complexity

To analyze the computational complexity of the proposed schemes, we can look at the primary signal design and information modulation at the BD from the perspective of primary signal design. As the primary signal design at the BS mainly consists of the subcarrier allocation to the Rx and BD in an OFDM symbol, the proposed scheme carries a computational complexity comparable to that of conventional OFDM systems for LTE and 5G standards [168]. Moreover, the second computation complexity is related to the operations performed at the BD to transmit the information with OOK, FSK-1, and FSK-2 modulation schemes. To transmit information with OOK, BD only shifts the signal while transmitting bit '1'; however, for FSK-1, and FSK-2, BD needs to perform frequency shift

for both information bits '1' and '0'. Thus, the OOK's computational complexity is less compared to the other two schemes for the BC.

2.3. Study II: Beam Selection for Ambient Backscatter Communication in Beamspace mmWave Symbiotic Radio

The mmWave frequency bands offer large bandwidths and provide very high data rates and long-range communication with the support of massive MIMO systems. Although these technologies are the critical enablers of 5G and beyond wireless systems, their full potential has not yet been experienced due to significant energy consumption and hardware cost from RF chains required to support a massive number of antennas. To overcome these problems, a beamspace MIMO system has been proposed to exploit the channel sparsity at mmWave frequency. In addition, different beam-selection methods are applied to select the beams with high path gains to reduce the number of RF chains and enhance the energy efficiency gains [60], [61]. For instance, a MM beam-selection method captures the maximum fraction of power from the channel by selecting dominant beams and leaving the weak ones. However, the conventional beam selection schemes are not suitable in the case of the mmWave AmBackCom system since BDs may exist in beams with low path gains and be out of coverage.

SR combines the benefits of mmWave and AmBackCom to achieve low-power high data rate communication. In [171], a mmWave SR with single BD is proposed to achieve high data rate in AmBackCom. In particular, a joint hybrid and passive beamforming approach is used at transmitter and BD. Unlike this work, we aim to provide the RF signal accessibility to BDs while selecting the beams for a user in mmWave SR system.

2.3.1. System model

We consider a SR comprising an AmBackCom system with a mmWave MIMO communication system. A beamspace hybrid analog-digital beamforming architecture at the mmWave MIMO system is assumed consisting of N_{Tx} and N_{Rx} antenna elements at transmitter (Tx) and Rx, respectively [61], [172]. With each antenna element having a uniform radiation in all directions, the array steering vectors at Rx $\mathbf{a}_R(\phi_R)$ and Tx $\mathbf{a}_T(\phi_T)$ as a

function of angle-of-departure (AoD) and angle-of-arrival (AoA) are given by

$$\mathbf{a}_{Rx}(\phi_R) = \left[1, e^{-j2\pi\varphi_R}, \dots, e^{-j2\pi\varphi_R(N_{Rx}-1)} \right]^T \quad (2.16)$$

and

$$\mathbf{a}_{Tx}(\phi_T) = \left[1, e^{-j2\pi\varphi_T}, \dots, e^{-j2\pi\varphi_T(N_{Tx}-1)} \right]^T. \quad (2.17)$$

where $\varphi = \frac{\Omega \sin(\phi)}{\lambda}$ represents the normalized spatial beamforming angles according to physical direction of AoA (AoD) $\phi_T(\phi_R) \in [-\frac{\pi}{2}, \frac{\pi}{2}]$. Ω denotes the antenna element spacing with $\Omega = \lambda/2$, where λ is the wavelength. Tx transmits N_s data streams to the Rx, where $N_s < N_{Rx} < N_{Tx}$.

AmBackCom system consists of N_b single antenna passive BDs i.e., IoT devices, which also send their data to Rx by modulating the incident RF signals/beams generated by Tx. The modulation at BD is performed by changing the load impedance and switching the antenna into reflecting and non-reflecting states. Specifically, the backscatter modulation at b -th BD with antenna switching can be expressed by the antenna reflection coefficient $\Gamma_b^{(c)}$ defined as,

$$\Gamma_b^{(c)} = \frac{Z_{L,b}^{(c)} - Z_{a,b}^*}{Z_{L,b}^{(c)} + Z_{a,b}}, \quad (2.18)$$

where $Z_{L,b}^{(c)}$ is the load impedance, $Z_{a,b}$ is the antenna impedance of b -th BD, $*$ is the complex conjugate, and $c = 1, 2$ are the switch states. We assume the information bit zero '0' is represented by load impedance matching with the antenna impedance i.e., $Z_{L,b}^{(c)} = Z_{a,b}^*$, when antenna absorbs the RF signal. On the other hand, the information bit one '1' is represented by impedance mismatch i.e., $Z_{L,b}^{(c)} \neq Z_{a,b}^*$, when antenna completely reflects the RF signal. $\Gamma_b^{(c)} \in [0, 1]$ controls the backscattered signal power at BD.

2.3.1.1. Channel model

We assume a sparse narrowband mmWave MIMO communication channel with only a few scattering clusters due to propagation characteristics of signals in mmWave frequencies [173]. In contrast to the traditional mmWave MIMO system, scatterers can either be common scattering objects or BDs in SR. As a result, we divide the scattering clusters into three categories, as depicted in **Figure 2.9**. Similar to normal clusters represented in mmWave MIMO systems, the first cluster type has just ordinary scatterers as outside

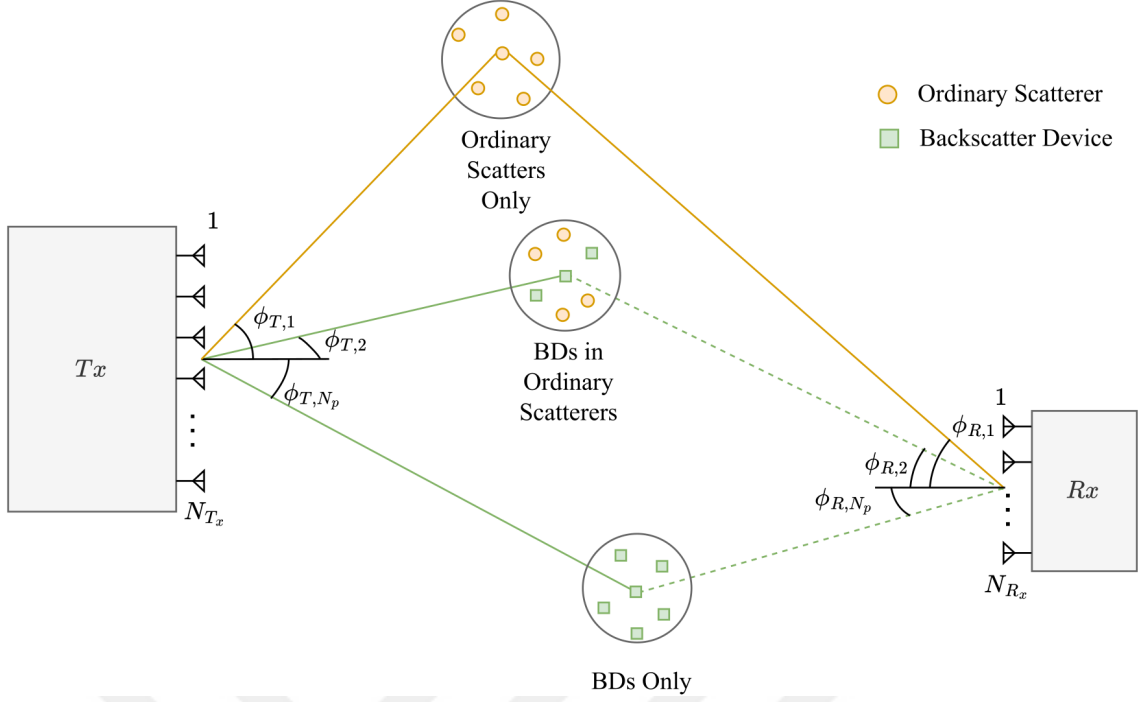


Figure 2.9: The mmWave MIMO SRad system model with three different types of clusters of scatterers.

sources. Ordinary scatterers and BDs exist in the second cluster type, but BDs are the only objects in the third cluster type. However, due to the high channel sparsity, there is only one path from either a BD or an ordinary scatterer in each cluster at mmWave bands. Thus, channel between Tx and Rx is modelled according to the extended Saleh-Valenzuela model [174],

$$\mathbf{H} = \sqrt{\frac{N_{Rx}N_{Tx}}{N_p}} \sum_{p=1}^{N_p} \alpha_p \mathbf{a}_{Rx}(\phi_{R,p}) \mathbf{a}_{Tx}^H(\phi_{T,p}), \quad (2.19)$$

where $\mathbf{H} \in \mathbb{C}^{N_{Rx} \times N_{Tx}}$ represents the channel between Rx and Tx, α_p with $p = 1, 2, \dots, N_p$, $\mathbf{a}_{Rx}(\phi_{R,p}) \in \mathbb{C}^{N_{Rx} \times 1}$, and $\mathbf{a}_{Tx}(\phi_{T,p}) \in \mathbb{C}^{N_{Tx} \times 1}$ are the complex path gain, steering vectors for AoA $\phi_{R,p}$ and AoD $\phi_{T,p}$ of the p -th path, respectively. Furthermore, uniform linear array (ULA) of antennas are considered at Tx and Rx in a horizontal placement, and $\phi_{R,p}$ and $\phi_{T,p}$ are azimuth AoA and AoD of the p -th path.

Since there can be ordinary scatterers or BDs in the paths (i.e., $p \in [b, l]$), we define $N_p = N_b + N_l$, where N_b , and N_l denote number of BDs and number of ordinary scatterers, respectively, which contribute to the N_p paths. In case there are no BDs, then $N_b = 0$ and $N_p = N_l$. Similarly, when there are only BDs, then $N_p = N_b$ and $N_l = 0$. In all three

cases, contributing scatterers are assumed to be non-vanishing and exist in the far-field of Tx and Rx. Besides, the number of paths are less than number of antennas at Tx and Rx (i.e., $N_p \leq N_{Rx} \leq N_{Tx}$). In our proposed system, each path between Tx and Rx represents a channel of a BD or an ordinary scatterer, and (2.19) is rewritten as,

$$\mathbf{H} = \gamma \left(\sum_{b=1}^{N_b} \alpha_b \mathbf{a}_{Rx}(\phi_{R,b}) \mathbf{a}_{Tx}^H(\phi_{T,b}) + \sum_{l=1}^{N_l} \alpha_l \mathbf{a}_{N_{Rx}}(\phi_{R,l}) \mathbf{a}_{N_{Tx}}^H(\phi_{T,l}) \right), \quad (2.20)$$

where $\gamma = \sqrt{\frac{N_{Rx}N_{Tx}}{N_b+N_l}}$ is the normalization factor. To describe the channel in a matrix form, (2.21) can also be written as,

$$\begin{aligned} \mathbf{H} &= \mathbf{A}_{Rx} \Delta_{\mathcal{B}} \mathbf{A}_{Tx}^H + \mathbf{A}_{Rx} \Delta_{\mathcal{L}} \mathbf{A}_{Tx}^H \\ &= \mathbf{H}_{\mathcal{B}} + \mathbf{H}_{\mathcal{L}} \end{aligned} \quad (2.21)$$

where $\mathbf{A}_{Rx} = [\mathbf{a}_{Rx}(\phi_{R,1}), \dots, \mathbf{a}_{Rx}(\phi_{R,N_p})]$ and $\mathbf{A}_{Tx} = [\mathbf{a}_{Tx}(\phi_{T,1}), \dots, \mathbf{a}_{Tx}(\phi_{T,N_p})]$ are the array response matrices of Rx and Tx, respectively, $\Delta_{\mathcal{B}} = \gamma \text{diag}[\alpha_{11} \ \alpha_{bb} \ \alpha_{N_b N_b} \ 0_{11} \ 0_{N_l N_l}]$, and $\Delta_{\mathcal{L}} = \gamma \text{diag}[0_{11} \ 0_{bb} \ 0_{N_b N_b} \ \alpha_{11} \ \alpha_{N_l N_l}]$ are matrices consisting of the complex path gains of BDs and ordinary scatterers, respectively. Now to obtain the finite dimensionality of the mmWave massive MIMO system, we use a beamspace representation with fixed beamforming at Tx and Rx. Thus, the beamspace representation of channel $\mathbf{H}$ is described as [175],

$$\begin{aligned} \mathbf{H} &= \sum_{i=1}^{N_{Rx}} \sum_{j=1}^{N_{Tx}} \tilde{H}(i, j) \mathbf{a}_{Rx}(\hat{\phi}_{R,i}) \mathbf{a}_{Tx}^H(\hat{\phi}_{T,j}) \\ &= \mathbf{U}_{Rx} \tilde{\mathbf{H}} \mathbf{U}_{Tx}^H \end{aligned} \quad (2.22)$$

where $\mathbf{U}_{Tx}$ and $\mathbf{U}_{Rx}$ represents the discrete Fourier transform matrices at Tx and Rx, respectively, which can be defined as [176],

$$\mathbf{U}_t = \frac{1}{\sqrt{N_t}} [\mathbf{a}_t(\hat{\phi}_v)]. \quad (2.23)$$

$\mathbf{U}_t$ with $t \in \{Tx, Rx\}$ is a $N_t \times N_t$ unitary matrix with $\mathbf{U}_t^H \mathbf{U}_t = \mathbf{U}_t \mathbf{U}_t^H = \mathbf{I}_{N_t}$, and $\hat{\phi}_v = \frac{1}{N_t} \left(v - \frac{N_t+1}{2} \right)$ for $v = 1, 2, \dots, N_t$ are pre-defined spatial directions. The transformation of $\mathbf{H}$ into beamspace domain gives the sparse representation at the mmWave frequencies. Furthermore, the beamspace channel matrix is unitarily equivalent to the physical channel

matrix, such that

$$\tilde{\mathbf{H}} = \mathbf{U}_{Rx}^H \mathbf{H} \mathbf{U}_{Tx}. \quad (2.24)$$

From $\tilde{\mathbf{H}}$, we can select the beams that contribute to BDs' paths to provide them signal accessibility and the beams for ordinary scatterers with high path gains.

2.3.1.2. Joint receiver design

Let $\mathbf{x}$ be the signal transmitted from Tx to Rx in the direction of BDs and ordinary scatterers. BD transmits its information signal $q_b \sim \mathcal{N}(0, 1)$ by modulating the incident beam coming from Tx [177]. The signal transmitted by Tx also serves the BDs as an RF carrier. BDs modulate their data by switching antennas while ordinary scatterers only reflect the incident signal. The final received signal containing the information of BD and Rx can be expressed in the antenna domain as,

$$\begin{aligned} \mathbf{y} &= (\mathbf{H}_{\mathcal{B}} \mathbf{q} + \mathbf{H}_{\mathcal{L}}) \mathbf{x} + \mathbf{z} \\ &= (\mathbf{A}_{Rx} \Delta_{\mathcal{B}}^{\mathbf{q}} \mathbf{A}_{Tx}^H + \mathbf{A}_{Rx} \Delta_{\mathcal{L}} \mathbf{A}_{Tx}^H) \mathbf{x} + \mathbf{z} \end{aligned} \quad (2.25)$$

where $\mathbf{y} \in \mathbb{C}^{N_{Rx} \times 1}$ is the received signal vector, $\mathbf{x} \in \mathbb{C}^{N_{Tx} \times 1}$ is the signal vector transmitted by Tx, $\Delta_{\mathcal{B}}^{\mathbf{q}} = \text{diag}([\alpha_1 \Gamma_1^{(c)} q_1 \ \alpha_2 \Gamma_2^{(c)} q_2 \ \alpha_{N_b} \Gamma_{N_b}^{(c)} q_{N_b} \ 0_{11} \ 0_{N_l N_l}])$ represents the signal vector containing information of BDs' $\mathbf{q} \in \mathbb{R}^{N_b \times 1}$, and $\mathbf{z} \sim \mathcal{CN}(0, \sigma^2 \mathbf{I})$ represents the noise vector. The system model provided in (2.25) can be re-written in equivalent beamspace representation,

$$\begin{aligned} \tilde{\mathbf{y}} &= \tilde{\mathbf{H}} \tilde{\mathbf{x}} + \tilde{\mathbf{z}} \\ &= \mathbf{U}_{Rx}^H (\mathbf{H}_{\mathcal{B}} \mathbf{q} + \mathbf{H}_{\mathcal{L}}) \mathbf{U}_{Tx} \tilde{\mathbf{x}} + \tilde{\mathbf{z}} \\ &= \mathbf{U}_{N_{Rx}}^H (\mathbf{A}_{Rx} \Delta_{\mathcal{B}}^{\mathbf{q}} \mathbf{A}_{Tx}^H + \mathbf{A}_{Rx} \Delta_{\mathcal{L}} \mathbf{A}_{Tx}^H) \mathbf{U}_{N_{Tx}} \tilde{\mathbf{x}} + \tilde{\mathbf{z}} \\ &= (\tilde{\mathbf{H}}_{Rx, \mathcal{B}} \Delta_{\mathcal{B}}^{\mathbf{q}} \tilde{\mathbf{H}}_{Tx, \mathcal{B}} + \tilde{\mathbf{H}}_{Rx, \mathcal{L}} \Delta_{\mathcal{L}} \tilde{\mathbf{H}}_{Tx, \mathcal{L}}) \tilde{\mathbf{x}} + \tilde{\mathbf{z}}, \\ &= (\tilde{\mathbf{H}}_{\mathcal{B}} \mathbf{q} + \tilde{\mathbf{H}}_{\mathcal{L}}) \tilde{\mathbf{x}} + \tilde{\mathbf{z}}, \end{aligned} \quad (2.26)$$

where $\tilde{\mathbf{y}} = \mathbf{U}_{N_{Rx}}^H \mathbf{y}$, $\tilde{\mathbf{x}} = \mathbf{U}_{N_{Tx}}^H \mathbf{x}$, and $\tilde{\mathbf{z}} = \mathbf{U}_{N_{Rx}}^H \mathbf{z}$, are the received signal, transmitted signal and noise vectors in the beamspace, respectively. $\tilde{\mathbf{H}}_{Tx, \mathcal{B}} (\tilde{\mathbf{H}}_{Tx, \mathcal{L}})$ represents beamspace channel matrix between Tx and BD (ordinary scatterers), and $\tilde{\mathbf{H}}_{Rx, \mathcal{B}} (\tilde{\mathbf{H}}_{Rx, \mathcal{L}})$ denotes the beamspace channel matrix between Rx and BDs (ordinary scatterers).

2.3.2. Signal accessibility to BD through beam selection at Tx and Rx

In this section, we present a beam selection scheme for ensuring signal accessibility to BDs at the Tx and Rx. Let us consider the MM beam selection, in which the dominant transmit and receive beams are selected from $\tilde{\mathbf{H}}$ to obtain a low-dimensional channel matrix, which is described as [178],

$$\bar{\mathbf{H}} = [\tilde{\mathbf{H}}(j, k)]_{j \in \mathcal{M}_{Rx}, k \in \mathcal{M}_{Tx}}, \quad (2.27)$$

where $\mathcal{M}_{Rx} = \{j \in \mathcal{J}(N_{Rx}) : (j, k) \in \mathcal{M}_c\}$, $\mathcal{M}_{Tx} = \{k \in \mathcal{K}(N_{Tx}) : (j, k) \in \mathcal{M}_c\}$, and $\mathcal{M}_c$ denotes the mask for the selection of dominant beams with a power difference of $\zeta \in [0, 1]$ from the strongest beam, and it is defined as [172],

$$\mathcal{M}_c = \left\{ (j, k) : |\tilde{\mathbf{H}}(j, k)|^2 \geq \zeta \max_{j, k} |\tilde{\mathbf{H}}(j, k)|^2 \right\}. \quad (2.28)$$

This scheme provides a set of beams $s_c = |\mathcal{M}_c|$ with high gains that captures a fraction of channel power. Selecting the beams with dominant path-gain while ignoring others may lead to limited or no signal accessibility to some BDs, and AmBackCom may not be possible in this case. Therefore, the sparsity mask is redefined in the proposed scheme while considering the channel paths of BDs. Assuming the availability of perfect CSI, we define $\mathbb{H}_{\mathcal{B}}$ and select the beams that provide signal accessibility to BDs with MM

$$\mathbb{H}_{\mathcal{B}} = [\tilde{\mathbf{H}}_{\mathcal{B}}(j_b, k_b)]_{j_b \in \mathcal{M}_{Rx, b}, k_b \in \mathcal{M}_{Tx, b}}, \quad (2.29)$$

where $\mathcal{M}_{Rx, b} = \{j_b \in \mathcal{J}(N_{Rx}) : (j_b, b) \in \mathcal{M}_{\mathcal{B}}\}$, $\mathcal{M}_{Tx, b} = \{k_b \in \mathcal{K}(N_{Tx}) : (k_b, b) \in \mathcal{M}_{\mathcal{B}}\}$, and $\mathcal{M}_{\mathcal{B}}$ denotes the beam selection mask for BDs. To determine $\mathcal{M}_{\mathcal{B}}$, another sparsity mask $\mathcal{M}_b$ is defined for dominating beams at Tx and Rx covering b -th backscatter,

$$\mathcal{M}_b = \left\{ \begin{array}{l} j_b : |\tilde{\mathbf{H}}_{Rx, \mathcal{B}}(j, b)|^2 = \max_{(j_b, b)} |\tilde{\mathbf{H}}_{Rx, \mathcal{B}}(j_b, b)|^2 \\ k_b : |\tilde{\mathbf{H}}_{Tx, \mathcal{B}}(k_b, b)|^2 = \max_{(k_b, b)} |\tilde{\mathbf{H}}_{Tx, \mathcal{B}}(k_b, b)|^2 \end{array} \right\} \quad (2.30)$$

$$\mathcal{M}_{\mathcal{B}} = \bigcup_{b=1, \dots, N_b} \mathcal{M}_b.$$

From $\mathcal{M}_{\mathcal{B}}$, a set of beams represented by $s_{\mathcal{B}} = |\mathcal{M}_{\mathcal{B}}|$ is selected that consists of beams which provide signal accessibility to BDs only. Furthermore, a final set of beams denoted by $s_F = |\mathcal{M}_F|$ is chosen by comparing $s_{\mathcal{B}}$ with s_c to select the high path gain beams correspond to Rx. By ensuring signal accessibility to BDs, $s_F = |\mathcal{M}_F|$ is described as

$$s_F = \left\{ \begin{array}{ll} s_c, & s_{\mathcal{B}} \subset s_c, \\ s_c \cup (s_{\mathcal{B}} - s_c) & s_{\mathcal{B}} \not\subset s_c. \end{array} \right. \quad (2.31)$$

After selecting the beams through the proposed scheme $\bar{\mathbf{H}}$ in (2.27) is redefined based on s_F and the received signal at Rx is given by

$$\tilde{\mathbf{y}} = \bar{\mathbf{H}}\tilde{\mathbf{x}} + \tilde{\mathbf{z}}; \bar{\mathbf{H}} = \mathbb{H}_{\mathcal{B}} + \mathbb{H}_{\mathcal{L}}, \quad (2.32)$$

where $\mathbb{H}_{\mathcal{L}}$ represents the channel matrices corresponding to ordinary scatterers, and it is determined similar to $\mathbb{H}_{\mathcal{B}}$.

The major complexity of the proposed scheme comes from the number of beams selected at Tx and Rx. It is comparable to the complexity of conventional MM beam selection scheme, which is expressed as $\mathcal{O}(s_c)$ [172], [176]. Besides, the transceiver needs additional RF chains to provide signal accessibility. In the case selected beams do not cover all BDs, then the complexity is determined as $\mathcal{O}(s_F)$, where s_F is given in (2.31). However, the additional complexity brings the sum-rate performance improvement of the SR system.

