

REPUBLIC OF TÜRKİYE
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

CLUSTER-BASED MAC PROTOCOL FOR UAVS
AD HOC NETWORKS IN 5G AND BEYOND

Md. Thouhidur RAHMAN

MASTER OF SCIENCE THESIS
Department of Electronics and Communication Engineering
Program of Communications

Supervisor
Assoc. Prof. Dr. AFM Shahan SHAH

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A thesis submitted by Md. Thouhidur RAHMAN in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 17.03.2025 in Department of Electronics and Communication Engineering, Program of Communications.

Assoc. Prof. Dr. AFM Shahen SHAH
Yildiz Technical University
Supervisor

Approved By the Examining Committee

Assoc. Prof. Dr. AFM Shahen SHAH, Supervisor
Yildiz Technical University

Prof. Dr. Ufuk SAKARYA, Member
Yildiz Technical University

Assoc. Prof. Dr. Muhammet Ali
KARABULUT, Member
National Defense University

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Md. Thouhidur RAHMAN

Signature



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*Dedicated to my family
and my best friend*



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Md. Thouhidur RAHMAN

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LIST OF SYMBOLS

T_{ACK}	Acknowledgement Time
σ_n	Additive White Gaussian Noise
F_{AL}	Allocated Frequency Range for Channel
α_d	Angle Between the Direction of the UAV and the Data Transmission Link
i	An Integer
$A_S(t)$	Area the CM is Located
E_A	Average Excessive LoS and NLoS PL Difference
β	Average Number of Buildings in the Area.
Q	Average Number of CMs in Each Cluster
η	Average Time Per State
ϕ_1	Azimuth Angle of the UAV1
ϕ_2	Azimuth Angle of the UAV2
$S_A(t)$	Backoff Stage
T_B	Backoff Time
$B_A(t)$	Backoff Time of CM Using DCF
A_{BS}	Base Station Coverage Area
R_{BS}	Base Station Radius
B_L	Battery Power Level
A	Blocking Probability
R_f	Buffers Fails Probability
X_o	Building Collapsed Obstruction Loss
γ	Building Height Distribution in the Rayleigh Probability Density Function

X_1	Cartesian Coordinates for UAV1 in X Axis
Y_1	Cartesian Coordinates for UAV1 in Y Axis
Z_1	Cartesian Coordinates for UAV1 in Z Axis
X_2	Cartesian Coordinates for UAV2 in X Axis
Y_2	Cartesian Coordinates for UAV2 in Y Axis
Z_2	Cartesian Coordinates for UAV2 in Z Axis
C_h	Channel
h	Channel Gain
ζ	Channel Idle Probability
Φ	Channel Idle Probability in 4D Markov Chain
P_{BCM}	CM Battery Power Level
d_L	CM to MS Distance
K_{Fog}	Coefficient for Attenuation Per Kilometer Liquid Water Density
T_{co}	Coherence Time
h_B	Collapsed Building Height
ε	Collision Probability
P	Collision Probability in Markov State
S_C	Collision Stage
T_{cl}	Collision Time
T_{col}	Collision Time in 4D Markov Chain
C	Constant
K	Constant for Count
C_W	Contention Window in 4D Markov Chain
C_{wi}	Contention Window Size
T_{CTS}	CTS Period Time
R_t	Data Transmission Rate
T_{DIFS}	DCF Inter Frame Space Time
δ	Delay Considering 3D Mobility in the Markov Chain
ϵ_d	Delay in 4D Markov Chain

T_{dl}	Delay Time
F_{Fog}	Density of Water
α	Developed Area to Total Area
X_d	Diffraction Loss Due to Earthquake
d_A	Distance Where Throughput Changes Noticeably
f_d	Doppler Shift
X_ϵ	During the Disaster Extra Environmental Characteristics
A_{UBS}	Each Base Station Coverage Area
P_{pmin}	Each CM Minimum Power to Support MSs
N_{MS}	Each CM Number of Supported MSs
θ_1	Elevation Angle of the UAV1
θ_2	Elevation Angle of the UAV2
ϵ_{LoS}	Excessive LoS PL
ϵ_{NLoS}	Excessive NLoS PL
X_{EL}	Extra Losses for the Different Disaster Environmental Scenarios
F_R	Falling Rain Rate
$L_{C,M}$	Flexible Connection Between CM to MS
b_a	Fixed Distribution Chain
X_{Fog}	Foggy Environment Loss
F_s	Fresnel-Kirchhoff Diffraction Parameter
X_{Rain}	Heavy Rain Attenuation Loss
$\Gamma(.)$	Gamma Function
C_{idle}	Idle Channel
S	Instantaneous Signal to Noise Ratio
L_{hd}	MAC and PHY Headers Length
S_t	Markov Chain State
S_m	Maximum Backoff Stage in 4D Markov Chain
d_{max}	Maximum CH to CM Distance
R_{max}	Maximum Coverage Radius

R_{tmax}	Maximum Retransmission Limit
$P_{ber}, (av)$	Mean BER for the SNR
$E[T_{msl}]$	Mean Duration of Slot Time
$E[T_{MSL}]$	Mean Slot Time in 4D Markov Chain
$E[T_{SU}]$	Mean Successful Packet Transmission Time
$E[T_S]$	Mean Successful Packet Transmission Time in 4D Markov Chain
M	Mean Number of UAVs Per Cluster
η_ϵ	Mention the Environmental Characteristics
d_{min}	Minimum CH to CM Distance
r	Minimum CH to CM/CH Distance in Polar Coordinates
C_{wimin}	Minimum Contention Window size
W_A	Minimum Contention Window of the Area
θ_{min}	Minimum Elevation Angle
B_{Lmin}	Minimum Required Power
h_m	Mobile Station Height
$I_o(.)$	Modified Bessel Function Zero Order
$I_K(.)$	Modified Bessel Function for the K_{th} Order
a_c	Modulation Constant
b_c	Modulation Constant
m	Nakagami-m Fading Channel Shape Parameter
N_c	Number of Cluster
A_S	Number of Cluster Area
P_M	Number of Multipath
A_N	Number of Multiple Antennas
A_{NR}	Number of Receiver Antenna
S_c	Number of Sub-channel
A_{NT}	Number of Transmitter Antenna
N	Number of UAVs
f	Operating Frequency

h_{opt}	Optimum Base Station Altitude
C_{wio}	Optimum Contention Window Size
P_o	Outage Probability
$P_{ber,all}$	Overall BER for the SNR
Δ	Packet Arrival Probability
q	Packet Arrival Probability in Each State
λ_p	Packet Arrival Rate
C_B	Packet Blocks
ξ	Packet Collision Probability Under 4D Markov Chain
λ_c	Packet Coming Rate
F	Packet Dropping Probability
R_{PD}	Packet Dropping Rate
θ_{PDR}	Packet Dropping Rate Considering 3D Mobility in the Markov Chain
Δ_{PDR}	Packet Dropping Rate in 4D Markov Chain
L_p	Packet Length
μ	Packet Sending Probability
Γ	Packet Sending Probability in Slot Time Under 4D Markov Chain
Z_D	Packet Transmission Delay
ω	Packet Transmission Probability in Slot Time Under 4D Markov Chain
a_l	Path Loss Exponent
Υ	Path Loss Exponent for Different Environmental Cases
Z_{ij}	Polynomial Coefficients
$P_{ber, (S_n)}$	Probability of BER for the SNR
P_c	Probability of Connectivity
R_{idle}	Probability of Idle Period Per State
P_e	Probability of the Error Frame in Nakagami-m Channel Fading
P_{er}	Probability of the Error Frame in Rician Channel Fading

E	Ratio of the Power of the LoS to the Power of Other Scattered Multipath
$l_{j,i}(P_M)$	Rayleigh Fading Coefficient
o	Received Signal Vector
r_A	Receiver Antenna
G_r	Receiver Antenna Gain
σ_r	Receiver Transmission Power
N_{CM}	Required Number of CM
V	Relative Velocity
T_{RTS}	RTS Period Time
d_{NC}	Selected Distance Where Throughput Changes Noticeably
S_L	Slot Stage
T_{SL}	Slot Time
∂	Series Coefficient
K_{Rain}	Series Coefficient for Rain
T_{SIFS}	Short Inter Frame Space Time
a	Sigmoid Function Parameters
b	Sigmoid Function Parameters
N_n	Signal Noise
ρ	Simultaneous Successful Packet Transmission Probability Under 4D Markov Chain
T_S	Simultaneous Successful Packet Transmission Time
t_d	Small Duration of CM to Move One Area to Another
F_{Snow}	Snowfall Rate
X_{Snow}	Snowy Environment Loss
R_p	Successful Packet Round Probability
Ω	Successful Packet Transmission Probability
T_{SS}	Successful Packet Transmission Time
S_S	Successful Transmission Stage

u	Supported User by Each Base Station
r_1	Take off Position to Last Position Polar Distance for UAV1
r_2	Take off Position to Last Position Polar Distance for UAV2
S_{th}	Threshold Signal to Noise Ratio
T_{h_1}	Throughput of the Nakagami-m Channel Fading in 2D Markov Chain
T_{hm}	Throughput in 3D Markov Chain with Mobility
T_{hd}	Throughput in 4D Markov Chain
T_{NAK}	Throughput in Nakagami-m Fading Environment in 3D Markov chain
T_h	Throughput in Rayleigh Fading Channel in 2D Markov Chain
T_{Ray}	Throughput in Rayleigh Fading Environment in 3D Markov chain
T_{h_2}	Throughput of the Rician Channel Fading in 2D Markov Chain
T_m	Total Elapsed Time in Each Markov State
X_A	Total Loss Due to Earthquake
U	Total Number of Supported User
T_p	Total Passed Time Considering 3D Mobility in the 3D Markov Chain
T_{pm}	Total Passed Time in 3D Markov Chain with Mobility
u_x	Total Signal to Noise Ratio
$P(tr)$	Transition Probability for All Cases
$P(trs)$	Transition Probability for Different Cases
P_{CO}	Transition Probability in Collision Time
P_{SL}	Transition Probability in Slot Time
P_{SS}	Transition Probability in Successful Packet Transmission Time
P_{coll}	Transition Probability When Collision Under 4D Markov Chain
P_{SLOT}	Transition Probability When Slot Time Under 4D Markov Chain
P_{Succ}	Transition Probability When Successful Packet Transmission Under 4D Markov Chain
ψ	Transmission Probability in 4D Markov Chain

s	Transmitter Antenna
G_t	Transmitter Antenna Gain
i_n	Transmitted Signal Vector
N_p	Time Orthogonal Cyclic Prefix Length
N_t	Time Orthogonal Cyclic Prefix Training Sequence Length
t_A	Time to Stay in the Cluster
T_{TP}	Total Passed Time in 4D Markov Chain
h_A	UAV Base Station Altitude
t	UAV Running Time
v_A	Velocity of CM in the Cluster
V_1	Velocity of UAV1 After Time t
V_2	Velocity of UAV2 After Time t
T_{wait}	Waiting Time
λ	Wavelength of the Operating Frequency

LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
4D	Four Dimensional
5G	Fifth Generation
6G	Sixth Generation
ACK	Acknowledgement
AR	Augmented Reality
ATAC	Appeal To Add in the Cluster
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift keying
CDF	Cumulative Distribution Function
CH	Cluster Head
CM	Cluster Member
CTAC	Confirmation To Add in the Cluster
CTS	Clear To Send
CW	Contention Window
DBS	Drone Base Station
DCF	Distributed Coordination Function
DFT	Discrete Fourier Transform
DIFS	DCF Inter Frame Space
ECV	Emergency Communication Vehicle
FANET	Flying Ad Hoc Network

FIR	Finite Impulse Response
GHz	Gigahertz
IoT	Internet of Things
ISI	Inter Symbol Interference
KKT	Karush Kuhn Tucker
LAPs	Low-altitude Aerial Platforms
LoS	Line of Sight
MAC	Medium Access Control
MAD	Mobility Adaptive Dynamic
MIMO	Multiple Input Multiple Output
mmWave	Milimeter Wave
MS	Mobile Station
NLoS	Non Line of Sight
NOMA	Non-orthogonal Multiple Access
NTN	Non Terrestrial Network
OFDMA	Orthogonal Frequency Division Multiple Access
OP	Outage Probability
PAR	Packet Arrival Rate
PDF	Probability Density Function
PDR	Packet Dropping Rate
PL	Path Loss
PPP	Poisson Point Process
PSO	Particle Swarm Optimization
QoS	Quality of Service
RIS	Reconfigurable Intelligent Surface
RTC	Request To Combine
RTS	Request To Send
RTSCH	Request To a Secondary Cluster Head
SIFS	Short Inter Frame Space

SM	Safety Message
SNR	Signal to Noise Ratio
TBS	Terrestrial Base Station
THz	Terahertz
TN	Terrestrial Network
UABS	Unmanned Aerial Base Station
UAV	Unmanned Aerial Vehicle
UE	User Equipment
VR	Virtual Reality



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ABSTRACT

Cluster-based MAC Protocol for UAVs Ad Hoc Networks in 5G and Beyond

Md. Thouhidur RAHMAN

Department of Electronics and Communication Engineering
Master of Science Thesis

Supervisor: Assoc. Prof. Dr. AFM Shahan SHAH

Unmanned aerial vehicles (UAVs) are autonomous platforms with versatile applications in military, commercial, environmental domains and more. With rapid advancements in technology, ensuring continuous wireless connectivity is crucial, especially for the evolution of 5G and beyond. Multi-UAV systems form flying ad-hoc networks (FANETs), especially vital in emergency scenarios where terrestrial base stations (BSs) fail. For that reason, UAV-based FANETs play a vital role due to their flexibility, quick deployment, and remote-control capabilities for providing required coverage as well as communication relays to send data over long distances. To establish this network, efficient communication between the UAVs is the most vital point. Additionally, due to mobility, topology changes frequently, leading to potential collisions and packet losses. Therefore, in this thesis, cluster-based FANETs have been proposed where the topology is controlled by a back-off mechanism and network connectivity is maintained even when the UAV is moving at different altitudes by calculating the relative velocity on a 3D platform while considering the 3D mobility model. An efficient cluster build-up process and a method for determining the position of the cluster head (CH) are introduced to control the cluster proficiently. To enhance throughput, a multiple input multiple output orthogonal frequency division multiple access (MIMO-OFDMA)-based medium access control (MAC) protocol has been introduced. Analytical models, including a 3D Markov chain, are developed to optimize coverage with a minimum number of UAVs supporting macro cell BS areas. The thesis also introduces a novel mobility adaptive dynamic (MAD-MAC) protocol, governed by packet arrival rate

(PAR) and mobility. System performance is evaluated in terms of throughput, delay, packet dropping rate (PDR), outage probability (OP), signal-to-noise ratio (SNR), and bit error rate (BER) under Rayleigh, Nakagami-m, and Rician fading channels, and various modulation schemes. Monte Carlo simulation results validate the analytical models, demonstrating significant improvements over existing methods.

Keywords: Cluster, FANET, MAC protocol, mobility, UAV.



5G ve Ötesindeki İHA'ların Tasarsız Ağları İçin Küme Tabanlı MAC Protokolü

Md. Thouhidur RAHMAN

Elektronik ve Haberleşme Mühendisliği Anabilim Dalı
Yüksek Lisans Tezi

Danışman: Doç. Dr. AFM Shahan SHAH

İnsansız hava araçları (İHA'lar), askeri, ticari, çevresel ve daha birçok alanda geniş uygulama alanına sahip otonom platformlardır. Teknolojik gelişmelerle birlikte sürekli kablosuz bağlantının sağlanması, özellikle 5G ve ötesi iletişim teknolojilerinin gelişimi açısından kritik hale gelmiştir. Çoklu İHA sistemleri, acil durumlarda kara baz istasyonlarının (base station, BS) yetersiz kaldığı durumlarda önemli rol oynayan uçan tasarsız ağlar (flying ad-hoc networks, FANETs) oluşturur. Bu nedenle, İHA tabanlı FANET'ler; esneklik, hızlı konuşlanma ve uzaktan kontrol özellikleri sayesinde gerekli kapsama alanı sağlama ve uzun mesafeli veri iletimi için iletişim röleleri kurma konusunda hayati öneme sahiptir. Bu ağı kurabilmek için İHA'lar arası verimli iletişim sağlanması gerekmektedir. Ancak, hareketlilik nedeniyle ağ topolojisi sürekli değişmekte, bu da çakışmalara ve paket kayıplarına yol açmaktadır. Bu tezde, topolojinin geri çekilme (back-off) mekanizmasıyla kontrol edildiği ve İHA'ların farklı irtifalarda hareket ederken ağ bağlantısının sürdürüldüğü küme tabanlı bir FANET yapısı önerilmektedir. Bu yapı, 3B hareketlilik modeli kullanılarak göreceli hız hesaplamalarıyla desteklenmiştir. Etkili küme oluşturma ve küme başı (cluster head, CH) belirleme yöntemleri sunulmuştur. Veri hızını artırmak amacıyla, çoklu giriş çoklu çıkış (multiple input multiple output, MIMO) ve ortogonal frekans bölme (orthogonal frequency division multiple access, OFDMA) tabanlı bir ortam erişim kontrol (medium access control, MAC) protokolü geliştirilmiştir. Ayrıca, makro hücre BS alanlarını minimum sayıda İHA ile desteklemek için 3B Markov zincir modeliyle kapsama optimizasyonu yapılmıştır. Paket varış hızı (packet arrival rate, PAR) ve

kapsama optimizasyonu yapılmıştır. Paket varış hızı (packet arrival rate, PAR) ve hareketliliğe bağılı olarak çalışan yeni bir hareketlilik uyumlu dinamik (mobility adaptive dynamic, MAD-MAC) protokolü önerilmiştir. Sistem performansı; veri hızı, gecikme, paket düşme oranı (PDR), kesinti olasılığı (outage probability, OP), sinyal-gürültü oranı (signal-to-noise ratio, SNR) ve bit hata oranı (bit error rate, BER) gibi ölçütlerle; Rayleigh, Nakagami-m ve Rician sönümleme kanalları altında değerlendirilmiştir. Monte Carlo benzetim sonuçları, analitik modelleri doğrulamakta ve mevcut yöntemlere göre önemli iyileşmeler göstermektedir.

Anahtar Kelimeler: Kümeleme, FANET, MAC protokolü, hareketlilik, İHA.



1

INTRODUCTION

1.1 FANETs in 5G and Beyond

An ad hoc network is a temporary platform that operates without relying on fixed infrastructure. If the network is supported by aerial platforms such as unmanned aerial vehicles (UAVs), satellites, airships, aircraft, balloons, or other aerial systems, it is referred to as a flying ad hoc network (FANET). In such networks, the aerial vehicles are interconnected with one another [1]. Due to being free from fixed infrastructure, FANETs operate in a highly dynamic three-dimensional (3D) aerial environment, making them an ideal platform for fifth generation (5G) and beyond technologies. In 5G, a FANET-based base station (BS) can provide high-speed internet access to users in inaccessible or high-demand areas. It also supports ultra-low-latency communication between Internet of Things (IoT) devices, enabling applications such as data collection, precision agriculture, and environmental monitoring. FANETs can interconnect with other non-terrestrial networks (NTNs) to facilitate adaptive, artificial intelligence (AI)-based, and real-time autonomous networking. In sixth generation (6G), next-generation technologies such as massive multiple input multiple output (MIMO), millimeter-wave (mmWave) communication, non-orthogonal multiple access (NOMA), and full-duplex communication may be difficult to implement using traditional BSs. As a result, FANETs are expected to play a crucial role in supporting these technologies. In summary, FANETs will have a ground breaking impact on the evolution of next-generation wireless communication systems [2].