The performance of the proposed beam selection scheme is measured in terms of the achievable sum-rate. To simplify the notation, we will use $p \in \{b, l\}$ instead of b and l as defined in (2.19). Rx considers the signal of BDs as interference and obtains its sum-rate in the following manner,

$$R_{Rx} = \log_2 \det \left(\mathbf{I} + \frac{\rho|\beta|^2}{N_p} \mathbf{G}_{Rx}^H \bar{\mathbf{H}} \bar{\mathbf{H}}^H \mathbf{G}_{Tx} \mathcal{R}^{-1} \right) \quad (2.33)$$

where $\mathbf{G}_t = \beta \mathbf{F}_t = \beta [\mathbf{f}_{t,1}, \mathbf{f}_{t,p}, \dots, \mathbf{f}_{t,N_p}]$ denotes the precoder for $t = Tx$ and filter matrix for $t = Rx$, respectively. In the case of linear transceivers, we use $\mathbf{F} = \bar{\mathbf{H}}$ as a matched filter. β satisfies the total power constraint as follows $\beta = \sqrt{\frac{\rho}{\text{tr}(\mathbf{F}_{Tx}^H \Delta_p \mathbf{F}_{Tx})}}$. $\mathcal{R}$ represents interference-plus-noise in the received signal, which is

$$\mathcal{R} = \sigma_n^2 + \frac{\rho|\beta|^2}{N_p} \mathbf{G}_{Rx}^H \mathbb{H}_{\mathcal{B}} \mathbb{H}_{\mathcal{B}}^H \mathbf{G}_{Tx}. \quad (2.34)$$

After performing the perfect successive interference cancellation of Rx signal $\mathbf{x}$, the sum-rate of the b -th BD can be measured as

$$R_b = \log_2 (1 + \text{SINR}_b), \quad (2.35)$$

where signal to interference-plus noise-ratio SINR_b at b -th BD can be described as

$$\text{SINR}_b = \frac{\frac{\rho|\beta|^2}{N_p} |\mathbf{f}_{Rx,p|b}^H \mathbf{h}_{Rx,p|b} \Delta_{p|b} \mathbf{h}_{Tx,p|b}^H \mathbf{f}_{Tx,p|b}|^2}{\frac{\rho|\beta|^2}{N_p} \sum_{m \neq (p|b)} |\mathbf{f}_{Rx,m}^H \mathbf{h}_{Rx,p} \Delta_m \mathbf{h}_{Tx,p}^H \mathbf{f}_{Tx,m}|^2 + \sigma_n^2}. \quad (2.36)$$

2.4. Study III: Secure Pilot Allocation for Integrated Sensing and Communication

2.4.1. System model

This study considers a system model consisting of two legitimate nodes, Alice and Bob, and a passive eavesdropper, Eve, as shown in **Figure 2.10**. We assume a time division duplexing (TDD) mode of communication and slowly varying block fading Rayleigh channels [69]. The channel between Alice and Bob is reciprocal, with perfect CSI availability to Alice. In contrast, the channels of Eve and Bob from Alice are uncorrelated since they are supposed to be a few wavelengths apart. Alice transmits the message signal to Bob that is described as

$$x[n] = \frac{1}{\sqrt{N_s}} \sum_{k=0}^{N_s-1} X[k] \exp^{j2\pi k(n-L)/N_s}, \quad (2.37)$$

$$n = 0, 1, \dots, N_s + L - 1,$$

where $x[n]$ is the time domain OFDM signal at n -th time domain sampling index. $X[k]$ denotes modulated data symbol over the k -th subcarrier with $k = 0, 1, \dots, N_s - 1$, L denotes the cyclic prefix length such that $L \geq L_b - 1$. N_s represents the OFDM symbol size, and L_b is the maximum excess delay of Bob's channel. The signal at Bob $y_b(n)$ can be written as

$$y_b(n) = \sum_{l=0}^{L_b-1} h_b(l)x(n-l) + z_b(n) \quad (2.38)$$

where $h_b(l)$ is the multi-path channel factor, $z_b(n)$ is additive white Gaussian Noise (AWGN) added to the signal with zero mean and variance σ_b^2 . After removing the cyclic prefix and taking the fast Fourier transform (FFT), the received signal in the frequency domain $\mathbf{Y}_b \in \mathbb{C}^{N_s \times 1}$ can be written as

$$\mathbf{Y}_b = \mathbf{X}\mathbf{H}_b + \mathbf{Z}_b, \quad (2.39)$$

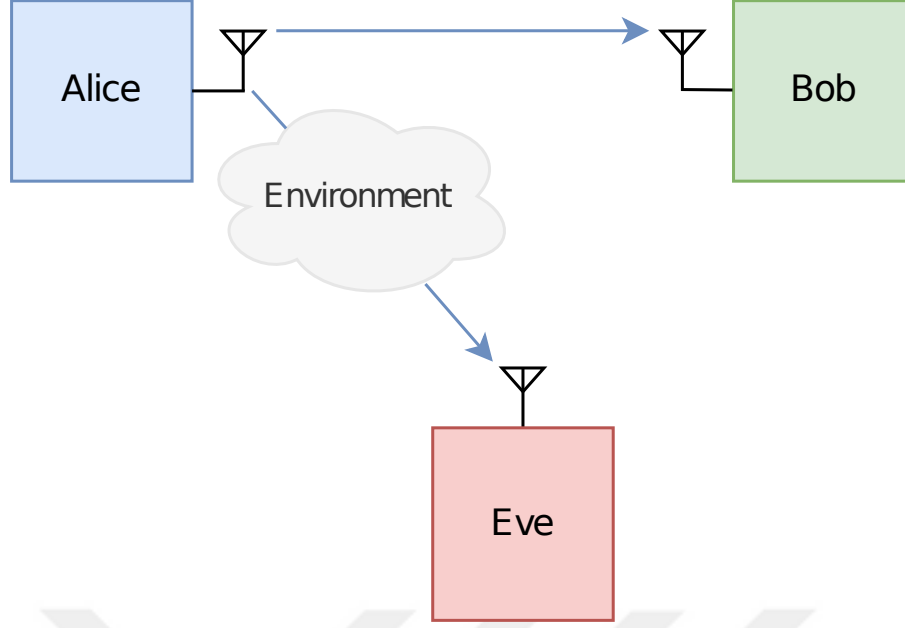


Figure 2.10: The system model for integrated sensing and communication.

where $\text{diag}\{\mathbf{X}\} \in \mathbb{C}^{N_s \times N}$, $\mathbf{H}_b \in \mathbb{C}^{N_s \times 1}$ and $\mathbf{Z}_b \in \mathbb{C}^{N_s \times 1}$ represent the transmitted signal diagonal matrix, channel frequency response with the Rayleigh distribution of $\mathcal{CN}(0, 1)$, and AWGN noise vector with $\mathcal{CN}(0, \sigma_{Z_b}^2)$, respectively. Similar to Bob, Eve also receives the signal transmitted by Alice, given by

$$y_e(n) = \sum_{l=0}^{L_e-1} h_e(l)x(n-1) + z_e(n) \quad (2.40)$$

where $h_e(l)$ is the multi-path channel between Alice and Eve with maximum excess delay of L_e , and $z_e(n)$ is AWGN with zero mean and variance σ_e^2 . For simplicity, we assume that the maximum excess delay of Eve's channel is less than or equal to L , i.e., $L_e - 1 \leq L$. Furthermore, the frequency domain representation of the signal received $\mathbf{Y}_e \in \mathbb{C}^{N_s \times 1}$ at Eve is given by

$$\mathbf{Y}_e = \mathbf{X}\mathbf{H}_e + \mathbf{Z}_e \quad (2.41)$$

where $\mathbf{H}_e \in \mathbb{C}^{N_s \times 1}$, and $\mathbf{Z}_e \in \mathbb{C}^{N_s \times 1}$ represent channel frequency response vector with the Rayleigh distribution of $\mathcal{CN}(0, 1)$, and frequency domain AWGN noise vector with $\mathcal{CN}(0, \sigma_{Z_e}^2)$, respectively. It should be noted that if Eve knows the pilot tones and their locations, she can probe into $\mathbf{Y}_e$ for extracting Bob's data in $\mathbf{X}$. Besides, she can also perform environment sensing by obtaining CSI of $\mathbf{H}_e$. Therefore, the information of pilots must be secured to prevent Eve from learning Bob's communication information and performing CSI-based sensing.

2.4.2. Proposed secure pilot allocation method for integrated sensing and communication

This section describes the proposed adaptive pilot allocation method, pilot location detection method, and APwA method for secure ISAC.

In the conventional OFDM systems, three types of pilot arrangements are available: block, comb, and lattice [179]. In a block-type structure, pilot tones are placed onto all subcarriers in an OFDM symbol over some time according to the coherence time. In comb-type arrangement, pilot tones are placed at subcarriers periodically in an OFDM symbol according to the coherence bandwidth, and interpolation is used to estimate the channel for all subcarriers. Inserting pilot tones on all subcarriers in an OFDM symbol or at all times over specific subcarriers creates an overhead, which can be minimized by inserting the pilot tones in both time and frequency with a given period, known as lattice-type arrangement. In all the pilot arrangements, equally-spaced pilot insertion is known to minimize the error in channel estimation, and the pilot's location is made available to everyone for ease of implementation [180]. However, the information about the pilot location may also be helpful for Eve in monitoring Alice's activity through CSI-based sensing or disrupting the communication between Alice and Bob. Therefore, we propose an adaptive pilot allocation based on the channel between Alice and Bob to conceal the pilot location from Eve.

2.4.2.1. Adaptive pilot allocation

For the secure pilot allocation, firstly, Alice creates N_u sub-channel blocks from H_b , with each consisting of N_c subcarriers as shown in **Figure 2.11a**. The u -th sub-channel block is defined as $I_u(c) = H_b(c)$ with $c = \{1, 2, \dots, N_c\}$. The Eve may detect the pilot location by exploiting the correlation properties in the case of correlated channel coefficients between the sub-channel blocks. Therefore, before deciding on the pilot locations, sub-channel blocks are interleaved to reduce the correlation between channel coefficients of adjacent sub-channel blocks. The sub-channel blocks are divided into two groups to perform interleaving and re-arranged by pairing the first sub-channel block from the first group with the first sub-channel block from the second group; afterward, other sub-channel blocks are paired in the same way as depicted in **Figure 2.11b**. The average power of each

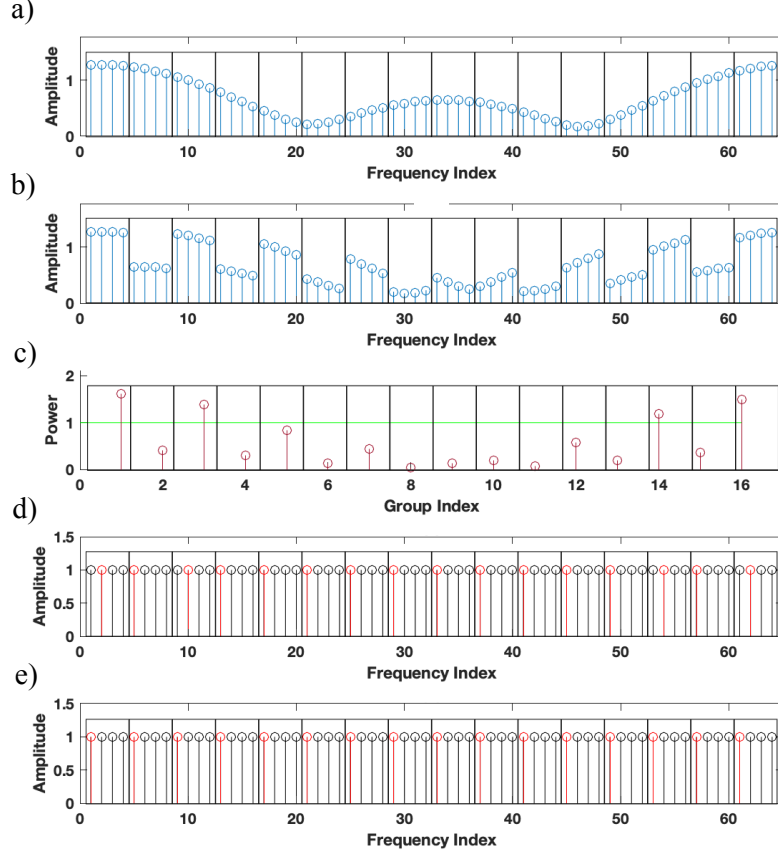


Figure 2.11: The proposed adaptive pilot allocation method for frequency selective channel; **a)** channel grouping, **b)** group interleaving, **c)** pilot location selection, **d)** pilot allocation with the proposed algorithm, **e)** conventional pilot allocation method with the equally spaced and known pilot location.

sub-channel block is measured as

$$\alpha_u = E[\hat{\mathbf{I}}_u^H \hat{\mathbf{I}}_u], \quad (2.42)$$

where $\hat{\mathbf{I}}_u \in \mathbb{C}^{N_c \times 1}$ denotes u -th interleaved sub-channel block vector, and α_u denotes its power. $E[.]$ represents the expected value, and $[.]^H$ denotes the conjugate transpose.

The next step is to decide the location of the pilot and data symbols after creating the sub-channel blocks and calculating the channel power of each block. Let's suppose Alice transmits the OFDM signal with N_s subcarriers, out of which N_ρ are the pilot subcarriers, and N_d are the data subcarriers such that $N_d = N_s - N_\rho$. N_s subcarriers are divided into N_u blocks similar to the sub-channel blocks, except interleaving is not performed in this step. Since the channel coefficients corresponding to the subcarriers within each

Algorithm 2.1 Secure Pilot Allocation

Require: $N_s, N_c, N_g, \mathbf{I}_u, N_\rho, \zeta, X_{d_u}$

```
1:  $N_u \leftarrow N_s / N_c$ 
2: procedure Block Interleaving ( $\mathbf{I}_u$ )
3:    $g = \{1, 2\}$ 
4:   if  $g = 1$  then
5:      $N_{g_1} = \{I_1, I_2, \dots, I_{N_u/2}\}$ 
6:   else if  $g = 2$  then
7:      $N_{g_2} = \{I_{(N_u/2)+1}, I_{(N_u/2)+2}, \dots, I_{N_u}\}$ 
8:   end if
9:    $\hat{\mathbf{I}}_u = \{N_{g_1}(i), N_{g_2}(i)\}, i = \{1, 2, \dots, I_{N_u/2}\}$ 
10: end procedure
11: procedure Pilot Location Selection ( $\rho_u$ )
12:   Calculate power of each interleaved sub-channel block
13:    $\alpha_u \leftarrow E[\hat{\mathbf{I}}_u^H \hat{\mathbf{I}}_u]$ 
14:   if  $\alpha_u < \zeta$  then
15:      $\rho_u \leftarrow a$ 
16:   else if  $\alpha_u \geq \zeta$  then
17:      $\rho_u \leftarrow b$ 
18:   end if
19: end procedure
20: procedure Adaptive Power Allocation ( $X_{d_u}$ )
21:   Set the power-gap  $\gamma$  value
22:   if  $\zeta - \gamma \leq \alpha_u \leq \zeta$  then
23:      $X_{d_u} * \sqrt{\zeta - \gamma}$ 
24:   else if  $\zeta \leq \alpha_u \leq \zeta + \gamma$  then
25:      $X_{d_u} * \sqrt{\zeta + \gamma}$ 
26:   end if
27: end procedure
```

subcarrier block are assumed to be approximately flat, one pilot symbol is allocated to each subcarrier block, i.e., $N_\rho = N_u$ to minimize the pilot overhead. The pilot location in the u -th subcarrier block is selected based on the following criteria

$$\rho_u = \begin{cases} a, & \alpha_u < \zeta \\ b, & \alpha_u \geq \zeta \end{cases} \quad (2.43)$$

where $\{a, b\} \in c$ are candidate pilot locations, $c = \{1, 2, \dots, N_c\}$ denotes subcarriers within a subcarrier block. The location of pilot subcarrier ρ_u in the u -th subcarrier block is selected by comparing α_u (i.e., different for Bob and Eve) with the known threshold ζ as illustrated in **Figure 2.11c**. The u -th subcarriers block after selecting pilot locations

can be written as

$$X_u[c] = \begin{cases} X_{\rho_u}, & c = \rho_u \\ X_{d_u}, & \text{otherwise}, \end{cases} \quad (2.44)$$

where X_{ρ_u} and X_{d_u} are the pilot and data symbols in the u -th subcarrier block, respectively. The final OFDM symbol vector at Alice in the frequency domain with all pilot and data symbols can be described as

$$\mathbf{X}_u = \{\mathbf{X}_1, \mathbf{X}_2, \dots, \mathbf{X}_{N_u}\}. \quad (2.45)$$

After taking the inverse fast Fourier transform (IFFT) and adding the CP according to (2.37), Alice transmits the signal to Bob. **Figure 2.11d** and **Figure 2.11e** show the difference between the proposed method and the conventional pilot allocation method. In particular, the locations of pilots are random in the proposed adaptive pilot allocation method compared to the conventional one with equally spaced known pilot locations. A detailed description of the procedures followed in the proposed method is presented in **Algorithm 2.1**.

2.4.2.2. Adaptive power allocation

Due to the dependency of PLER on signal-to-noise-ratio (SNR), a rise in PLER is expected at a high noise level as the sub-channel block's power approaches the threshold value ζ . Therefore, we propose an adaptive power location mechanism described in **Algorithm 2.1**, which reduces the PLER by maintaining a power gap γ between α_u and ζ to minimize the noise effect.

$$\hat{X}_{d_u} = \begin{cases} X_{d_u} \sqrt{\zeta - \gamma} & \zeta - \gamma \leq \alpha_u \leq \zeta \\ X_{d_u} \sqrt{\zeta + \gamma} & \zeta \leq \alpha_u \leq \zeta + \gamma, \end{cases} \quad (2.46)$$

where $\hat{X}_{d_u}$ is the transmit data symbols within u -th block of subcarriers. The signal power reduces with a value of $\sqrt{\zeta - \gamma}$ when α_u is less or equal to ζ , or greater than or equal to the difference between ζ and γ , and vice versa.

2.4.2.3. Pilot location detection

To find the pilot location, Bob first removes the CP and performs FFT to convert the $\mathbf{Y}_b$ into the frequency domain as described in (2.39). Afterwards, Bob divides the subcarriers

Algorithm 2.2 Pilot Location Detection

Require: $N_s, N_c, N_q, \hat{\mathbf{I}}_r, N_\rho, \zeta$

```

1:  $N_r \leftarrow N_s / N_c$ 
2: procedure Block De-interleaving ( $\hat{\mathbf{I}}_r$ )
3:    $q = \{1, 2\}$ 
4:   if  $g = 1$  then
5:      $N_{q_1} = \{I_1, I_3, \dots, I_{N_r} - 1\}$ 
6:   else if  $g = 2$  then
7:      $N_{q_2} = \{I_2, I_4, \dots, I_{N_r}\}$ 
8:   end if
9:    $\mathbf{I}_r = \{N_{q_1}(i), N_{q_2}(i), i = \{1, 2, \dots, I_{N_r}/2\}$ 
10: end procedure
11: procedure Pilot Location Delection ( $\rho_r$ )
12:   Calculate power of each interleaved sub-channel block
13:    $\alpha_r \leftarrow E[\mathbf{I}_r^H \mathbf{I}_r]$ 
14:   if  $\alpha_r < \zeta$  then
15:      $\rho_r \leftarrow a$ 
16:   else if  $\alpha_r \geq \zeta$  then
17:      $\rho_r \leftarrow b$ 
18:   end if
19: end procedure

```

in $\mathbf{Y}_b$ into N_r blocks (i.e., $N_r = N_u$), where r -th subcarrier block with N_c subcarriers is defined as $\mathbf{I}_r(c) = \mathbf{Y}_b(c)$, $c = \{1, 2, \dots, N_c\}$. The de-interleaving of subcarrier blocks is performed according to **Algorithm 2.2**. Then the average power of each de-interleaved subcarrier block vector $\hat{\mathbf{I}}_r \in \mathbb{C}^{N_c \times 1}$ is measured, i.e., $\alpha_r = E[\mathbf{I}_r^H \mathbf{I}_r]$ and compared with known ζ . The location of the pilot in the r -th subcarrier block ρ_r is detected as

$$\rho_r = \begin{cases} a, & \alpha_r < \zeta \\ b, & \alpha_r \geq \zeta. \end{cases} \quad (2.47)$$

The detection mechanism is repeated until the pilot locations are known in all subcarrier blocks. The probability of erroneous pilot location detection is given by

$$p_{ler} = \frac{1}{N_r} \sum_{r=1}^{N_r} [P(\rho_r = b | \rho_r = a) + P(\rho_r = a | \rho_r = b)]. \quad (2.48)$$

Now PLER can be measured by dividing the pilot locations in error by N_ρ . The similar approach as Bob is applied to calculate PLER at Eve. After finding the pilot locations in all subcarrier blocks, the pilot symbols from the received signal can be extracted as

$$Y_{b,\rho}[\rho_r] = I_r[\rho_r] \quad (2.49)$$

where $Y_{b,\rho}[\rho_r]$ is the pilot symbol present in un-interleaved I_b subcarrier block of received signal, and pilot symbol vector is defined as $\mathbf{Y}_\rho \in \mathbb{C}^{N_\rho \times 1}$. We consider LSE for channel estimation from the received detected pilots. The estimated channel vector $\tilde{\mathbf{H}}_b \in \mathbb{C}^{N_\rho \times 1}$ at Bob is given by

$$\tilde{\mathbf{H}}_b = \mathbf{X}_\rho^{-1} \mathbf{Y}_\rho, \quad (2.50)$$

where $\mathbf{X}_\rho \in \mathbb{C}^{N_\rho \times 1}$ denotes the pilot symbols generated at Bob, respectively. Furthermore, interpolation is performed to estimate the CSI of all subcarriers [181]. We measure the performance in terms of MSE between Bob's actual channel and the estimated channel that is defined as

$$MSE_{Bob} = \mathbb{E}[(\mathbf{H}_b - \tilde{\mathbf{H}}_b)^2]. \quad (2.51)$$

Since Bob's channel is different from Eve's channel, she cannot estimate Bob's channel, and the MSE for each of them is measured according to their estimated channels. It should be noted that Eve tries to estimate the CSI of its channel from the received signal following the similar mechanism as Bob. Therefore, we define the MSE for channel estimation at Eve as

$$MSE_{Eve} = \mathbb{E}[(\mathbf{H}_e - \tilde{\mathbf{H}}_e)^2]. \quad (2.52)$$

where $\tilde{\mathbf{H}}_e = \mathbf{X}_\rho^{-1} \mathbf{Y}_{e,\rho}$ is the estimated channel while $\mathbf{Y}_{e,\rho}$ represent the detected pilot symbols at Eve. If all the pilots' locations are detected correctly and the perfect channel estimation is performed, then BER of the proposed system is expected to approach the BER of the benchmark OFDM, which can be defined in the following manner

$$p_{ber} = \frac{1}{2} \left(1 - \sqrt{\frac{\beta}{1 + \beta}} \right), \quad (2.53)$$

where $\beta = E_b/N_0$ denotes the bit-energy-to-noise ratio.

2.5. Study IV: User Pairing and Power Allocation Strategies for 3D VLC-NOMA Systems

2.5.1. VLC system and channel models

We consider a living room in which multiple users are distributed randomly in the coverage area of an access point access point (AP) with a single light-emitting diode (LED).

Each user is located at different vertical and horizontal distances from the LED and other users. An AP can serve multiple users through NOMA in line-of-sight (LoS) link. The considered 3D VLC-NOMA system setup is shown in **Figure 2.12**, in which a single LED serves U_k users located at a distance d_k from the LED, where $k = \{1, 2, \dots, K\}$. L_k is the distance between the LED plane and the receiver's plane, and r_k denotes the horizontal distance from the cell center for the k th user. VLC channel with LoS link can be modeled using the Lambertian channel model [182]. Thus, the channel gain between LED and k th user can be calculated as

$$h_k = \frac{(v+1)\cos^v(\Phi_k)}{2\pi d_k^2} A_k T_k \cos(\theta_k) g(\theta_k), \quad (2.54)$$

where Φ_k , and θ_k represent the angle of irradiance, and the angle of incidence of k th user, respectively. A_k denotes the area of photodiode (PD) and T_k is the optical filter gain. $v = \frac{-\ln(2)}{\ln(\cos(\Phi_{1/2}))}$ is the Lambertian emission order with LED's semi-angle $\Phi_{1/2}$, $g(\theta_k)$ is the optical concentrator gain, whose value is $q^2/\sin^2(\theta_k)$ if $0 < \theta_k < \Theta_{Fk}$, otherwise it is 0. q is the refractive index, and Θ_{Fk} is the PD's field of view.

Alternatively, the LoS channel gain can be represented in terms of L_k and r_k by substituting $d_k = \sqrt{r_k^2 + L_k^2}$ and $\frac{A_k g(\theta_k) T_k}{2\pi} = \rho_k$ in (2.54), which yields

$$h_k = \frac{\rho_k (v+1) L_k^{v+1}}{(r_k^2 + L_k^2)^{\frac{v+3}{2}}}. \quad (2.55)$$

In NOMA, different users are allocated with different powers depending on their distances from the transmitter. Specifically, users with poor channel conditions get more power than users with better channel conditions. Suppose M users are selected out of K users for pairing with channel gains $h_1 \leq h_2 \leq h_3 \dots \leq h_m \leq \dots \leq h_M$, where h_m denotes the channel gain of m th user in a pair. Let x_m be the information signal of the m th user in a pair, where $m = \{1, 2, \dots, M\}$, then the superposed NOMA signal z_m received by m th user can be expressed as

$$z_m = \Gamma P_t h_m \sum_{m=1}^M \sqrt{\beta_m} x_m + w_m, \quad (2.56)$$

where Γ , P_t , h_m are respectively, the conversion energy efficiency constant, total transmit power, and the channel gain of the m th user. β_m is the power allocation coefficient which follows $\beta_1 \geq \beta_2 \geq \dots \geq \beta_m \geq \dots \geq \beta_M$. w_m represents the additive white Gaussian noise with zero mean, and $\sigma_m^2 = \eta_0 T_B$ is the variance, in which η_0 denotes the constant power

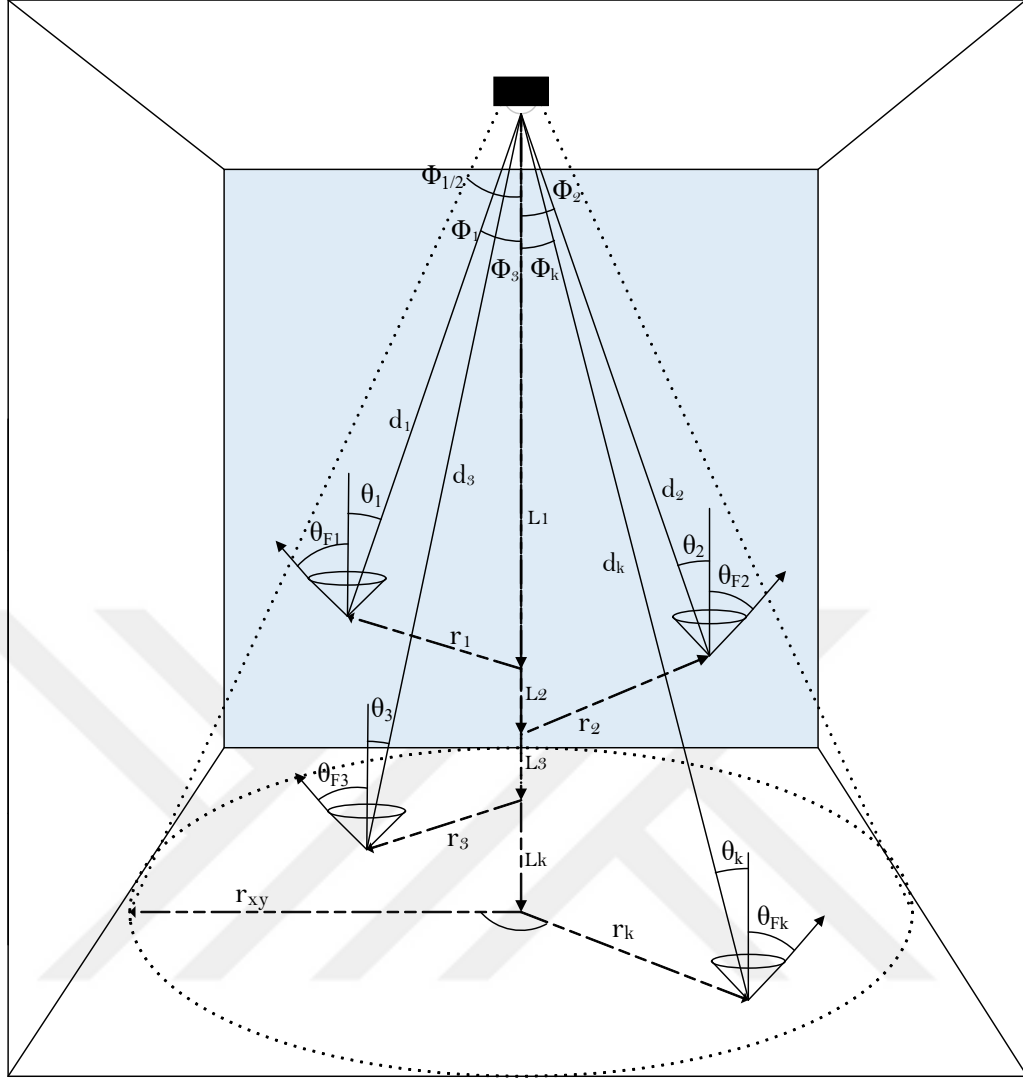


Figure 2.12: 3D VLC-NOMA system model.

spectral density and T_B denotes the transmission bandwidth of the signal [77].

2.5.2. User pairing and power allocation schemes

In 3D VLC systems, when compared to its 2D version, it is more probable to have users with similar channel gains because of different users' heights. This is one of the main reasons for the performance degradation of NOMA schemes. Thus, smart user pairing schemes group the users with maximum channel gain differences for high-performance gains and reduced complexity. Next, we describe the two proposed user pairing schemes for two different situations: an even number of users and an odd number of users.