1.2 MAC for FANETs in Disaster

Medium access control (MAC) protocol is an essential part of wireless communication. It controls the packet transmission for common channels. UAV-based FANETs would be the ideal platform to support the terrestrial network (TN) [3]. During disasters such as earthquakes, floods, and other hazards, TNs may

be damaged and unable to support network services [4]. Retooling TNs takes time; however, for emergency relief and search-and-rescue operations, the first 48 hours are the most crucial. In this context, FANETs are the most favorable platform to support terrestrial facilities using NTN platforms. It is the reason of the fact that UAV-BS provide flexible advantages such as controllable mobility, ensured line of sight (LoS) stable connection and quality of services (QoS), yieldable extension, services in different environmental areas, ensuring demand for facilities, robustness, scalability, reliability, flexible service level, considering public safety, desired capacity, energy efficiency and so on [4], [5] and [6]. Moreover, cluster-based FANETs are more favorable than a single UAV because if one UAV encounters any issues, the entire network could fail, like BS [4], [5]. Despite such merits, there are some challenges to operating UAVs-BSs. Due to high speed, mobility causes changes in the network topology, resulting in signal strength loss and disconnections [4]. Furthermore, topology changes can lead to collisions, packet losses, lower throughput, and higher latency. Additionally, a higher rate of interference, power limitations, frequent handover positions in 3D space, bandwidth allocation, and many other issues need to be considered [7]. The MAC protocol plays a vital role in ensuring that UAVs in FANETs can communicate effectively, efficiently, and reliably. Due to these mobility-induced challenges, a specialized MAC protocol for FANETs needs to be designed, focusing on flexibility and dynamic adaptation.

1.3 Closely Related Works

There is a growing demand for UAV applications in various fields, such as communications, delivery services, military operations, environmental monitoring, agriculture, construction, traffic monitoring, medical support, and more [6]. Significant work has already been carried out in UAV-based communication systems. A UAV-assisted emergency network in disasters was proposed in [3]. In this approach, only a single UAV was used, which has several disadvantages. For instance, if there is a problem with a single UAV, the entire network would be collapsed. Additionally, the cost of management is very high. The architecture of emergency communications systems in disasters using UAVs in 5G and beyond was first designed by A. F. M. S. Shah [8] where a FANET is organized to work as a BS. Shah's model [8] is very efficient, but the altitude of the UAVs is fixed. Thus, it would not work effectively when the cluster members (CMs) are at different altitudes. Cooperative terahertz (THz) communication for UAVs in 6G and beyond was proposed by N. Mustari et al., where mobility was not considered [9]. But for efficient FANETs, it is essential to consider the mobility effect for a stable connection. The mobility model of canonical position drone cellular networks

proposed by M. Banagar et al. is inappropriate in 3D platforms [10]. The downlink wireless system by fixed-wing UAVs in a 3D platform was proposed [11], but it is complex to calculate due to difficulties in finding the exact position. Using a UAV built-up unmanned aerial base station (UABS) was employed to collect sales data [12]. Where only a single UAV was used but no mobility model was presented. In this circumstance, cluster-based UAV networks would be the best solution. Furthermore, the proposed work [12] failed to establish an efficient MAC protocol. A deep Q-network (DQN) based vertical routing scheme in 5G FANETs was represented [13]. The network efficiently controls topology changes and ensures a stable connection by introducing macro, pico, and femto-planes. However, extra UAVs are consumed for the control gateway and vertical control gateway, which is costly and consumes additional UAVs for building up clusters. A dual cluster head (CH)-based MAC in ad-hoc networks to support a large number of UAVs was proposed in [14]. Dual CHs can alleviate the overload of a single CH in a cluster, but there is no exact planning of the mobility model. Improvement of emergency cluster-based network systems was established [15]. The optimization of cluster size was performed using the Cuckoo search algorithm (CUCO) and particle swarm optimization (PSO) algorithm. However, the exact position or efficient cluster build-up process was not introduced. An intelligent clustering routing approach for UAV Ad-hoc networks was introduced by J. Guo et. al. [16]. Where a separate cluster control procedure was described but the cooperative operation of CH-CH communication was not considered. Air-to-ground communications by using UAV swarms were introduced [17]. The article described the downlink communication efficiently, but no control system algorithm was introduced. The impact of mobility on throughput was analyzed in [7], where the system's MAC changes based on the Markov chain process. The optimization of UAV altitude for maximizing coverage was proposed by A. A. Hourani et al. [18]. This work also evaluated the performance of path loss (PL) for different environmental cases: suburban, urban, dense urban and high-rise urban areas. The work did not provide details on how the UAV supports the core network. Using the heuristic algorithm to minimize the number of drone BSs to provide services for a set of users was investigated by E. Kalantari et al. [19]. The evaluation of the coverage area was overlooked. For optimization, a PSO was used to introduce the channel model. The investigation of maximizing downlink coverage with minimum transmit power is presented in [20]. The UAVs were deployed on a 3D platform at an optimum altitude and supported by directional antennas. To maximize UAV-BS-supported users with minimum transmit power, a method was introduced [21]. In this scenario, the UAV-BS replaces the horizontal dimension with a vertical dimension to minimize transmit power.

The performance improvement of cellular networks achieved using UAV-BS is examined in [22]. The coverage of a circular area by a UAV-based cellular network was investigated in [23]. In this work, the BSs are distributed according to the Poisson point process (PPP), and the UAV is positioned in the air at the center of a circular area to support the emergency network. A stochastic geometry approach to UAV-aided post-disaster cellular networks was inspected in [24]. This approach examined the QoS of user equipment (UE) both inside and outside the disaster area. The UAV-based cellular network was analyzed in [25], where the user-built clusters were formed around the UAV-BS and LoS and non line of sight (NLoS) PL were calculated for different altitudes. The distribution process of UAV-BS to support the desired number of users was introduced in [26]. In this scenario, the UAVs are connected by a controller, which device is responsible for imposing the centralized and distributed algorithms for various cases. During the disaster period, the efficient process of covering the cellular network while ensuring the desired throughput was inspected in [27].

The UAV-BS connected to the core network or terrestrial base stations (TBS) for maximizing coverage with the minimum number of UAVs was evaluated in [28]. Here, a centralized greedy search algorithm was proposed for the minimum number of UAVs, along with a distributed motion algorithm for positioning the UAVs. Adjusting the optimal altitude of the drone base station (DBS) to ensure LoS connection to fulfill the minimum transmit power was analyzed in [29]. In this case, the DBS first serves users with equal transmit power and then applies a decoupling-based placement algorithm to optimize its altitude. The development of UAV-BS on a 3D platform to support cellular network services was introduced in [4]. The process of building networks consists of three steps. First, determine the theoretical solution for maximum coverage and optimal altitude using the Karush-Kuhn-Tucker (KKT) conditions. Secondly, construct a cluster of users using the bee colony-based algorithm to support the maximum number of users per UAV. Then, in the final step, optimize the UAV-BS position and allocate the bandwidth to minimize interference. A novel stochastic geometry-based system was imposed in the rural areas where TBS coverage is insufficient; therefore, the implemented UAV-BS was examined in [30]. In the era of IoT, UAV-BS used to collect data from different IoT devices was investigated in [31]. Setting up a decentralized algorithm to maintain connection UAV-BS and minimize UAV-user distance was evaluated in [32].

A full-duplex UAV-based orthogonal frequency division multiple access (OFDMA) system operating at mmWave frequencies was designed by J. J. Sadique for cooperative communication between BSs and mobile users in high-density urban

areas [33]. A UAV-aided flying BS speed control technique was analyzed in [34], where the relationship between UAV speed and uplink data transmission was introduced. Mathematical models for UAV-based wireless communication in emergency disaster recovery were established in [35]. Additionally, multiple UAVs for long-range communication in disaster situations were investigated in [36]. The positioning and trajectory of flying BSs for managing emergency situations were analyzed in [37]. THz communication using MIMO-OFDM was introduced in [38]. A comparative study of aerial reconfigurable intelligent surface (RIS) technology and UAV-BS for creating cellular networks was conducted in [39]. UAV-enabled emergency communication was analyzed in [40] using stochastic geometry and an optimum radius to maximize performance. The ability of MIMO-OFDM technology in UAV communication networks to effectively improve data transmission was investigated in [41].

The optimization of flight routes using the minimum number of UAVs to achieve maximum coverage was proposed in [42]. UAV-BS deployment in 3D to cover the maximum number of mobile users while ensuring QoS was established in [43]. Coverage and throughput analysis for different UAV-BS positions were examined in [44]. Avoiding collisions and ensuring connectivity with distant BSs through UAV cooperation was studied in [45]. Considering the packet arrival traffic rate, an access point control protocol was designed for transmission in [46], where queuing theory and a Markov chain model were used for analytical performance analysis. A scheduling-based channel access mechanism for simultaneous ultra-high data transmission in virtual reality applications was proposed in [47]. A multi-user full-duplex MAC with OFDMA was introduced in [48], which provided an excellent access mechanism for both downlink and uplink communication. A MAC protocol for mmWave and massive MIMO, considering space division multiple access (SDMA), was designed in [49]. A group-based multi-user full-duplex OFDMA MAC protocol was proposed in [50]. In this protocol, packets are transmitted over sub-channels in a cascading mode. Instead of the IEEE 802.11 backoff method, a new backoff mechanism based on cluster size was introduced for FANETs in [8]. A two dimensional (2D) Markov chain-based model was used for performance analysis. A novel MIMO-OFDM-based channel access mechanism for vehicular ad hoc networks (VANETs) was introduced in [51], where a 3D Markov chain-based model was presented.

In FANETs, a half-duplex, contention-based channel access mechanism is more favorable than a scheduling-based full-duplex MAC protocol. This is because FANETs employ a system that does not distinguish between uplink and downlink. In these networks, mobility and packet arrival (traffic) are key issues, while

synchronization is the primary challenge in OFDMA systems. Therefore, the system is designed with a MIMO-OFDMA-based fast backoff mechanism for efficient synchronization, and the contention period is adjusted to account for mobility and packet arrival rate. Consequently, this is the first FANET model that considers contention or backoff time for four dimensional (4D) simultaneous parameters, which has noticeably improved system performance.

1.4 Objective of the Thesis

The objective of this research is to design and develop an efficient cluster-based ad hoc networking system using UAVs, considering the increasing demand for flexible and wide-ranging applications in dynamic environments. Instead of relying on a single UAV, cluster-based network architectures are proposed to enhance scalability and coverage. Given that network performance is highly influenced by altitude, the proposed cluster-based networks are developed on 3D mobility platforms to accommodate varying altitudes. To ensure efficient communication within the network, robust and adaptive cluster control mechanisms have been designed. Furthermore, to support simultaneous multiple communication links, MIMO-OFDM-based FANET architecture has been introduced. Considering the mobility of UAVs and the resulting frequent topology changes, the proposed system is designed to be highly adaptive to dynamic network conditions. In disaster scenarios, optimizing the coverage area of the TBS through UAV-based BS deployment is critical. Therefore, the system has been optimized to achieve maximum coverage radius in diverse environmental conditions. To enhance medium access efficiency, a mobility-adaptive dynamic MAC protocol has been developed by considering packet arrival traffic and node mobility. Overall, the proposed system is evaluated through comprehensive performance analysis at both the MAC and physical layers to ensure reliability and efficiency in real-world applications.

1.5 Core Contributions

The core contributions are as follows:

- Instead of a single UAV, cluster-based network is designed thus it has lots of flexible advantages. The system has overcome the altitude issue, so it is possible to build up a cluster with even different altitudes. It is designed for efficient cluster build-up structure and algorithm implementation. UAVs maintain connectivity even as the UAV moves in a 3D platform by developing

a 3D mobility model using rotary-wing micro-UAVs in a close-range cluster system. The system's performance is scrutinized using both analytical and Monte Carlo simulations to study throughput values concerning variations in system distance, velocity, and cluster size under different channel models: Rayleigh, Nakagami-m, and Rician. The system's performance is also analyzed through the outage probability (OP) versus signal-to-noise ratio (SNR), packet dropping rate (PDR), and delay for the three channels and various cluster sizes with a comparison of existing work.

- The network system is designed based on a MIMO-OFDM cluster-based architecture, where network performance is analyzed using a 3D Markov chain model within a 3D mobility platform. To meet the growing demands, the system demonstrates noticeably stronger results pertaining to throughput and delay related to existing work. The work has also analyzed the system performance in terms of throughput with varying distance, velocity, and number of UAVs, considering different MIMO-OFDM configurations, cluster sizes, and channel characteristics such as Rayleigh and Nakagami-m. The overall delay, BER and SNR are determined by the function of the number of UAVs.
- A novel MAC protocol is proposed for FANETs in which the MAC protocol adapts to mobility within CM areas by dividing the cluster into smaller areas to avoid collisions, renewing the contention window size accordingly. A method is developed to determine the optimum altitude for maximum coverage supported by the UAV-BS and relate it with MAC. An algorithm is proposed for supporting a macro cell BS area with a minimum number of UAVs and maximum coverage in different environmental scenarios. By setting up a fixed LoS PL flexible connection, an algorithm has been established for maximum coverage using a minimum number of CMs. Therefore, the main novel contribution of the work is that here addresses both core network support through FANETs and the optimization of the downlink coverage system. The performance of the work has been analyzed using a 3D Markov chain, considering Rayleigh and Nakagami-m fading channel environments. Simulation results are presented and compared with the recent Shah's model [8]. Moreover, a performance comparison table with closely related works is also provided. The results demonstrate superior performance compared to previous studies in terms of throughput, PDR, and delay.
- MAC protocol designed for FANETs in which mobility-adaptive dynamic

(MAD)-MAC has been introduced for cluster-based FANETs. A novel fast backoff process has been developed, in which the contention window size dynamically adjusts according to the mobility within the cluster area. Additionally, the system also considers the packet arrival rate (PAR). As a result, the network has reduced the packet collision rate caused by topology changes and has improved overall system performance. MIMO-OFDM integrated simultaneous packet transmission algorithm has been established that considered the mobility of the UAVs. A 4D Markov-chain-based theoretical analysis has been presented in which the packet transmission process is considered four diameters those are PAR, mobility, packet contention backoff time and stage. According to theory, simulation results are provided by considering Rayleigh and Nakagami-m channel fading in terms of throughput, distance, number of CMs, number of sub-channels, contention window size, PAR, PDR, delay, bit error rate (BER) and modulation techniques under MIMO conditions. Additionally, the results exhibited better results than the existing work.

The thesis is organized in the following way: chapter 2 presents cluster-based emergency communication systems with 3D mobility, chapter 3 expresses cluster-based FANETs with MIMO-OFDM and 3D Markov chain, chapter 4 covers adaptive cluster-based MAC with mobility and coverage optimization, chapter 5 discusses MAD-MAC protocols for FANETs and finally concludes by chapter 6.

Cluster-based Emergency Communication Systems with 3D Mobility

2.1 Introduction

UAVs specially recognized as a drone, can be controlled remotely as a flying vehicle for immense applications, including wireless communication, military operation, delivery services, traffic surveillance, medical support, agriculture, construction and environmental monitoring. These applications are redoubled by integrated new-generation technologies such as augmented reality (AR), virtual reality (VR), IoT, cloud computing, edge computing, fog computing, cellular networks and so on [6], [52], [53] and [54]. Due to the multitude of appliances and advancements in wireless technologies, both current and future, controlling and managing FANETs pose critical challenges. These include with many UAVs, issues such as interference, collisions, security, power limitations, UAV selection, path planning, and more [55]. Because UAVs are mobile devices and the network topology changes frequently, this can cause link breakages and packet loss. Additionally, numerous UAVs can result in higher latency, lower throughput, and increased collision rates [3]. However, to provide efficient services in 5G and beyond technology devices it is essential to keep higher throughput and lower latency [56].

For these reasons, cluster-based emergency networks for FANETs are introduced where the network can be controlled efficiently. Because cluster-based networks offer many advantages such as coverage area can be easily increased, reduced channel contention and delay, improved reliability, scalability, fault tolerance, energy efficiency, latency minimization, stable connection and so on [56], [57]. The designed network structure is given in Figure 2.1. Where during natural disasters such as earthquakes, floods, cyclones etcetera BSs can be damaged so mobile communication can be disabled but for fast rescue and reducing loss emergency communication is the most important. In this situation, the proposed cluster-based FANETs create an emergency network by flying BS so that people can connect with

mobile networks very quickly in disaster-occurring areas. In every cluster, there is a CH and other UAVs of the same cluster work as a CM. The CH is accountable for communicating with the other CM and the emergency communication vehicle (ECV) [8].

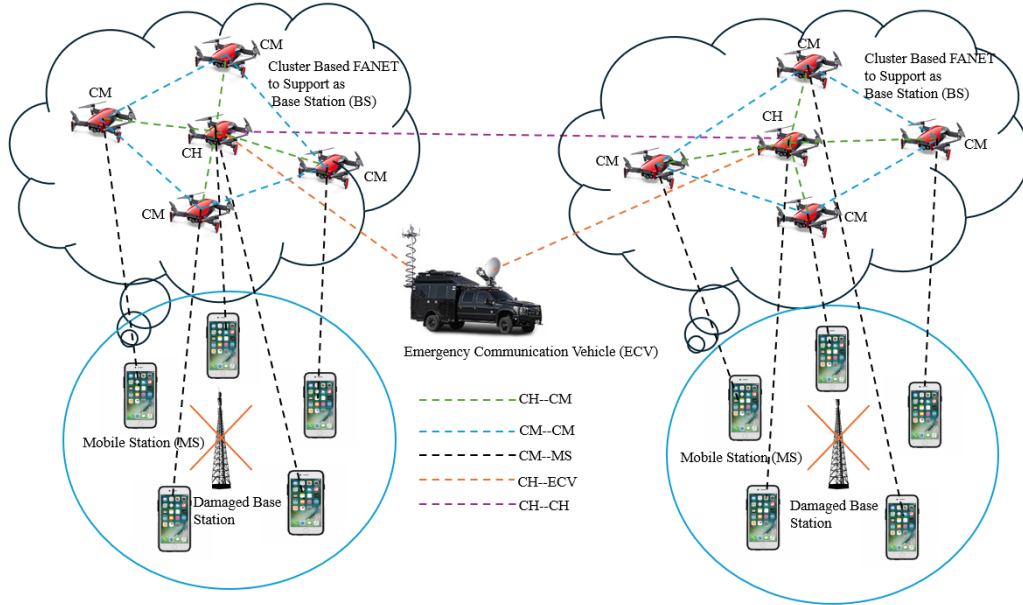


Figure 2.1 Cluster based proposed network structure.

The arrangement of the chapter is the following way: Section 2.2 describes the cluster control mechanism, section 2.3 presents the 3D mobility model, section 2.4 discusses packet transmission and performance analysis, section 2.5 represents the simulation results and finally concludes through section 2.6.

2.2 Cluster Control Mechanism

2.2.1 Cluster Build up Process

When a UAV starts to fly, its main concern is to either build up a cluster or become a member of an existing cluster. After building the cluster, the UAVs are available to function as UABs. In the same cluster, the velocities of the UAVs are in the same direction. In every cluster, there is one CH accountable for intra-cluster communication with CMs, inter-cluster communication with other CHs, and communication with the ECV.