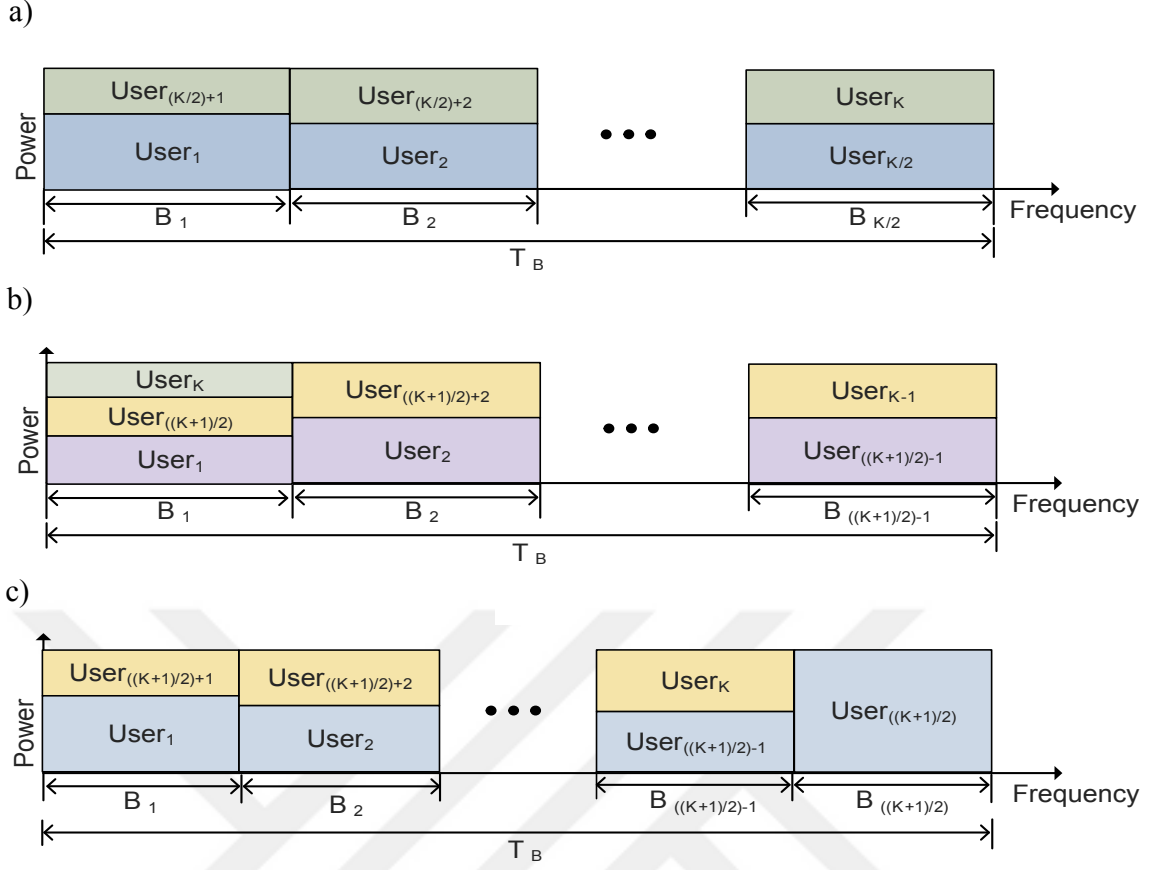


Figure 2.13: Proposed user pairing schemes and resource allocation: **a)** even number of users, **b)** UP Scheme-I for an odd number of users, **c)** UP Scheme-II for an odd number of users.

2.5.3. Even number of users

Both schemes follow the same user grouping and pairing strategies for U_k users when there are even number of users deployed in the coverage area. Specifically, these users are first sorted out in ascending order based on their channel gains. Then, they are divided into g groups, i.e., $g \in \{1, 2\}$, where group g_1 contains users first half of the sorted users starting from U_1 to $U_{K/2}$, and group g_2 contains second half users starting from $U_{(K/2)+1}$ to U_K . In order to perform user pairing, one user is selected from each group starting from low channel gain users and paired them together as shown in **Figure 2.13a**. By following a similar pattern, all the users are divided into pairs, and e_l represents the pair of l th user of each group, where $l = \{1, 2, \dots, N_{(k/2)}\}$. A significant channel gain difference is maintained among users within each pair.

2.5.4. Odd number of users

In the case of odd number of users, three groups of users are formed, i.e., $g \in \{1, 2, 3\}$, in which group g_1 contains users from U_1 to $U_{((K+1)/2)-1}$, group g_2 contains users from $U_{((K+1)/2)+1}$ to U_K , and group g_3 contains only the middle user $U_{((K+1)/2)}$. Both schemes follow the similar grouping strategy but the users are paired differently in each scheme.

In UP Scheme-I, after dividing the users into three groups, users are divided into pairs in which a_l represents the pair of l th user in a group, where $l = \{1, 2, \dots, N_{((K+1)/2-1)}\}$, as shown in **Figure 2.13b**. The first pair contains three users, which are: The first user (weakest user) from group g_1 , a middle user from group g_3 , and the last user (strongest user) from group g_2 . However, the rest of the pairs are made from the remaining users in groups g_1 and g_2 by selecting one user from each group sequentially according to **Algorithm 2.3**.

In UP Scheme-II, b_l represents the pair of l th user in a group, where $l = \{1, 2, \dots, N_{((K+1)/2)}\}$. The first user (weakest user) from group g_1 is chosen and paired with the first user (weakest user) from group g_2 , as shown in **Figure 2.13c**. Other pairs are formed in the same manner, as described in **Algorithm 2.4**. The only difference between UP Scheme-I and UP Scheme-II is that the middle user is not paired with the latter, and contains separate power and bandwidth resources.

2.5.5. Complexity

Complexity behind the proposed schemes maybe evaluated in terms of the number of users K who carry out SIC. Keeping this in mind, for an even number of users, both schemes have exactly the same complexity, i.e., $K/2$. On the other hand, assuming an odd number of users, UP Scheme-I and UP Scheme-II have computational complexities of $((K+1)/2)+1$ and $(K-1)/2$, respectively, which are indeed quite similar. For instance, assuming $K = 23$, UP Scheme-I and UP Scheme-II have complexities of 13 and 11, respectively.

2.5.6. Power and resource allocation strategies

In order to analyze the performance of the NOMA in the proposed 3D VLC system, FTPA and IPLS are used, which are based on GRPA. In the FTPA scheme, the power to each

Algorithm 2.3 User Pairing Scheme I

```
1: procedure Total Users( $U_K$ )
2:    $k = \{1, 2, \dots, K\}$ 
3:   Sort user in ascending order based on channel gains
4:    $\{h_1 < h_2 < \dots < h_K\}$ 
5:   if  $\text{mod}(K/2) = 0$  then
6:     User Grouping
7:      $g_1 = \{U_1, U_2, \dots, U_{K/2}\}$ 
8:      $g_2 = \{U_{(K/2)+1}, U_{(K/2)+2}, \dots, U_K\}$ 
9:     User pairing into  $N_{K/2}$  pairs
10:     $e_l = \{g_1(l), g_2(l)\}, l = \{1, 2, \dots, N_{K/2}\}$ 
11:  else
12:    User Grouping
13:     $g_1 = \{U_1, U_2, \dots, U_{((K+1)/2)-1}\}$ 
14:     $g_2 = \{U_{((K+1)/2)+1}, U_{((K+1)/2)+2}, \dots, U_K\}$ 
15:     $g_3 = \{U_{((K+1)/2)}\}$ 
16:    User pairing into  $N_{(K+1)/2-1}$  pairs
17:     $a_l = \{g_1(l), g_3(l), g_2((K+l)/2 - 1)\}, l = \{1\}$ 
18:     $a_l = \{g_1(l), g_2(l)\}, l = \{2, \dots, N_{(K+1)/2-1}\}$ 
19:  end if
20: end procedure
```

Algorithm 2.4 User Pairing Scheme II

```
1: procedure Total Users( $U_K$ )
2:    $k = \{1, 2, \dots, K\}$ 
3:   Sort user in ascending order based on channel gains
4:    $\{h_1 < h_2 < \dots < h_K\}$ 
5:   if  $\text{mod}(K/2) = 0$  then
6:     User Grouping
7:      $g_1 = \{U_1, U_2, \dots, U_{K/2}\}$ 
8:      $g_2 = \{U_{(K/2)+1}, U_{(K/2)+2}, \dots, U_K\}$ 
9:     User pairing into  $N_{K/2}$  pairs
10:     $e_l = \{g_1(l), g_2(l)\}, l = \{1, 2, \dots, N_{K/2}\}$ 
11:  else
12:    User Grouping
13:     $g_1 = \{U_1, U_2, \dots, U_{((K+1)/2)-1}\}$ 
14:     $g_2 = \{U_{((K+1)/2)+1}, U_{((K+1)/2)+2}, \dots, U_K\}$ 
15:     $g_3 = \{U_{((K+1)/2)}\}$ 
16:    User pairing into  $N_{(K+1)/2}$  pairs
17:     $b_l = \{g_1(l), g_2(l)\}, l = \{1, 2, \dots, N_{(K+1)/2-1}\}$ 
18:     $b_l = \{g_3\}, l = \{N_{(K+1)/2}\}$ 
19:  end if
20: end procedure
```

user in a pair is allocated using the following expression as [183]:

$$\beta_m = \frac{(h_m^2)^{-\alpha}}{\sum_{j=1}^M (h_j^2)^{-\alpha}}, \quad (2.57)$$

where $0 < \alpha < 1$ is the power allocation coefficient. The second scheme that is used for

power allocation is improved form of PLS. Power allocation to the m th user in a group using IPLS scheme can be described as [184]:

$$\beta_m = \begin{cases} \frac{1}{1 + \left(\frac{h_1}{h_2}\right) + \dots + \left(\frac{h_1}{h_m}\right)}, m = 1 \\ \frac{\left(\frac{h_1}{h_m}\right)}{1 + \left(\frac{h_1}{h_2}\right) + \dots + \left(\frac{h_1}{h_m}\right)}, 2 \leq m \leq M. \end{cases} \quad (2.58)$$

The bandwidth resource is divided equally among all the pairs of users and the total bandwidth can be written as $T_B = B_l \times N$, where B_l , and N transmission bandwidth of each pair, and the total number of pairs, respectively.

CHAPTER 3

3. EXPERIMENTAL PART

3.1. Study I: Interference-Free Backscatter Communications for OFDM-Based Symbiotic Radio

The Rx receives the signal expressed in (2.8). After removing the CP and taking the N -point discrete Fourier transform (DFT), the received signal can be written as

$$\begin{aligned} Y[k] &= Y_d[k] + Y_b[k] + W[k] \\ &= H_d[k]X[k] + \Gamma_b H_f[k]H_b[k]X[k]B[k] + W[k] . \end{aligned} \quad (3.1)$$

where $Y[k]$ denotes the received symbol on the k -th subcarrier with $Y_d[k]$, $Y_b[k]$, $H_f[k]$, $H_b[k]$ and $W[k]$ representing $y_d[n]$, $y_b[n]$, $h_f[n]$, $h_b[n]$ and $w[n]$ in the frequency domain, respectively. $B[k]$ is the Fourier transform of $b[n]$. Since the data from the BD and BS are received at the different subcarriers, we can write the received signal from BS and BD separately as

$$\hat{Y}_d[\hat{k}] = Y[\hat{k}] = H_d[\hat{k}]X[\hat{k}] + W_d[\hat{k}] , \quad (3.2)$$

and

$$\hat{Y}_b[\tilde{k}] = Y[\tilde{k}] = \Gamma_b H_f[\tilde{k}]X[\tilde{k}]H_b[\tilde{k}] + W_b[\tilde{k}] , \quad (3.3)$$

where $\hat{k} \in \mathcal{K}_d$ and $\tilde{k} \in \mathcal{K}_b$ represent the index of subcarriers containing data of the BS and BD, respectively. According to the the BD's modulation, we can express $X[\tilde{k}]$ as

$$X[\tilde{k}] = \begin{cases} 0, & b[n] = 0 \\ \Gamma_b X_d[k + \zeta], & b[n] = e^{\frac{-j2\pi f_\zeta n}{N}} \\ \Gamma_b X_d[k - \zeta], & b[n] = e^{\frac{j2\pi f_\zeta n}{N}} \end{cases} . \quad (3.4)$$

3.1.1. Non-coherent detector for OOK

In the case of binary transmission from the BD with OOK modulation, $\hat{Y}_b[\tilde{k}]$ can be expressed as

$$\hat{Y}_b[\tilde{k}] \triangleq \begin{cases} W_b[\tilde{k}], & b = 0 \\ Y_b[\tilde{k}] + W_b[\tilde{k}], & b = 1 \end{cases}, \quad (3.5)$$

where the $W_b[\tilde{k}] \sim \mathcal{CN}(0, \sigma_{W_b}^2)$. For a large value of N , the OFDM signal backscatter by BD with OOK $Y_b[\tilde{k}]$ is a sequence of random variables and follows the circularly-symmetric complex Gaussian distribution with zero mean and variance $\sigma_{Y_b}^2 = |\Gamma_b|^2 |H_b|^2 \sum_{\tilde{k}=0}^{N_b-1} |H_f(\tilde{k})|^2$. Without the loss of generality, we assume here that $\zeta = 1$ then $|\mathcal{K}_b| = |\mathcal{K}_d| = N_b$, and $N_b = N_d = N/2$ because received BD signal detection depends on data symbols transmitted by BS. N_b and N_d represent the total number of null subcarriers and data subcarriers in an OFDM symbol transmitted by the BS. After receiving the signal from BS and BD, the Rx needs to detect these signals to retrieve the information. To detect the signal of BD, a non-coherent detector is used at Rx while considering that the data of the Rx is detected in a conventional manner using a coherent detector because both devices' data are received over the orthogonal subcarriers. As the non-coherent detector does not require phase information, it can be used in different types of SR systems with common Rx for BS and BD or separate Rx for each such as user equipment and ambient Rxs. However, in coherent detection, Rx needs to know H_d , H_f , and H_d at Rx, which can be estimated at the common receiver by joint pilot design [49], but may not be easily estimated by the ambient Rx.

To detect the OOK signal, Rx only needs to know the placement of the data and null-subcarriers in the transmitted OFDM signal without the knowledge of the $S[\hat{k}]$ or the channels h_d , h_f , and h_b . The information in $B[\tilde{k}]$ transmitted by shifting or not shifting the $S[\hat{k}]$ from $X[\hat{k}]$ to $X[\tilde{k}]$ can be acquired by detecting the energy at $X[\tilde{k}]$ subcarriers. Let $\mathcal{H}_0$ be the hypothesis for the likelihood of detecting the signal (i.e., $b = 1$) at the receiver when no signal was transmitted, (i.e., $b = 0$). This situation occurs when the received signal energy exceeds a predefined threshold. On the other hand, let $\mathcal{H}_1$ be the hypothesis for the likelihood of detecting no signal, i.e., $b = 0$ when the signal was transmitted, i.e., $b = 1$. This situation occurs when the received signal energy is below a threshold. To test

these two hypotheses, we define a test statistic r based on $\hat{Y}_b[\tilde{k}]$

$$r = \sum_{\tilde{k}=0}^{N_b-1} |\hat{Y}_b[\tilde{k}]|^2. \quad (3.6)$$

We can also write the r according to the information transmitted by BD as

$$r = \begin{cases} \sum_{\tilde{k}=0}^{N_b-1} |W_b[\tilde{k}]|^2, & b = 0 \\ \sum_{\tilde{k}=0}^{N_b-1} |H_f[\tilde{k}]X[\tilde{k}]H_b[\tilde{k}] + W_b[\tilde{k}]|^2, & b = 1 \end{cases}. \quad (3.7)$$

Under $\mathcal{H}_0$ when BD transmits bit '0', the subcarriers allocated for BC only contain noise, and $r = r_0$ is the sum of the square of the $2N_b$ Gaussian random variables. We need to find the distribution of $\Pr(r|B = 0)$ by considering that the square of the sum of two Gaussian random variables (i.e., the real and imaginary part of the noise signal) follows the exponential distribution. However, to find the distribution of the sum of N_b exponential random variables, we need to perform $N_b - 1$ convolution operation equivalent to taking $N_b - 1$ integrals, which is a very cumbersome task. As W_b is a circularly symmetric complex Gaussian random variable, the characteristic function of $|W_b|^2$ is $(1 - it\lambda^{-1})^{-1}$, which is the Fourier transform of its probability density function (PDF). For the given $r = r_0$, we can find the characteristic function as

$$\Phi_{r_0}(t) = E[e^{itx}] = \prod_{\tilde{k}=1}^{N_b} \frac{1}{1 - it\lambda_{\tilde{k}}^{-1}}, \quad (3.8)$$

where $\lambda_{\tilde{k}}^{-1} = 2\sigma_{w,\tilde{k}}^2$. Then, the PDF of $\Pr(r|B = 0)$ is obtained from characteristic function as

$$f_{r_0}(x) = \int_{-\infty}^{\infty} \frac{1}{2\pi jt} \Phi_{r_0}(t) e^{-jtz} dt. \quad (3.9)$$

On the other hand, under $\mathcal{H}_1$, the distribution of $\Pr(r|B = 1)$ becomes complicated because of the dependence on the cascaded channels $h_f[n]$ and $h_b[n]$. For a given $h_b[n]$, the PDF of the cascaded backscatter channel is derived in **Lemma 3.1.1**.

Lemma 3.1.1. *Let $h_b[n]$ have a single path and have a constant value during one OFDM symbol due to the short distance between BD and Rx. Then, considering $v = |h_b|$ the PDF of $r = r_1$ becomes*

$$f_{r_1|v}(x) = \int_{-\infty}^{\infty} \frac{1}{2\pi jt} \Phi_{r_1|v}(t) e^{-jtz} dt, \quad (3.10)$$

where $\Phi_{r_1}(t) = (1 - it\lambda_{\tilde{k}}^{-1})^{-1}$ is the characteristic function, and $\lambda_{\tilde{k}}^{-1} = 2\Gamma_b v^2 \sum_{\tilde{k}=0}^{N_b-1} \sigma_{h,\tilde{k}}^2 +$

$$\sigma_w^2.$$

Proof. The proof of **Lemma 3.1.1** is given in **Appendix A.1**. $\square$

In the present system design, we measure the performance in terms of the probability of error for the non-coherent detector, which is obtained by summing the probability of false alarm (PFA) and probability of miss detection (PMD). The probability of error for given PFA and PMD is expressed as

$$P_e = \frac{1}{2}P_{MD} + \frac{1}{2}P_{FA}. \quad (3.11)$$

We can find the P_{MD} and P_{FA} for a given threshold value η as

$$\begin{aligned} P_{FA}(\eta) &= \Pr(r > \eta | B = 0) \\ &= 1 - \Pr(r < \eta | B = 0) \\ &= 1 - F_r(\eta), \end{aligned} \quad (3.12)$$

and,

$$\begin{aligned} P_{MD}(\eta) &= \Pr(r < \eta | B = 1). \\ &= F_r(\eta). \end{aligned} \quad (3.13)$$

where $F_r(\eta)$ is the cumulative distribution function (CDF) of r , which can be calculated from (3.9) according to the inversion formula given in [185]:

$$F_r(\eta; v) = \frac{1}{2} - \int_{-\infty}^{\infty} \frac{1}{2\pi jt} \Phi_{r_1|v}(t) e^{-jtz} dt. \quad (3.14)$$

The decision threshold should be chosen such that it minimizes P_e as

$$\tilde{\eta} = \underset{\eta}{\operatorname{argmin}} P_e(\eta). \quad (3.15)$$

If we consider a fixed P_{FA} and try to minimize P_{MD} , we can find $\tilde{\eta}$ that minimizes P_e . After fixing P_{FA} , we search for a given $\sigma_{w_b}^2$ by using a one-dimensional linear search to find the optimal threshold [155]. Then, we use $\tilde{\eta}$ to calculate the minimum P_e .

Now, we can find the CDF for v as a Rayleigh random variable, which is written as

$$\begin{aligned} F_r(\eta) &= \int_0^{\infty} F_r(\eta; v) f(v) dv \\ &= \int_0^{\infty} \left(\frac{1}{2} - \int_{-\infty}^{\infty} \frac{1}{2\pi jt} \Phi_{r_1|v}(t) e^{-jtz} dt \right) f(v) dv \\ &= \frac{1}{2} \int_0^{\infty} f(v) dv - \int_0^{\infty} \int_{-\infty}^{\infty} \left(\frac{1}{2\pi jt} \Phi_{r_1|v}(t) e^{-jtz} dt \right) f(v) dv, \end{aligned} \quad (3.16)$$

where $f(v) = \frac{v}{\sigma_v^2} e^{-\frac{v^2}{\sigma_v^2}}$. There is no closed-form solution of $F_r(\eta)$; however, we can compute the integrals using any software.

3.1.2. Non-coherent detector for FSK

Let $\mathcal{K}_{b_0}$, and $\mathcal{K}_{b_1}$ represent the set of null subcarriers dedicated for BD bit '0' and bit '1', respectively. The RX then calculates metrics for information bits '0' and '1' as

$$\begin{aligned} r_0 &\triangleq \sum_{\tilde{k} \in \mathcal{K}_{b_0}} |Y[\tilde{k}]|^2 \\ &= \sum_{\tilde{k} \in \mathcal{K}_{b_0}} |H_d[\tilde{k}]X[\tilde{k}] + H_f[\tilde{k}]\Gamma_b X[\tilde{k}]H_b[\tilde{k}] + W[\tilde{k}]|^2, \end{aligned}$$

and,

$$\begin{aligned} r_1 &\triangleq \sum_{\tilde{k} \in \mathcal{K}_{b_1}} |Y[\tilde{k}]|^2 \\ &= \sum_{\tilde{k} \in \mathcal{K}_{b_1}} |H_d[\tilde{k}]X[\tilde{k}] + H_f[\tilde{k}]\Gamma_b X[\tilde{k}]H_b[\tilde{k}] + W[\tilde{k}]|^2. \end{aligned}$$

Finally, it detects the BD's information by comparing the values of r_0 and r_1 as

$$\tilde{b} = \begin{cases} 0, & r_0 > r_1 \\ 1, & r_0 < r_1 \end{cases}, \quad (3.17)$$

where $\tilde{b}$ is the detected BD information.

The BER of the non-coherent detector can be expressed as

$$P_e = \frac{1}{2} \Pr(\tilde{b} = 1 | b = 0) + \frac{1}{2} \Pr(\tilde{b} = 0 | b = 1), \quad (3.18)$$

where

$$\begin{aligned} \Pr(\tilde{b}|b) &\triangleq \begin{cases} \Pr(r_0 - r_1 < 0), & b = 0 \\ \Pr(r_0 - r_1 > 0), & b = 1 \end{cases}, \\ &= \begin{cases} F_{r_0-r_1}(\eta), & b = 0 \\ 1 - F_{r_0-r_1}(\eta), & b = 1 \end{cases}, \end{aligned} \quad (3.19)$$

where $F_{r_0-r_1}(\eta)$ is the CDF of $r_0 - r_1$, obtained as follows:

Theorem 3.1.2. The CDF of $r_0 - r_1$ can be calculated as:

$$F_{r_0-r_1}(\eta) = \int_0^\infty F_{r_0-r_1}(\eta; \nu) f(\nu) d\nu, \quad (3.20)$$

where

$$F_{r_0-r_1}(\eta; \nu) = \frac{1}{2} - \int_{-\infty}^\infty \left(\frac{\Phi_{r_0|\nu}(t) \Phi_{r_1|\nu}(t)^*}{2\pi j t} e^{-j t z} \right) dt, \quad (3.21)$$

where $\nu = |h_b|$ is the backscatter channel gain with $f(\nu) = (\nu/\sigma_v^2) \exp(-\nu^2/\sigma_v^2)$. The characteristic functions $\Phi_{r_0|\nu}(t)$, and $\Phi_{r_1|\nu}(t)$ are given by

$$\Phi_{r_0|\nu}(t) = \frac{1}{1 - i t \lambda_{\tilde{k}}^{-1}}, \quad (3.22)$$

and,

$$\Phi_{r_1|\nu}(t) = \frac{1}{1 - i t \lambda_{\tilde{k}}^{-1}}, \quad (3.23)$$

respectively, for $\lambda_{\tilde{k}}^{-1} = 2\Gamma_b \nu^2 \sum_{\tilde{k}=0}^{N_b-1} \sigma_{h,\tilde{k}}^2 + \sigma_w^2$.

Proof. The proof of **Theorem 3.1.2** is given in **Appendix A.2**. $\square$

Although $F_{r_0-r_1}(\eta)$ in (3.20) is not a closed-form expression, it is an analytical solution that can be easily evaluated via numerical integration, and the BER in (3.19) can be calculated accordingly.

In the experimental part, we first study the performance of the primary user in OFDM-based SR in the presence of BC and compare it with the techniques in [1], [2]. We consider a primary system with binary phase shift keying (BPSK) modulation for $N \in \{64, 128, 256, 512\}$, and cyclic prefix length $N_{CP} = N/8$. The information at the BD is modulated with binary FSK modulation. We consider various reflection coefficients with $\Gamma_b \in \{0.1, 0.25, 0.50, 0.75, 0.9, 1\}$.

3.2. Study II: Beam Selection for Ambient Backscatter Communication in Beamspace mmWave Symbiotic Radio

We consider the following set of parameters for the simulations: $N_{Tx} = 256$, $N_{Rx} = 16$, $N_s = N_p = 4$. The path gains $|\alpha_b|^2$ and $|\alpha_l|^2$ are considered to be between -5dB to -10dB for single bounce paths [176]. Furthermore, we assume $\Gamma_b = 0.1$ when the BD is non-reflecting and $\Gamma_b = 0.9$ when BD is reflecting.

3.3. Study III: Secure Pilot Allocation for Integrated Sensing and Communication

We assume 5-tap frequency selective channels in the simulations. The data bits are modulated using BPSK modulation. The number of total subcarriers N_s in an OFDM symbol is considered 64, which is divided into the number of subcarrier blocks of 4, 8, and 16, respectively. Each subcarrier block contains one pilot tone; thus, the total number of pilot symbols is equal to the number of sub-channel blocks, i.e., $N_u = N_r = N_p$. We consider the first two subcarriers as possible pilot symbol locations $a = 1$ and $b = 2$ where the pilot symbol is inserted on one of these locations based on the proposed adaptive pilot allocation scheme described in **Subsection 2.4.2.1**. The value of the channel power threshold ζ is 1. The power gap threshold γ is assumed to be 0.2 to analyze the performance gains of APwA presented in **Subsection 2.4.2.2**. We have performed Monte Carlo simulations with independent trials of 10^{-5} to ensure the validity of the simulation results.

3.4. Study IV: User Pairing and Power Allocation Strategies for 3D VLC-NOMA Systems

In the NOMA scheme, users with different power levels are superposed together, so users with high channel gains receive interference from users with low channel gains. In order to recover the signal, stronger users perform SIC to remove the signals of weak users from the received signal. The data rate of the m th user can be calculated as

$$D_m = \frac{T_B}{2N} \log_2 \left(1 + \frac{\Gamma \zeta (h_m \beta_m)^2}{\zeta (h_m)^2 \sum_{e=m+1}^M (\beta_e)^2 + 1} \right), \quad (3.24)$$

where SNR is denoted by $\zeta = P_t / \eta_0 T_B$. From (3.24), AUDR can be calculated as

$$S = \frac{1}{N \cdot M} \sum_{n=1}^N \frac{T_B}{2N} \left[\sum_{m=1}^{M-1} \cdot \log_2 \left(1 + \frac{\Gamma \zeta (h_m \beta_M)^2}{\zeta (h_m)^2 \sum_{e=m+1}^M (\beta_e)^2 + 1} \right) + \log_2 \left(1 + \Gamma \zeta (h_M \beta_M)^2 \right) \right], \quad (3.25)$$

where N denotes the total number of pairs, and it depends on the user pairing scheme being used.

We analyze the AUDR gains of the proposed NOMA user pairing schemes in 3D VLC sys-

Table 3.1: Simulation parameters

Symbol	Parameters	Value
R_s	Room Size	$6 \times 6 \times 3 \text{ m}^3$
P_t	Transmitted Power	2 W
T_B	Bandwidth of LED	20 MHz
L_h	LED Height from ground	3 m
Φ_k	Semi-angle of LED	60°
Ω	Conversion energy efficiency constant	0.53 A/W
T_k	Optical-filter gain	1
q	Refractive Index	1.5
L_k	Heights of user (m)	0.6, 0.9, 1.1, 1.7
A	Area of PD	10^{-4} m^2
Θ_{Fk}	PD's Field of View	70°
η_0	Noise power spectral density	$10^{-19} \text{ A}^2/\text{Hz}$

tems with two power allocation schemes, i.e., FTPA and IPLS. Furthermore, it is assumed that NOMA with perfect SIC is performed for intra-pair users and OMA is performed for inter-pair users. The performance of the proposed NOMA user pairing schemes is compared with NOMA-WP and OMA. Simulation parameters for VLC systems, given in **Table 3.1**, are selected from the studies reported in [76], [183], [184], to sustain the validity of proposed UP schemes. Users are located randomly at four-different heights, which can be height of man in standing-position at 1.7 m, man sitting on couch holding the device near to his ear at 1.1 m, device over dinner table at 0.9 m, and device over coffee table at 0.6 m, as proposed in IEEE 802.15.7r1 reference model for living room [186].

CHAPTER 4

4. RESULTS AND DISCUSSION

This chapter presents the results and discussions pertaining to the research outlined in previous chapters. **Section 4.1** provides numerical and simulation results for interference-free BC in OFDM-based SR. In **Section 4.2**, we explore simulation results related to beam selection for AmBackCom in mmWave SR. **Section 4.3** discusses simulation outcomes for secure pilot allocation in ISAC systems. Finally, we present results and discussions on user pairing and power allocation strategies for 3D VLC NOMA systems in **Section 4.3**.

4.1. Results of Study I

4.1.1. Numerical results

In this section, we evaluate the proposed scheme numerically. We first study the performance of the primary user in OFDM-based SR in the presence of BC and compare it with the techniques in [1], [2]. The baseline scheme in [2] utilizes the guard subcarriers for the BC, which are left in the OFDM symbol in the LTE standard for interference mitigation. Furthermore, the number of guard subcarriers is selected according to the channel bandwidth and subcarrier spacing. For instance, 64 subcarriers are left in the LTE with a 10 MHz bandwidth [187]. Since the primary signals in [1] and [2] are not designed symbiotically, they cause interference to data subcarriers, resulting in increasing BER for the primary communication. We consider a primary system with BPSK modulation for $N \in \{64, 128, 256, 512\}$, and $N_{CP} = N/8$. The information at the BD is modulated with binary FSK modulation. We consider various reflection coefficients with $\Gamma_b \in \{0.1, 0.25, 0.50, 0.75, 0.9, 1\}$, and the value of $\tilde{\eta}$ is selected according to (3.15) assuming $P_{FA} = 10^{-3}$.

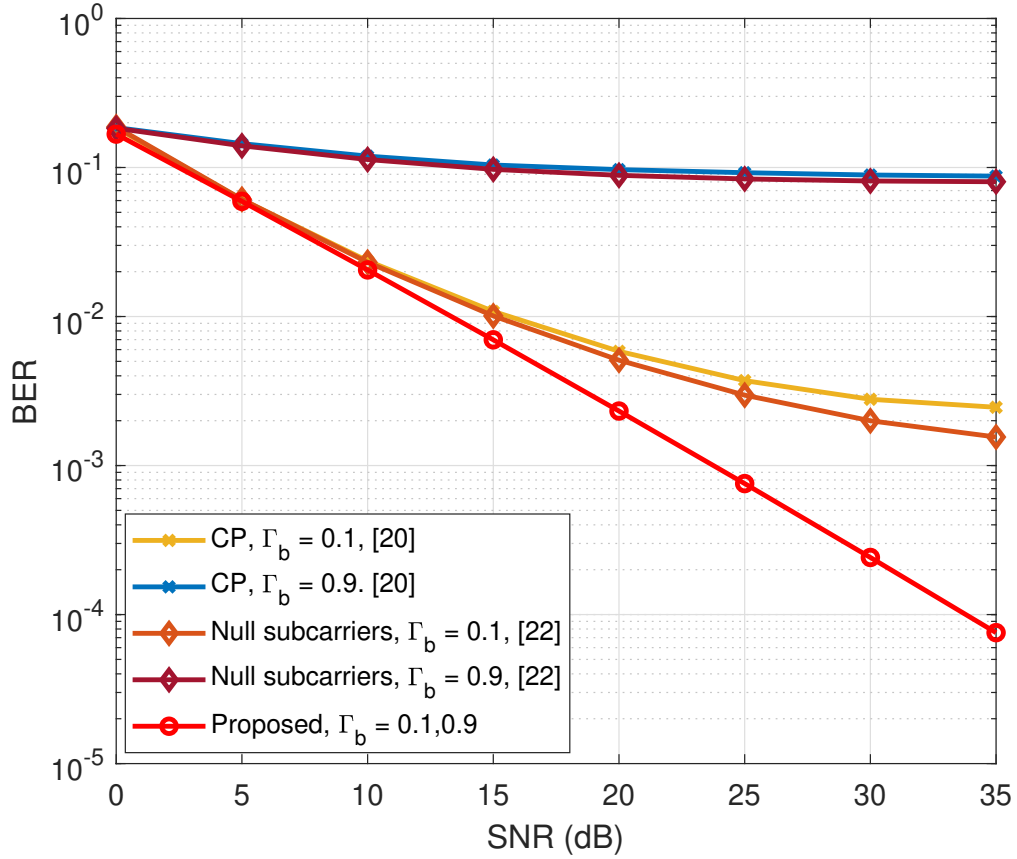


Figure 4.1: A comparison of the primary communication performance of the proposed scheme with the CP-based and null-subcarrier-based BC schemes in [1], and [2], respectively, when $\Gamma_b \in \{0.1, 0.9\}$ and $N = 64$.

In **Figure 4.1**, we analyze the BER performance of different schemes for $\Gamma_b \in \{0.1, 0.9\}$ and $N = 64$. The BER of both CP-based and null-subcarriers-based approaches in [1] and [2] increases as the value of Γ_b increases. For instance, the BER of these schemes increases from 10^{-4} to 10^{-3} at a SNR of 30 dB due to the interference from BC. However, for $\Gamma_b \geq 0.9$, the BD reflects the majority of the received power, and the BER for the primary communication in earlier schemes increases drastically. Comparatively, the proposed approaches for OFDM-based SR prevents the interference from BC to primary communication by strategically placing null subcarriers between data subcarriers.

4.1.1.1. Simulation results for OOK scheme

In **Figure 4.2**, we analyze the PMD for non-coherent detection of OOK modulated BC signals with $\zeta = 1$, $N_b/2$, $\text{PFA} = 10^{-3}$, $N = 128$, $N_b = 64$ and $\Gamma_b \in \{0.25, 0.5, 0.75, 1\}$. As can be seen from **Figure 4.2**, the PMD decreases with increasing SNR for a specific

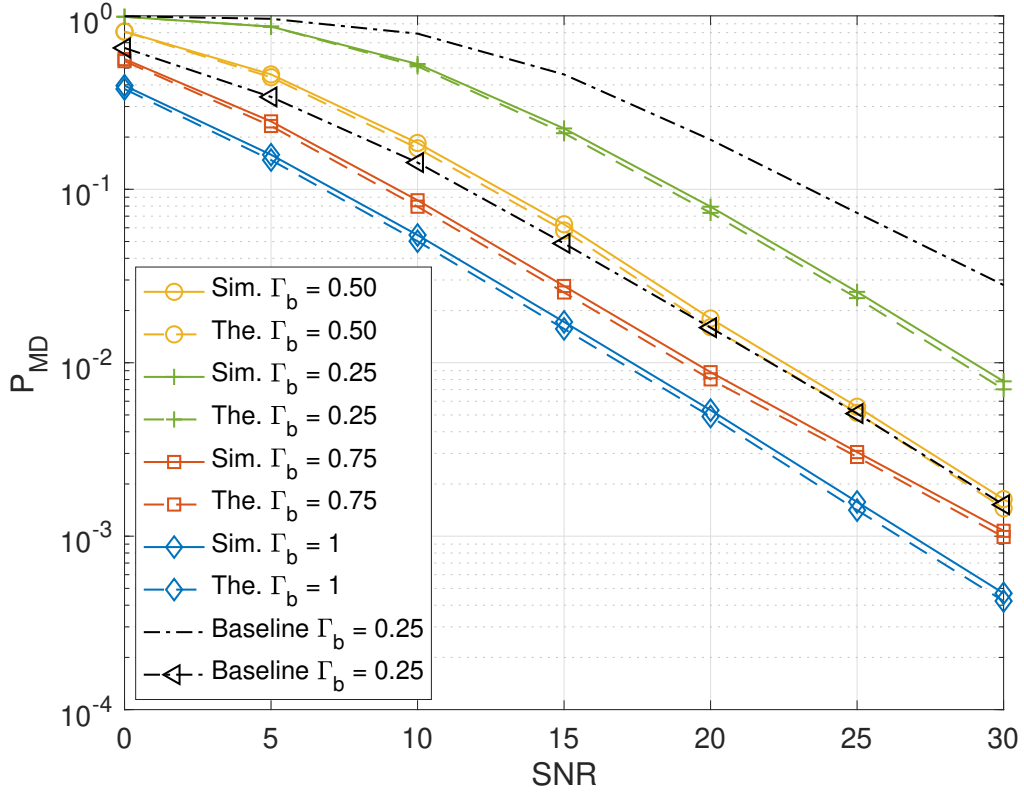


Figure 4.2: The PMD of BD for different values of SNR obtained from the non-coherent detector with $N = 64$ and $PFA = 10^{-3}$.

value of Γ_b due to the decrease in the noise power. Furthermore, the increase in the Γ_b results in low PMD, and the minimum PMD is achieved when $\Gamma_b = 1$ because the BD reflects the incident signal with the same input power without loss. Specifically, as the BD's reflected power increases from $\Gamma_b = 0.25$ to $\Gamma_b = 1$, the PMD decreases from 10^{-2} to more than 10^{-3} at 30 dB SNR. We compare the performance of the proposed scheme with the baseline BC in [2]. The proposed scheme achieves the P_{MD} same as that of the baseline BC at $\Gamma_b = 1$ and 25 dB SNR but with a lower reflection coefficient of $\Gamma_b = 0.50$. Also, the theoretical PMD results are aligned with the simulation results. The difference is due to the channel correlation.

In **Figure 4.3**, we analyze the PMD for non-coherent detection of OOK-modulated BC signals with $\zeta = 1$, $N_b/2$, $PFA = 10^{-3}$, $\Gamma_b = 0.25$ and $N \in \{64, 128, 256, 512\}$. From **Figure 4.3**, it is obvious that the PMD depends on the total number of null subcarriers N_b such that as the value of N_b increases from 64 to 512, PMD reduces to 10^{-2} at 20 dB SNR. Compared to the baseline BC scheme in [2], OOK achieves significantly lower P_{MD} for different values of N . For instance, the OOK scheme achieves P_{MD} much higher than

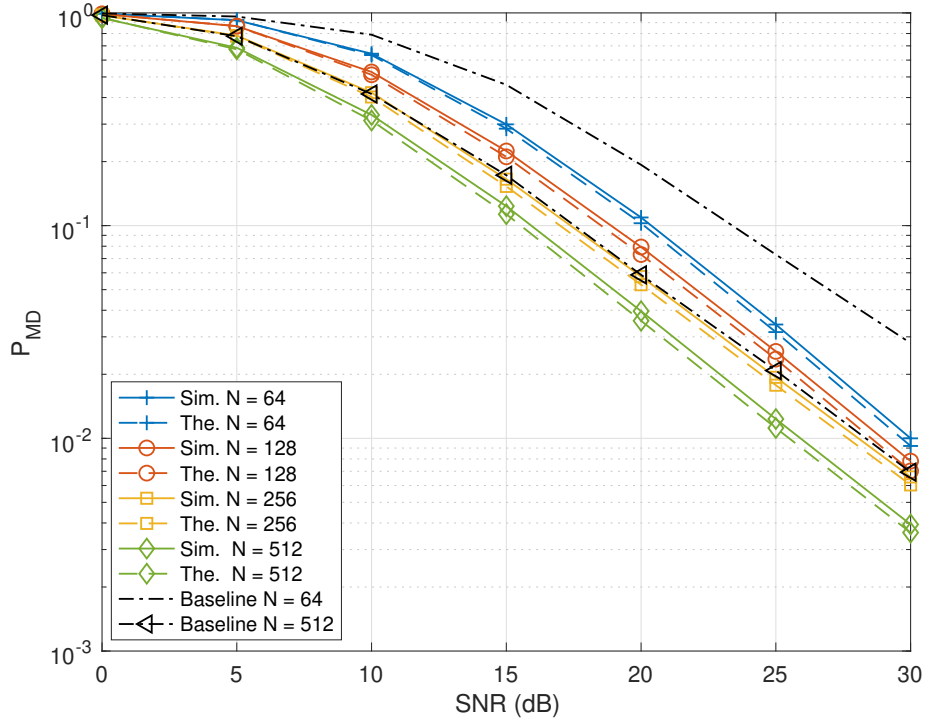


Figure 4.3: The PMD of BD for different values of SNR and $N \in \{64, 128, 256, 512\}$ obtained from the non-coherent detector with $\Gamma_b = 0.25$.

10^{-3} for $N = 512$ while the baseline's P_{MD} is lower than 10^{-3} at 30 dB SNR. The simulation results match the theoretical results; however, there is a difference due to channel correlation. Thus, one way to decrease the PMD of the OOK-modulated BC system is to increase N_b , which is only possible if the OFDM symbol with a large N is transmitted.

In **Figure 4.4**, we analyze the receiver operating characteristic (ROC) of the OOK modulated BC system with $\Gamma_b = 0.25$, $N = 64$, and $N_b = 32$ for $\text{SNR} \in \{0, 5, 10\}$ dB. The ROC curve in **Figure 4.4** shows that at 0 dB and 10% PFA, around 22% of the probability of detection (PoD) is achieved. As SNR increases with 5 dB, PoD increases up to 27% with the same value of PFA. Furthermore, when the SNR is increased by 5 dB more, the PoD increases up to 75% at 10% PFA. Besides, ROC curves obtained through simulations are aligned with the theoretical ROC curves for the proposed system with subcarrier allocation for OOK modulated BC. Thus, the system achieves a higher detection accuracy with the non-coherent detector for OOK.

4.1.1.2. Simulation results for FSK schemes

In **Figure 4.5**, we consider FSK-1 with $N = 64$, $N_b = N_d + 2$, and $N_d = \lfloor (N - 1)/2 \rfloor$. Out

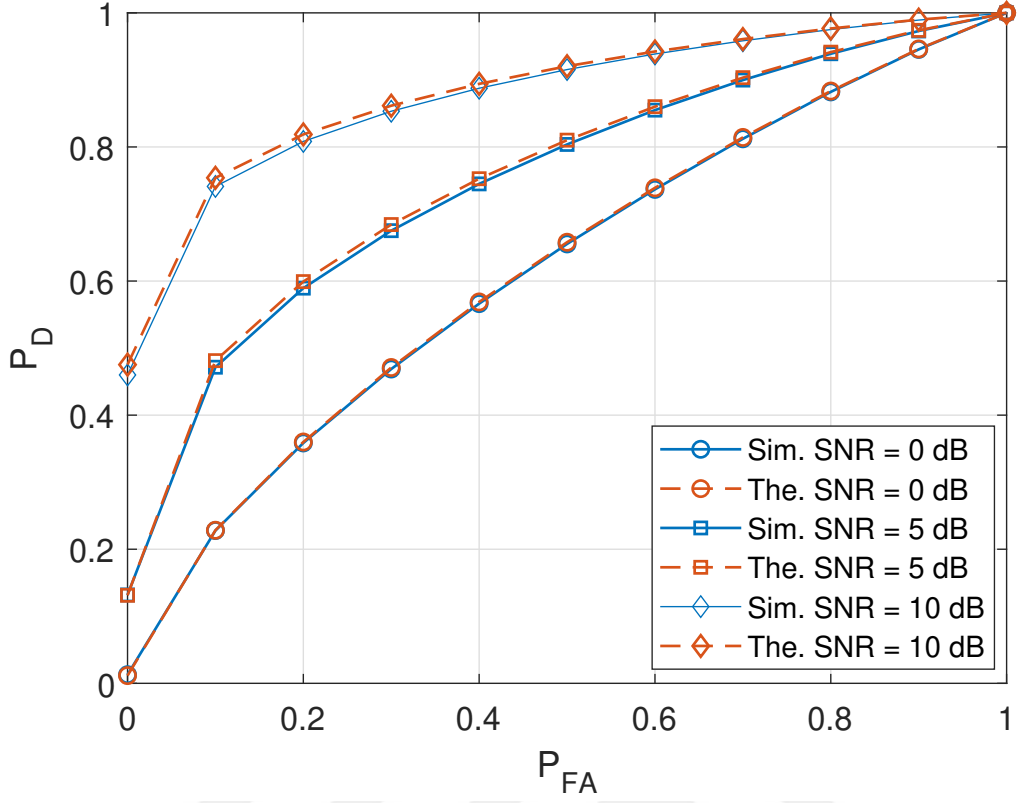


Figure 4.4: The ROC of the SR system with a non-coherent detector for $\Gamma_b = 0.25$ and $N = 64$.

of $N_b = 33$, only two null subcarriers are used to detect the signal according to the sub-carrier allocation for FSK-1 modulation. The selection of two specific null subcarriers for non-coherent detection is motivated by the fact that the remaining null subcarriers, except for the first and last subcarriers, typically exhibit equal power at the Rx for the transmission of both bit '0' and bit '1'. Hence, the RX can obtain the transmitted bits based on the power discrepancies observed at the Rx. The FSK-1 approach enables the non-coherent detector to receive the transmitted data reliably in the presence of the null subcarriers. The system performance is analyzed in terms of BER versus SNR for different values of $\Gamma_b \in \{0.25, 0.50, 0.75, 1\}$. It can be seen from **Figure 4.5** that the minimum BER is higher than 10^{-2} at SNR 30 dB and $\Gamma_b = 0.25$ but with increasing the value Γ_b to 0.50, BER reduces to 10^{-2} . However, as the value of the Γ_b is increased further to 1 (i.e., a maximum reflection of power at BD), the BER goes below 10^{-2} . The simulation results are also perfectly aligned with the theoretical curves for the proposed non-coherent detection method. We compare the performance of the proposed scheme with the baseline BC scheme presented in [155], which utilizes the guard subcarriers to transmit the

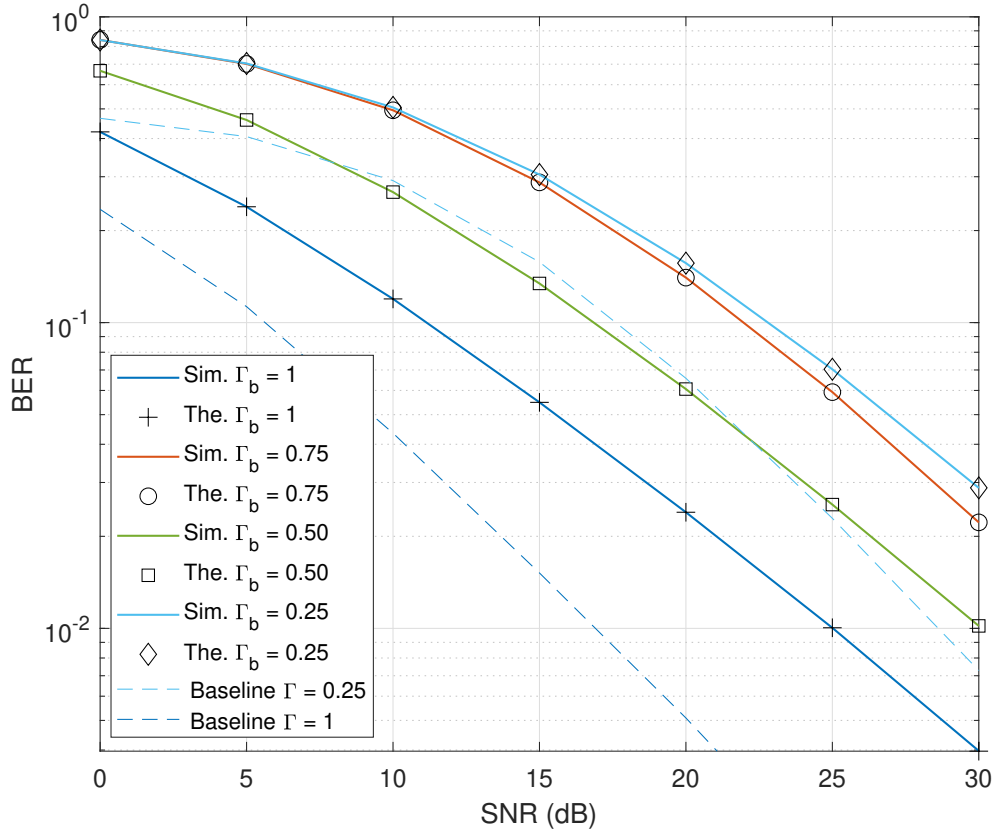


Figure 4.5: The BER of the non-coherent detector for FSK-1 and $N = 64$.

data of the BD. The baseline scheme outperforms the FSK-1 approach when multiple guard subcarriers are used for BC. If only one guard subcarrier is used, FSK-1 achieves performance similar to the baseline scheme. However, the performance gains of FSK-1 are primarily derived from the primary communication in the SR. In contrast, the primary communication performance degrades significantly in the baseline scheme due to interference between adjacent data subcarriers when FSK-based BC is employed.

In **Figure 4.6**, we present the results of non-coherent detection for the proposed FSK-2 scheme in terms of BER versus SNR with $N = 64$, $N_b = 2N_d + 1$, and $N_d = (N - 1)/3$. We assume that N_b is 42 and 21 null subcarriers are used to detect the one information bit transmitted by the BD. The BER performance is analyzed for different values of $\Gamma_b \in \{0.25, 0.50, 0.75, 1\}$. Selecting the higher value of Γ_b results in low BER due to an increase in the backscatter signal power. For instance, when SNR is 30 dB, the BER decreases notably from 10^{-3} to 10^{-4} by increasing Γ_b from 0.25 to 1. Furthermore, the BER performance of FSK-2 is better than that of FSK-1 and the baseline scheme [155], as

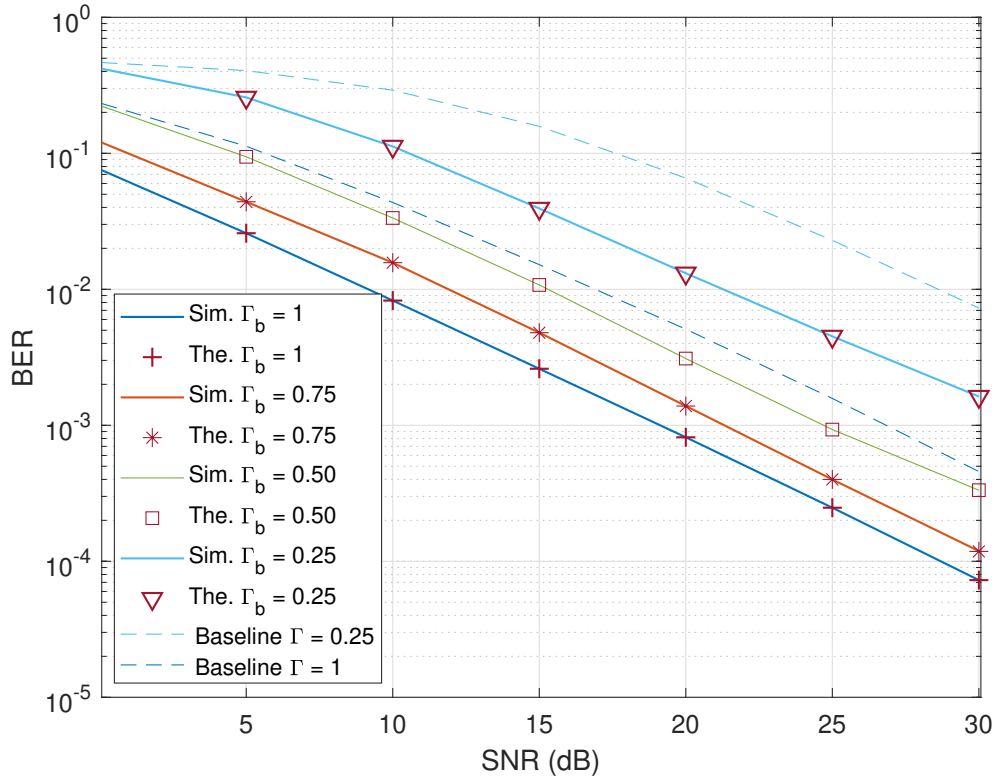


Figure 4.6: The BER of the non-coherent detector for FSK-2 and $N = 64$.

shown in **Figure 4.5** and **Figure 4.6**. FSK-2 achieves nearly 10^{-1} better than the baseline scheme at $\Gamma_b = 0.25$ and $\Gamma_b = 1$ for SNR is 30 dB. The BER of FSK-2 is 10^{-1} times less than FSK-1 for 20 dB SNR and $\Gamma_b = 0.25$. The theoretical results also match the simulation results.

In **Figure 4.7**, we evaluate the BER performance of FSK-2 for different values of N and compare it with the baseline approach [155]. As N increases, N_b also increases, which results in a lower BER. For instance, for 20 dB SNR, the BER decreases from 10^{-2} to 10^{-3} when N increases from 64 to 512. Therefore, one way to improve the performance of the SR with a non-coherent detector for FSK-2 BC is to increase N without changing Γ_b . Furthermore, FSK-2 achieves significantly better performance than that of the baseline scheme. For example, at 30 dB SNR value, FSK-2 achieves close to 10^{-3} where the baseline approach's BER is close to 10^{-2} for $\Gamma_b = 0.25$.

In **Figure 4.8**, we analyze the performance of FSK-1 and FSK-2 and compare them with the baseline approach in [155] for different values of Γ_b . Similar to [2], the baseline approach uses the guard subcarrier instead of dedicated null subcarriers in the OFDM for

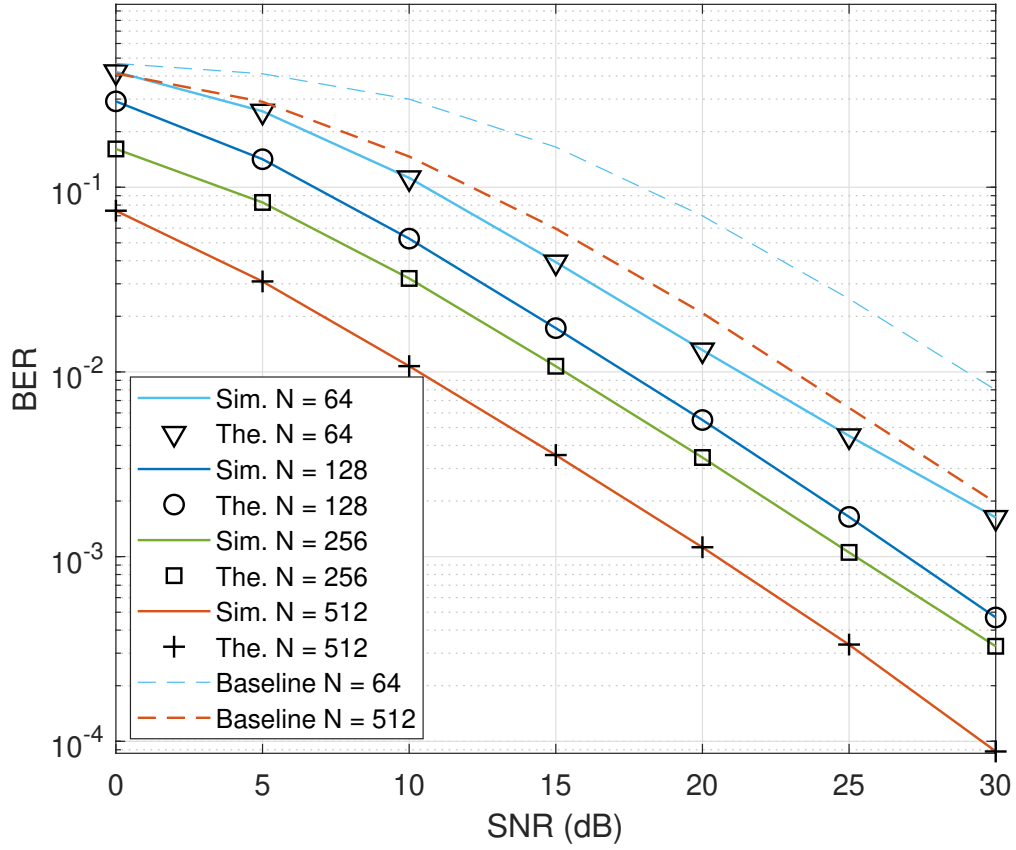


Figure 4.7: The BER of the non-coherent detector for FSK-2 and $\Gamma_b = 0.25$.