To maintain cluster formation and communication, there are four types of packets: 1. ATAC (Appeal To Add in the Cluster), 2. CTAC (Confirmation To Add in the Cluster), 3. RTSCH (Request To a Secondary Cluster Head), and 4. RTC (Request To Combine). Efficient cluster formation is given in algorithm 1. For clarity, the

flowchart is represented by the algorithm in two cases, as shown in Figure 2.2. In the first case, the UAV will try to become either a CM or a CH. To do this, in the first step, the UAV will send an ATAC and wait for a CTAC. If the UAV receives the CTAC, it becomes a CM. Otherwise, in step 2, it will send the ATAC again and wait for $T_{wait} = T_{SIFS}$. In the second attempt, if the CTAC is received, the UAV becomes a CM of the cluster. Otherwise, the UAV will be introduced as a CH and will try to form a cluster by accepting ATAC and sending CTAC. After the completion of cluster formation, it is essential to control the cluster efficiently. The CH will move to the center position so it can control the CMs properly with minimum distance. Because the circular area represents the minimum distance from the center. The flowchart of case 2, which represents the process of CH positioning in 2D and 3D platforms, is given in Figure 2.3.

Algorithm 1 Efficient cluster build up Algorithm:

1. Sent ATAC by the UAV
 2. **If** the UAV receives CTAC with Cluster Information
 3. Become CM
 4. **End**
 5. **Else If** sent again ATAC
 6. Wait $T_{wait} = T_{SIFS}$
 7. **If** receive CTAC become CM
 8. **End**
 9. **Else** become CH
 10. **End**
 11. **If** all the CM in same altitudes $Z_i = Z_j$ where i, j is the CMs No.
 12. Then CH moves to the center of the 2D circle with radius of maximum CM distance from CH
 13. **End**
 14. **Else** $Z_i \neq Z_j$ then CH moves to the center of the 3D circle with radius of maximum CM distance
 15. **End**
-

If all the CMs are at the same altitude, the CH will move to the center of the 2D circle with a radius ($d_{max} = r$) equal to the maximum CM distance from the CH. Otherwise, if the CMs are at different altitudes, the CH will move to the center of the 3D circle using the same process.

2.2.2 How to Become Secondary CH

Every CH has a time-limited performance. However, to maintain a continuous connection, it is mandatory to keep the cluster structure. If the CH is disconnected for any reason, a new secondary CH will be elected from the CMs. The election

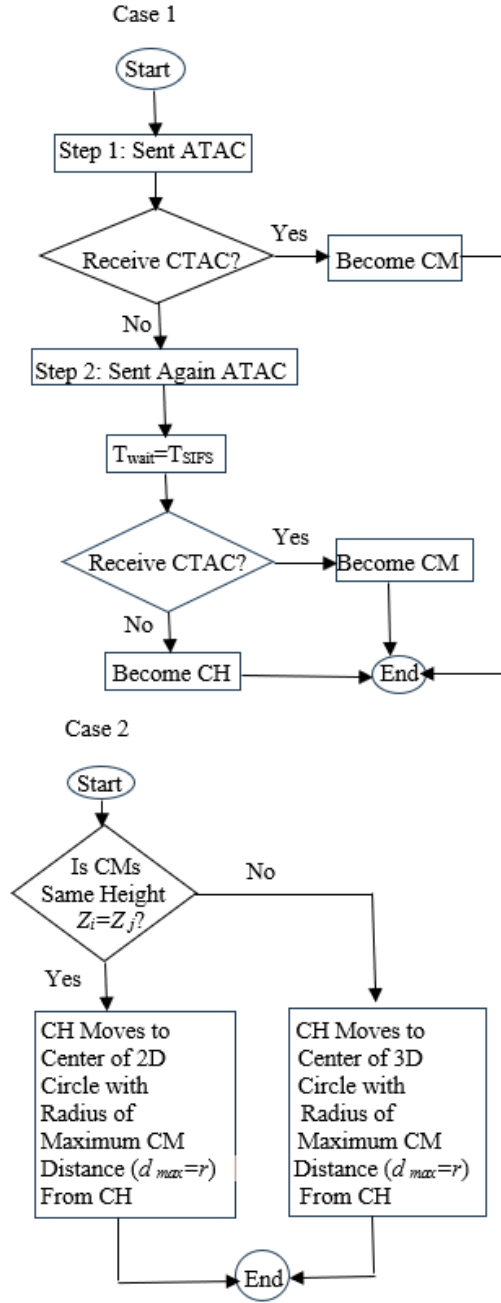


Figure 2.2 Flow chart of efficient cluster build up process.

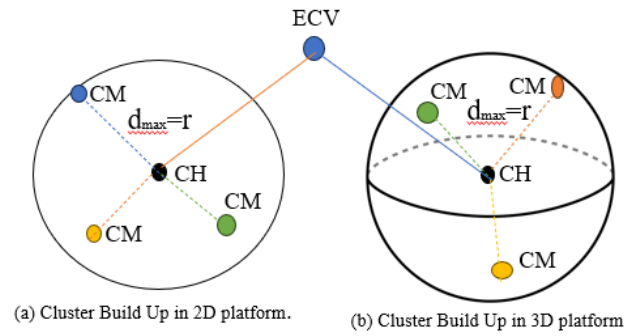


Figure 2.3 The efficient cluster build up process in (a) 2D, (b) 3D platform.

process of the CM for secondary CH is based on the minimum distance (d_{min}) from the oldest CH, determined by sending the RTSCH.

2.2.3 CM Disconnection Process

Every CM also has a time-limited performance. So, it is mandatory to update the CM list of every cluster to maintain service of the required coverage area. The process can be initiated from both CH and CM. First, the CH sends a safety message (SM) to CM and then waits in short interframe space (SIFS) time for acknowledgment (ACK). If the ACK could not receive then retransmit and wait again for short inter frame space (SIFS) for ACK. In this second attempt, if the CH is unable to receive the ACK, then it is considered that the CM has left the cluster, and the CH updates the cluster list. The same disconnection process is considered if CM initiates the process.

2.2.4 Combining Process

If more than two CHs have CMs in the same network, they will coordinate. One of the CHs will then take responsibility for controlling the network and send an RTC to all the CHs to update the CM list.

2.3 3D Mobility Model

This part designs a 3D mobility model for analyzing the proposed network architecture, as shown in Figure 2.4. In this figure, according to the center position $O(0,0,0)$, the four UAVs are at A, B, C and D positions. For UAV1 position is at coordinates $A(X_1, Y_1, Z_1)$ with elevation angle θ_1 and azimuth angle ϕ_1 . Same criteria for the UAV2 at position is $B(X_2, Y_2, Z_2)$ with elevation angle θ_2 and azimuth angle ϕ_2 . The polar distance between the center position to UAV1 is r_1 and UAV2 is r_2 . The Cartesian coordinates for UAV1 are as follows:

$$X_1 = r_1 \cos \theta_1 \cos \phi_1, \quad (2.1a)$$

$$Y_1 = r_1 \cos \theta_1 \sin \phi_1, \quad (2.1b)$$

$$Z_1 = r_1 \sin \theta_1. \quad (2.1c)$$

The elevation angle can be calculated by:

$$\theta_1 = \sin^{-1} \left(\frac{Z_1}{r_1} \right). \quad (2.1d)$$

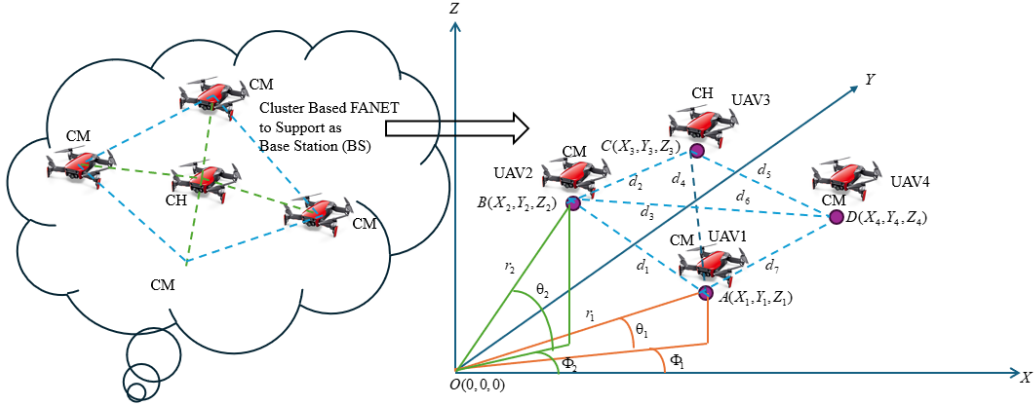


Figure 2.4 3D mobility model of UAVs in cluster.

The azimuth angle can be calculated by:

$$\phi_1 = \tan^{-1} \left(\frac{Y_1}{X_1} \right). \quad (2.1e)$$

The Cartesian coordinates for UAV2 are as follows:

$$X_2 = r_2 \cos \theta_2 \cos \phi_2, \quad (2.2a)$$

$$Y_2 = r_2 \cos \theta_2 \sin \phi_2, \quad (2.2b)$$

$$Z_2 = r_2 \sin \theta_2. \quad (2.2c)$$

The elevation angle can be calculated by:

$$\theta_2 = \sin^{-1} \left(\frac{Z_2}{r_2} \right). \quad (2.2d)$$

The azimuth angle can be calculated by:

$$\phi_2 = \tan^{-1} \left(\frac{Y_2}{X_2} \right). \quad (2.2e)$$

Where the distance from the origin to UAV1 and UAV2 is calculated by:

$$r_1 = \sqrt{X_1^2 + Y_1^2 + Z_1^2}, \quad (2.3a)$$

$$r_2 = \sqrt{X_2^2 + Y_2^2 + Z_2^2}. \quad (2.3b)$$

The distance between the two UAVs d_{min} can be calculated by:

$$\begin{aligned} d_{min} &= \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2 + (Z_2 - Z_1)^2} \\ &= \sqrt{\begin{aligned} &(r_2 \cos \theta_2 \cos \phi_2 - r_1 \cos \theta_1 \cos \phi_1)^2 + \\ &(r_2 \cos \theta_2 \sin \phi_2 - r_1 \cos \theta_1 \sin \phi_1)^2 + \\ &(r_2 \sin \theta_2 - r_1 \sin \theta_1)^2 \end{aligned}}. \end{aligned} \quad (2.4a)$$

By equations (2.3a) and (2.3b), the distance between two UAVs in polar form can be calculated as:

$$\begin{aligned} r &= r_2 - r_1 \\ &= \sqrt{r_2 [\cos^2 \theta_2 \cos^2 \phi_2 + \cos^2 \theta_2 \sin^2 \phi_2 + \sin^2 \theta_2]} - \\ &\quad \sqrt{r_1 [\cos^2 \theta_1 \cos^2 \phi_1 + \cos^2 \theta_1 \sin^2 \phi_1 + \sin^2 \theta_1]} \end{aligned} \quad (2.4b)$$

Let the velocity of UAV1 at the “A” position after the time t be $V_1(r_1)$, and UAV2 at the “B” position be $V_2(r_2)$. So, the relative velocity can be expressed as:

$$V(r) = |V_2(r_2) - V_1(r_1)|. \quad (2.5)$$

Here, $X = X_2 - X_1$, $Y = Y_2 - Y_1$, and $Z = Z_2 - Z_1$. Therefore, $r^2 = X^2 + Y^2 + Z^2$. Now, using the Fokker-Plank formulation, it can be shown that the steady-state probability density function (PDF) of (X, Y, Z) is given by [12], [58]:

$$f(X, Y, Z) = C_o e^{-\frac{2V(r)}{\sigma^2}}. \quad (2.6)$$

Regarding the relationship between Cartesian and polar coordinates in (2.4), employing a Cartesian-to-polar transformation leads to the steady-state PDF of d :

$$f_R(r) = C r^2 e^{-\frac{2V(r)}{\sigma^2}}. \quad (2.7a)$$

for $r > 0$ and to find the constant value C by [12]:

$$\int_0^\infty C r^2 e^{-\frac{2V(r)}{\sigma^2}} dr = 1. \quad (2.7b)$$

By performing the following calculations, we can evaluate the performance of UAVs in the cluster.

2.4 Packet Transmission and Performance Analysis

The traditional IEEE 802.11 backoff method is appropriate for direct communication but inappropriate for the cluster-based network. So, a backoff method is introduced that is an adaptive backoff mechanism where the CW C_{wi} changes considering the network load [58].

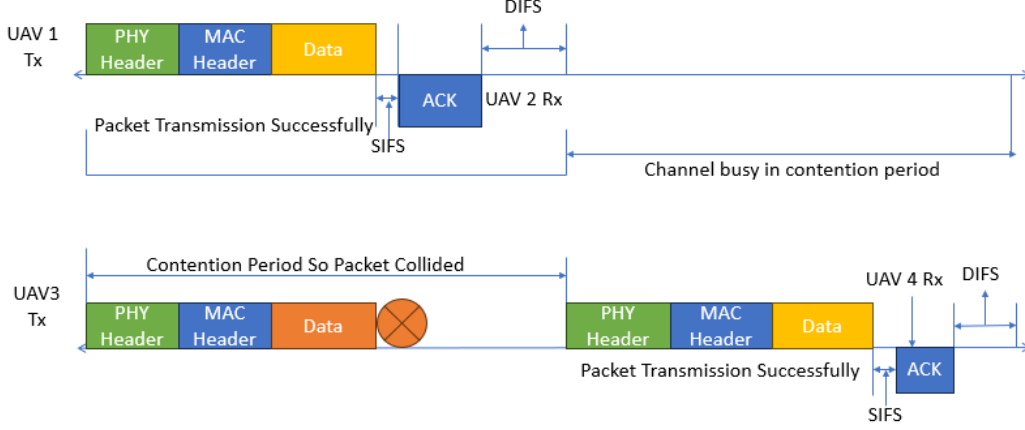


Figure 2.5 Backoff packet transmission successful and collision mechanism.

2.4.1 Backoff Mechanism

In this case, the network load is influenced by the number of CMs. Therefore, if the number of CMs is denoted as N , then C_{wi} must be a function of N .

Let there be a total number of N_c clusters. Then, the mean number of CMs per cluster can be calculated as [8]:

$$M = \frac{N}{N_c}. \quad (2.8)$$

Then the optimal C_{wi} can be denoted as [58]:

$$C_{wio} = \left(\frac{C_{wi \min}}{2} M \right) - 1. \quad (2.9)$$

If a CM transmits data before analyzing whether the channel condition is idle or not then it is The time interval is designated as the DCF interframe space (DIFS). the distributed coordination function (DCF) [58]. The time interval is designated as the DCF interframe space (DIFS). When it senses that the channel is idle during the DIFS interval, it sends a SM. Upon receiving the message, the receiver sends an ACK. Following this, a short interval is designated as SIFS. If a UAV sends

an SM within the DIFS time, then the packet collides [59]. The representation of packet success and collision is shown in Figure 2.5. From Figure 2.5, it is observed that packets collide when two or more UAVs transmit data within the same interval without receiving the ACK. If the waiting time exceeds DIFS, the contention window size is doubled by reducing the backoff value by 1 and then retransmitting. The transmission process is performed by carrier-sense multiple access with collision avoidance (CSMA/CA). The mechanism is given in algorithm 2.

Algorithm 2 Packet Transmission Process:

1. **If** sense $C = C_{idle}$
 2. $T_{DIFS} = T_w$ sense $C = C_{idle}$
 3. Transmit
 4. End
 5. $T_{DIFS} < T_w$
 6. $T_B = [0, W_{cwio} - 1]$
 7. **If** $T_B > 0$, sense C continuously but don't transmit
 8. **If** $T_B = 0$
 9. Transmit
 10. End
 11. End
-

Where C_h and C_{idle} are expressed as channel and idle channel, respectively. T_w and T_B symbolize the waiting and backoff time individually. If the waiting time T_w is equal to T_{DIFS} and the channel is sensed as idle, the UAV will transmit the packet. During T_w is greater than T_{DIFS} , then the backoff time will decrease 1 by 1 from the maximum equal to C_{wio} and sense the channel simultaneously. Finally, when T_B comes to zero, the packet will be transmitted. In every cluster, there is a CH, so the average number of CMs in each cluster is [8]:

$$Q = M - 1 = \frac{N - N_c}{N_c}. \quad (2.10)$$

Where Q represents the arithmetic mean number of CMs per cluster. The packet sending probability in a specific time slot is calculated by:

$$\mu = \frac{Q}{M} = \frac{N - N_c}{N}. \quad (2.11)$$

μ , expresses the available packet sending probability in each cluster. If the channel

idle probability is symbolized by ζ , then I can represent the probability by:

$$\zeta = (1 - \mu)^{M-1}. \quad (2.12)$$

Let A , be the probability that a single CM can transmit the packet so the other CM can't transmit so it can be expressed as [51]:

$$A = 1 - \zeta = 1 - (1 - \mu)^{M-1}. \quad (2.13)$$

ε , signifies the collision probability, the probability can be quantified as:

$$\varepsilon = 1 - (1 - \mu)^{M-2}. \quad (2.14)$$

Finally, the available packet on the channel successfully transmission probability implies by Ω , this can be denoted as [60]:

$$\Omega = \frac{(M-1)\mu(1-\mu)^{M-2}}{A} = \frac{(M-1)\mu(1-\mu)^{M-2}}{1 - (1-\mu)^{M-1}} \quad (2.15)$$

Now, if we express the packet coming rate by λ_c then using the poison process the probability Δ can be calculated by [61]:

$$\Delta = 1 - e^{-\lambda_c T_m}. \quad (2.16)$$

So, the total elapsed time in each Markov state is denoted by T_m which can be expressed as [8]:

$$T_m = \zeta T_{SL} + A\Omega T_{SS} + A(1 - \Omega)T_{co}. \quad (2.17)$$

Here, T_{SL} is the slot time, T_{SS} is the successful packet transmission time and finally the T_{co} is the collision time. The T_{SS} and T_{co} can be denoted as [59]:

$$T_{SS(CH-CM)} = T_{SIFS} + \frac{L_p + L_{hd}}{R_t} + T_{ACK} + T_{dl}, \quad (2.18)$$

$$T_{SS(CM-CM)} = T_{DIFS} + T_{SIFS} + \frac{(M+1)L_p + L_{hd}}{R_t} + (M+1)T_{ACK} + T_{dl}, \quad (2.19)$$

$$T_{co} = T_{DIFS} + T_{dl}, \quad (2.20)$$

where L_p is the packet length, L_{hd} is the length of the MAC and PHY headers, and R_t is the data transmission rate. Finally, the T_{ACK} represents the acknowledgment time and T_{dl} represents the delay time.

2.4.2 Rayleigh Channel Fading

To find the probability of connectivity using this 3D mobility model. The distance between two UAVs is d , and at time t in a Rayleigh fading environment, the PL exponent is Υ , so the instantaneous SNR is $S = Ad^{-\Upsilon}|h|^2$. Where h is the channel gain while the threshold SNR is S_{th} . So, the probability of the connectivity P_c is [62]:

$$\begin{aligned} P_c &= P(S > S_{th}) = P(Ad^{-\Upsilon}|h|^2 > S_{th}) \\ &= E[P(d < (\frac{A|h|^2}{S})^{\frac{1}{\Upsilon}})] \\ &= \int_0^\infty F_R(r) D x^{\frac{1}{\Upsilon}} e^{-x} dx. \end{aligned} \quad (2.21)$$

Where $D = (\frac{A}{S})^{\frac{1}{\Upsilon}}$, and $F_R(r)$ is the steady state cumulative distribution function (CDF) of d . If we calculate the outage factor, the probability of connectivity is [62]:

$$P_c = \int_0^\infty e^{-x} \int_0^{d_1} c r^2 e^{-V(r)} dr dx. \quad (2.22a)$$

After some simplification, it comes into:

$$P_c = 1 - \frac{d_1^3}{3} e^{-V(r)}. \quad (2.22b)$$

Here, $d_1 = D x^{\frac{1}{\Upsilon}}$. After building up the cluster, the UAVs are available to serve as BSs. Therefore, we should ignore the time spent constructing the cluster when calculating the throughput. If the packet payload size is L_p , the throughput value T_h is written by [8]:

$$T_h = \frac{P_c \Omega A L_p}{T_m} = \frac{P_c \Omega A L_p}{\zeta T_{SL} + A \Omega T_{SS} + A(1 - \Omega) T_{co}}. \quad (2.23)$$

2.4.3 Nakagami-m Channel Fading

The Nakagami-m channel fading model is more favorable for fast fading at larger distances. For the $\bar{h}$ Nakagami-m distribution, the PDF can be denoted as [63]:

$$f(S) = \frac{1}{\Gamma(m)\bar{S}} \left(\frac{mS}{\bar{S}}\right)^m e^{-\left(\frac{mS}{\bar{S}}\right)}. \quad (2.24)$$

Here, m conveys the shape parameter and $\gamma(\cdot)$ represents the Gamma function, $S = \frac{E|h|^2}{\sigma_n}$ and the mean of SNR is $\bar{S} = \frac{\sigma_r E|h|^2}{\sigma_n}$. Where $E[\cdot]$ conveys the expectation operator. When, the instantaneous SNR is lower than the threshold SNR (S_{th}) then it is called the OP (P_o), and it can be calculated as [64]:

$$\begin{aligned} P_o &= P(S < S_{th}) = \int_0^{S_{th}} f(S) dS = F(S_{th}) \\ &= \int_0^{S_{th}} \frac{1}{\Gamma(m)\bar{S}} \left(\frac{mS}{\bar{S}}\right)^m e^{-\left(\frac{mS}{\bar{S}}\right)} dS. \end{aligned} \quad (2.25a)$$

After some calculation it comes into [64]:

$$\begin{aligned} P_o &= 1 - e^{-\left(\frac{mS_{th}}{\bar{S}}\right)} \sum_{n=0}^{m-1} \frac{\left(\frac{mS_{th}}{\bar{S}}\right)^n}{n!} \\ &= 1 - e^{-\left(\frac{mS_{th}\sigma_n(4\pi)^2 d^{a_l}}{G_r G_t \lambda^2 \sigma_r}\right)} \sum_{n=0}^{m-1} \frac{\left(\frac{mS_{th}\sigma_n(4\pi)^2 d^{a_l}}{G_r G_t \lambda^2 \sigma_r}\right)^n}{n!}. \end{aligned} \quad (2.25b)$$

Here, σ_n expresses the variance of additive white Gaussian noise (AWGN), d is the link distance between two UAVs, a_l represents the PL exponent, and λ indicates the wavelength at the operating frequency. G_t and G_r represent the transmitter and receiver antenna gain respectively. Finally, σ_r expresses the receiver transmission power. To communicate between two UAVs, we consider block fading, where the packet that is sent is divided into C_B blocks. C_B value changes proportionally with the speed of the UAV and packet size. It is expressed as [51], [64]:

$$C_B = \frac{L_p}{T_{co} \log(1 + S_{th})}. \quad (2.26)$$

Here, T_{co} is the coherence time which is denoted as [9], [64]:

$$T_{co} = \sqrt{\frac{9}{16\pi f_d^2}}. \quad (2.27)$$

Where f_d is the Doppler shift which is expressed as [9], [65]:

$$f_d = \frac{V}{c_1} f \cos \alpha_d. \quad (2.28)$$

Where α_d is the angle between the direction of the UAV and the data transmission link. Now, we can relate the probability of the error frame with the OP by the following equation [8], [38]:

$$\begin{aligned} P_e &= 1 - (1 - P_o)^{C_B} \\ &= 1 - e^{\left(-\frac{C_B m S_{th} \sigma_n (4\Pi)^2 d^{a_l}}{G_r G_t \lambda^2 \sigma_r}\right)} \left[\sum_{n=0}^{m-1} \frac{\left(\frac{m S_{th} \sigma_n (4\Pi)^2 d^{a_l}}{G_r G_t \lambda^2 \sigma_r}\right)^n}{n!} \right]^{C_B}. \end{aligned} \quad (2.29)$$

Now, the normalized throughput T_{h_1} value can be signified as the ratio of the transmitted total payload to the total elapsed time [8], [66]:

$$T_{h_1} = \frac{\Omega A (1 - P_e) L_p}{T_m}. \quad (2.30)$$

2.4.4 Rician Channel Fading

The Rician fading channel is considered the dominant LoS path between the transmitter and receiver. The PDF $f(S)$ value for the Rician fading channel can be denoted as [64]:

$$f(S) = \frac{E+1}{\bar{S}} e^{(-E - \frac{(E+1)S}{\bar{S}})} \times I_o\left(2\sqrt{\frac{E(E+1)S}{\bar{S}}}\right). \quad (2.31)$$

Here, E is the ratio of the power of the LoS to the power of other scattered multipath. S and $\bar{S}$ are the parameters like same as Rayleigh and Nakagami-m parameters. $I_o(\cdot)$ represents the modified Bessel function. The normal format of the Bessel function is denoted as [62]:

$$I_o(y) = \sum_{m=0}^{\infty} \frac{1}{m! \Gamma(m+i+1)} \left(\frac{y}{2}\right)^{2m+i}. \quad (2.32)$$

Where $\Gamma(\cdot)$ is the gamma function and i , is an integer. So, the OP P_o can be expressed as [63], [67], and [68]:

$$P_o = \int_0^{S_{th}} \frac{E+1}{\bar{S}} e^{(-E - \frac{(E+1)S}{\bar{S}})} \times I_o\left(2\sqrt{\frac{E(E+1)S}{\bar{S}}}\right) dS. \quad (2.33)$$

This equation can be expressed by using the Marcum-Q function in the following way [64], [67] and [69]:

$$Q_N(i, j) = e^{-\frac{i^2+j^2}{2}} \sum_{K=1-N}^{\infty} \left(\frac{i}{j}\right)^K I_K(i, j). \quad (2.34)$$

Here, $I_K(\cdot)$ is the modified Bessel function for the K_{th} order. So, we can calculate the packet error probability P_{er} by using the Marcum-Q function as [64], [65], and [70]:

$$P_{er} = 1 - \left[Q_1 \left(\sqrt{2E}, \sqrt{\frac{2(E+1)S_{th}\sigma_n(4\pi)^2 d^{a_i}}{G_r G_t \lambda^2 \sigma_r}} \right) \right]^{C_B}. \quad (2.35)$$

Therefore, in case of Rician channel fading the throughput T_{h_2} can be calculated by [8], [66], and [71]:

$$T_{h_2} = \frac{\Omega A(1 - P_{er})L_p}{T_m}. \quad (2.36)$$

2.4.5 Packet Dropping Rate (PDR) Calculation

When two UAVs transmit safety messages with the same time slot the packet will collide. Then it is needed to retransmit the packet. After attempting the maximum retransmission limit it is assumed that the packet dropped. If we denote the maximum retransmission limit by R_{tmax} then the PDR, R_{PD} value can be denoted by [8], [72]:

$$R_{PD} = (1 - \beta)^{R_{tmax}}. \quad (2.37)$$

When two or more UAVs transmit packets at the same time slot, there is the possibility of collision. So, when the packet has collided, it is necessary to retransmit the packet, resulting in a delay in the packet transmission. The delay Z_D can be calculated by [8], [73], and [74]:

$$Z_D = T_m \left(N - \frac{F}{1-F} \times \frac{2}{1 + C_{wi} + \frac{R_{tmax} C_{wi}}{2}} \right). \quad (2.38)$$

Where F is the packet dropping probability.

2.5 Numerical Result

Let, when $t = t_0$ be the time when both UAVs are at position $O(0, 0, 0)$. After a time t , UAV1 is at position $A(X_1, Y_1, Z_1)$ with azimuth angle $\phi_1 = 20^\circ$, elevation

Table 2.1 The Simulation Parameters Values

Parameters	Value
$T_{SIFS}, T_{SL}, T_{DIFS}, T_{dl} (\mu s)$	10, 20, 50, 1
L_{hd}, L_p, ACK (bytes)	50, 300, 14
$R_t, C_{wimin} G_r, G_t$	11, 64, 1, 1
N, V	30, 10-30m/s
$\sigma_n, \sigma_r, S_{th}(dB), R_{tmax}, C_{wi}$	-50, 10, 5, 7, 64
$f(\text{GHz}), a, P_t, L_s, h$	5, 3, 50, 1, 1

angle $\theta_1 = 40^\circ$, while UAV2 is at position $B(X_2, Y_2, Z_2)$ with azimuth angle $\phi_2 = 25^\circ$, elevation angle $\theta_2 = 60^\circ$. Additionally, the distance from the standstill position to the final position is $r_1 = 200m$ for UAV1 and $r_2 = 150m$ for UAV2. According to this assumption, the throughput value considering distance change and velocity chance is given below by MATLAB simulations with the 1000 Monte Carlo iterations. Table 2.1 shows the simulation parameter values.

Figure 2.6 represents the throughput value changes concerning the communication links between two UAVs for analytical and 1000 Monte Carlo simulation results. From Figure 2.6, it is observed that with increasing distance between two UAVs, the throughput value decreases. The system is operated at a high frequency of 5 GHz. Therefore, with increasing distance, the throughput value decays rapidly. However, the variations of channels show different levels of throughput values with distance variation. With upgrading the value of m the throughput is rising in the same distance. With escalating the shape parameter value m , the throughput level increases because it helps reduce the BER, resulting in more accurate packet transmissions. The Rician fading channel exhibits higher throughput values compared to other channels because it operates based on a LoS dominant connection. Another important observation is that as the distance increases, the throughput drops to zero at 165m, 160m, 95m, and 115m for Rician, Nakagami- $m=4$, Nakagami- $m=2$, and Rayleigh fading channels, respectively. Therefore, it can be concluded that these values represent the maximum radius of the circular cluster area, or the maximum allowable distance between the CH and CM to CM.

UAVs are in all the time in motion, the velocity is counted as relative velocity. From Figure 2.7, it is observed that as velocity increases, the throughput value decreases. This occurs because increasing velocity leads to topology changes, link breakages, collisions, and packet losses. In Figure 2.7, the analytical and 1000 Monte Carlo simulation results are almost the same in the system performance.

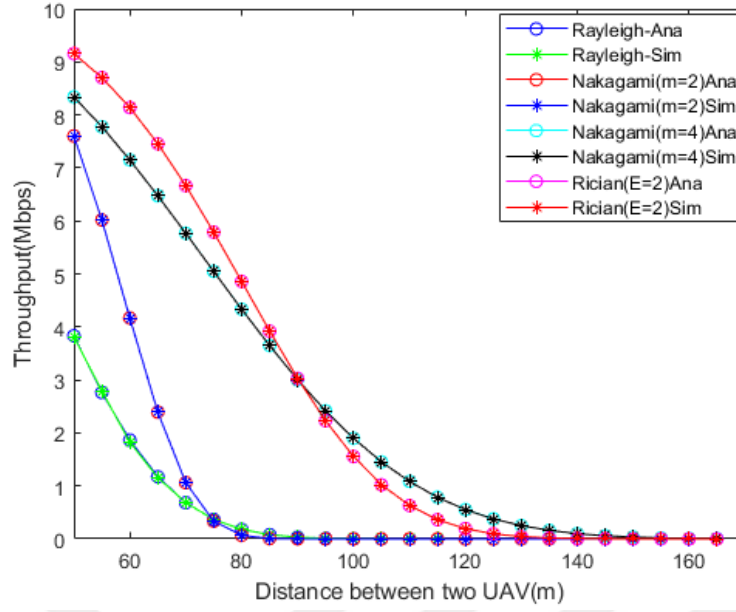


Figure 2.6 Throughput variation with respect to transmission ranges change for different types of channels with analytical and Monte Carlo simulations results.

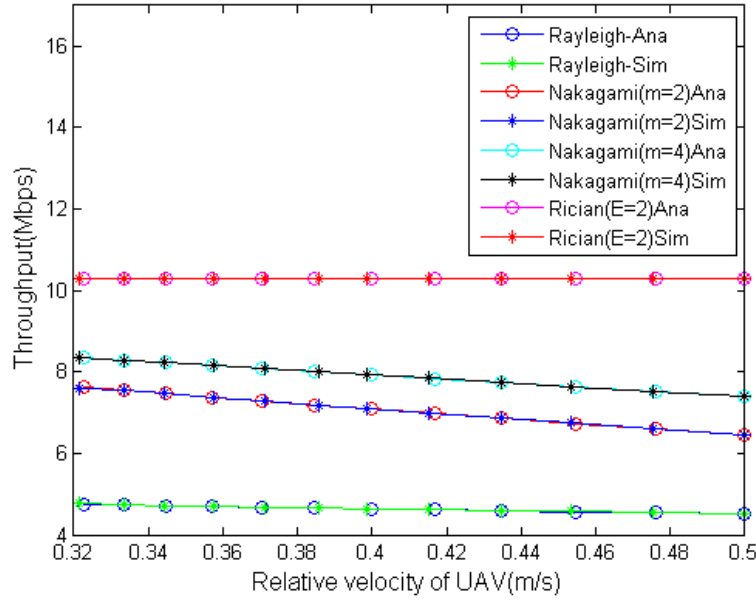


Figure 2.7 Throughput vs relative velocity for different types of channels with analytical and Monte Carlo simulations results.

Figure 2.8 represents the OP response concerning SNR and includes the results of 1000 Monte Carlo simulations. With the rising SNR, the OP decreases because higher SNR increases signal strength, thereby reducing OP. Another contributing factor is the dominance of LoS channels in Rician fading, which exhibits lower OPs.

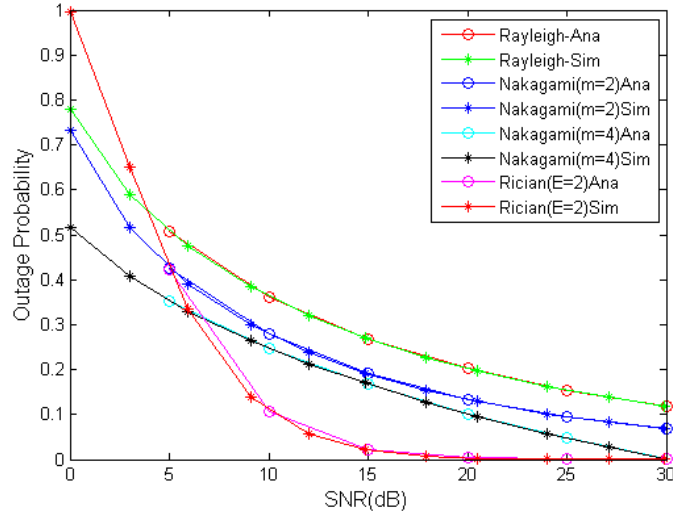


Figure 2.8 OP vs SNR response curve for different types of channels with analytical and Monte Carlo simulations results.

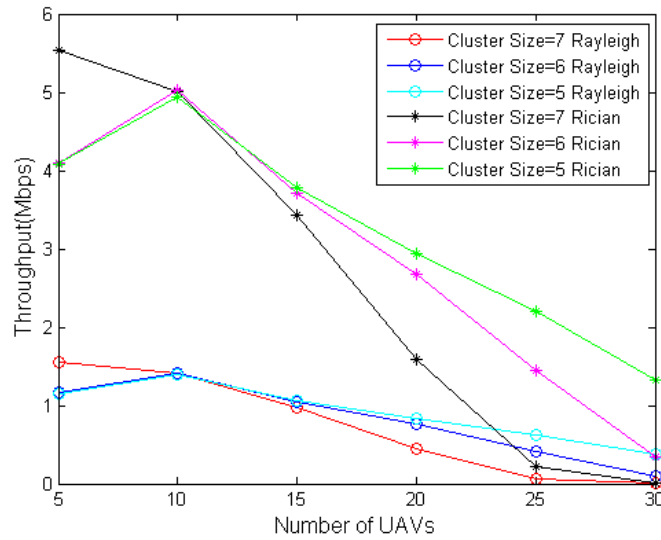


Figure 2.9 Throughput vs number of UAVs for different cluster sizes in Rayleigh and Rician fading environment.

On the other hand, as the value of m increases, indicating a lower BER, throughput also increases. Monte Carlo simulation results are almost identical to analytical results but show slight variations for the Rayleigh fading channel. To sum up, the work has shown a significant improvement with lower OP compared to [8], [9], [11] and [38] concerning the SNR.

Figures 2.9 and Figure 2.10 depict the throughput variations as a function of the number of UAVs across different cluster sizes, considering simultaneous variations in channel environments. Cluster size means the mean number of UAVs per cluster. Figure 2.9 illustrates the throughput variations in both Rayleigh and Rician fading

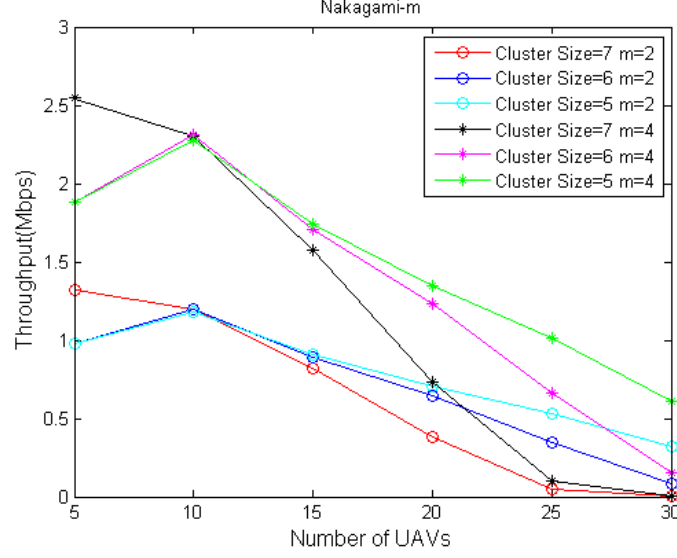


Figure 2.10 Throughput vs number of UAVs for different cluster sizes in the Nakagami-m fading environment.

environments. At a specific number of 10 UAVs, the throughput increases for cluster sizes 5 and 6. The reason is that with fewer UAVs, there is a lower possibility of packet dropping, allowing more packets to transmit successfully with lower delay.

In the case of a cluster size of 7, which means a higher number of UAVs, the throughput starts decreasing with a lower number of UAVs. After 10 UAVs, the throughput decreases simultaneously with increasing UAVs. Because more UAVs increase the possibility of collisions. In the same scenario, cluster size 7 shows lower throughput compared to cluster sizes 5 and 6. In terms of channel conditions, Rician channels show higher throughput than Rayleigh channels because the channel operates with a shorter direct LoS path. Therefore, under the Rician fading environment, the network performs significantly better with a higher throughput value than the existing works [14] and [63].

Similarly, Figure 2.10 exhibits the same trend for the Nakagami-m channel as the previous one. For the higher shape parameter value, $m = 4$ shows better performance than $m = 2$ as higher m ensures better signal strength at the receiver that boosts up the system capability.