BC. FSK-2 outperforms the baseline for different values of Γ_b because the value of N_b is greater than the in-band guard subcarriers in an LTE OFDM, which can be used for BC. For example, the BER of FSK-2 at $\Gamma_b = 0.50$ is higher than the BER of the baseline approach at $\Gamma_b = 1$, which means that the FSK-2 can achieve better with 50% reflection of incident power compared to overcome the performance achieved by the baseline with maximum power reflection. Comparatively, FSK-1's performance is poor due to the fixed number of null subcarriers for BC (i.e., $N_b = 1$).

In **Figure 4.9**, we analyze the BER performance of the non-coherent detector for different CFO values. Since FSK-1 and FSK-2 schemes shift the incoming signal with a frequency equal to or multiple of the subcarrier spacing (e.g., 15 kHz in LTE and 312.5 kHz in Wi-Fi). A CFO can introduce an extra frequency shift in the primary signal, leading to inter-carrier interference and degrading the quality of the received signal. Hence, the interference between subcarriers causes poor signal detection of primary and BD signals at Rx. For example, a CFO with a value of 0.05 results in a 10 times increase in the

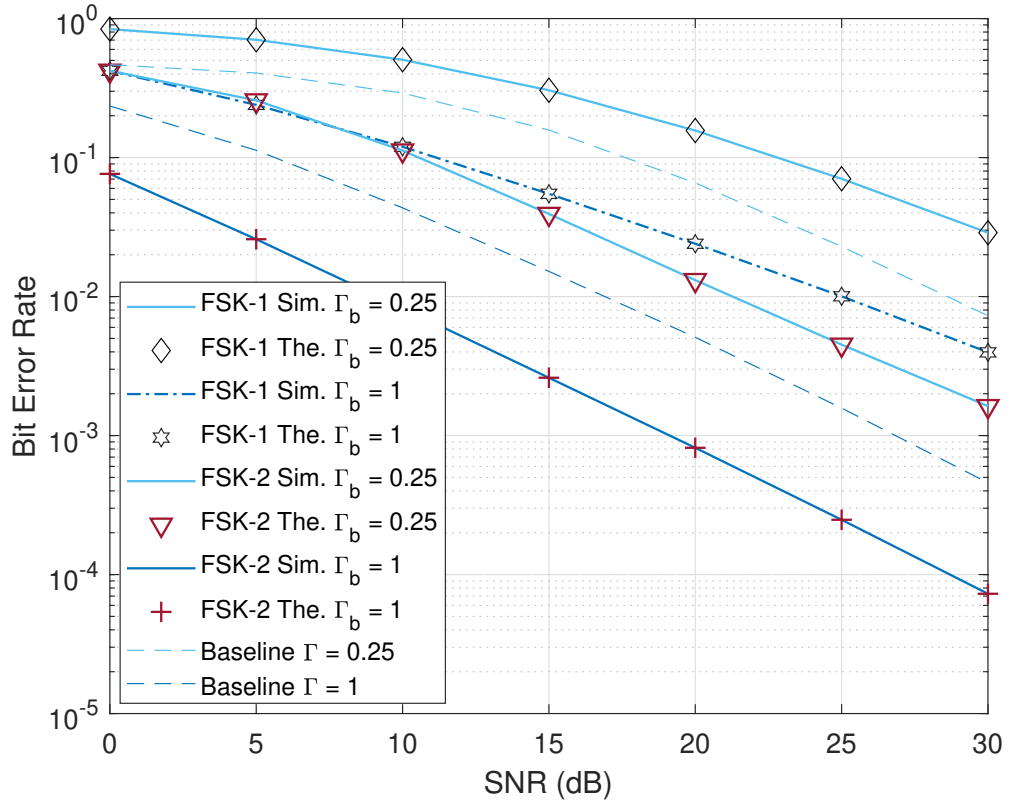


Figure 4.8: The BER comparison of the non-coherent detector for FSK-1 and FSK-2 with the baseline approach [2] when $N = 64$.

BER of FSK-2 at 30 dB. The performance of FSK-1 also degrades due to CFO but is comparatively less than that of FSK-2. The reduced performance of the FSK-2 scheme compared to FSK-1 can be attributed to the difference in their subcarrier utilization for backscatter communication detection. In the FSK-1 scheme, only the edge subcarriers are used for BD's data detection, whereas the FSK-2 scheme utilizes all the subcarriers dedicated to BC. When CFO occurs, the data symbols of the primary communication signal shift and encroach onto the null subcarriers, causing interference. This interference affects the performance of both FSK-1 and FSK-2 schemes. However, the impact is more pronounced in the FSK-2 scheme due to the utilization of all the subcarriers dedicated to BC. As the CFO increases, the interference from the primary communication data symbols to the null subcarriers becomes more severe. This increased interference has a more detrimental effect on the FSK-2 scheme, as all the subcarriers used for backscatter communication are affected. In contrast, the FSK-1 scheme, relying only on the edge subcarriers, is relatively less susceptible to this interference, leading to better performance compared to the FSK-2 scheme under large CFO conditions.

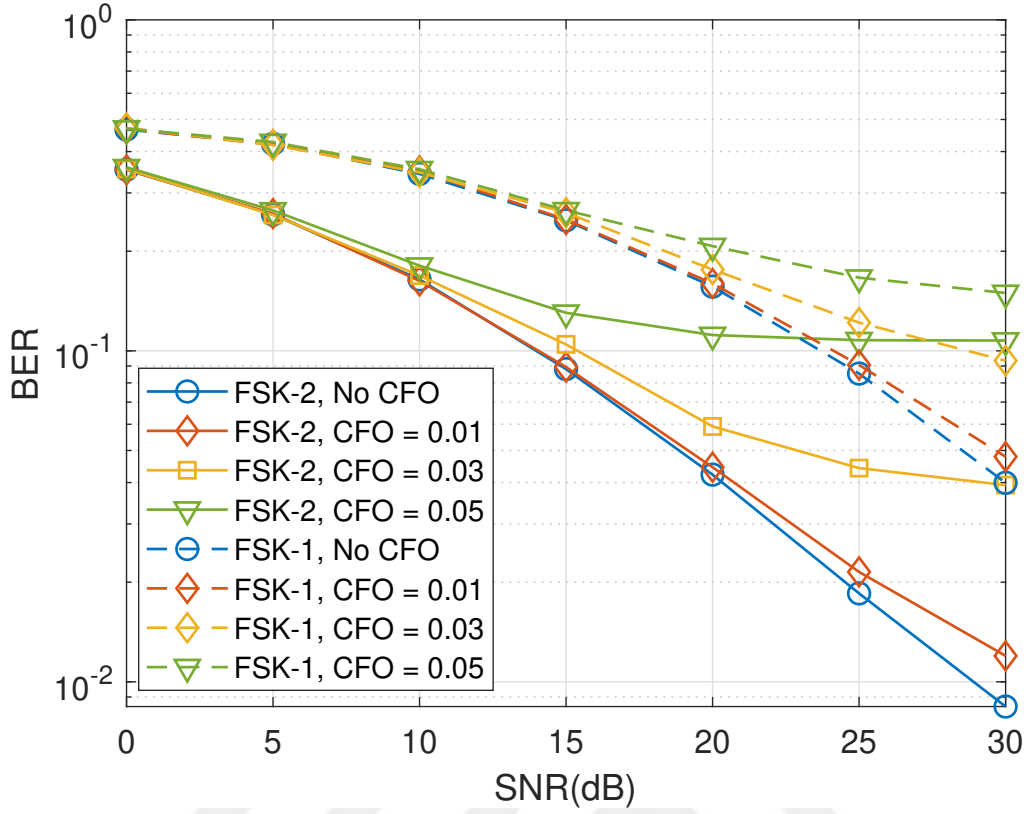


Figure 4.9: The BER of non-coherent detector for FSK-1 and FSK-2 under CFO impairment.

4.1.2. Retransmission probability

In this section, we evaluate the retransmission probability (i.e., the ratio of the retransmitted frames to the total number of transmitted frames) for the non-coherent detector for the proposed schemes based on CRC. We assume a 5-bit CRC encoder/decoder according to the RFID Gen2 standard [44]. The CRC bits are generated using the polynomial $x^5 + x^3 + 1$. BD append CRC bit to the information bits before transmission. The Rx receives the backscatter signal and applies the CRC decoder after CP removal, IDFT, demodulation, and non-coherent detection processes. If the CRC fails, the Rx requests the retransmissions of the data frame through the automatic repeat requests (ARQ) protocol.

In **Figure 4.10**, we present the retransmission probability versus SNR for the proposed OOK, FSK-1, and FSK-2 schemes with non-coherent detection. The frame length is 12 BD bits including 5 CRC bits. The performance is evaluated for $N = 64$. It can be seen from **Figure 4.10** that the FSK-1 provides a lower retransmission probability than OOK at SNR greater than 10 dB. However, FSK-2 outperforms both OOK and FSK-1 by achieving

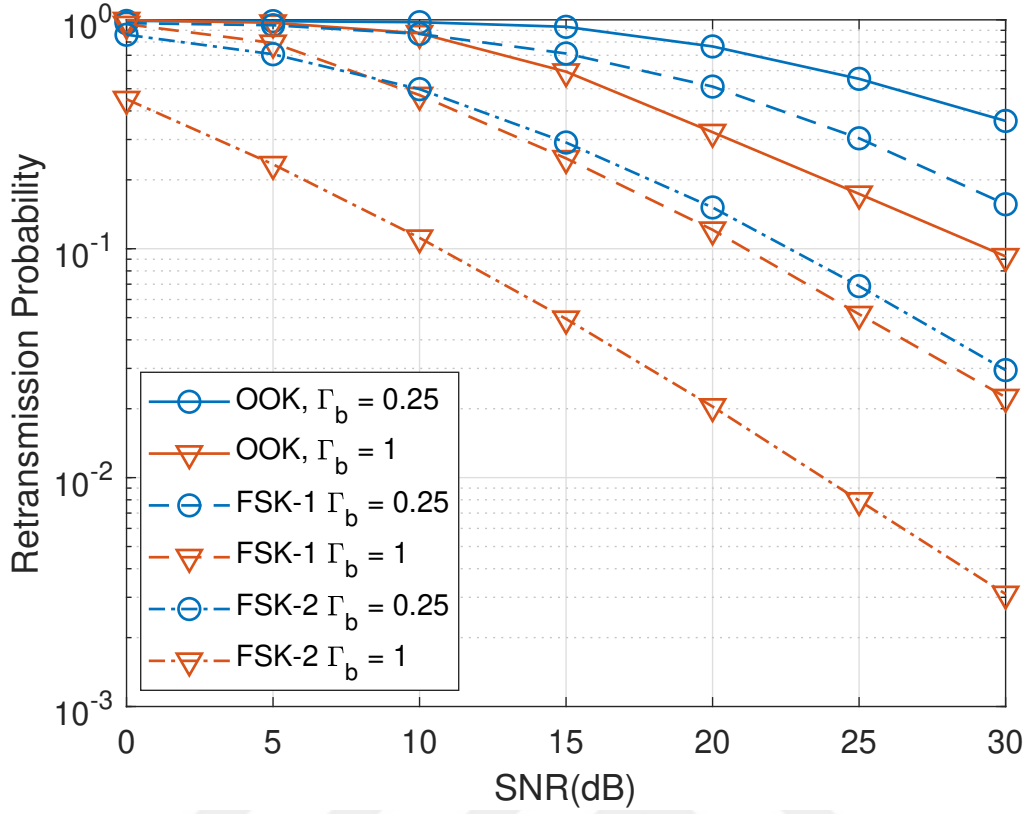


Figure 4.10: The comparison of the retransmission probabilities of OOK, FSK-1, and FSK-2 with $N = 64$.

the lowest retransmission probability at different values of $\Gamma_b \in \{0.25, 1\}$. Therefore, to achieve a smaller number of retransmissions in SR for BC, the FSK-2 scheme is preferred even at low Γ_b with fixed N .

4.2. Results of Study II

Figure 4.11 compares the achievable sum-rate of the symbiotic radio system versus the number of BDs for the proposed signal accessibility scheme and the benchmark MM beam-selection scheme. We consider three values of $\zeta = \{0.80, 0.90, 0.95\}$ for comparison as the value of ζ is selected close to 1 to capture most of the channel power [176]. It is observed from the results of **Figure 4.11** that the sum-rate of the SR changes significantly with the change in the value of ζ and several BDs with the application of benchmark MM scheme. However, the proposed scheme achieves a higher sum rate compared to the benchmark. Furthermore, the proposed scheme sustains similar performance at different values of ζ . This performance sustainability results from signal accessibility to BDs with-

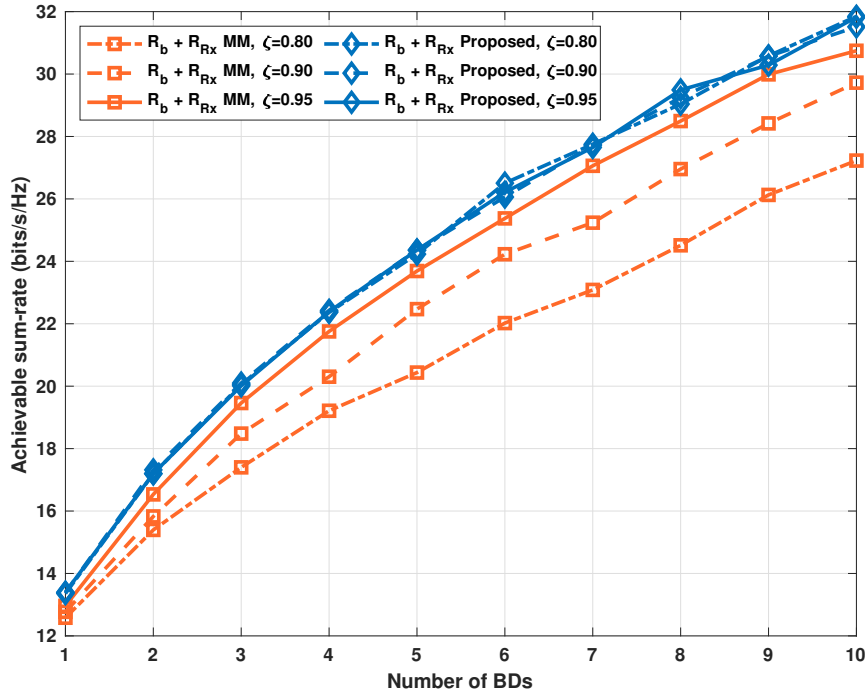


Figure 4.11: Achievable sum-rate in SRad system with a different number of BDs.

out signals. Another point to be noted is that in the benchmark scheme, as the ζ value increases, more BDs get access to RF signals; consequently, the number of RF chains also increases.

Figure 4.12 shows the achievable sum-rate versus SNR for $N_b = 1$ and different values $N_l = \{1, 2, 3\}$ and $\Gamma_b = \{0.1, 0.9\}$. The number of selected beams at Tx and Rx are according to N_b and N_l in each case. It is shown that the value of R_{Rx} is maximum when $N_l = 3$ and $\Gamma_b = 0.9$. For instance, at 10 dB of SNR, R_{Rx} is around 16 bits/sec/Hz when $N_b = 1, N_l = 3, \Gamma_b = 0.9$ but it drops to 15 bits/sec/Hz when $\Gamma_b = 0.1$. R_{Rx} also decreases with the decreasing value of N_l ; for example, it reduces to 11 bits/sec/Hz with $N_l = 1$ and $\Gamma_b = 0.1$. Although changing the value of Γ_b affects R_{Rx} ; during the beam-selection through the proposed signal accessibility scheme, we consider maximum reflection $\Gamma_b = 1$ at all BDs.

Figure 4.13 shows the achievable sum-rate of SR system with multiple BDs and ordinary scatterers. The sum-rate is obtained with different values of N_b , and N_l . For example, at the SNR value of 10 dB, the highest values of R_b , R_{Rx} and $R_b + R_{Rx}$ are achieved when $N_b = N_l = 2$, and all BDs transmit with the maximum reflection coefficient $\Gamma_b =$

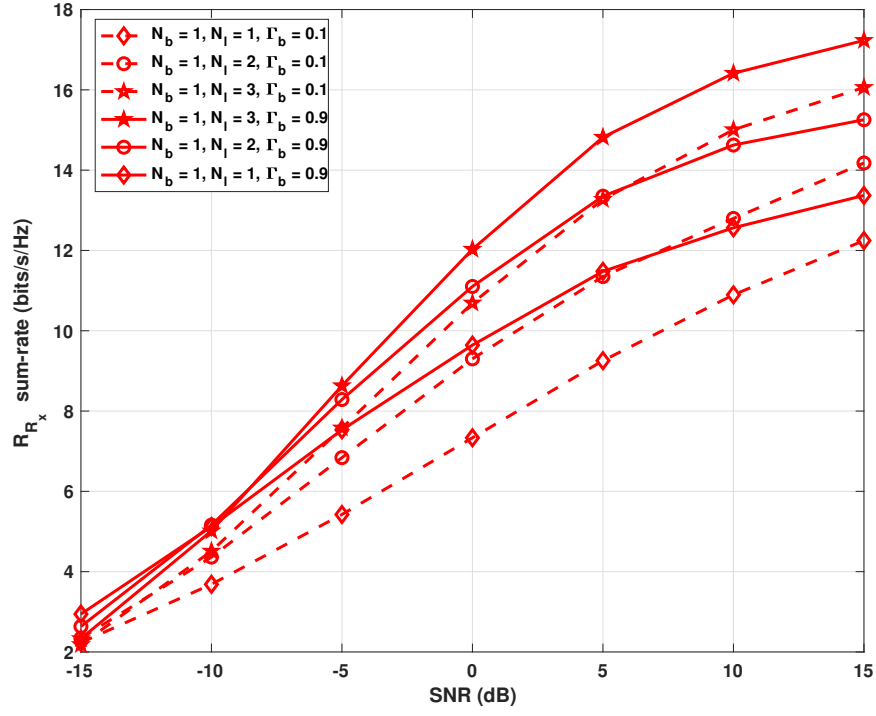


Figure 4.12: R_{R_x} sum-rate vs SNR for single BD and multiple ordinary scatterers.

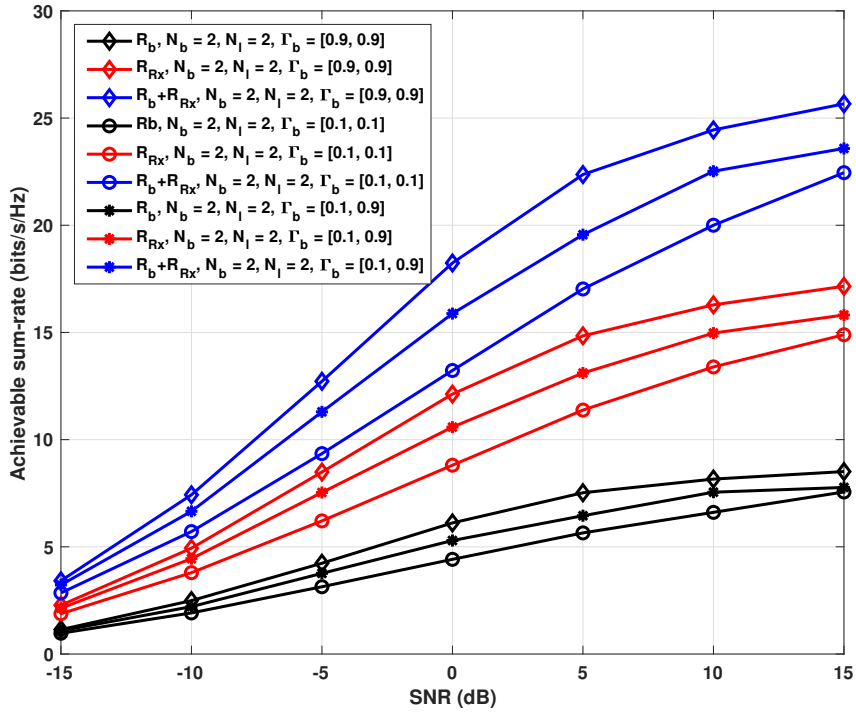


Figure 4.13: Achievable sum-rate vs SNR for multiple BDs and multiple ordinary scatterers.

[0.9, 0.9]. As one BD reflects with low reflection coefficient i.e., $\Gamma_b = [0.1, 0.9]$, the sum-rate decreases and it reaches to minimum when both BDs backscatter with minimum $\Gamma_b = [0.1, 0.1]$. Furthermore, **Figure 4.13** shows that BDs with $\Gamma_b = [0.9, 0.9]$ improve the achievable sum-rate of the system up to 30% compared to BDs with $\Gamma = [0.1, 0.1]$. Thus, simulation results validate the sum-rate enhancement with the beam selection and also the selection of the paths with different type of scatterers such as BD and ordinary scatterers in the environment.

4.3. Results of Study III

The performance of Bob and Eve in terms of PLER vs. SNR with and without APwA strategies are plotted in **Figure 4.14**. It is assumed that both Bob and Eve use the same method for pilot location detection described in **Subsection 2.4.2.3**. At the low SNR value, PLER is higher due to the high noise power for both Bob and Eve. As the value of SNR increases, PLER decreases for Bob but not for Eve due to the uncorrelated channel between

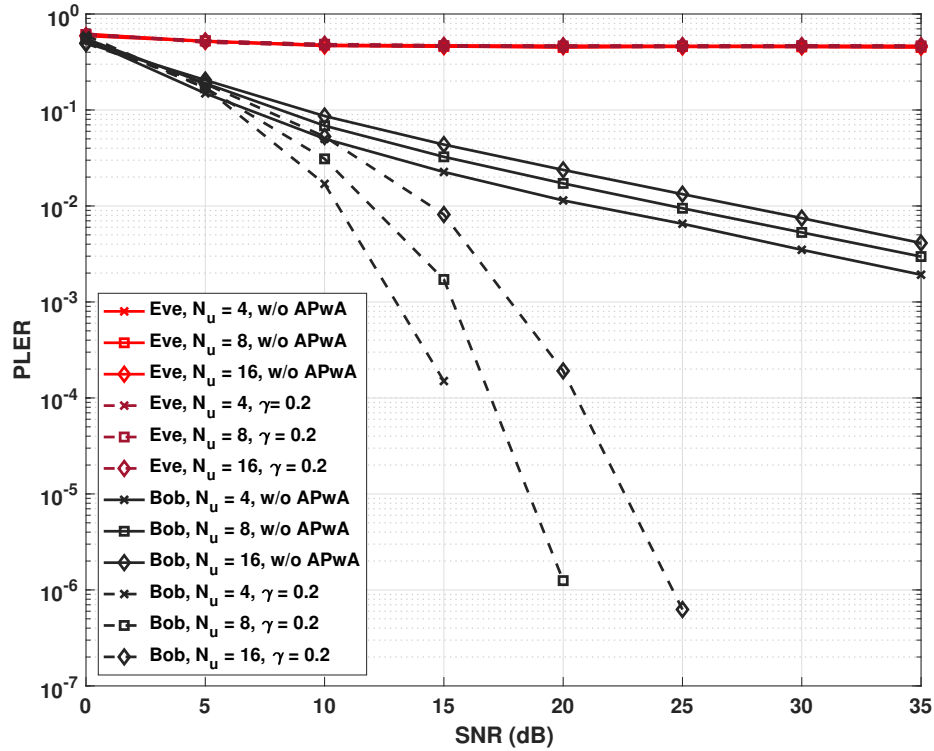


Figure 4.14: PLE versus SNR performance for Bob and Eve with a different number of subcarriers blocks.

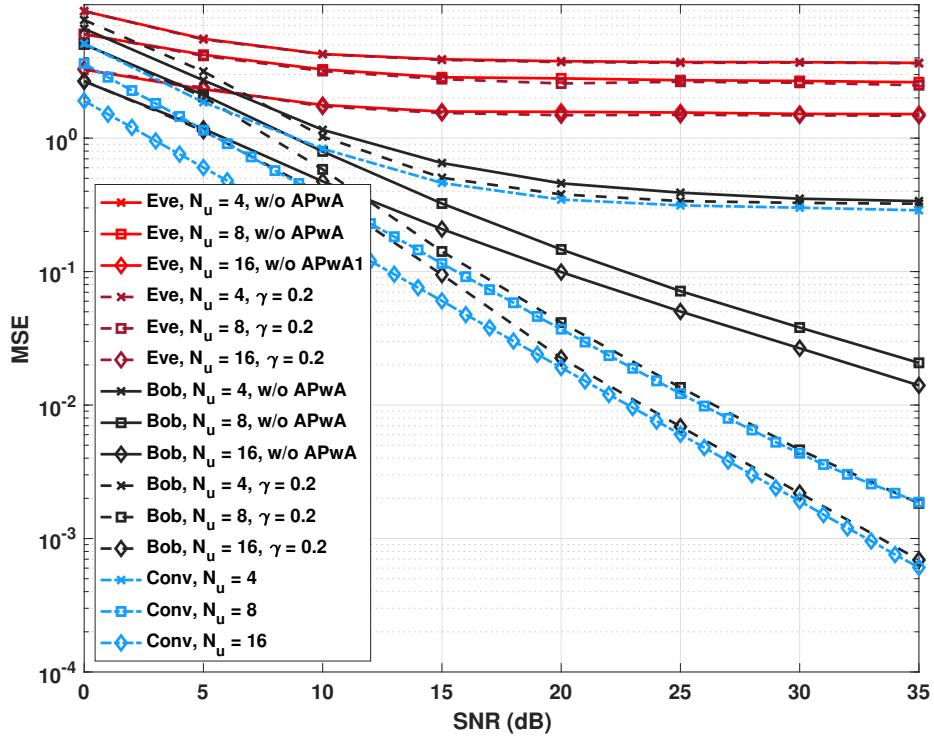


Figure 4.15: MSE versus SNR performance of least square estimator for Bob and Eve using adaptive pilot allocation for a different number of subcarriers blocks.

them. Thus, Eve is restricted from finding the exact location of the pilot subcarriers. Besides, increasing block size reduces PLER at Bob. However, when the APwA is not considered the performance of PLER is around 10^{-2} at 30dB SNR value with $N_u = 16$. Since increasing only the subcarrier block bandwidth, i.e., $N_u = 8$, reduces PLER due to noise averaging, it is not significant compared to the performance gains achieved by APwA. For instance, by employing APwA method with $\gamma = 0.2$, Bob achieves PLER of 10^{-2} around 15dB SNR value with $N_u = 16$, which further reduces when $N_u = 8$, and $N_u = 4$, respectively. Certainly, APwA improves the performance of Bob without providing the performance gains to Eve.