Figure 2.11 indicates the PDR vs the number of UAVs changes for different types of cluster sizes. When the number of UAVs is very few such as 10 and 15 the PDR values are very negligible. But with increasing the number of UAVs the PDR values are increasing proportionally. More UAVs mean more data traffic which creates more collision that results in packet dropping. Correspondingly, a larger cluster size means a higher number of UAVs, showing higher PDR than a smaller

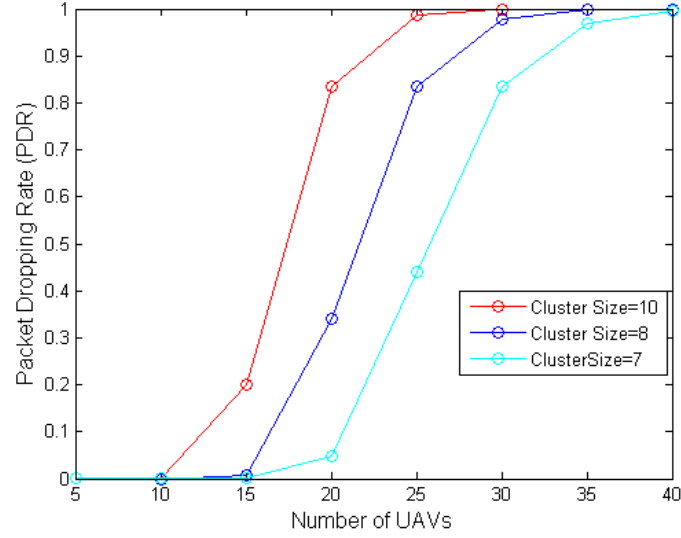


Figure 2.11 Packet dropping rate vs the number of UAVs for different cluster sizes.

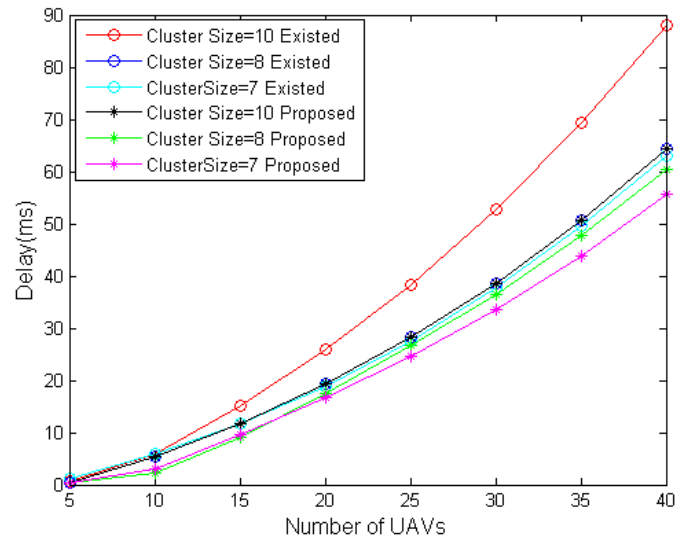


Figure 2.12 Transmission delay vs the number of UAVs characteristic curve for the different cluster sizes with existed and proposed work comparison.

cluster size. For a total of 40 UAVs, the network could function properly with a cluster size of 7 or fewer.

Figure 2.12 represents the delay characteristics curve considering the number of UAVs for the different cluster sizes. Additionally, the figure also compares the performance between the proposed system and the existing work [8]. In the case of three types of cluster sizes, the proposed network shows better performance with lower delay. From the figure it is observed that the delay values are increasing proportionally with the number of UAVs. The reason for this proportional characteristic is that increasing the number of UAVs creates more data

traffic, leading to collisions and necessitating retransmission, thereby increasing transmission delays. Correspondingly, larger cluster sizes exhibit greater delays compared to smaller cluster sizes. For 40 UAVs, in three types of cluster sizes (10, 8, and 7), the maximum delays are 64.22ms, 60.36ms, and 55.57ms, respectively. Conversely, the existing work [8] shows 87.91ms, 72.22ms, and 62.98ms for the three cluster sizes (10, 8, and 7). Moreover, the proposed work shows better delay results than [57] and [59]. Finally, the most promising outcome is that the proposed design overcomes the 100ms delay barrier for SMs.

2.6 Conclusion

In this chapter, cluster-based FANET with a 3D mobility platform is considered. An efficient cluster build-up process and control mechanism are designed that demonstrates better throughput value and lower delay compared to existing work. The network system is analyzed on an efficient 3D mobility model so the system performs properly even when the UAVs are moving. All the analytical studies, such as throughput, OP, SNR, packet transmission and collision probability, PDR, delay, etcetera, are performed by using the Markov chain model while considering the different types of channels, such as Rayleigh, Nakagami-m, and Rician channels. Under the Rician channel environment, the network shows better results than other approaches. The simulation results are analyzed by considering randomly taking values for 1000 Monte Carlo simulations.

Cluster-based FANETs with MIMO-OFDM and 3D Markov Chain

3.1 Introduction

UAVs are essential for autonomous systems due to their efficiency, cost-effectiveness, versatility, and ability to perform tasks in challenging environments. They contribute significantly to advancements in technology, safety, and data collection, making them indispensable in various sectors. FANETs are designed for communication among a fleet of UAVs. Today, FANETs have become a more innovative [3], [8], [53], [75], [76], and [77]. As there are a vast number of applications of FANETs, there is a crying need to control a significant amount of UAVs [14]. Because UAVs are dynamic devices, frequent topology changes can cause link breakage and packet loss [76]. In this circumstance, MIMO-OFDM-based MAC protocol with a 3D Markov chain-based backoff method in a 3D mobility platform would be the best choice [9], [51]. In a MIMO system, the transmitter and receiver use multiple antennas simultaneously, which increases the data rate and reduces the BER [16]. Besides, OFDM eliminates inter-symbol interference (ISI) and improves system performance with efficient spectral utilization [9]. Figure 3.1 conveys the schematic structure of the MIMO-OFDM cluster-based network.

During the period of natural disasters such as earthquakes, floods, cyclones etcetera the BS is damaged so, mobile communication is stopped [8]. In such emergency situations, our MIMO cluster-based FANETs can establish an emergency network, allowing mobile communication to resume and thereby reducing disaster losses and improving the effectiveness of rescue operations [9], [16], and [62]. In each cluster, there is a CH responsible for communication with other CMs and ECVs [77]. Cluster-based networks offer a wide range of advantages, such as flexible coverage area deployment, reduced channel contention and delay, increased reliability, scalability, fault tolerance, energy efficiency, latency minimization,

stable connections, and more [8], [14] , and [77]. Cluster-based system can ensure QoS [61].

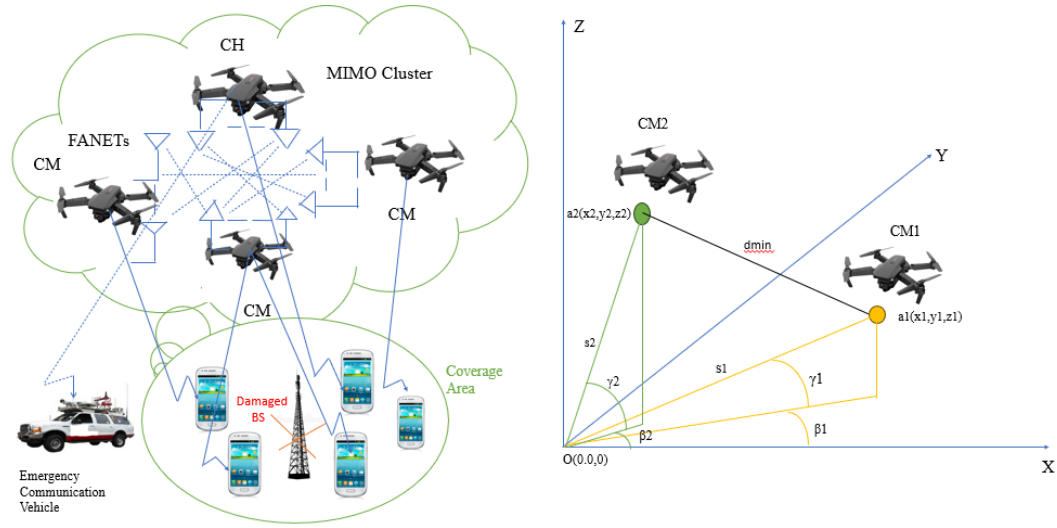


Figure 3.1 The schematic structure of MIMO-OFDM cluster based network with 3D Mobility model.

The chapter is organized in the following way: Section 3.2 expresses the backoff mechanism with a 3D Markov chain, Section 3.3 expresses the MIMO-OFDM physical layer, Section 3.4 discusses simulation result analysis by comparing existing works and finally concludes through Section 3.5.

3.2 Backoff Mechanism with 3D Markov Chain

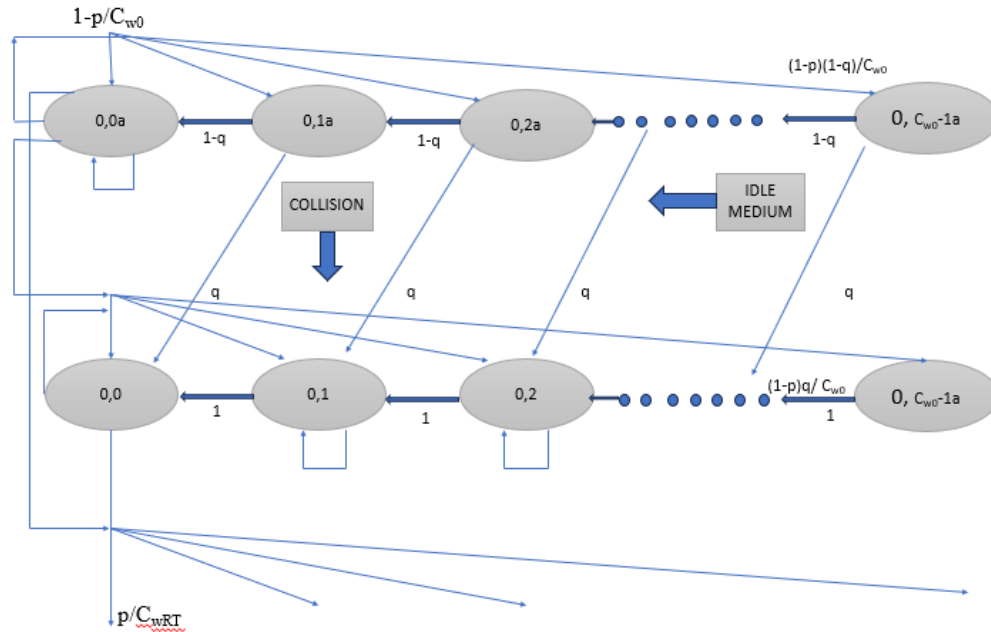


Figure 3.2 The backoff process of 3D Markov chain.

The diagrammatic layout of the 3D Markov chain is depicted in Figure 3.2 Where traffic characteristics should be considered and control PAR [9]. In each state, every CM buffers only one packet. So, it is designated as state $(0, Z)_a$ for $Z \in [0, C_{wi} - 1]$. In this case, no one is waiting to send packet when $S_t = 0$. And if $S_t > 0$ that case when a collision happens the packet sends again. To sum up, it is assumed that when no CM waiting for transmission the CMs buffer a constant probability of $1 - q$. p is the change of the Markov chain state matrix, and b is the distribution of the fixed chain. Finally, η is the stationary distribution probability. Another important point is that the Markov chain is not real-time so we need to calculate the average time [71]. To calculate η of Markov chain $b(S, Z)$ in Fig. 3 it is [51]:

$$1 = \sum_{S=0}^{R_{tmax}} \sum_{Z=0}^{C_{wi}-1} b(S, Z) + \sum_{K=0}^{C_{wi}-1} b(0, Z)_a. \quad (3.1)$$

After some simplifications of equation (3.1) of [59]:

$$\begin{aligned} \frac{1}{b(0, 0)_a} &= 1 - q + \frac{q^2 C_{wio} (C_{wio} + 1)}{2(1 - (1 - q)^{C_{wio}})} + \frac{q(1 + C_{wio})}{2(1 - q)} \times \\ & \left(\frac{q^2 C_{wio}}{1 - (1 - q)^{C_{wio}}} + p(1 - q) - q(1 - p)^2 \right) + \frac{pq^2}{2(1 - p)(1 - q)} \\ & \left(\frac{C_{wio}}{1 - (1 - q)^{C_{wio}}} - (1 - p)^2 \right) \times \left(2C_{wio} \frac{1 - p - p(2p)^{R_{tmax}-1}}{1 - 2p} \right. \\ & \left. + 1 \right). \end{aligned} \quad (3.2)$$

So, the equation of η comes into [51]:

$$\eta = b(0, 0)_a \frac{q^2}{(1 - q)} \times \left(\frac{C_{wio}}{(1 - p)(1 - (1 - q)^{C_{wio}})} - (1 - q)^{N-1} \right). \quad (3.3)$$

Now, we can relate q with the exponential PAR with time at λ_c in Poisson manner [59]:

$$q = 1 - e^{-\lambda_c T_m}. \quad (3.4)$$

The successful packet transmission probability can be represented by [51]:

$$\begin{aligned} \Omega(N) &= A_N \left(\frac{N\eta(1 - \eta)^{N-1}}{1 - (1 - \eta)^N} \times \frac{(N - 1)\eta(1 - \eta)^{N-2}}{1 - (1 - \eta)^{N-1}} \times \right. \\ & \left. \dots \times \frac{(N - (Z - 1))\eta(1 - \eta)^{N-Z}}{1 - (1 - \eta)^{N-(K-1)}} \right). \end{aligned} \quad (3.5)$$

Where A_N is number of multiple antennas used. Therefore, the mean number of

buffers fails probability can be expressed by [51]:

$$R_f = \frac{1 - \Omega(N)}{\Omega(N)}. \quad (3.6)$$

For the first time N number of UAVs want to transmission opportunities in the idle period with the probability of η . It can be designated as [51]:

$$R_{idle} = \frac{(1 - \eta)^N}{1 - (1 - \eta)^N}. \quad (3.7)$$

So, the total passed time T_p after build up the cluster in the Markov chain can be calculated by [8]:

$$T_p = R_f T_{co} + T_{SS} + (R_f + 1) T_{SL}. \quad (3.8)$$

So, the throughput value in Rayleigh fading environment T_{Ray} is written by [8],[64]:

$$T_{Ray} = \frac{P_c A \eta L_p}{T_p}. \quad (3.9)$$

Now, the normalized throughput in Nakagami-m fading environment T_{NAK} value can be represented by the ratio of total payload to the total passed time [8],[64]:

$$T_{NAK} = \frac{(1 - P_e) A \eta L_p}{T_p}. \quad (3.10)$$

3.3 MIMO-OFDM Physical Layer

For the MIMO-OFDM system, there are multiple transmitters and receivers. So, we need to consider from transmitter to receiver antenna a finite impulse response (FIR) filter where $l_{j,i}(P_M)$ represents the Rayleigh fading coefficient. Here, $P_M = 0 \dots M_P - 1$, M_P expresses the number of multipath. For n_{th} frequency subcarrier, after applying Discrete Fourier Transform (DFT) at $N(M_P < N)$, we found that [38], [51]:

$$L_{j,i} = \frac{1}{\sqrt{N}} \sum_P^{N-1} l_{j,i}(P) e^{-j \frac{2\pi P n}{N}}, 0 \leq n \leq N - 1. \quad (3.11)$$

When all the antennas are not correlated to each other the SNR value of the MIMO-OFDM can be expressed as [38]:

$$S_n = \frac{1}{a_t} \sum_{j=0}^{a_t} \sum_{i=0}^{a_r} \frac{e_s}{\epsilon} |L_{j,i}(n)|^2. \quad (3.12)$$

Table 3.1 The Parameters Values for Simulation

Parameters	Value
$T_{SIFS}, T_{SL}, T_{DIFS}, T_{dl} (\mu s)$	10, 20, 50, 1
$L_{hd}, L_p, ACK(bytes)$	50, 300, 14
$R_t, C_{wimin}, G_r, G_t, N, V$	11, 64, 1, 1, 30, 10-30m/s
$\sigma_n, \sigma_r, S_{th}(dB), R_{tmax},$	-50, 10, 5, 7,
$f(GHz), a_l, P_t, L_S, h$	5-6, 3, 50, 1, 1
$TotalNumberofSub - carrier$	64

Now, the moment generating function can be written by [9]:

$$\Gamma_{S_n}(m) = E[e^{mS_n}] = \int_0^\infty e^{mS_n} f_{S_n}(S_n) dS_n. \quad (3.13)$$

Here, $f_{S_n}(S_n)$ is the PDF of the SNR. The probability of BER for the SNR can be calculated by $P_{ber}(S_n) = Q(\sqrt{2S_n})$. Where $Q(\cdot)$ is the Gaussian Q function which symbolized as [38]:

$$Q(y) = \int_0^{\frac{\pi}{2}} e^{-\frac{y^2}{2 \sin^2 \theta}} d\theta. \quad (3.14)$$

Therefore, BER mean for SNR can be calculated by [38]:

$$\begin{aligned} P_{ber,av} &= \int_0^\infty P_{ber}(S_n) f_{S_n}(S_n) dS_n \\ &= \frac{1}{\pi} \int_0^\infty \int_0^{\frac{\pi}{2}} (S_n) f_{S_n}(S_n) dS_n d\theta \\ &= \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \Gamma_{S_n}(m_e = -\frac{1}{\sin^2 \theta}) d\theta = \frac{1}{\pi a} \int_0^{\frac{\pi}{2}} (1 + \frac{S_n}{a \sin^2 \theta})^{-a^2} d\theta. \end{aligned} \quad (3.15)$$

Finally, the overall mean BER of the OFDM system for the multiple receiver antennas can be calculated as [9], [38]:

$$P_{ber,all} = 1 - (1 - P_{ber,av})^N. \quad (3.16)$$

3.4 Simulations Result Analysis

Let, when $t = t_o$ both the CM at position $O(0, 0, 0)$. After a time, $t = t$, CM1 at position $a_1(x_1, y_1, z_1)$ with azimuth angle $\phi_1 = 20^\circ$, elevation angle $\theta_1 = 40^\circ$ and CM2 at position $a_2(x_2, y_2, z_2)$ with azimuth angle $\phi_2 = 25^\circ$, elevation angle $\theta_2 = 45^\circ$. Besides, the distance from the standstill position final position is for CM1 at $r_1 = 200m$ and for CM2 at $r_2 = 150m$.

Figure 3.3 represents the throughput value changes with respect to the 3D distance

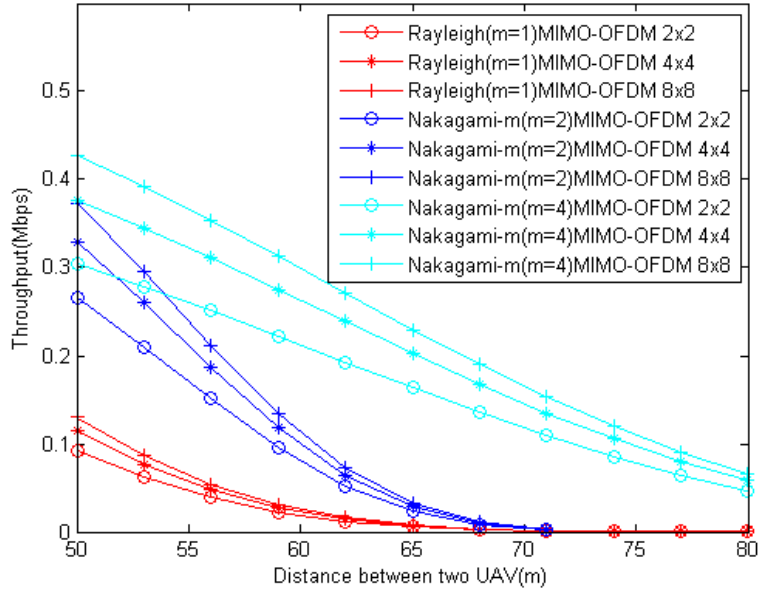


Figure 3.3 Throughput values for distance between two UAVs for different channels and MIMO-OFDM channels criteria.

changes between two CMs for the different channels criteria Rayleigh, Nakagami $m = 2$ and $m = 4$. The throughput value also changes if we operate the network for different MIMO-OFDM scenarios. Overall, it is observed that with distance increasing throughput value reduces for every criterion as the network is operated in a high frequency of GHz range. Other case, the number of antennas increases from transmitter to receiver, multiple paths are created, which enhances the receiver's capability and reduces the BER, leading to increased throughput values. For the same reason as earlier stated with increasing the value of m decreasing BER results boast up throughput values.

Figure 3.4 expresses the throughput value changes with the relative velocity for different MIMO-OFDM criteria and channel models. With increasing the relative velocity values the throughput value is decreasing. When increasing the velocity that means the topology changes more frequently which results in throughput decays. In the case of the Nakagami- m , rising m results in higher throughput because the BER decreases. For the MIMO-OFDM case with increasing antenna number the throughput value rises. Figure 3.5 represents the throughput value concerning the number of UAV changes for different channels and MIMO-OFDM. Overall, for all the cases throughput values are increased until the number of UAVs is 15. After that, more UAVs led to increased collisions and thus reduced throughput. Rayleigh fading channels are showing lower throughput than Nakagami- m channels. With increasing the values of m , the throughput value

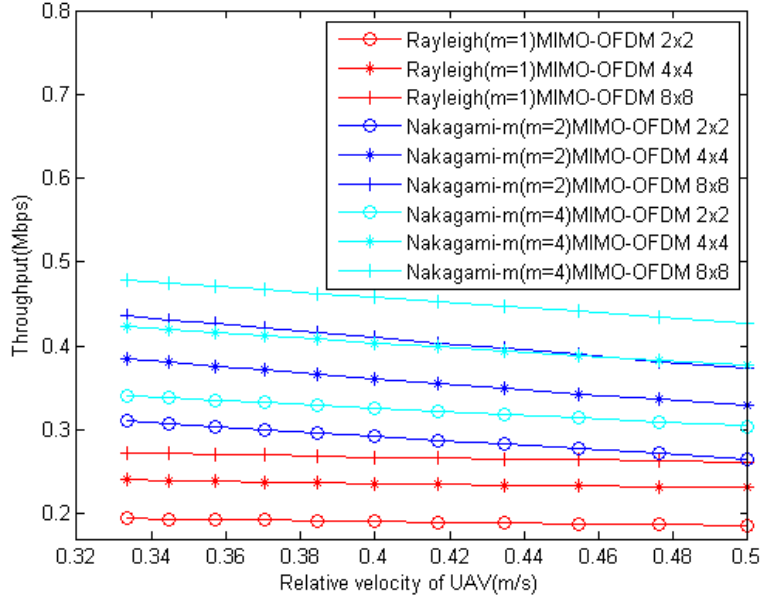


Figure 3.4 Throughput changes with respect to the relative velocity.

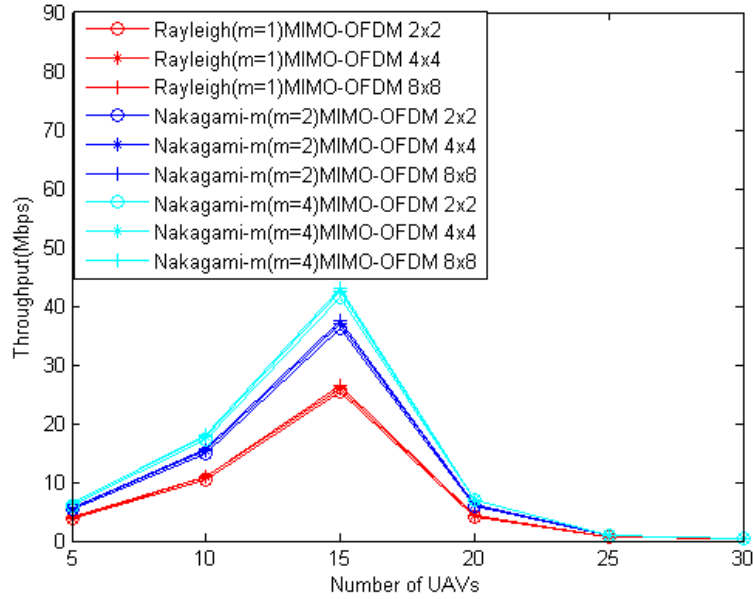


Figure 3.5 Throughput vs number of UAVs for various channels and MIMO-OFDM.

increased. For Nakagami- $m = 4$ shows the best performance than others. The mean quantity of CMs per cluster represents the cluster size. Figure 3.6 shows the packet delay characteristics for different cluster sizes in the Nakagami- m ($m = 4$) channel environment and MIMO-OFDM 8×8 criteria. As the number of UAVs and cluster sizes increase, the delay values rise. It showed a noticeably improved performance with comparing the related existing work. Figure 3.7 shows the

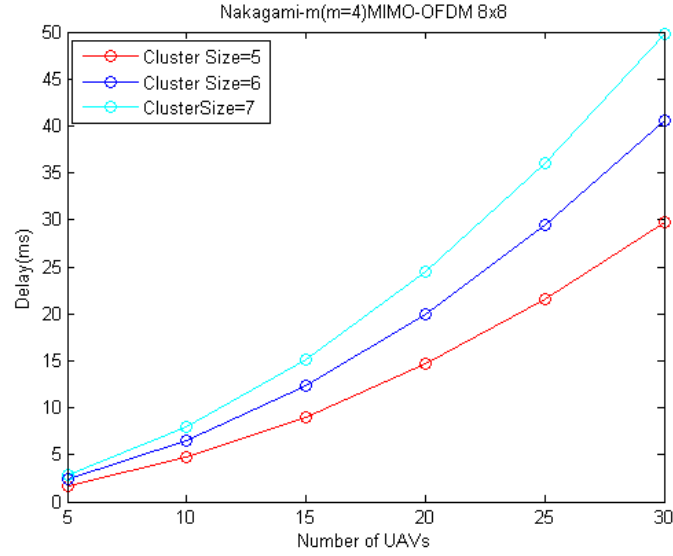


Figure 3.6 Number of UAVs vs delay characteristics curve.

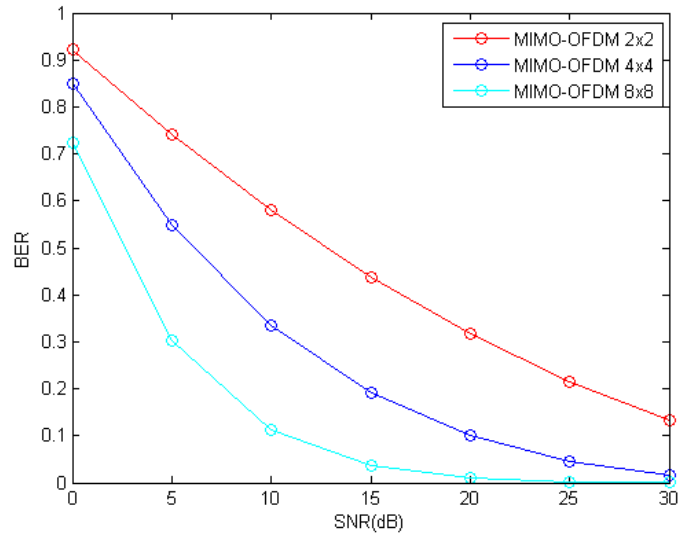


Figure 3.7 BER vs SNR (dB) responses with various MIMO-OFDM criteria.

BER vs. SNR curves for different MIMO-OFDM configurations. As the SNR increases, the BER values decrease. Higher signal strength at the receiver leads to better performance with lower BER. Similarly, increasing the number of antennas enhances the receiver's signal capacity, which reduces the BER. Figure 3.8 shows the OP characteristics curve concerning the SNR for various channels. Because of the SNR rises, the OP reduces. Because SNR increases that means more signal strength that results in less BER so the OP is reduced. On the other criteria increasing Nakagami-m channel m values results in reduced BER so that the error frame transmission is reduced throughput increases and OP is reduced.

From the Table 3.2, it is observed that the proffered work demonstrates noticeably

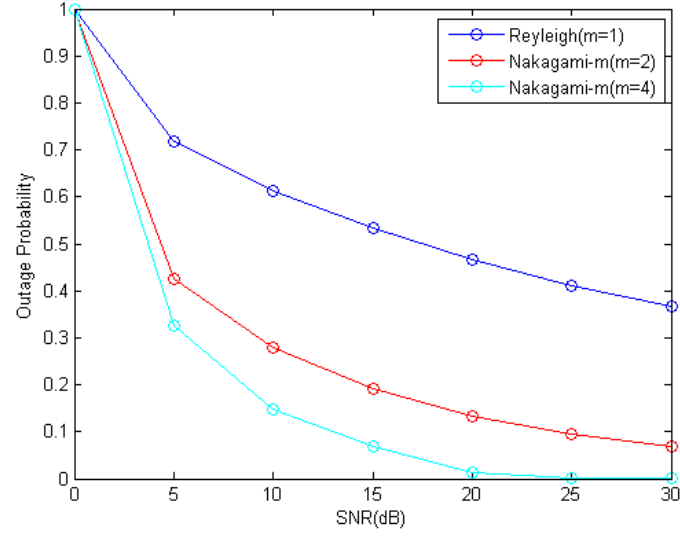


Figure 3.8 OP vs SNR for various types of channels.

Table 3.2 Performance Comparison with Existing Work

Ref. No.	Max. Throughput(Mbps)	Min. Delay (ms)
[3]	N/A	N/A
[78]	6.5	100
[14]	0.9(Normalized)	N/A
[8]	26	70
[9]	4	N/A
[38]	14	N/A
This Work	43	30

better performance compared to existing work.

3.5 Conclusion

The chapter represents the cluster-based FANETs MAC protocol with MIMO-OFDM in the 3D Mobility platform. A 3D Markov chain-based backoff method is introduced to improve the performance. The efficient cluster control mechanism is described and simulation results are presented. The simulation results are analyzed by special throughput with the function of the range between two UAVs, the relative velocity of the two UAVs, and the quantity of UAVs for several types of channels and MIMO-OFDM criteria. The performance analysis is also investigated regarding BER, OP, and delay.

Adaptive Cluster-Based MAC with Mobility and Coverage Optimization

4.1 Introduction

Today NTN platforms are the most promising platform. Satellites, airships, aircraft, balloons and other aerial space vehicles are the platforms to support NTNs. Because TNs cannot provide sufficient support to meet the current demands for 5G and beyond technologies, they are increasingly being supplemented by alternative solutions [39], [78], [79]. Additionally, the IoT involves many objects and devices connected to the internet, enabling the sharing of numerous data streams with higher throughput and lower latency. Therefore, it is impossible to provide the desired facilities using TNs. Moreover, during disasters such as earthquakes, floods, and other hazards, TNs may be damaged and unable to support network services [4]. Retooling TNs takes time; however, for emergency relief and search-and-rescue operations, the first 48 hours are the most crucial. In this context, FANETs are the most favorable platform to support terrestrial facilities using NTN platforms. It is the reason of the fact that UAV-BS provide flexible advantages such as controllable mobility, ensured LoS stable connection and QoS, yieldable extension, services in different environmental areas, ensuring demand for facilities, robustness, scalability, reliability, flexible service level, considering public safety, desired capacity, energy efficiency and so on [4], [5], [6]. Moreover, cluster-based FANETs are more favorable than a single UAV because if one UAV encounters any issues, the entire network could fail, like BS [4], [5].

Despite such merits, there are some challenges to operating UAVs-BSs. Due to high speed, mobility causes changes in the network topology, resulting in signal strength loss and disconnections [4]. Furthermore, topology changes can lead to collisions, packet losses, lower throughput, and higher latency. Additionally, a higher rate of interference, power limitations, frequent handover positions in 3D space, bandwidth allocation, and many other issues need to be considered [4], [5],

[6], [7]. The MAC protocol plays a vital role in ensuring that UAVs in FANETs can communicate effectively, efficiently, and reliably. Mobility significantly affects the performance and operation of the MAC protocol. In [8], a recent emergency communication system through FANETs has been proposed for disaster situations; however, mobility is not considered. Due to these mobility-induced challenges, a specialized MAC protocol for FANETs needs to be designed, focusing on flexibility and dynamic adaptation.

To support the downlink air-to-ground coverage, low-altitude aerial platforms (LAPs) or FANETs have been the most talkable systems in recent times [18]. Because it provides LoS connection based on different elevation angles. In different urban environments, the LoS PL varies due to scattering and other factors. Additionally, link distances, UAV altitudes, and maximum coverage radius are interrelated [18]. To provide services with the minimum number of CMs required to cover the BS area, it is essential for maximum coverage.

The arrangement of the chapter is in the following way: Section 4.2 covers cluster member adding and leaving procedure, section 4.3 describes the proposed adaptive MAC with mobility, section 4.4 presents the mathematical background for performance analysis, section 4.5 discusses UAV-supported coverage area optimization, section 4.6 includes the simulation results and finally concluded in section 4.7.

4.2 Cluster Member Adding and Leaving Procedure

This section presents the proposed clustering mechanism. To establish the cluster, one CH is responsible for managing it. The CH maintains communication with other cluster's CHs and the members of its own cluster, called CMs. Additionally, the CH is connected to the ECV, which provides core network services and delivers UAVs for joining the cluster. The cluster area is divided into multiple areas based on mobility. Packet transmission is controlled using a 3D Markov chain-based backoff process. To prevent topology-changing packet losses, the CW size is adjusted based on mobility. Therefore, system throughput improved noticeably. A transmission algorithm is introduced to adjust the MAC when the CMs move on a 3D platform.

To provide network support for the TBS cell area, the CMs are deployed at the required altitude to serve the maximum coverage area. The supported coverage areas vary based on different environmental conditions, such as suburban, urban, dense urban, and high-rise urban scenarios. Because of different environments (diverse building ratios), the LoS PL variable is based on contrasting elevation

angles. Therefore, an algorithm to achieve maximum coverage is introduced while using the minimum number of CMs for different environmental scenarios.

To support UAV-BS, first, needs to build up the cluster. When the UAV floats in the air, its initial target is to become CM. To function as a CM, the UAV sends ATAC. After that, the CH sends a message CTAC. If the UAV does not receive any CTAC, it sends the ATAC again. If the second attempt fails, the UAV assumes the role of CH. It accepts the ATAC, sends the CTAC, and establishes the cluster. The velocity direction of the same cluster CMs is in the same direction. The CM nearest to the CH functions as the subordinate CH. If the chief CH is disconnected for any cause, the subordinate CH will take over as the chief CH. The CH is always active in maintaining the connection with all the CMs. It is performed by sending messages to the CM. If the CM sends ACK, it means that the CM is active in the cluster; otherwise, CH functions as CM disconnected from the cluster. The CH continuously updates the inventory of CMs. The format of the cluster control packet was discussed in [8]. The waiting time to receive messages is denoted by T_W . Let the instantaneous battery power level of the CM be B_L and the minimum required power be B_{Lmin} . The cluster make-up and control mechanism algorithm are given in algorithm 3.

Algorithm 3 Cluster Make Up and Control Mechanism Algorithm:

1. Send ATAC by the UAV
 2. **If** the UAV receives CTAC
 3. The UAV become CM
 4. **End**
 5. **Else If** send again ATAC
 6. Wait $T_w = T_{sifs}$
 7. **If** receive CTAC become CM
 8. **End**
 9. **Else** become CH
 10. **End**
 11. Check B_L
 12. **If** $B_L > B_{Lmin}$ keep support
 13. **Else** leave cluster by sending message to CH
 14. **End**
 15. The CH sends message to ECV for delivering new UAV for adding
 16. **End**
-

4.3 Proposed Adaptive MAC with Mobility

The network system is divided into two parts. The first part involves the construction of the core network, which is established using a cluster-based MAC.

The second part involves downlink coverage to support mobile station (MS) services. The proposed UAV-BS network structure is shown in schematic form in Figure 4.1.

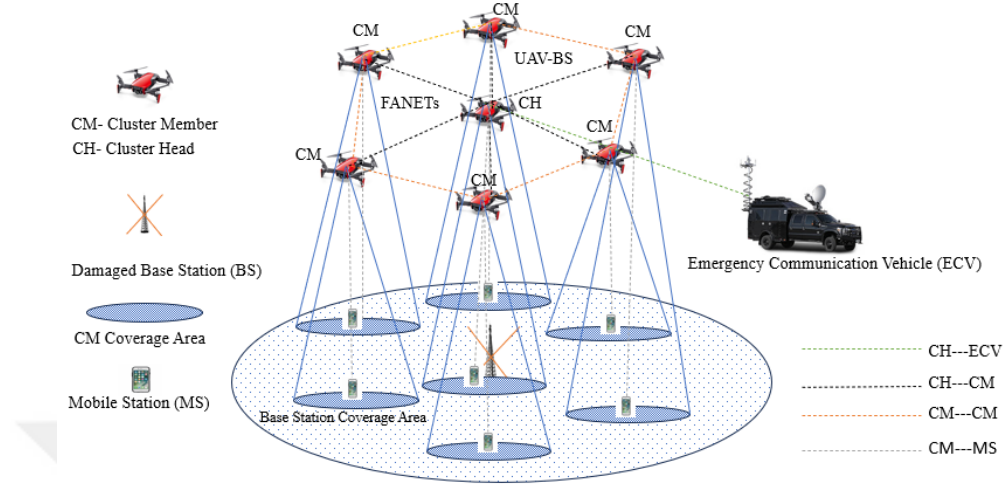


Figure 4.1 Proposed cluster-based network structure with coverage network support.

The cluster area is divided into multiple smaller areas denoted as $A_S = \{1, 2, 3, \dots, n\}$ where each area is selected as a specific vector distance d_A for the CM or CH. The value of d_A is selected where the throughput changes noticeably. The sub-division of the cluster area into different smaller areas is given in Figure 4.2.

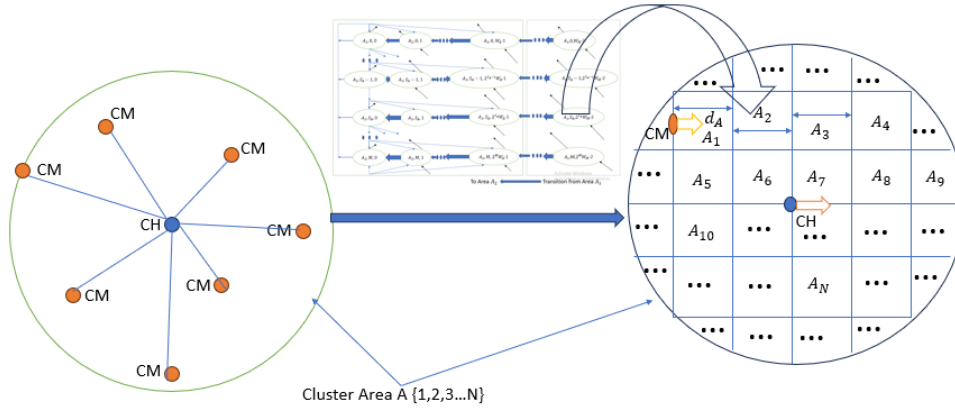


Figure 4.2 Dividing cluster area into different smaller areas based on mobility.