As discussed earlier, Eve aims to obtain accurate CSI to perform CSI-based sensing in ISAC system. Therefore, our objective is to restrict Eve from getting the CSI using Alice's channel while ensuring the availability of accurate CSI at Bob. We consider the least square channel estimation method for Bob and Eve and analyze its performance in terms of MSE. **Figure 4.15** shows the performance graph of least square estimation for Bob with and without APwA and different values of N_u and its comparison with the performance of

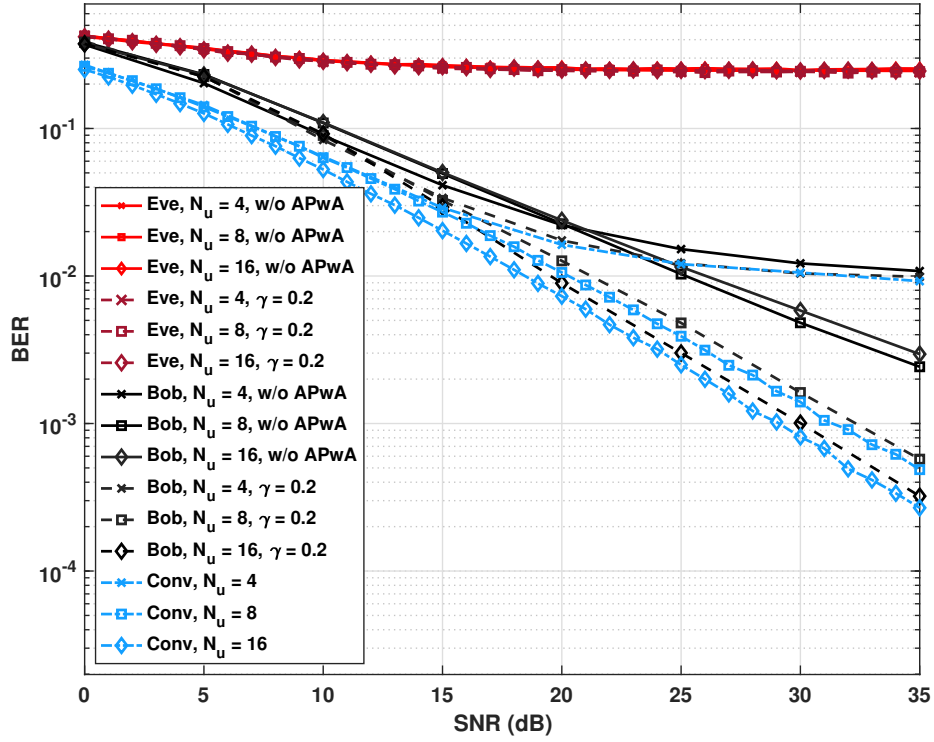


Figure 4.16: BER performance for Bob and Eve with different numbers of subcarrier blocks.

Eve and conventional least square estimator with known pilot locations. The graphs show that MSE of Eve is high as compared to Bob due to high PLER even at high SNR with different values of N_u and power allocation strategies. On the other hand, Bob's MSE decreases with the increasing SNR and γ values. For instance at 25dB SNR and $N_u = 16$ Bob's MSE value is around 10^{-1} without APwA; however, MSE reduces to 10^{-2} while applying APwA with $\gamma = 0.2$. Therefore, the least square estimation scheme with a secure pilot location results in poor channel estimation for Eve, but for Bob, its performance is close to the MSE with known pilot locations. It should be noted that sensing and communication information in ISAC can be secured by restricting Eve from obtaining the correct CSI.

BER is the third key performance metric used to analyze the performance of the proposed method for Bob and Eve. **Figure 4.16** shows the BER vs. SNR graph with and without APwA for different values of N_u . Similar to PLER, the BER of Eve is significantly higher than the BER of Bob, which validates that Eve cannot detect the communication information transmitted by Alice to Bob. In addition, APwA only enhances Bob's performance

in terms of BER reduction by adding the power gap γ between the power of α_u and ζ . As the value of γ increases, Bob's BER reduces, for instance, in the case of Bob with $N_u = 8$, BER around 10^{-2} is achieved at 30dB without APwA; however, the same BER can be achieved by Bob around at 22dB with APwA at $\gamma = 0.2$. Lastly, when compared to BER of the conventional least square estimator with known pilot locations, APwA provides a similar BER for Bob.

4.4. Results of Study IV

A performance graph of AUDR versus the number of users is plotted in **Figure 4.17**, where an even number of users is considered in the coverage area. In this scenario, both UP schemes follow the same strategy for user pairing; therefore, the AUDR is the same for each power allocation scheme. When there are two users, only a single pair is formed; therefore, both UP schemes provide AUDR similar to NOMA-WP but higher than OMA. In addition, it can be seen that the proposed UP schemes offer higher AUDR than NOMA-WP and OMA when there are more users in the coverage area.

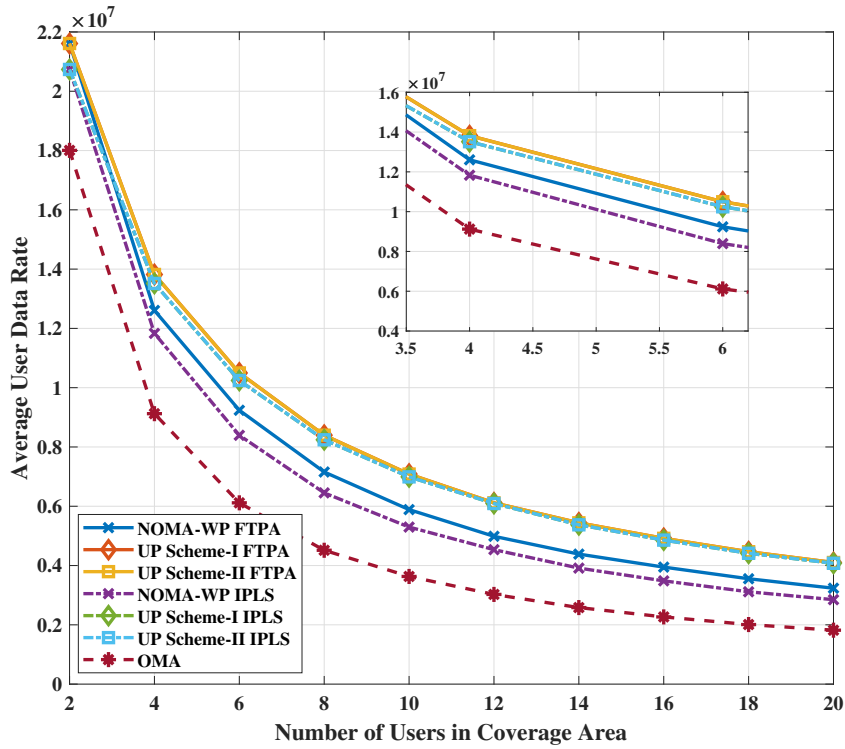


Figure 4.17: AUDR versus number of users assuming FTPA and IPLS (even number of users).

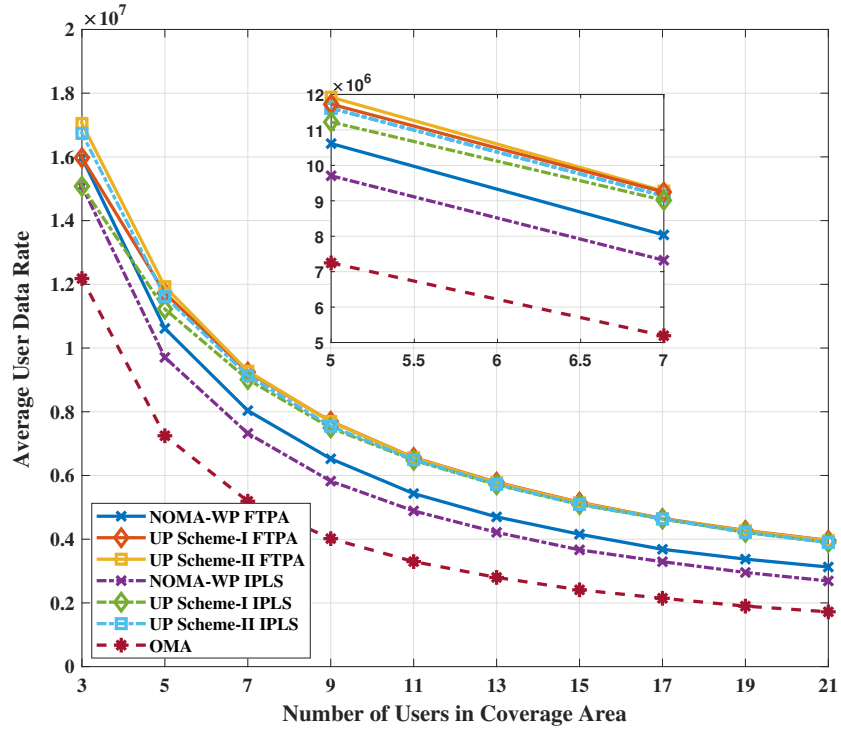


Figure 4.18: AUDR versus the number of users assuming FTPA and IPLS (odd number of users).

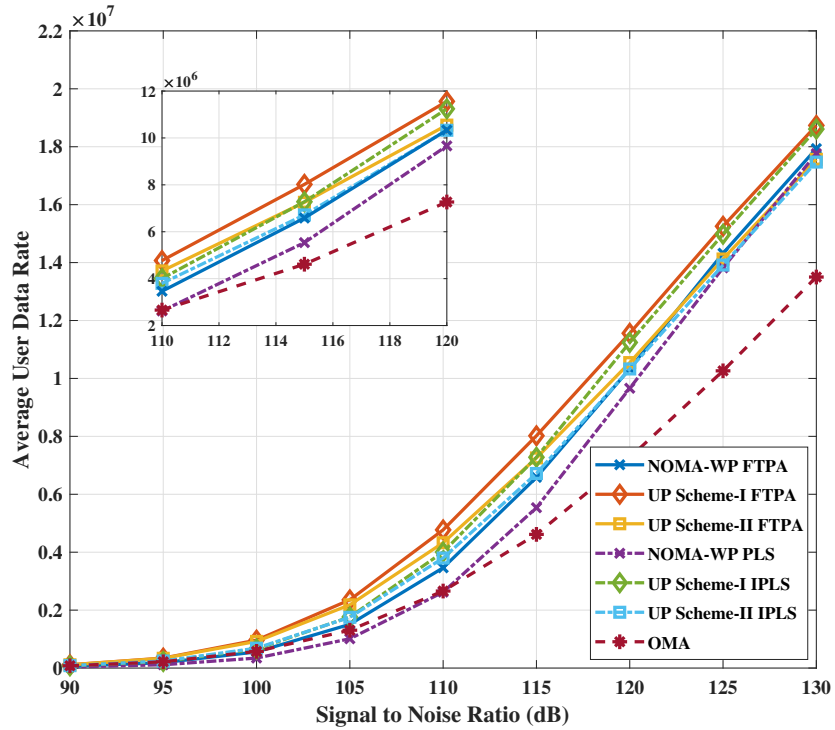


Figure 4.19: AUDR versus SNR assuming FTPA and IPLS ($K = 5$).

The case of the odd number of users is presented in **Figure 4.18**, where UP Scheme-II provides higher AUDR than UP Scheme-I, NOMA-WP, and OMA schemes when the number of users is low but similar at a high number of users. This behavior is due to the reason that UP Scheme-II divides the users into NOMA pairs and the remaining user employs OMA. However, in UP Scheme-I all users are divided into NOMA pairs, and there is one NOMA group of three as well. Therefore, UP Scheme-I has more decoding issues than UP Scheme-II, which leads to low AUDR. Finally, when the number of users reaches 7, both schemes tend to give similar performance but higher than NOMA-WP and OMA. Finally, UP schemes can achieve up to 13 % and 17 % higher AUDR than NOMA-WP in the case of even and odd numbers of users, respectively.

In **Figure 4.19**, AUDR gains of both schemes are shown in terms of transmitting SNR with five users in the coverage area. UP Scheme-I with FTPA gives the best performance among all other schemes. However, UP Scheme-I with FTPA gives similar performance to UP Scheme-II FTPA at low SNR but at high SNR its performance reaches close to NOMA-WP.

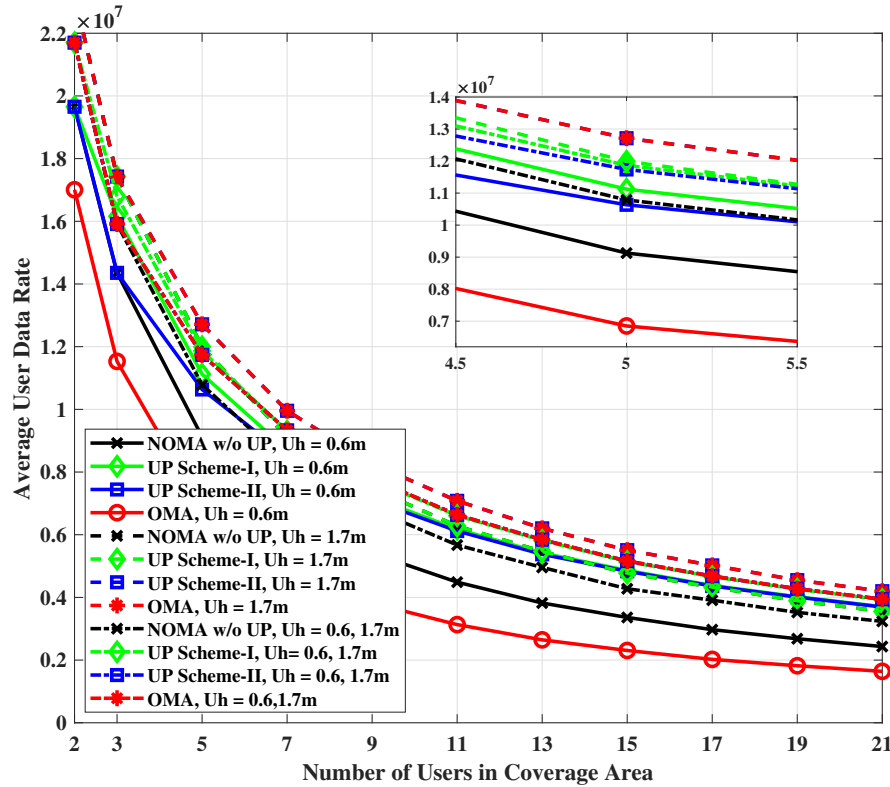


Figure 4.20: AUDR versus the number of users assuming FTPA and different user heights.

The effect of 3D VLC users deployment on the performance of NOMA is shown in **Figure 4.20**. When the users are located at the same height, it is obvious that the performance increases as the users get closer to the transmitter. For instance, at user height $L = 0.6$ m the achievable AUDR is lower than when $L = 1.7$ m. Assuming two different heights, it can be seen that the performance of NOMA-WP slightly decreases at low users' heights. Also, our proposed schemes for the lowest user's height $L = 0.6$ m show better performance than NOMA-WP and OMA. Therefore, it can be concluded that, for all scenarios, the proposed user pairing approaches are more robust to 3D users' deployment as compared to NOMA-WP and OMA.



CHAPTER 5

5. CONCLUSIONS AND FUTURE WORK

In this chapter, we provide conclusions and future research directions related to the studies discussed in the previous chapters. We draw the following conclusions and potential research directions:

- Meeting the needs of future wireless systems within limited radio resources is a challenging task. The rapid proliferation of IoT devices and sensors exacerbates the problem, and existing radio resource-sharing mechanisms are inadequate. Therefore, new paradigms for spectrum sharing and coexistence need to be explored. SR is a promising solution to ensure spectral efficient coexistence between systems with different services and requirements. Given the existing research advancements in the field of SR, various challenges call for attention to pave the way for future research directions. Addressing these challenges is essential to enhancing the efficiency of SR, in terms of resource allocation, improving the coexistence of active and passive radio systems, and simplifying decision-making processes within SR networks. The research challenges in SR are listed as follows:
 - Channel modeling and estimation: Accurately modeling and estimating the channel between the different nodes in the network are the critical challenges in SR system. The channel in SR system is typically composed of both active and passive links, making it difficult to estimate accurately. The active links are formed by the traditional wireless communication between the AUs and their corresponding user equipment, while the passive links are formed by the BC between the BDs and the ATs. The CSI of both the active and passive links is required for efficient resource allocation and signal processing in SR system. In the literature, various channel estimation techniques have

been proposed for SR systems. For example, in [188], the authors propose an expectation maximization algorithm to design a blind channel estimator for acquiring channel parameters. In [133], a novel two-phase uplink-training-based channel estimation scheme is proposed for cell-free SR systems, which is based on the linear minimum mean square error estimation. The authors in [189] use deep learning to design for joint pilot design and channel estimation in SR systems. The interference and noise between different channels are canceled through successive interference cancellation and deep residual neural networks. However, these channel estimation schemes typically face challenges such as high computational complexity and the need for linear optimization. It is essential to investigate and improve channel estimation techniques to enhance the performance and energy efficiency of SR systems. This can be achieved by developing new channel estimation algorithms that are more computationally efficient and by incorporating machine learning techniques to better model the SR channel.

- Synchronization challenges: In an SR system, the signal transmission of two systems can be sporadic. BD needs the incident RF signal every time there are data to be transmitted. In case of signal unavailability, the BD must wait until AT transmits the signal, which causes a delay in the transmission. In critical applications such as healthcare and transportation, the delay in transmission can cause severe damage. One promising solution is to enable synchronization between BD and AT for the pre-knowledge of signal transmission time. However, it is challenging in an SR system due to the low processing capabilities of BD. The circuits used in AU for timing and phase recovery are power-consuming and unsuitable for low-power devices. Also, the synchronization methods developed for active radio transceivers are inapplicable to passive devices due to hardware and power limitations. Although MIMO and active load assisted BD are used for synchronization, their power consumption and complexity constraints limit their applicability. Research can be directed to multi-antenna BD design for developing simple synchronization algorithms. Full-duplex BD can also be explored as it allows simultaneous energy harvesting and data detection from the received signal.

- Downlink/uplink feedback: The low power and simple processing constraints limit the capabilities of the BD as a receiver. However, the downlink control channel is necessary to design a physical layer protocol for an SR system. Besides, the uplink channel design is also crucial for feedback and data transfer. A non-coherent receiver design is comparatively simpler than a coherent one, but its performance is low. Moreover, an energy detector requires a much larger symbol length of BD signal than an active radio signal to average out the underlying modulated signal. Developing a new low-processing downlink signaling/feedback mechanism is a promising research direction.
- Interference management: Managing interference between radio systems in parasitic or competitive relationships is a complex task. In general, the direct signal from the AT causes significant interference to the BD signal at the receiver. However, the BD signal can also interfere with the AU in both commensal and competitive relationships during uplink transmission. Furthermore, intra-BD interference may occur when multiple BDs are communicating over the same carrier signal in an SR system. This type of interference can lead to a higher packet error rate. To reduce the error rate, various methods can be employed such as successive interference cancellation and beamforming. In the successive interference cancellation method, the direct path signal must be eliminated before decoding the backscattered signal. In contrast, the beamforming approach involves directing the antenna's null towards the direction of the interfering signal, followed by sampling the weak backscattered signal using a traditional analog-to-digital converter and detecting it using a non-coherent receiver. Additionally, coding and robust signal processing techniques can be implemented at the BD to further improve performance.
- Multi-antenna design problems: Multi-antenna technology and its implementation protocols and algorithms have been explored extensively in active radio systems but they are not directly applicable to passive radio systems due to high power consumption and complexity. Nowadays, multiple antenna BDs with beamforming are considered for improving achievable rates of active and passive radios in SR systems. A hybrid beamforming scheme for SR system

with mmWave and passive IoT system is investigated in [171], where the authors perform active beamforming at AU and passive beamforming at BD to achieve high data rates. However, the proposed beamforming mechanisms are computationally complex and impractical for low-power IoT devices. New low-complex signal processing algorithms and passive beamforming techniques are needed for SCm. Besides, joint beamforming strategies can also be explored in the mutualistic SR system.

- Network design and management issues: SR systems involve the integration of active and passive devices due to which several unique challenges arise in terms of network design and management. One major issue is the selection of the appropriate RF source in a heterogenous network to achieve the desired balance between energy harvesting, backscattering, energy efficiency, and data rates. This can be further complicated by the fact that the propagation and availability of ambient signals can vary significantly depending on the environment, making it difficult to predict the best RF source for a given scenario. Another key challenge is the management of multiple AUs and BDs in the system. This requires real-time channel estimation of all active and passive users, which can be challenging to achieve in practice. Additionally, there is the problem of determining the optimal user association to maximize the overall system sum rate. Scalability is also an important consideration in the design of symbiotic radio systems, as the number of BDs can vary significantly depending on the environment. This can make it difficult to develop effective resource allocation and management strategies that can adapt to changing network conditions. In [190], the authors present two deep learning methods, centralized deep reinforcement learning (CDRL) and distributed deep reinforcement learning (DDRL), to infer the current CSI from past CSI. Both methods achieve optimal AU and BDs association, which is close to the one with perfect real-time CSI. Furthermore, in terms of scalability for a large number of BDs, the DDRL method surpasses the CDRL approach. CDRL, on the other hand, requires less information than the DDRL to solve the association issue. However, the use of deep learning methods for user association in an SR system with heterogeneous networks is an open

area of research. Overall, the network design and management issues in SR systems are complex and multifaceted. Further research is needed to develop effective solutions that can address these challenges and enable the successful deployment of SR systems in real-world scenarios.

- Security and privacy concerns: The sharing of radio resources between different radio systems and the broadcast nature of passive devices makes the SR vulnerable to attacks. Common types of attacks include eavesdropping, jamming, and spoofing [66]. For instance, an illegitimate user in the network can exploit the broadcast nature of BDs to listen to their sensitive information by eavesdropping. It can also disrupt the SCm by jamming the signal of AT so that the AU and BD can not communicate in SR system. Besides, in a spoofing attack, a malicious AU in the network can pretend to be a legitimate receiver to get the data of BD in passive IoT. It is essential to secure the design of low-complexity security algorithms to secure passive devices in the SR system. The conventional cryptography-based encryption and authentication methods designed for active radio systems are inapplicable in processing-restricted BDs due to their higher computational complexity and key management issues [67]. On the other hand, physical layer security is a promising solution for providing security and privacy by leveraging the dynamic aspects of the wireless environment [11]. Different approaches can be used to secure the SR system at the physical layer. The authentication can be performed by exploiting the RF fingerprint BDs and AUs as each one of them has a unique RF fingerprint due to hardware impairments. The active jamming or beam nulling techniques can be exploited to prevent malicious BDs from using the radio resources and creating interference in the network. Besides, artificial noise can be added to the carrier signal for covert SCm. The artificial noise can be added at AT before transmission of the carrier signal or AU can transmit an artificial noise signal that is known to the receiver during the BC. These techniques are suitable for securing single BD from security attacks but not scalable to the network level where multiple BDs and AUs perform concurrent transmission. There is an urgent need to develop scalable physical layer security techniques, especially for jamming and eavesdropping.

Other than that, in a SR system with heterogeneous networks, it is vital to ensure that only authorized devices have access to shared radio resources.

- Defining key performance metrics: In an SR system with a commensal symbiotic relationship, BD can provide multipath diversity to AU to increase their reliability. By utilizing a mutualism symbiotic relationship, the overall capacity of the system can also be increased by jointly increasing the sum rate. Investigating new methods for spectral efficiency enhancement through SR with various symbiotic relationships between active and passive radio systems is an exciting research area to be explored. Moreover, in the SR system, radio resources are shared across multiple dimensions, such as spectrum, energy, and infrastructure. These new forms of resource sharing require novel performance metrics to accurately measure system performance, as opposed to traditional metrics.
- Symbiotic communication and sensing: SR can be designed not only for communication but also for sensing in an obligatory symbiosis which leads to the idea of symbiotic communication and sensing (SCaS). To enable SCaS, a passive radio system can coexist with an active radio system that performs joint RADAR/sensing and communication. The signal transmitted for cooperative sensing and communication can also be utilized by BD to backscatter its information. Then, the active radio transceiver can detect the data of BD while performing sensing and communication. In [191], a frequency-modulated continuous wave signal is used to perform localization and BC. The authors also propose a framework for joint processing of BC and RADAR signals and a line coding-based filter for clutter removal to detect the target of interest within clutter return. In [192], the author proposes an extension of this work for distributed sensing and communication. We anticipate three use cases of SCaS, including non-terrestrial networks, V2X, and passive RADAR. Firstly, SR can be applied in air-to-air and air-to-ground SCaS scenarios in a non-terrestrial network. In such scenarios, a satellite transmits a communication signal to UAV and a ground station. The UAV backscatters the signal to send

its data with BC, and when the ground station receives the backscattered signal it performs SCaS to find the location of UAV along with the data. In contrast, SCaS for autonomous driving in V2X, where an autonomous vehicle transmits the frequency-modulated continuous wave signal to sense the environment and communicates with traffic light control system while an IoT device e.g., smartwatch, attached to cyclist sends the data to the vehicle through BC. The third application of SCaS is related to a passive RADAR system, in which the passive RADAR uses the signal of the cellular base station to detect the presence of a UAV and also receive its information through transmitted by BC. The SR technology for SCaS is still in its infancy, and future research can be focused on SCaS waveform design, channel estimation through sensing signal, joint RADAR and sensing parameter extraction, and backscattered signal interference cancellation from joint communication and sensing signal at the receiver. Development of SR system for SCaS can enable new paradigms for spectrum sharing and the coexistence of multiple radio systems with individual functionalities.

- In the study for interference-free BC in an OFDM-based SR system, we design the primary OFDM signal to eliminate the direct link interference to BC. In particular, our approach involves the allocation of the subcarriers for BD and RX within the OFDM symbol, and BD utilizes an FSK modulation to transmit its data over the dedicated null subcarriers. We consider three subcarrier allocation strategies for BC, i.e., OOK, FSK-1 and FSK-2. The FSK-1 is more spectrally efficient than FSK-2, but it results in a higher BER. FSK-2 and OOK achieve higher reliability at the cost of reducing spectral efficiency. Besides, FSK-2 provides a lower retransmission probability than OOK and FSK-1. A non-coherent detector is also designed to detect the BD's data at the RX without being affected by interference. We theoretically derive and validate the detector's BER performance through simulation results. The numerical results demonstrate that increasing the OFDM symbol size or reflection coefficient results in a low BER of BC. Furthermore, the proposed approach can be widely integrated into current OFDM-based wireless systems to support sensors, ambient power-enabled IoT devices, and passive IoT devices. Our

proposed scheme is also beneficial in scenarios where the primary user and BC receiver are separated from each other but are part of the SR; they can independently detect their signal from the received OFDM signal using coherent and non-coherent detectors, respectively.

- In the beam selection study we try to maximize the RF signal accessibility to backscatter devices in the mmWave SR system. As the AmBackCom system relies on the signals of ambient RF sources, resource availability is crucial for such a system to operate. Due to the sparsity of the mmWave channel, the incident signal may be inaccessible to BD for communication. Therefore, beam selection in the beamspace domain is performed based on the MM of the channel and choosing the dominant paths between Tx and Rx while ensuring the signal accessibility to BDs. The performance of the beam selection scheme is measured in terms of the achievable sum-rate of the system. The simulation results validate that when beams are selected considering the presence of BDs, it results in sum-rate enhancement of the overall system. Future studies may consider the interference issues when the same beam is selected for multiple BDs.
- The study on secure ISAC proposes a secure pilot allocation to protect the sensing and communication information. An APwA mechanism is also developed to enhance the performance gains of the proposed method. PLE, BER and MSE are considered key performance indicators to demonstrate that legitimate users can communicate securely while the illegitimate user is restricted from obtaining the sensing and communication information. Simulation results validate that the performance gains of adaptive pilot allocation with APwA in terms of BER and MSE are comparable to the conventional methods with the known pilot locations. Besides, it is observed that PLE is the function of subcarrier block size and power gap. A significant decrease in PLE occurs by increasing the power gap or subcarrier block size. Moreover, a large block size with one pilot may result in high MSE; thus, more pilots may be needed within a block to achieve the high-performance gain. Future research may aim at increasing the possible pilot subcarrier locations within a block, considering both the power and phase of the channel.

- In the 3D VLC-NOMA systems' study, we proposed two UP schemes and analyzed their performance in terms of AUDR. Simulation results validated the proposed UP schemes and indicated that UP Scheme-I with FTPA provides the best AUDR gains for a large number of users. However, in the case of a small number of users, UP Scheme-II with FTPA provided higher AUDR than NOMA-WP and OMA schemes. Furthermore, considering different users' heights, the proposed UP schemes have significant AUDR gains and robustness to the 3D users' deployment. Therefore, providing smart user pairing, even for similar channel gain users, results in high AUDR in 3D VLC-NOMA systems. Future studies may include the effect of shadowing and the presence of non-line-of-sight links to analyze the performance of proposed user pairing schemes. Also, a multi-cell 3D-VLC system can be considered with multi-user access and user pairing between adjacent cell users.

BIBLIOGRAPHY

- [1] G. Yang and Y.-C. Liang, "Backscatter communications over ambient OFDM signals: Transceiver design and performance analysis," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Washington, DC, USA, Dec. 2016, pp. 1–6.
- [2] M. A. ElMossallamy *et al.*, "Backscatter communications over ambient OFDM signals using null subcarriers," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2018, pp. 1–6.
- [3] M. A. Rahman, M. S. Hossain, N. A. Alrajeh, and N. Guizani, "B5G and explainable deep learning assisted healthcare vertical at the edge: COVID-19 perspective," *IEEE Netw.*, vol. 34, no. 4, pp. 98–105, 2020.
- [4] S. Dang, O. Amin, B. Shihada, and M.-S. Alouini, "What should 6G be?" *Nat. Electron.*, vol. 3, no. 1, pp. 20–29, 2020.
- [5] Matinmikko-Blue *et al.*, "White Paper on 6G Drivers and the UN SDGs," *arXiv preprint arXiv:2004.14695*, 2020.
- [6] Y. H.-C. Da Costa Daniel Benevides, "Grand challenges in wireless communications," *Front. Commun. Netw.*, vol. 1, p. 1, 2020. [Online]. Available: <https://www.frontiersin.org/article/10.3389/frcmn.2020.00001>
- [7] I. F. Akyildiz, A. Kak, and S. Nie, "6G and beyond: The future of wireless communications systems," *IEEE Access*, vol. 8, pp. 133 995–134 030, 2020.
- [8] J. Vora *et al.*, "Ensuring privacy and security in e-health records," in *2018 Int. Conf. Comput. Inf. telecomm. Syst. (CITS)*. IEEE, 2018, pp. 1–5.
- [9] N. Van Huynh *et al.*, "Ambient backscatter communications: A contemporary survey," *IEEE Commun. Surv. Tutor.*, vol. 20, no. 4, pp. 2889–2922, 2018.
- [10] S. J. Nawaz, S. K. Sharma, S. Wyne, M. N. Patwary, and M. Asaduzzaman, "Quantum machine learning for 6G communication networks: State-of-the-art and vision for the future," *IEEE Access*, vol. 7, pp. 46 317–46 350, 2019.
- [11] J. M. Hamamreh, H. M. Furqan, and H. Arslan, "Classifications and applications of physical layer security techniques for confidentiality: A comprehensive survey," *IEEE Commun. Surv. Tutor.*, vol. 21, no. 2, pp. 1773–1828, 2018.
- [12] S. Tanwar, K. Parekh, and R. Evans, "Blockchain-based electronic healthcare record system for healthcare 4.0 applications," *J. Inf. Secur. Appl.*, vol. 50, p. 102407, 2020.
- [13] Turkcell, "Turkcell group," *Our Initial Take on COVID-19*, vol. April, 2020.
- [14] M. B. Janjua, A. E. Duranay, and H. Arslan, "Role of wireless communication in healthcare system to cater disaster situations under 6G vision," *Frontiers Commun. Netw.*, vol. 1, no. December, pp. 1–10, 2020.
- [15] E. Basar *et al.*, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116 753–116 773, 2019.
- [16] S. E. Zegrar, L. Afeef, and H. Arslan, "A general framework for RIS-aided mmWave communication networks: Channel estimation and mobile user tracking," *arXiv preprint arXiv:2009.01180*, 2020.

- [17] S. Naderi, D. B. da Costa, and H. Arslan, "Joint random subcarrier selection and channel-based artificial signal design aided PLS," *IEEE Wirel. Commun.*, vol. 9, no. 7, pp. 976–980, 2020.
- [18] H. M. Furqan, M. S. J. Solaija, and H. Arslan, "Intelligent physical layer security approach for V2X communication," *arXiv preprint arXiv:1905.05075*, 2019.
- [19] M. Di Renzo *et al.*, "Smart radio environments empowered by reconfigurable AI meta-surfaces: An idea whose time has come," *EURASIP J. Wirel. Commun. Netw.*, vol. 2019, no. 1, pp. 1–20, 2019.
- [20] H. Yang *et al.*, "A programmable metasurface with dynamic polarization, scattering and focusing control," *Scientific reports*, vol. 6, p. 35692, 2016.
- [21] I. Markit, "The internet of things: A movement, not a market," *IHS Market*, vol. 1, no. 1, p. 1, 2022.
- [22] 3rd Generation Partnership Project (3GPP), "Study on Passive IoT," Technical Report 38.XXX, ver 21.900, Dec. 2021.
- [23] C. Boyer and S. Roy, "—invited paper—Backscatter communication and RFID: Coding, energy, and MIMO analysis," *IEEE Trans. Commun.*, vol. 62, no. 3, pp. 770–785, 2013.
- [24] S. Véronneau and J. Roy, "RFID benefits, costs, and possibilities: The economical analysis of RFID deployment in a cruise corporation global service supply chain," *Int. J. Prod. Econ.*, vol. 122, no. 2, pp. 692–702, 2009.
- [25] J.-P. Niu and G. Y. Li, "An overview on backscatter communications," *J. Commun. Inf. Netw.*, vol. 4, no. 2, pp. 1–14, 2019.
- [26] V. Liu *et al.*, "Ambient backscatter: Wireless communication out of thin air," *ACM SIGCOMM Comp. Commun. Rev.*, vol. 43, no. 4, pp. 39–50, 2013.
- [27] G. Wang, F. Gao, R. Fan, and C. Tellambura, "Ambient backscatter communication systems: Detection and performance analysis," *IEEE Trans. Commun.*, vol. 64, no. 11, pp. 4836–4846, 2016.
- [28] G. Vougioukas and A. Bletsas, "24 μ watt 26m range batteryless backscatter sensors with fm remodulation and selection diversity," in *Int. Conf. RFID Tech. Appl. (RFID-TA)*, Warsaw, Poland, Sept. 2017, pp. 237–242.
- [29] —, "Switching frequency techniques for universal ambient backscatter networking," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 2, pp. 464–477, 2018.
- [30] G. Vougioukas, P. N. Alevizos, and A. Bletsas, "Coherent detector for pseudo-fsk backscatter under ambient constant envelope illumination," in *19th Int. Workshop Signal Process. Adv. Wirel. Commun. (SPAWC)*, Kalamata, Greece, 25–28 June 2018, pp. 1–5.
- [31] Y. Peng *et al.*, "Plora: A passive long-range data network from ambient lora transmissions," in *Proc. 2018 conf. ACM Special Interest Group Data Commun.*, Budapest, Hungary, August 2018, pp. 147–160.
- [32] G. Yang, Y.-C. Liang, R. Zhang, and Y. Pei, "Modulation in the air: Backscatter communication over ambient OFDM carrier," *IEEE Trans. Commun.*, vol. 66, no. 3, pp. 1219–1233, 2017.

- [33] R. Takahashi and K. Ishibashi, "Ambient OFDM pilot-aided delay-shift keying and its efficient detection for ultra low-power communications," in *Proc. IEEE Global Conf. Signal Inf. Process. (GlobalSIP)*, Nov. 2019, pp. 1–5.
- [34] T. Hara, R. Takahashi, and K. Ishibashi, "Ambient OFDM pilot-aided backscatter communications: Concept and design," *IEEE Access*, vol. 9, pp. 89 210–89 221, 2021.
- [35] A. N. Parks, A. Liu, S. Gollakota, and J. R. Smith, "Turbocharging ambient backscatter communication," in *ACM SIGCOMM Comput. Commun. Rev.*, New York, NY, USA, October 2014, pp. 619–630.
- [36] H. Guo, Q. Zhang, S. Xiao, and Y.-C. Liang, "Exploiting multiple antennas for cognitive ambient backscatter communication," *IEEE Internet of Things J.*, vol. 6, no. 1, pp. 765–775, 2018.
- [37] R. Duan, R. Jäntti, M. ElMossallamy, Z. Han, and M. Pan, "Multi-antenna receiver for ambient backscatter communication systems," in *Proc. IEEE 19th Int. Workshop Signal Process. Adv. Wirel. Commun. (SPAWC)*, Jun. 2018, pp. 1–5.
- [38] A. De Bary, "The phenomenon of symbiosis," *Karl J. Trubner, Strasbourg, Germany*, 1879.
- [39] Y.-C. Liang, R. Long, Q. Zhang, and D. Niyato, "Symbiotic communications: Where marconi meets darwin," *IEEE Wirel. Commun.*, vol. 29, no. 1, pp. 144–150, 2022.
- [40] R. Long, Y.-C. Liang, Y. Pei, and E. G. Larsson, "Active-load assisted symbiotic radio system in cognitive radio network," in *IEEE 21st Int. Workshop Signal Process. Adv. Wirel. Commun. (SPAWC)*, Atlanta, GA, USA, 26-29 May 2020, pp. 1–5.
- [41] T. Huang *et al.*, "A survey on green 6G network: Architecture and technologies," *IEEE Access*, vol. 7, pp. 175 758–175 768, 2019.
- [42] X. Lin, "The Bridge Toward 6G: 5G-Advanced Evolution in 3GPP Release 19," *arXiv preprint arXiv:2312.15174*, 2023.
- [43] M. M. Butt, N. R. Mangalvedhe *et al.*, "Ambient IoT: A missing link in 3GPP IoT Devices Landscape," *arXiv preprint arXiv:2312.06569*, 2023.
- [44] EPCglobal, "EPC Radio-frequency identity protocols generation-2 UHF RFID standard, specification for RFID air interface protocol for communications at 860 MHz – 930 MHz, version 3.0," Jan. 2024. [Online]. Available: <https://ref.gs1.org/standards/gen2/>
- [45] K. Han and K. Huang, "Wirelessly powered backscatter communication networks: Modeling, coverage, and capacity," *IEEE Trans. Wirel. Commun.*, vol. 16, no. 4, pp. 2548–2561, 2017.
- [46] W. Liu, K. Huang, X. Zhou, and S. Durrani, "Next generation backscatter communication: systems, techniques, and applications," *EURASIP J. Wirel. Commun. Netw.*, vol. 2019, no. 1, pp. 1–11, 2019.
- [47] M. Stanacevic, A. Athalye, Z. J. Haas, S. R. Das, and P. Djuric, "Backscatter communications with passive receivers: From fundamentals to applications," *ITU J.*, vol. 1, no. 1, 2020.

- [48] R. Long, Y.-C. Liang, H. Guo, G. Yang, and R. Zhang, "Symbiotic radio: A new communication paradigm for passive Internet of Things," *IEEE Internet Things J.*, vol. 7, no. 2, pp. 1350–1363, 2019.
- [49] Y.-C. Liang, Q. Zhang, E. G. Larsson, and G. Y. Li, "Symbiotic radio: Cognitive backscattering communications for future wireless networks," *IEEE Trans. Cogn. Commun. Netw.*, vol. 6, no. 4, pp. 1242–1255, 2020.
- [50] Q. Zhang, Y.-C. Liang, H.-C. Yang, and H. V. Poor, "Mutualistic mechanism in symbiotic radios," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2021, pp. 1–6.
- [51] J. Xu, Z. Dai, and Y. Zeng, "Enabling full mutualism for symbiotic radio with massive backscatter devices," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2021, pp. 1–6.
- [52] L. Zhang, Y.-C. Liang, and D. Niyato, "6G Visions: Mobile ultra-broadband, super internet-of-things, and artificial intelligence," *China Commun.*, vol. 16, no. 8, pp. 1–14, 2019.
- [53] L. Bariah *et al.*, "A prospective look: Key enabling technologies, applications and open research topics in 6G networks," *IEEE Access*, vol. 8, pp. 174 792–174 820, 2020.
- [54] S. Chen *et al.*, "Vision, requirements, and technology trend of 6G: How to tackle the challenges of system coverage, capacity, user data-rate and movement speed," *IEEE Wirel. Commun.*, vol. 27, no. 2, pp. 218–228, 2020.
- [55] S. J. Nawaz, S. K. Sharma, B. Mansoor, M. N. Patwary, and N. M. Khan, "Non-coherent and backscatter communications: Enabling ultra-massive connectivity in 6G wireless networks," *IEEE Access*, vol. 9, pp. 38 144–38 186, 2021.
- [56] M. B. Janjua and H. Arslan, "A Survey of Symbiotic Radio: Methodologies, Applications, and Future Directions," *Sensors*, vol. 23, no. 5, p. 2511, 2023.
- [57] M. B. Janjua, A. Şahin, and H. Arslan, "Interference-free backscatter communications for ofdm-based symbiotic radio," *arXiv preprint arXiv:2408.09192*, 2024.
- [58] L. Zhang, Y.-C. Liang, and M. Xiao, "Spectrum sharing for Internet of Things: A survey," *IEEE Wirel. Commun.*, vol. 26, no. 3, pp. 132–139, 2018.
- [59] M. Maier, A. Ebrahimzadeh, S. Rostami, and A. Beniiiche, "The Internet of No Things: Making the Internet Disappear and“ See the Invisible”,” *IEEE Commun. Mag.*, vol. 58, no. 11, pp. 76–82, 2020.
- [60] A. Sayeed and J. Brady, "Beamspace MIMO for high-dimensional multiuser communication at millimeter-wave frequencies," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2013, pp. 3679–3684.
- [61] P. V. Amadori and C. Masouros, "Low RF-complexity millimeter-wave beamspace-MIMO systems by beam selection," *IEEE Trans. Commun.*, vol. 63, no. 6, pp. 2212–2223, 2015.
- [62] F. Liu *et al.*, "Integrated sensing and communications: Towards dual-functional wireless networks for 6G and beyond," *IEEE J. Sel. Areas Commun.*, 2022.

- [63] D. K. P. Tan *et al.*, “Integrated sensing and communication in 6G: Motivations, use cases, requirements, challenges and future directions,” in *2021 1st IEEE Int. Online Symp. Joint Commun. Sens. (JC&S)*. IEEE, 2021, pp. 1–6.
- [64] Z. Wang, B. Guo, Z. Yu, and X. Zhou, “Wi-Fi CSI-based behavior recognition: From signals and actions to activities,” *IEEE Commun. Mag.*, vol. 56, no. 5, pp. 109–115, 2018.
- [65] Z. Wang *et al.*, “CSI-based human sensing using model-based approaches: a survey,” *J. Comput. Des. Eng.*, vol. 8, no. 2, pp. 510–523, 2021.
- [66] H. M. Furqan, M. S. J. Solaija, H. Türkmen, and H. Arslan, “Wireless communication, sensing, and REM: a security perspective,” *IEEE Open J. Commun. Soc.*, vol. 2, pp. 287–321, 2021.
- [67] M. S. J. Solaija, H. Salman, and H. Arslan, “Towards a Unified Framework for Physical Layer Security in 5G and Beyond Networks,” *IEEE Open J. Veh. Technol.*, 2022.
- [68] H. Wei, B. Zheng, and X. Hou, “Compressive channel sensing based on random pilot for physical layer communication security,” in *22nd Wirel. Opt. Commun. Conf.* IEEE, 2013, pp. 693–698.
- [69] M. Soltani, T. Baykaş, and H. Arslan, “Achieving secure communication through pilot manipulation,” in *26th Annu. Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*. IEEE, 2015, pp. 527–531.
- [70] Q. Zhu, S. Wu, and Y. Hua, “Optimal pilots for anti-eavesdropping channel estimation,” *IEEE Trans. Signal Process.*, vol. 68, pp. 2629–2644, 2020.
- [71] M. Biagi, S. Pergoloni, and A. M. Vegni, “Last: A framework to localize, access, schedule, and transmit in indoor vlc systems,” *J. Lightw. Technol.*, vol. 33, no. 9, pp. 1872–1887, 2015.
- [72] Z. Tahira *et al.*, “Optimization of non-orthogonal multiple access based visible light communication systems,” *IEEE Commun. Lett.*, vol. 23, no. 8, pp. 1365–1368, 2019.
- [73] X. Liu *et al.*, “Placement and power allocation for NOMA-UAV networks,” *IEEE Wirel. Commun. Lett.*, vol. 8, no. 3, pp. 965–968, 2019.
- [74] O. Maraqa, A. S. Rajasekaran, S. Al-Ahmadi, H. Yanikomeroglu, and S. M. Sait, “A survey of rate-optimal power domain NOMA schemes for enabling technologies of future wireless networks,” *arXiv preprint arXiv:1909.08011*, 2019.
- [75] Z. Ding, M. Peng, and H. V. Poor, “Cooperative non-orthogonal multiple access in 5G systems,” *IEEE Commun. Lett.*, vol. 19, no. 8, pp. 1462–1465, 2015.
- [76] H. Marshoud, V. M. Kapinas, G. K. Karagiannidis, and S. Muhaidat, “Non-orthogonal multiple access for visible light communications,” *IEEE Photon. Technol. Lett.*, vol. 28, no. 1, pp. 51–54, 2015.
- [77] L. Yin, W. O. Popoola, X. Wu, and H. Haas, “Performance evaluation of non-orthogonal multiple access in visible light communication,” *IEEE Trans. Commun.*, vol. 64, no. 12, pp. 5162–5175, 2016.

- [78] H. Marshoud, P. C. Sofotasios, S. Muhaidat, G. K. Karagiannidis, and B. S. Sharif, "On the performance of visible light communication systems with non-orthogonal multiple access," *IEEE Trans. Wirel. Commun.*, vol. 16, no. 10, pp. 6350–6364, 2017.
- [79] Z. Ding, P. Fan, and H. V. Poor, "Impact of user pairing on 5G nonorthogonal multiple-access downlink transmissions," *IEEE Trans. Veh. Technol.*, vol. 65, no. 8, pp. 6010–6023, 2015.
- [80] X. Zhang, Q. Gao, C. Gong, and Z. Xu, "User grouping and power allocation for NOMA visible light communication multi-cell networks," *IEEE Commun. Lett.*, vol. 21, no. 4, pp. 777–780, 2016.
- [81] V. Chawla and D. S. Ha, "An overview of passive RFID," *IEEE Commun. Mag.*, vol. 45, no. 9, pp. 11–17, 2007.
- [82] H. Stockman, "Communication by means of reflected power," *Proc. of the IRE*, vol. 36, no. 10, pp. 1196–1204, 1948.
- [83] A. R. Koelle, S. W. Depp, and R. W. Freyman, "Short-range radio-telemetry for electronic identification, using modulated RF backscatter," *Proc. of the IEEE*, vol. 63, no. 8, pp. 1260–1261, 1975.
- [84] J. Landt, "The history of RFID," *IEEE Potentials*, vol. 24, no. 4, pp. 8–11, 2005.
- [85] P. K. Rai, A. Kumar, M. Z. A. Khan, and L. R. Cenkeramaddi, "Lte-based passive radars and applications: a review," *Int. J. Remote Sens.*, vol. 42, no. 19, pp. 7489–7518, 2021.
- [86] S. Chen, M. Zhang, J. Zhao, W. Gong, and J. Liu, "Reliable and practical blue-tooth backscatter with commodity devices," *IEEE/ACM Trans. Netw.*, vol. 29, no. 4, pp. 1717–1729, 2021.
- [87] Y. Li, S. Yan, J. Gong, and F. Zeng, "SNR enhancement of back scattering signals for bistatic radar based on BeiDou GEO satellites," *Remote Sens.*, vol. 13, no. 7, p. 1254, 2021.
- [88] H. Kuschel, D. Cristallini, and K. E. Olsen, "Tutorial: Passive radar tutorial," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 34, no. 2, pp. 2–19, 2019.
- [89] M. Cooper, "The myth of spectrum scarcity," *DYNALC, Tech. Rep.*, Mar, 2010.
- [90] S. Bhattarai, J. M. Park, B. Gao, K. Bian, and W. Lehr, "An overview of dynamic spectrum sharing: Ongoing initiatives, challenges, and a roadmap for future research," *IEEE Trans. Cogn. Commun. Netw.*, vol. 2, no. 2, pp. 110–128, 2016.
- [91] A. M. Voicu, L. Simić, and M. Petrova, "Survey of spectrum sharing for inter-technology coexistence," *IEEE Commun. Surv. Tut.*, vol. 21, no. 2, pp. 1112–1144, 2019.
- [92] Q. Zhao and B. M. Sadler, "A survey of dynamic spectrum access," *IEEE Signal Process. Mag.*, vol. 24, no. 3, pp. 79–89, 2007.
- [93] C. B. Papadias, T. Ratnarajah, and D. T. Slock, *Spectrum sharing: the next frontier in wireless networks*. John Wiley & Sons, 2020.

- [94] C. Han, Y. Wu, Z. Chen, and X. Wang, "Terahertz communications (TeraCom): Challenges and impact on 6G wireless systems," *arXiv preprint arXiv:1912.06040*, 2019.
- [95] G. L. Rosston, "Increasing the efficiency of spectrum allocation," *Rev. Ind. Org.*, vol. 45, no. 3, pp. 221–243, 2014.
- [96] D. Tarek, A. Benslimane, M. Darwish, and A. M. Kotb, "Survey on spectrum sharing/allocation for cognitive radio networks Internet of Things," *Egyptian Inform. J.*, vol. 21, no. 4, pp. 231–239, 2020. [Online]. Available: <https://doi.org/10.1016/j.eij.2020.02.003>
- [97] S. H. Mousa, M. Ismail, R. Nordin, and N. F. Abdullah, "Effective wide spectrum sharing techniques relying on CR technology toward 5G: A survey," *J. Commun.*, vol. 15, no. 2, pp. 122–147, 2020.
- [98] F. Hu, B. Chen, and K. Zhu, "Full Spectrum Sharing in Cognitive Radio Networks Toward 5G: A Survey," *IEEE Access*, vol. 6, pp. 15 754–15 776, 2018.
- [99] M. Amjad, F. Akhtar, M. H. Rehmani, M. Reisslein, T. Umer, "Full-duplex communication in cognitive radio networks: A survey," *IEEE Commun. Surv. Tut.*, vol. 19, no. 4, pp. 2158–2191, 2017.
- [100] A. Mamadou Mamadou, J. Toussaint, and G. Chalhoub, "Survey on wireless networks coexistence: Resource sharing in the 5G era," *Mobile Netw. App.*, vol. 25, no. 5, pp. 1749–1764, 2020.
- [101] M. S. Gupta and K. Kumar, "Progression on spectrum sensing for cognitive radio networks: A survey, classification, challenges and future research issues," *J. Netw. Comput. App.*, vol. 143, no. January, pp. 47–76, 2019. [Online]. Available: <https://doi.org/10.1016/j.jnca.2019.06.005>
- [102] L. Zhang *et al.*, "A survey of advanced techniques for spectrum sharing in 5G networks," *IEEE Wirel. Commun.*, vol. 24, no. 5, pp. 44–51, 2017.
- [103] M. Amjad, M. H. Rehmani, and S. Member, "Wireless multimedia cognitive radio networks: A comprehensive survey," *IEEE Commun. Surv. Tut.*, vol. 20, no. 2, pp. 1056–1103, 2018.
- [104] H. Maloku, Z. L. Fazliu, and M. Ibrani, "A survey on coexistence in heterogeneous wireless networks in TV white spaces," *Wirel. Commun. Mob. Comput.*, vol. 2018, 2018.
- [105] J. D. Alejandrino, R. S. Concepcion, S. C. Laugico, E. T. Trinidad, and E. P. Dadios, "Feasibility of television white space spectrum technologies for wide range wireless sensor network: A survey," in *2019 IEEE 11th Int. Conf. Humanoid Nanotechnol. Inf. Technol. Commun. Control Environ. Manage. (HNICEM)*, Laoag, Philippines, 29 November 2019 - 01 December 2019, pp. 1–6.
- [106] D. Zhang, Q. Liu, L. Chen, and W. Xu, "Survey on coexistence of heterogeneous wireless networks in 2.4 GHz and TV white spaces," *Int. J. Distrib. Sensor Netw.*, vol. 13, no. 4, 2017.
- [107] Y. Peng *et al.*, "A review of dynamic resource allocation in integrated satellite and terrestrial networks," in *Int. Conf. Netw. Netw. App. (NaNA)*, Xi'an, China, 12-15 October 2018, pp. 127–132.