The Markov chain process, when the CM transfers from area A_{S_1} to A_{S_2} is shown in Figure 4.3. Let the CM stays in a specific area in time t_A with velocity v_A , where $t_A = \frac{d_A}{v_A}$. Assume t_d be the small duration during which the CM either moves to the next area with probability $\frac{t_d}{t_A}$ or stays in the same area with probability $1 - \frac{t_d}{t_A}$.

W_A represents the minimum CW of the area. R_{tmax} denotes the highest number of backoff stages. We examine the DCF performance of each CM using a 3D Markov chain $A_S(t), S_A(t), B_A(t)$ at time t .

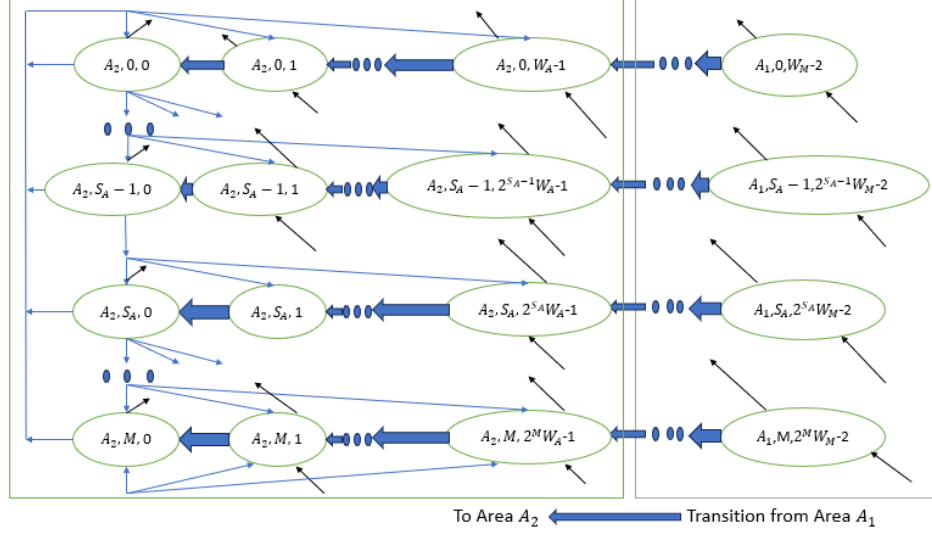


Figure 4.3 Markov chain process when the CM transfer from area A1 to A2.

$A_S(t)$ depicts the area the CM is located. $S_A(t)$ denotes the backoff stage, and $B_A(t)$ conveys the backoff time of CM using DCF. The CM either stays in the same area or moves to a new area with renewed C_{wimin} and transition probabilities. Using the Markov process the CM moves from A_{S_1} to A_{S_n} . There are three types of possibilities when transition occurs. Those are the transition when in slot time, the transition during successful transmission and the transition at the moment of collision. The transition probability when the CM moves from area A_{S_1} to A_{S_2} in the slot backoff time can be calculated as [7]:

$$P_{SL}(A_{S_2}, S_A, B_A | A_{S_1}, S_A, B_A + 1) = \left(\frac{E[T_{msl}]}{t_{A2}} \right), \quad (4.1)$$

$$A_S \in [1, n], S_A \in [0, R_{tmax}], B_A \in [0, W_A - 1].$$

Here, $t_{A2} = \frac{d_{A2}}{V_{A2}}$ and $E[T_{msl}]$ expresses the mean duration of slot time. The transition probability when the CM transmits successfully can be expressed as [7], [80]:

$$P_{SL}(A_{S_2}, 0, B_A | A_{S_1}, S_A, 0) = \left(\frac{\Omega E[T_{SU}]}{W_A t_{A2}} \right), \quad (4.2)$$

$$A_S \in [2, n], S_A \in [0, R_{tmax}], B_A \in [0, W_A - 1].$$

Ω represents the successful packet transmission probability and $E[T_{SU}]$ expresses the mean successful packet transmission time. Now, when the CM falls on collision after the maximum number of retransmissions, then the transition probability can be denoted as [7]:

$$P_{CO}(A_{S_2}, R_{tmax}, B_A | A_{S_1}, R_{tmax}, 0) = \left(\frac{(1 - \Omega)T_{cl}}{2^{R_{tmax}} W_A t_{A2}} \right), \quad (4.3)$$

$$A_S \in [2, n], B_A \in [0, 2^{R_{tmax}} W_A - 1].$$

Here, T_{cl} is the mean collision time. The selected distance at which the throughput changes noticeably is denoted as d_{NC} . Let the transition probability be expressed by $P(tr)$. The cases are in slot stage (S_L), successful transmission stage (S_S) and collision stage (S_C). The adjusting MAC for transmission when CM in mobility is given in algorithm 4.

Algorithm 4 Moving CM Adjusting MAC for Transmission:

1. Divide Cluster Area $A = 1, 2, 3, \dots, n$
 2. Set $\vec{d}_A = d_{NC}$
 3. If $\vec{d}_A = d_{NC}$
 4. $A = 1, 2, 3, \dots, n$
 5. $C_{wimin} = \text{renew } C_{wimin}$
 6. If in S_L period $P(tr) = P_{SL}, A_S \in [1, n], S_A \in [0, R_{tmax}], B_A \in [0, W_A - 1]$
 7. End
 8. If in S_S period $P(tr) = P_{SS}, A_S \in [2, n], S_A \in [0, R_{tmax}], B_A \in [0, W_A - 1]$
 9. End
 10. If in S_C period $P(tr) = P_{CO}, A_S \in [2, n], B_A \in [0, 2^{R_{tmax}} W_A - 1]$
 11. End
 12. End
-

4.4 Mathematical Background for Performance Analysis

The mean duration of the slot time can be calculated by [7]:

$$E[T_{mst}] = T_{SL} + \Omega T_{SU} + (1 - \Omega)T_{cl}. \quad (4.4)$$

The total passed time T_{pm} , considering 3D mobility in the Markov chain, can be calculated by [8], [61]:

$$T_{pm} = \zeta T_{SL} P_{SL} + A \Omega P_{SS} T_{SS} + A(1 - \Omega) T_{cl} P_{co}. \quad (4.5)$$

The data transmission per second, which refers to throughput, can be calculated as [8], [66]:

$$T_{hm} = \frac{(1 - P_{er})A\Omega L_p}{T_{pm}}. \quad (4.6)$$

When the maximum retransmission limit R_{tmax} is crossed, the packet is dropped. In the case of an area transition situation PDR can be calculated by [8], [72]:

$$\theta_{PDR} = [(1 - \omega)P_{CO}]^{R_{tmax}}. \quad (4.7)$$

Due to collision or packet drops, the packets are not transmitted in time. Therefore, the delay δ can be expressed as [8], [74], [81]:

$$\delta = T_{pm} \left(N - \frac{F}{1 - F} \times \frac{2}{1 + C_{wio} + \frac{R_{tmax}C_{wio}}{2}} \right), \quad (4.8)$$

where F represents the packet dropping probability.

4.5 UAV Supported Coverage Area Optimization

During natural disasters, when the BS is damaged, the BS network is supported by a UAV-BS. The schematic structure of the supported coverage area is illustrated in Figure 4.4. Let U represent the total number of users supported by the BS, along with a coverage area A_{BS} and a radius R_{BS} . Where u represents the number of users supported by each UAV-BS, and A_{UBS} is the coverage area. The users are connected to the UAV-BS via a LoS connection. Therefore, when the UAV-BS is at optimum altitude, the supported coverage area is maximized, with a radius of R_{max} . The probability of a LoS connection depends on the elevation angle θ and environmental factors.

Three parameters α , β , and γ change with the urban environment. α is a dimensionless parameter and expresses the ratio of developed area to total area. The values are 0.1, 0.3, 0.5, and 0.5 for suburban, urban, dense urban and high-rise urban respectively. β represents the average number of buildings in the area. The values are 750, 500, 300, and 300 for suburban, urban, dense urban and high-rise urban respectively. γ expresses the building height distribution in the Rayleigh probability density function. The values are 8, 15, 20, and 50 for suburban, urban, dense urban and high-rise urban, respectively [18], [29], and [30]. The probability of LoS connection with the function of elevation angle θ is expressed as [18], [82]:

$$P(\theta) = \frac{1}{1 + ae^{-b(\theta-a)}}, \quad (4.9)$$

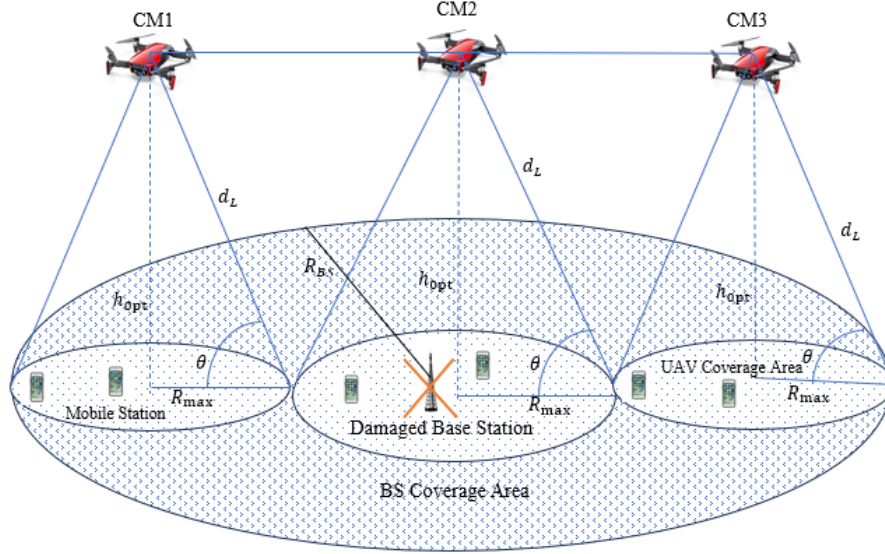


Figure 4.4 Schematic diagram of damaged BS coverage area covered by UAV-BS.

where a and b are the sigmoid function parameters and those values are calculated from the environment parameters value α , β and γ . The equation can be expressed as [18], [83]:

$$x = \sum_{j=0}^3 \sum_{i=0}^{3-j} Z_{ij} (\alpha\beta)^i \gamma^j. \quad (4.10)$$

Here, x denotes the values of a and b . By using the surface fitting of α and β we can calculate the value of a and from γ we can find the value of b . Finally, Z_{ij} expresses the polynomial coefficients. Now, to find out the LoS PL, which is a function of the link distance, operating frequency, and environmental issues. The maximum LoS PL can be found from the following equation [18], [29], [75], [84], [85], [86], and [87]:

$$PL_{\max} = \frac{E_A}{1 + ae^{-b(\theta-a)}} + 10 \log(d_L^2) + F_L + X_{EL}. \quad (4.11)$$

Where E_A is the average excessive LoS and NLoS PL difference and $F_L = 20 \log f + 20 \log \frac{4\pi}{c} + \epsilon_{NLoS}$. The excessive LoS PL ϵ_{LoS} values are 0.1, 1, 1.6, and 2.3 and NLoS PL ϵ_{NLoS} values are 21, 20, 23, and 34 respectively [18], [30]. Where X_{EL} is the extra losses for the different disaster environmental scenarios. In the case of heavy rain, the attenuation loss $X_{EL} = X_{\text{Rain}} = K_{\text{Rain}} F_R^{\partial}$. Where F_R is the falling rain rate and K_{Rain} and ∂ are the series coefficient [88]. In the case of a foggy environment, $X_{EL} = X_{\text{Fog}} = K_{\text{Fog}} F_{\text{Fog}}$. Where K_{Fog} expresses the coefficient

for attenuation per kilometer liquid water density and F_{Fog} represents the density of water [89]. In snowy environment, $X_{EL} = X_{snow} = 0.00349 \frac{F_{snow}^{1.6}}{\lambda^4} + 0.00224 \frac{F_{snow}}{\lambda}$. Where F_{snow} is the snowfall rate and λ is the operating wavelength [89]. At the time of the earthquake, the buildings collapsed. Therefore, the LoS diffraction occurs. The diffraction loss $X_d = 20 \log_{10} \sqrt{(F_s - 0.1)^2 + 1} + F_s - 0.1$. Where F_s is the Fresnel-Kirchhoff diffraction parameter. Due to the building collapsed obstruction loss $X_o = 20 \log_{10}(h_B - h_m)$. Where h_B is the collapsed building height and h_m expresses the MS height. Thus, the total loss due to earthquake building collapsed $X_{EL} = X_A = X_d + X_o$ [89], [90]. From equation 4.30, we can find the coverage radius equation as [4], [14] and [18]:

$$R = \sqrt{10 \left(\frac{PL_{max} - \frac{EA}{1+ae^{-b(\Theta-a)}}}{10} \right)} - h_A^2. \quad (4.12)$$

To find out the optimum altitude h_{opt} , we need to find out $\frac{dR}{dh}$ and then set $\frac{dR}{dh} = 0$. Thus, the maximum coverage radius R_{max} can be calculated as follows [77]:

$$R_{max} = \sqrt{10 \left(\frac{PL_{max} - \frac{EA}{1+ae^{-b(\Theta-a)}}}{10} \right)} - h_{opt}^2. \quad (4.13)$$

The radii of macro, micro, and pico cell BSs are 1-30km, 50m-1km, and 50m, respectively. So, the area of the BS can be calculated by [91]:

$$A_{BS} = \frac{3\sqrt{3}}{2} R_{BS}^2. \quad (4.14)$$

Therefore, the maximum coverage area per UAV-BS can be calculated as follows [91]:

$$A_{UBS} = \pi R_{max}^2. \quad (4.15)$$

Then the number of CM to cover the BS coverage by UAV-BS can be denoted by [75]:

$$N_{CM} = \frac{A_{BS}}{A_{UBS}}. \quad (4.16)$$

Flexible connection between CM to MS is expressed by $L_{C,M} \in [0, 1]$. If the CM connected with MS then $L_{C,M} = 1$; otherwise $L_{C,M} = 0$. The exchange of environmental characteristics is denoted by $\eta_\epsilon \in [1, 2, 3, 4]$. Here 1,2,3 and 4 symbolize suburban, urban, dense urban and high-rise urban respectively. During the disaster scenario, the extra environmental issues $X_\epsilon \in [1, 2, 3, 4]$. Where 1, 2, 3 and 4 symbolize the heavy rain, snowy, foggy and earthquake respectively.

Each CM minimum power to support MSs is P_{pmin} with the number of supported MSs being N_{MS} and the CM battery power level is P_{BCM} . To support maximum coverage by using the minimum number of CMs and relates to MAC layer, the mechanism is implemented by algorithm 5.

Algorithm 5 Maximum coverage by using minimum number of CMs and relates to MAC layer:

1. Set PL_{max} for $L_{C,M} = 1$
 2. If $PL \leq PL_{max}$, $d_L \leq d_{Lmax}$ and $\theta = \theta_{min}$
 3. Connected $L_{C,M} = 1$
 4. Else disconnected $L_{C,M} = 0$
 5. End
 6. Set $h = h_{opt}$ on PL_{max} and d_{Lmax} for $\eta_\epsilon \in [1, 2, 3, 4]$ and $X_\epsilon \in [1, 2, 3, 4]$
 7. If $h = h_{opt}$ for $\eta_\epsilon \in [1, 2, 3, 4]$ and $X_\epsilon \in [1, 2, 3, 4]$
 8. $R = R_{max}$, $A_U = A_{Umax}$, $N_{Cmin} = \frac{A_{BS}}{A_{Umax}}$ for $\eta_\epsilon \in [1, 2, 3, 4]$ and $X_\epsilon \in [1, 2, 3, 4]$
 9. Calculate each $P_{pmin} = \sum_{n=1}^{N_{MS}} PL$ for $\eta_\epsilon \in [1, 2, 3, 4]$ and $X_\epsilon \in [1, 2, 3, 4]$
 10. If $P_{BCM} < P_{pmin}$
 11. The CM sends the CH the CM will leave
 12. The CM leaves the cluster
 13. Another CM join the cluster through ATAC and CTAC
 14. End
 15. End
-

4.6 Numerical Results

This section presents the numerical results obtained after implementing the developed algorithm, which adjusts the MAC protocol based on mobility. It also demonstrates, under various environmental scenarios, the maximum PL in terms of distance, the maximum coverage radius at the optimal altitude, and the coverage area per CM. Finally, the section illustrates how the macro cell BS area can be covered with the minimum number of CMs after applying the algorithm. The analytical simulation was conducted using MATLAB. All simulation parameters are listed in Table 4.1, and the constants for environmental issue factors are provided in Table 4.2. The simulation results are compared with the recent Shah's model [8] and traditional MAC based on IEEE 802.11 standard [59].

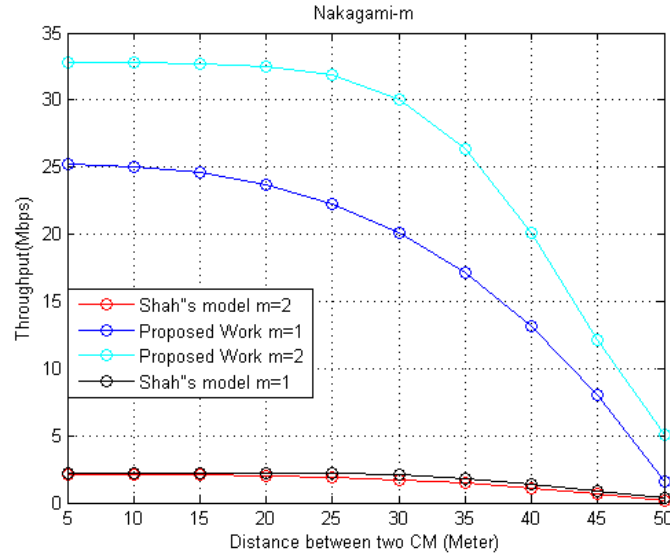
Figure 4.5 illustrates the variation in throughput with changes in the distance between two CMs in a Nakagami-m fading environment. It is revealed by the figure that as the distance increases, the throughput value decreases. This is because the increased distance results in higher PL, as the system operates a 5GHz high-frequency range. In the case of Nakagami-m=1, it was also found that a 20m

Table 4.1 The Constant Parameters Values

Parameters	Value
$T_{SIFS}, T_{SL}, T_{DIFS}, T_{dl} (\mu s)$	10, 20, 50, 1
L_{hd}, L_p, ACK (bytes)	50, 512, 14
R_t, C_{wimin}, G_r, G_t	11, 64, 1, 1
N, V	50, 1-35m/s
$\sigma_n, P(tr), S_{th}(dB), R_{tmax}, C_{wimin}$	-50, 10, 5, 7, 64
$f(\text{GHz}), a_l, \vec{d}_A, PL_{max}, R_{BS}$	5, 3, 20-25m, 20, 30 km

Table 4.2 Environmental Factor Constant

Constant	Suburban	Urban	Dense Urban	Highrise Urban
α	0.1	0.3	0.5	0.5
β	750	500	300	300
γ	8	15	20	50
ϵ_{LOS}	0.1	1	1.6	2.3
ϵ_{NLOS}	21	20	23	34

**Figure 4.5** The throughput changes with the variation of distance under Nakagami-m fading channel environment.

change in distance resulted in a reduction of approximately 2Mbps in throughput. Therefore, the vector distance for changes in the cluster area is selected as 20m. For the case of Nakagami-m=2, it is also observed that for 25m changes the throughput was reduced by approximately 1Mbps. So, the vector distance for changes in the cluster area was selected as 25m. In the case of Nakagami-m channel fading, the proposed work demonstrates better results than the existing Shah's model.