- [108] X. Wang, S. Mao, and M. X. Gong, "A survey of LTE Wi-Fi coexistence in unlicensed bands," *GetMobile: Mob. Comput. Commun.*, vol. 20, no. 3, pp. 17–23, 2017.
- [109] M. Labib, V. Marojevic, A. F. Martone, J. H. Reed, and A. I. Zaghloul, "Coexistence between communications and radar systems - A survey," *URSI Radio Sci. Bull.*, vol. 2, no. 362, pp. 74–82, 2017.
- [110] S. Mazahir, S. Ahmed, and M.-S. Alouini, "A survey on joint communication-radar systems," *Frontiers Commun. Netw.*, vol. 1, p. 9, 2021. [Online]. Available: <https://www.frontiersin.org/article/10.3389/frcmn.2020.619483>
- [111] J. Choi, V. Marojevic, C. B. Dietrich, J. H. Reed, and S. Ahn, "Survey of spectrum regulation for intelligent transportation systems," *IEEE Access*, vol. 8, pp. 140 145–140 160, 2020.
- [112] Y. Han, E. Ekici, H. Kremo, and O. Altintas, "Spectrum sharing methods for the coexistence of multiple RF systems: A survey," *Ad Hoc Netw.*, vol. 53, pp. 53–78, 2016. [Online]. Available: <http://dx.doi.org/10.1016/j.adhoc.2016.09.009>
- [113] B. D. S. E. Martin, "Symbiosis : " Living Together " in Chaos," *Stud. Hist. Biol.*, vol. 4, no. 4, pp. 7–25, 2012.
- [114] E. Montesinos Seguí, "Plant-associated microorganisms: a view from the scope of microbiology," *Int. Microbiol.*, 2003, vol. 6, núm. 4, p. 221–223, 2003.
- [115] Z. Wang *et al.*, "Symbiotic Sensing and Communications Towards 6G: Vision, Applications, and Technology Trends," 2021. [Online]. Available: <http://arxiv.org/abs/2106.15197>
- [116] A. K. Mishra and M. Inggs, "FOPEN capabilities of commensal radars based on whitespace communication systems," in *Int. Conf. Electron., Comput. Commun. Technol. (CONECCT), Bangalore, India.* IEEE, 06-07 January 2014, pp. 1–5.
- [117] —, "White space symbiotic radar: A new scheme for coexistence of radio communications and radar," in *IEEE Radar Conf., Johannesburg, South Africa*, 27-30 October 2015, pp. 56–60.
- [118] H. Guo, Y. C. Liang, R. Long, and Q. Zhang, "Cooperative Ambient Backscatter System: A Symbiotic Radio Paradigm for Passive IoT," *IEEE Wirel. Commun. Lett.*, vol. 8, no. 4, pp. 1191–1194, 2019.
- [119] H. Guo, Y. C. Liang, R. Long, S. Xiao, and Q. Zhang, "Resource allocation for symbiotic radio system with fading channels," *IEEE Access*, vol. 7, pp. 34 333–34 347, 2019.
- [120] D. K. P. Asiedu and J.-H. Yun, "Power resource optimization for backscatter-aided symbiotic full-duplex secondary transmission with hardware impairments in a cognitive radio framework," *Sensors*, vol. 22, no. 1, p. 375, 2022.
- [121] Z. Chu, W. Hao, P. Xiao, M. Khalily, and R. Tafazolli, "Resource allocations for symbiotic radio with finite blocklength backscatter link," *IEEE Internet of Things J.*, vol. 7, no. 9, pp. 8192–8207, 2020.
- [122] R. S. Yeganeh and M. J. Omid, "Energy consumption in multi-BD symbiotic radio system assisted 6G Network: A QoS constraint approach," *TechRxiv preprint*, 2022.

- [123] Y. Liu, P. Ren, and Q. Du, "Symbiotic communication: Concurrent transmission for multi-users based on backscatter communication," in *Int. Conf. Wirel. Commun. Signal Process. (WCSP), Nanjing, China*, 21-23 October 2020, pp. 835–839.
- [124] S. Han, Y. C. Liang, and G. Sun, "The design and optimization of random code assisted Multi-BD symbiotic radio system," *IEEE Trans. Wirel. Commun.*, vol. 1276, no. c, pp. 1–12, 2021.
- [125] X. Chen, H. V. Cheng, K. Shen, A. Liu, and M. J. Zhao, "Stochastic transceiver optimization in multi-tags symbiotic radio systems," *IEEE Internet of Things J.*, vol. 7, no. 9, pp. 9144–9157, 2020.
- [126] H. Yang, Y. Ye, K. Liang, and X. Chu, "Energy efficiency maximization for symbiotic radio networks with multiple backscatter devices," *IEEE Open j. Commun. Soc.*, vol. 2, pp. 1431–1444, 2021.
- [127] Q. Zhang, L. Zhang, Y. C. Liang, and P. Y. Kam, "Backscatter-NOMA: A symbiotic system of cellular and Internet-of-things networks," *IEEE Access*, vol. 7, pp. 20 000–20 013, 2019.
- [128] Y. Liao, G. Yang, and Y. C. Liang, "Resource allocation in NOMA-enhanced full-duplex symbiotic radio networks," *IEEE Access*, vol. 8, pp. 22 709–22 720, 2020.
- [129] A. Raza *et al.*, "A NOMA-enabled cellular symbiotic radio for mMTC," *Wirel. Pers. Commun.*, vol. 122, no. 4, pp. 3545–3571, 2022.
- [130] Y. Tuo and C. Zhang, "Outage analysis of parasitic ambient backscatter communication in decode-and-forward relay networks with SWIPT," *Sensors*, vol. 20, no. 5, 2020.
- [131] S. Kutty and D. Sen, "Beamforming for millimeter wave communications: An inclusive survey," *IEEE Commun. Surv. Tutor.*, vol. 18, no. 2, pp. 949–973, 2015.
- [132] T. Wu, M. Jiang, Q. Zhang, Q. Li, and J. Qin, "Beamforming design in multiple-input-multiple-output symbiotic radio backscatter Systems," *IEEE Commun. Lett.*, no. 1, pp. 1–5, 2021.
- [133] Z. Dai, R. Li, J. Xu, Y. Zeng, and S. Jin, "Cell-free symbiotic radio: Channel estimation method and achievable rate analysis," in *IEEE/CIC Int. Conf. Commun. China (ICCC Workshops), Xiamen, China*, 28-30 July 2021, pp. 25–30.
- [134] J. Xu, Z. Dai, and Y. Zeng, "MIMO symbiotic radio with massive passive devices: Asymptotic analysis and precoding Optimization," *arXiv preprint arXiv:2206.13203*, 2022.
- [135] M. B. Janjua, H. T. Abbas, K. A. Qaraqe, and H. Arslan, "Beam selection for ambient backscatter communication in beamspace mmwave symbiotic radio," *IEEE Wirel. Commun. Lett.*, 2023.
- [136] Y. Li, M. Jiang, Q. Zhang, and J. Qin, "Secure beamforming in MISO NOMA backscatter device aided symbiotic radio networks," *arXiv preprint arXiv:1906.03410*, 2019.

- [137] L. Dai *et al.*, “Reconfigurable intelligent surface-based wireless communications: Antenna design, prototyping, and experimental results,” *IEEE Access*, vol. 8, pp. 45 913–45 923, 2020.
- [138] H. Chen, G. Yang, and Y. C. Liang, “Joint active and passive beamforming for reconfigurable intelligent surface enhanced symbiotic radio system,” *IEEE Wirel. Commun. Lett.*, vol. 10, no. 5, pp. 1056–1060, 2021.
- [139] H. Zhou, Y.-C. Liang, X. Kang, and S. Sun, “Cooperative beamforming for large intelligent surface assisted symbiotic radios,” in *Proc. IEEE Global Commun. Conf. (GLOBECOM), Taipei, Taiwan*, 07-11 December 2020, pp. 1–6.
- [140] Q. Zhang, Y. C. Liang, and H. V. Poor, “Symbiotic radio: A new application of large intelligent surface/antennas (LISA),” in *Wirel. Commun. Netw. Conf. (WCNC)*. Seoul, Korea (South): IEEE, 2020, pp. 1–6.
- [141] X. Xu, Y. C. Liang, G. Yang, and L. Zhao, “Reconfigurable intelligent surface empowered symbiotic radio over broadcasting signals,” *IEEE Trans. Commun.*, vol. 6778, no. c, pp. 1–16, 2021.
- [142] Q. Zhang, Y. C. Liang, and H. Vincent Poor, “Reconfigurable intelligent surface assisted MIMO symbiotic radio networks,” *IEEE Trans. Commun.*, pp. 1–30, 2021.
- [143] X. Lei *et al.*, “Reconfigurable intelligent surface-based symbiotic radio for 6G: Design, challenges, and opportunities,” *IEEE Wirel. Commun.*, 2021.
- [144] R. Long, H. Guo, L. Zhang, and Y. C. Liang, “Full-Duplex Backscatter Communications in Symbiotic Radio Systems,” *IEEE Access*, vol. 7, pp. 21 597–21 608, 2019.
- [145] J.-F. Bousquet, S. Magierowski, and G. G. Messier, “A 4-GHz active scatterer in 130-nm CMOS for phase sweep amplify-and-forward,” *IEEE Trans. Circuits Syst. I: Regular Papers*, vol. 59, no. 3, pp. 529–540, 2011.
- [146] S. Khaledian, F. Farzami, H. Soury, B. Smida, and D. Erricolo, “Active two-way backscatter modulation: An analytical study,” *IEEE Trans. Wirel. Commun.*, vol. 18, no. 3, pp. 1874–1886, 2019.
- [147] D. Li, “Two birds with one stone: Exploiting decode-and-forward relaying for opportunistic ambient backscattering,” *IEEE Trans. Commun.*, vol. 68, no. 3, pp. 1405–1416, 2020.
- [148] F. Jameel *et al.*, “Applications of backscatter communications for healthcare networks,” *IEEE Netw.*, vol. 33, no. 6, pp. 50–57, 2019.
- [149] Z. Mao, F. Hu, Z. Ling, and S. Li, “Bidirectional intra-network mutual ambient backscatter communications in distributed wireless wearable measurement networks,” *Meas.*, vol. 183, p. 109863, 2021.
- [150] M. Kotaru, P. Zhang, and S. Katti, “Localizing low-power backscatter tags using commodity WiFi,” in *Proc. of the 13th Int. Conf. Emerg. Netw. Experiments Technol., Incheon, Republic of Korea*, November 2017, pp. 251–262.
- [151] P. Tokekar, J. Vander Hook, D. Mulla, and V. Isler, “Sensor planning for a symbiotic uav and ugv system for precision agriculture,” *IEEE Trans. Robot.*, vol. 32, no. 6, pp. 1498–1511, 2016.

- [152] F. Pereira *et al.*, “When backscatter communication meets vehicular networks: Boosting crosswalk awareness,” *IEEE Access*, vol. 8, pp. 34 507–34 521, 2020.
- [153] W. Zhang *et al.*, “A green paradigm for internet of things: Ambient backscatter communications,” *China Commun.*, vol. 16, no. 7, pp. 109–119, 2019.
- [154] R. Angeles, “RFID technologies: Supply-chain applications and implementation issues,” *Inf. Syst. Manage.*, vol. 22, no. 1, pp. 51–65, 2005.
- [155] M. ElMossallamy *et al.*, “Noncoherent frequency shift keying for ambient backscatter over OFDM signals,” in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2019, pp. 1–6.
- [156] M. Nemati, M. Soltani, J. Ding, and J. Choi, “Subcarrier-wise backscatter communications over ambient OFDM for low power IoT,” *IEEE Trans. Veh. Technol.*, vol. 69, no. 11, pp. 13 229–13 242, 2020.
- [157] H. Chen, Q. Zhang, R. Long, Y. Pei, and Y.-C. Liang, “Pilot Design and Signal Detection for Symbiotic Radio over OFDM Carriers,” *IEEE Trans. Wirel. Commun.*, 2023.
- [158] M. A. ElMossallamy *et al.*, “Noncoherent backscatter communications over ambient OFDM signals,” *IEEE Trans. Commun.*, vol. 67, no. 5, pp. 3597–3611, 2019.
- [159] J. Liao, X. Wang, K. Ruttik, R. Jäntti, and D.-T. Phan-Huy, “In-band ambient FSK backscatter communications leveraging LTE cell-specific reference signals,” *IEEE J. Radio Freq. Identif.*, 2023.
- [160] D. Bharadia, K. R. Joshi, M. Kotaru, and S. Katti, “Backfi: High throughput wifi backscatter,” *ACM SIGCOMM Comput. Commun. Rev.*, vol. 45, no. 4, pp. 283–296, 2015.
- [161] C. Xu, L. Yang, and P. Zhang, “Practical backscatter communication systems for battery-free Internet of Things: A tutorial and survey of recent research,” *IEEE Signal Process. Mag.*, vol. 35, no. 5, pp. 16–27, 2018.
- [162] W. Wu, X. Wang, A. Hawbani, L. Yuan, and W. Gong, “A survey on ambient backscatter communications: Principles, systems, applications, and challenges,” *Comput. Netw.*, vol. 216, p. 109235, 2022.
- [163] V. Iyer, V. Talla, B. Kellogg, S. Gollakota, and J. Smith, “Inter-technology backscatter: Towards internet connectivity for implanted devices,” in *Proc. 2016 ACM SIGCOMM Conf.*, 2016, pp. 356–369.
- [164] J. Kimionis and M. M. Tentzeris, “Pulse shaping: The missing piece of backscatter radio and RFID,” *IEEE Trans. Microw. Theory Tech.*, vol. 64, no. 12, pp. 4774–4788, 2016.
- [165] Y. Ding, R. Lihakanga, R. Correia, G. Goussetis, and N. B. Carvalho, “Harmonic suppression in frequency shifted backscatter communications,” *IEEE Open j. Commun. Soc.*, vol. 1, pp. 990–999, 2020.
- [166] M. Alhassoun, “Spectrally-efficient backscatter systems: A hardware-oriented survey,” *IEEE Access*, 2023.
- [167] P.-H. P. Wang *et al.*, “A low-power backscatter modulation system communicating across tens of meters with standards-compliant Wi-Fi transceivers,” *IEEE J. Solid-State Circuits*, vol. 55, no. 11, pp. 2959–2969, 2020.

- [168] B. Farhang-Boroujeny and H. Moradi, "OFDM inspired waveforms for 5G," *IEEE Commun. Surv. Tutor.*, vol. 18, no. 4, pp. 2474–2492, 2016.
- [169] M. Özdemir and H. Arslan, "Channel estimation for wireless OFDM systems," *IEEE Commun. Surv. Tutor.*, vol. 9, no. 2, 2007.
- [170] J. K. Devineni and H. S. Dhillon, "Ambient backscatter systems: Exact average bit error rate under fading channels," *IEEE Trans. Green Commun. Netw.*, vol. 3, no. 1, pp. 11–25, 2018.
- [171] G. Yang, T. Wei, and Y.-C. Liang, "Joint Hybrid and Passive Beamforming for Millimeter Wave Symbiotic Radio Systems," *IEEE Wirel. Commun. Lett.*, vol. 10, no. 10, pp. 2294–2298, 2021.
- [172] J. Brady, N. Behdad, and A. M. Sayeed, "Beamspace MIMO for millimeter-wave communications: System architecture, modeling, analysis, and measurements," *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3814–3827, 2013.
- [173] T. S. Rappaport *et al.*, "Millimeter wave mobile communications for 5G cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, 2013.
- [174] O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath, "Spatially sparse precoding in millimeter wave MIMO systems," *IEEE Trans. Wirel. Commun.*, vol. 13, no. 3, pp. 1499–1513, 2014.
- [175] B. He and H. Jafarkhani, "Low-complexity reconfigurable MIMO for millimeter wave communications," *IEEE Trans. Commun.*, vol. 66, no. 11, pp. 5278–5291, 2018.
- [176] G. H. Song, J. Brady, and A. Sayeed, "Beamspace MIMO transceivers for low-complexity and near-optimal communication at mm-wave frequencies," in *Proc. IEEE Int. Conf. Acoust. Speech Signal Process.*, May 2013, pp. 4394–4398.
- [177] B. Clerckx, Z. B. Zawawi, and K. Huang, "Wirelessly powered backscatter communications: Waveform design and SNR-energy tradeoff," *IEEE Commun. Lett.*, vol. 21, no. 10, pp. 2234–2237, 2017.
- [178] R. W. Heath, N. Gonzalez-Prelcic, S. Rangan, W. Roh, and A. M. Sayeed, "An overview of signal processing techniques for millimeter wave MIMO systems," *IEEE J. Sel. Top. Signal Process.*, vol. 10, no. 3, pp. 436–453, 2016.
- [179] Y. S. Cho, J. Kim, W. Y. Yang, and C. G. Kang, *MIMO-OFDM wireless communications with MATLAB*. John Wiley & Sons, 2010.
- [180] I. Barhumi, G. Leus, and M. Moonen, "Optimal training design for MIMO OFDM systems in mobile wireless channels," *IEEE Trans. Signal Process.*, vol. 51, no. 6, pp. 1615–1624, 2003.
- [181] S. Colieri, M. Ergen, A. Puri, and B. A., "A study of channel estimation in OFDM systems," in *Proc. IEEE 56th Veh. Technol. Conf.*, vol. 2, 2002, pp. 894–898 vol.2.
- [182] X. Tao, H. Chen, S. N. Li, and S. R. Hui, "A new noncontact method for the prediction of both internal thermal resistance and junction temperature of white light-emitting diodes," *IEEE Trans. Power Electron.*, vol. 27, no. 4, pp. 2184–2192, 2011.

- [183] S. Tao, H. Yu, Q. Li, and Y. Tang, "Strategy-based gain ratio power allocation in non-orthogonal multiple access for indoor visible light communication networks," *IEEE Access*, vol. 7, pp. 15 250–15 261, 2019.
- [184] —, "Performance analysis of gain ratio power allocation strategies for non-orthogonal multiple access in indoor visible light communication networks," *EURASIP J. Wirel. Commun. Netw.*, vol. 2018, no. 154, pp. 1–14, 2018.
- [185] L. A. Waller, B. W. Turnbull, and J. M. Hardin, "Obtaining distribution functions by numerical inversion of characteristic functions with applications," *The Amer. Statistician*, vol. 49, no. 4, pp. 346–350, 1995.
- [186] M. Uysal, F. Miramirkhani, O. Narmanlioglu, T. Baykas, and E. Panayirci, "IEEE 802.15. 7r1 reference channel models for visible light communications," *IEEE Commun. Mag.*, vol. 55, no. 1, pp. 212–217, 2017.
- [187] A. Ghosh, J. Zhang, J. G. Andrews, and R. Muhamed, *Fundamentals of LTE*. Pearson Education, 2010.
- [188] S. Ma, G. Wang, R. Fan, and C. Tellambura, "Blind channel estimation for ambient backscatter communication systems," *IEEE Commun. Lett.*, vol. 22, no. 6, pp. 1296–1299, 2018.
- [189] Z. Wang, H. Xu, L. Zhao, X. Chen, and A. Zhou, "Deep learning for joint pilot design and channel estimation in symbiotic radio communications," *IEEE Wirel. Commun. Lett.*, vol. 11, no. 10, pp. 2056–2060, 2022.
- [190] Q. Zhang, Y. C. Liang, and H. V. Poor, "Intelligent user association for symbiotic radio networks using deep reinforcement learning," *IEEE Trans. Wirel. Commun.*, vol. 19, no. 7, pp. 4535–4548, 2020.
- [191] I. Cnaan-On, S. J. Thomas, M. S. Reynolds, and J. L. Krolik, "Multichannel radar backscatter communication and localization," in *IEEE Int. Conf. Acoust. Speech Signal Process. (ICASSP), Florence, Italy*, 04-09 May 2014, pp. 76–80.
- [192] I. Cnaan-On, S. J. Thomas, J. L. Krolik, and M. S. Reynolds, "Multichannel backscatter communication and ranging for distributed sensing with an FMCW radar," *IEEE Trans. Microw. Theory Tech.*, vol. 63, no. 7, pp. 2375–2383, 2015.
- [193] A. Şahin and X. Wang, "Reliable majority vote computation with complementary sequences for UAV waypoint flight control," *arXiv preprint arXiv:2309.15193*, 2023.

APPENDIX A

Appendix A1 The Proof of Lemma 3.1.1

Proof. The received signal is the function of the product of two random variables: $|h_b|$, a Rayleigh random variable, and the other channel $|h_f|^2$, an exponential random variable. Let,

$$u = \sum_{m=1}^{N_b} |h_f[m]|^2, \quad (\text{A1.1})$$

be the sum of the exponential random variables while the characteristic function of an exponential random variable $f(x; \lambda_m) = \lambda_m e^{-\lambda_m x}$ for λ_m is

$$\Phi_m(t) = \lambda_m \int e^{(it - \lambda_m)x} dx = \left(1 + it\lambda^{-1}\right)^{-1}, \quad (\text{A1.2})$$

where $\Phi_m(t)$ is the Fourier transform of $f(x; \lambda_m)$.

To find the distribution of u , we need to find the convolution of N_b exponential random variables, which is equivalent to the product of its characteristic functions

$$\begin{aligned} \Phi_u &= \int e^{itz} (\lambda_1 e^{-\lambda_1 z} * \lambda_1 e^{-\lambda_2 z} * \dots * \lambda_{N_b} e^{-\lambda_{N_b} z}) dz \\ &= \prod_{m=1}^{N_b} \frac{1}{1 + it\lambda_m}. \end{aligned} \quad (\text{A1.3})$$

Now, the PDF of u can be found by taking the inverse Fourier transform of $\Phi_u(t)$ as

$$f_u(u) = \int_{-\infty}^{\infty} \frac{1}{2\pi jt} \prod_{m=1}^{N_b} \frac{1}{1 + it\lambda^{-1}} dt. \quad (\text{A1.4})$$

□

Appendix A2 The Proof of Theorem 3.1.2

Proof. The received signal is the function of the product of two random variables: $|h_b|$, a Rayleigh random variable, and the other channel $|h_f|^2$, an exponential random variable. Let, be expressed as

$$u = \sum_{m=1}^{N_b} |h_f[m]|^2, \quad (\text{A2.5})$$

be the sum of the exponential random variables while the characteristic function of an

exponential random variable $f(x; \lambda_m) = \lambda_m e^{-\lambda_m x}$ for λ_m is

$$\Phi_m(t) = \lambda_m \int e^{(it - \lambda_m)x} dx = \left(1 + it\lambda^{-1}\right)^{-1}, \quad (\text{A2.6})$$

where $\Phi_m(t)$ is the Fourier transform of $f(x; \lambda_m)$.

To find the distribution of u , we need to find the convolution of N_b exponential random variables, which is equivalent to the product of its characteristic functions

$$\begin{aligned} \Phi_u &= \int e^{itz} (\lambda_1 e^{-\lambda_1 z} \times \lambda_1 e^{-\lambda_2 z} \times \dots \times \lambda_{N_b} e^{-\lambda_{N_b} z}) dz \\ &= \prod_{m=1}^{N_b} \frac{1}{1 + it\lambda_m}. \end{aligned} \quad (\text{A2.7})$$

Now, the PDF of u can be found by taking the inverse Fourier transform of $\Phi_u(t)$ as [193]

$$f_u(u) = \int_{-\infty}^{\infty} \frac{1}{2\pi jt} \prod_{m=1}^{N_b} \frac{1}{1 + it\lambda^{-1}} dt. \quad (\text{A2.8})$$

Hence, we obtain the CDF of $r_0 - r_1$ as

$$\begin{aligned} F_{r_0-r_1}(\eta) &= \int_0^{\infty} F_{r_0-r_1}(\eta; v) f(v) dv \\ &= \int_0^{\infty} \left(\frac{1}{2} - \int_{-\infty}^{\infty} \frac{1}{2\pi jt} \Phi_{r_1|v}(t) e^{-jtz} dt \right) f(v) dv \\ &= \frac{1}{2} \int_0^{\infty} f(v) dv - \int_0^{\infty} \int_{-\infty}^{\infty} \frac{1}{2\pi jt} \Phi_{r_1|v}(t) e^{-jtz} dt f(v) dv. \end{aligned}$$

□

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PUBLICATIONS, PRESENTATIONS, AND PATENTS ON THE THESIS:

- M. B. Janjua, A. Şahin, and H. Arslan, “Interference-Free Backscatter Communications for OFDM-Based Symbiotic Radio,” submitted to IEEE Transactions on Cognitive Communications and Networking, 2024.
- M. B. Janjua, A. Şahin, and H. Arslan, “Improving interference immunity for backscatter communications in OFDM-based symbiotic radio,” accepted in IEEE Globecom Workshops (GC Wkshps), 2024.

- M. B. Janjua, H. T. Abbas, K. A. Qaraqe, and H. Arslan, “Beam selection for ambient backscatter communication in beamspace mmwave symbiotic radio,” *IEEE Wireless Communications Letters*, March 2023.
- M. B. Janjua, and H. Arslan, “A survey of symbiotic radio: methodologies, applications, and future directions,” *Sensors*, February 2023.
- M. B. Janjua, Memişoğlu, E., Qaraqe, K.A. and Arslan, H., “Secure pilot allocation for integrated sensing and communication,” presented in *IEEE Globecom Workshops (GC Wkshps)*, December 2022.
- M. B. Janjua, A. E. Duranay, and H. Arslan, “Role of wireless communication in healthcare system to cater disaster situations under 6G vision,” *Frontiers in Communications and Networks*, December 2020.
- M. B. Janjua, D. B. Da Costa, and H. Arslan, “User pairing and power allocation strategies for 3D VLC-NOMA systems,” *IEEE Wireless Communications Letters*, June 2020.
- M. B. Janjua, A. Şahin, H. Arslan, “A method for interference-free and reliable backscatter communication in OFDM based symbiotic radio,” Turk Patent (EPATS), App. No: 2023/014437
- M. B. Janjua, S. Rafique, H. Arslan, “Simbiyotik radyo kullanarak seyrek kanal-daki geri saçılım cihazları için kaynak tahsisi (Resource allocation for backscatter devices in the sparse channel using symbiotic radio),” *Turkish Patent Application* 2021/019879
- M. B. Janjua, E. Memişoğlu, H. Arslan, “Entegre algılama ve iletişim için güvenli pilot tahsisi (Secure Pilot Allocation for Integrated Sensing and Communication),” *Turkish Patent Application* 2021/019870

OTHER PUBLICATIONS, PRESENTATIONS, AND PATENTS:

- H. Salman, M. B. Janjua, and H. Arslan, “Improving connectivity via multi-user scheduling in 5G and beyond networks,” presented in *IEEE Wireless Communications and Networking Conference (WCNC)*, March 2021.
- M. S. J. Solaija, M. B. Janjua, L. Afeef, A. Tusha, A.E. Duranay, H. Arslan, and O. Hasekioğlu, “Quantum laboratory setup for future wireless communication systems,” presented in *Turkish Physical Society – International Physics Conference*, September 2019.
- S. Rafique, M. B. Janjua, H. Arslan, “Milimetre dalga ve terahertz frekanslarında pürüzlü ve düzgün yüzeyler kullanılarak birleşik algılama ve iletişime yönelik yeni bir yöntem (A New Method for Combined Detection and Communication using Rough and Smooth Surfaces at Millimeter Wave and Terahertz Frequencies),” *Turkish Patent Application* 2021/019907.
- F. Kilinc, H. Arslan, M. M. A. A. Alayasra, M. B. Janjua, “Yansıtma ve aktarma modlarında çalışan bir akıllı tekrarlayıcı (A Smart Repeater Operating in Reflecting and Transmit Modes),” *Turkish Patent Application* 2023/008274

- F. Kilinc, H. Arslan, M. M. A. A. Alayasra, M. B. Janjua, “Akıllı tekrarlayıcı cihazın kullanılmasıyla spektral kaynakların artırılması için sistem ve yöntem (System and Method for Increasing Spectral Sources Using an Intelligent Repeater Device),” *Turkish Patent Application* 2023/008132
- F. Kilinc, H. Arslan, M. M. A. A. Alayasra, M. B. Janjua, “Artırılmış uzaysal serbestlik derecelerine sahip ağ kontrollü yineleyici (Network-Controlled Repeater with Increased Spatial Degrees of Freedom),” *Turkish Patent Application* 2022/021990
- M. B. Janjua, S. E. Zegrar, H. Arslan, “Statik ve mobil geri saçılım cihazlarına yönelik dikey zaman frekans alanı (otfs) dalga formu kullanılarak geri saçılım iletişimde çoklama (Multiplexing in Backscatter Communication using Vertical Time Frequency Domain (OTFS) Waveform For Static and Mobile Backscatter Devices),” *Turkish Patent Application* 2021/019866



SYMBIOTIC BACKSCATTER COMMUNICATION

ORJİNALLİK RAPORU

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BENZERLİK ENDEKSİ

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2

Tanuja Dogra, Manoranjan Rai Bharti. "A clustering-based user pairing scheme for downlink 3D non-orthogonal multiple access-based visible light communication systems", International Journal of Communication Systems, 2024

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