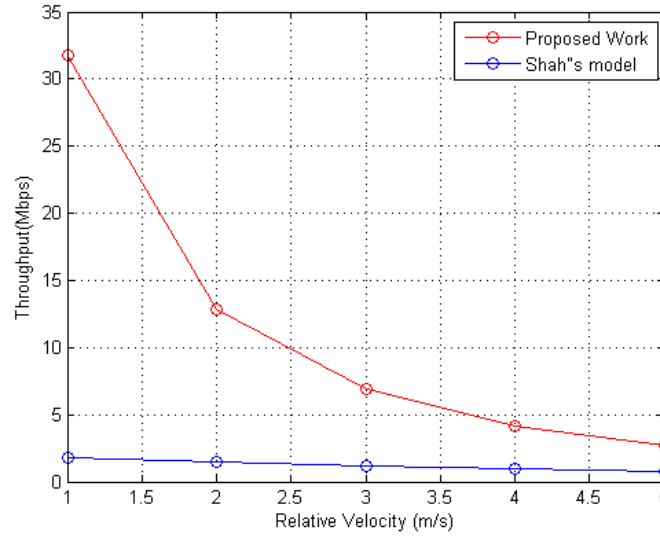


Figure 4.6 Throughput variation with velocity changes.

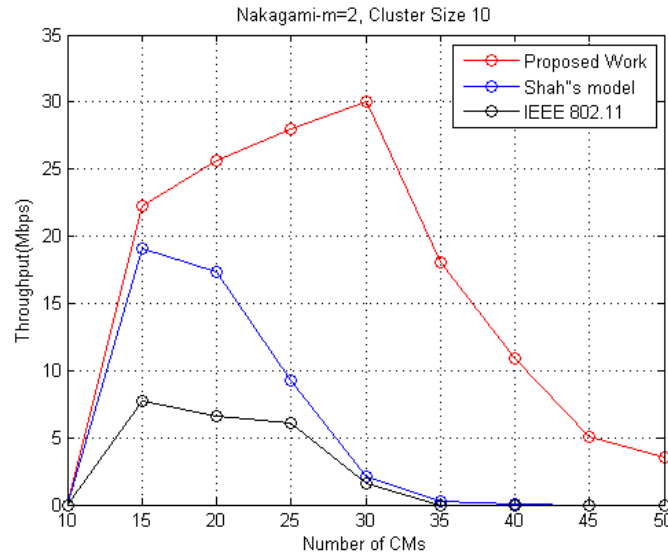


Figure 4.7 Throughput vs number of CMs characteristics curve.

Figure 4.6 presents the changes in throughput values with variations in velocity. As velocity increases, the throughput value decreases simultaneously. It is due to the fact that an increase in velocity means a higher chance of topology changes, which increase packet collisions and reduce throughput. Therefore, the cluster area is divided into multiple smaller areas so that when CMs move a noticeable distance affecting throughput, the CW size adjusts to avoid collisions in the event of topology changes. The proposed system demonstrates better results compared to existing methods.

Figure 4.7 expresses the throughput response when the number of CMs changes. The proposed work shows better results than the Shah's model and IEEE 802.11.

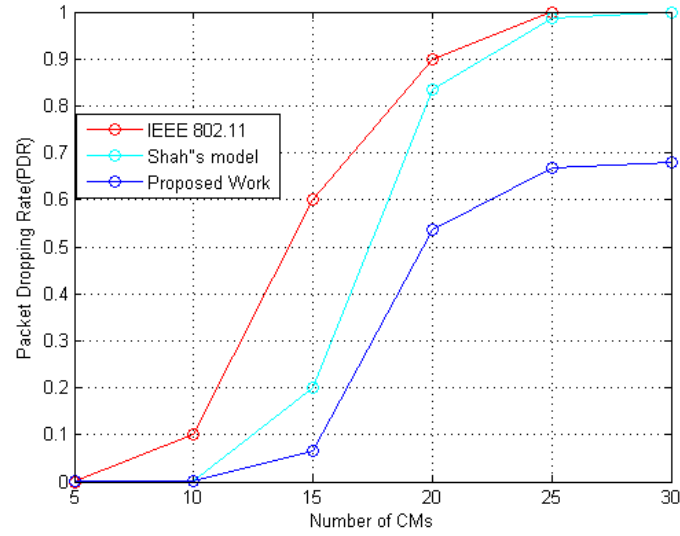


Figure 4.8 Packet dropping rate (PDR) vs number of CMs characteristics curve.

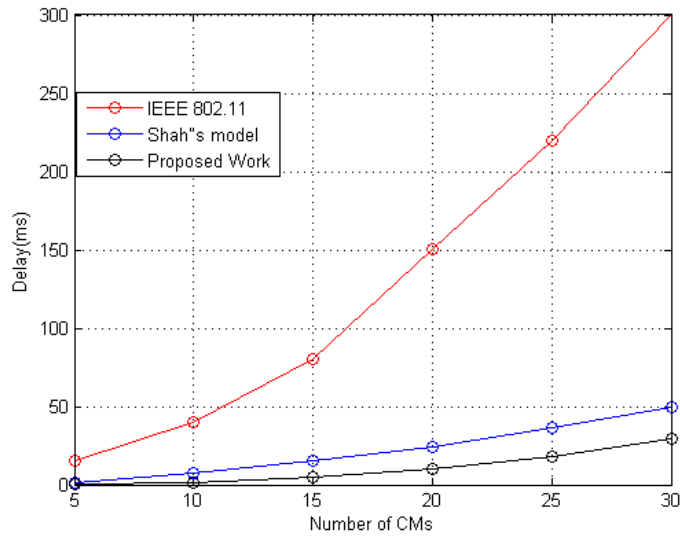


Figure 4.9 Delay performance with the variation of number CMs.

The results can be divided into two phases. First, up to 30 CMs, the throughput value increases with the number of CMs. Because when the number of CMs is low, there is a possibility of fewer packet collisions resulting in increased throughput. In the second phase, as the number of CMs increases more, there are more possibilities of collision and packet loss so throughput reduces with increasing the number of CMs. The previous work exhibits similar characteristics in the results but demonstrates lower throughput and fewer CMs. Throughput increased up to 15 CMs.

Figure 4.8 shows the PDR value concerning the number of CMs. With increasing the number of CMs the PDR values rise. It is the reason of the fact that increasing

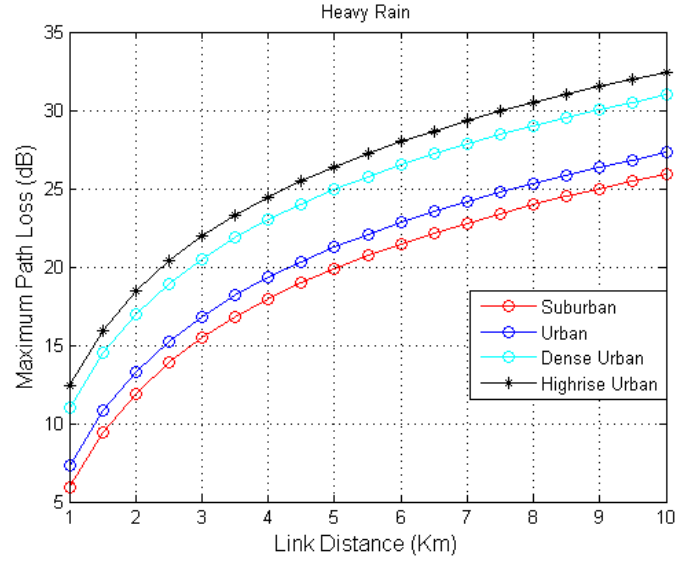


Figure 4.10 BS to MS link distance vs maximum path loss characteristics curve for different cases of rainy environments.

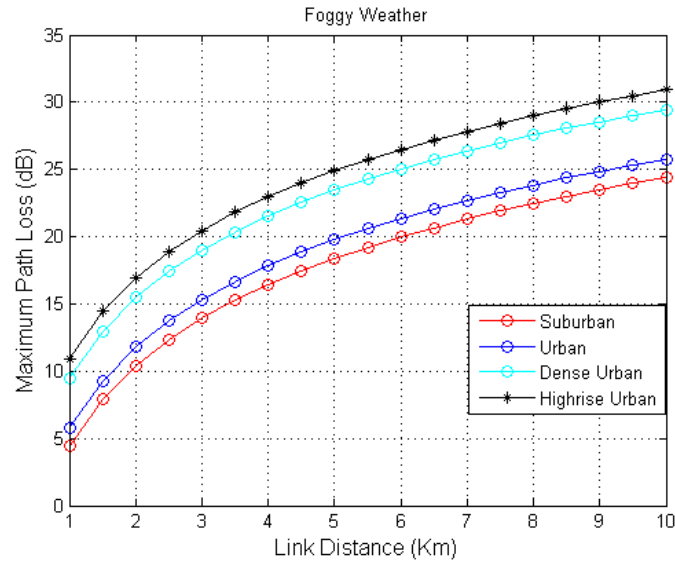


Figure 4.11 BS to MS link distance vs maximum path loss characteristics curve for different cases of foggy environments.

the number of CMs means more packet transmission that results in collision raising the PDR values. The proposed system oppressed the mobility effect collision so the PDR values noticeably reduced with considering Shah's model and IEEE 802.11 standard.

Figure 4.9 represents the delay results considering the number of CMs, the delay(ms) values are rising proportionally. This is because a higher number of CMs increases the likelihood of collisions due to the greater availability of packets. Therefore, when the packets are dropped, retransmitting them results in additional

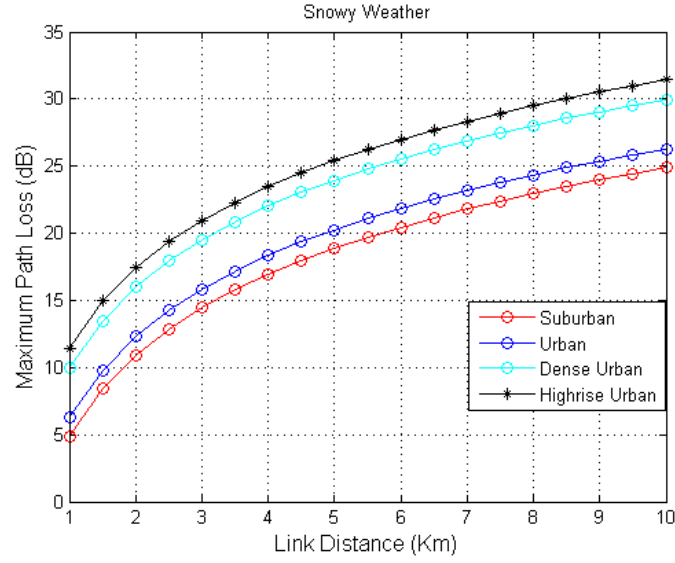


Figure 4.12 BS to MS link distance vs maximum path loss characteristics curve for different cases of snowy environments.

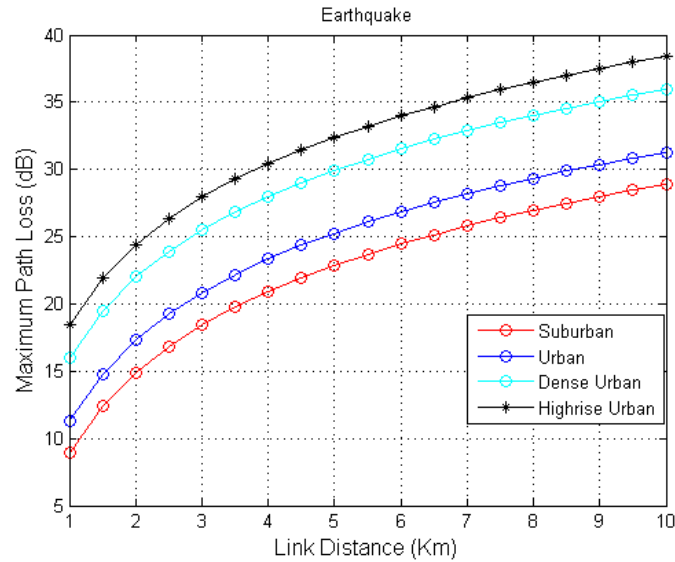


Figure 4.13 BS to MS link distance vs maximum path loss characteristics curve for different cases of after earthquake environments.

delays. The proposed model controls the collision due to mobility which results lower delay than Shah's model and IEEE 802.11 standard.

Figure 4.10, Figure 4.11, Figure 4.12, and Figure 4.13, illustrate the maximum PL responses concerning the link distance. As the link distance between the CM and MS increases, the PL increases proportionally. However, due to different environmental issues in suburban, urban, dense urban and high-rise urban areas, the loss values vary. It is the reason of the fact that the density of buildings differs, affecting the loss values. In suburban areas, the lower building density

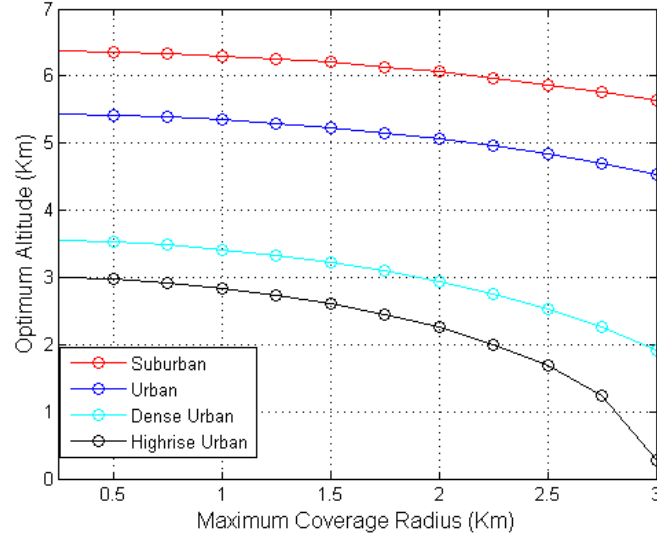


Figure 4.14 Optimum altitude vs maximum coverage radius characteristics curve for different environments.

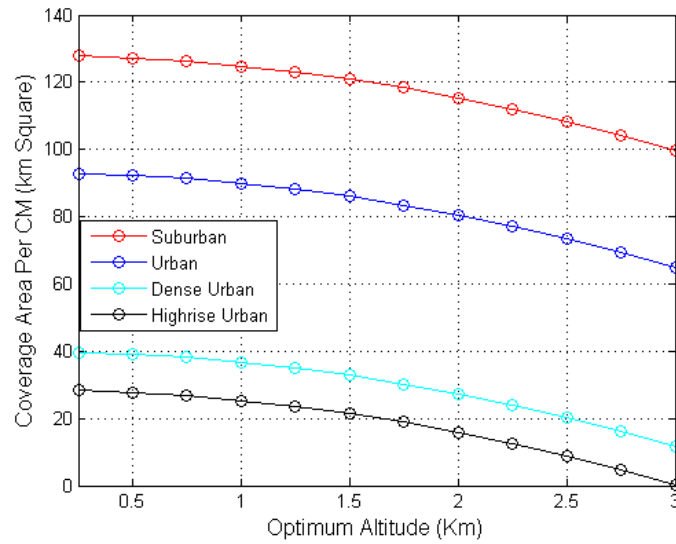


Figure 4.15 Optimum altitude vs coverage area per UAV-BS characteristics curve for different environments.

results in lower loss values compared to other areas. Similarly, for high-rise urban areas, the density of buildings is higher which results in higher PLs. On the other hand, in different disaster environments—such as heavy rain, fog, snowy conditions, and post-earthquake weather—the maximum loss values vary. This is because different weather conditions cause different signal obstructions. When comparing them, earthquake-affected environments exhibit higher PL than others due to obstructions from collapsed buildings. Symbolically, this can be represented as: $PL_{earthquake} > PL_{rain} > PL_{snow} > PL_{fog}$.

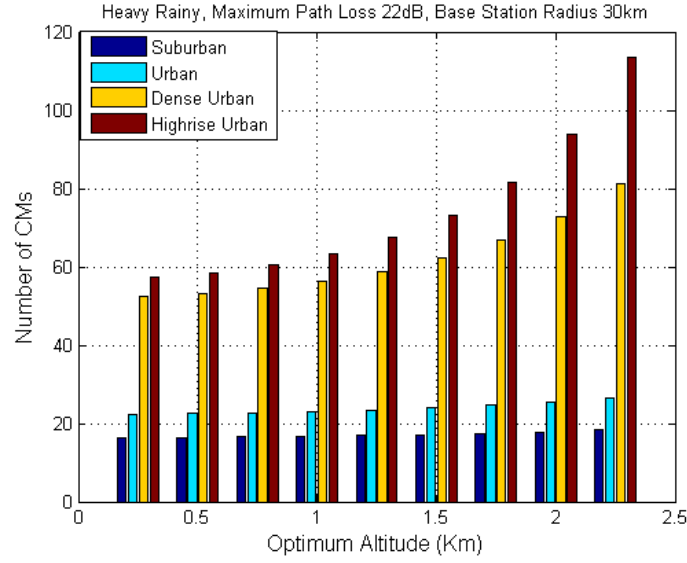


Figure 4.16 Optimum altitude vs number of CMs to cover the Macro cell area of 30 km radius for different cases in heavy rain environment.

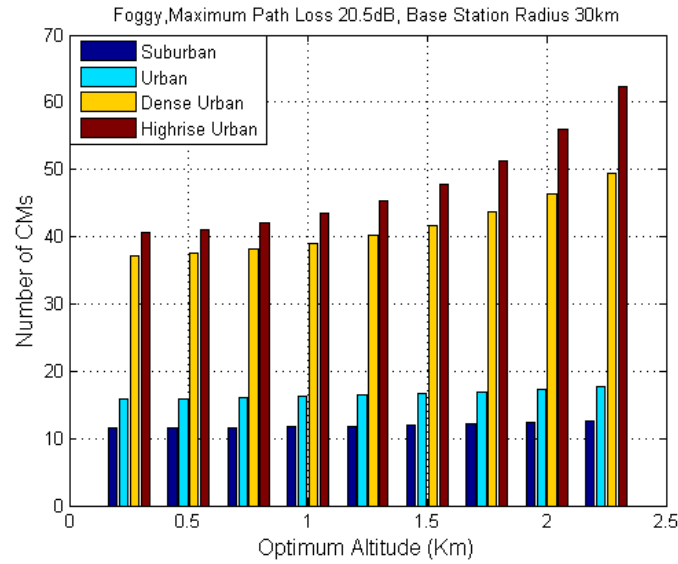


Figure 4.17 Optimum altitude vs number of CMs to cover the Macro cell area of 30 km radius for different cases in foggy environment.

When the CM is in optimum altitude the coverage area radius is maximum. Figure 4.14 shows the optimal altitude required to cover the maximum radius for different environmental scenarios. For all the environmental cases, increasing the maximum coverage radius the optimum altitude is reduced. If the density of buildings is higher, the optimum altitude is reduced. So, the coverage area is shortened. Therefore, in high-rise urban areas, the optimum altitude is lower than in suburban areas.

Figure 4.15 expresses when the CM's optimum altitude changes then the maximum

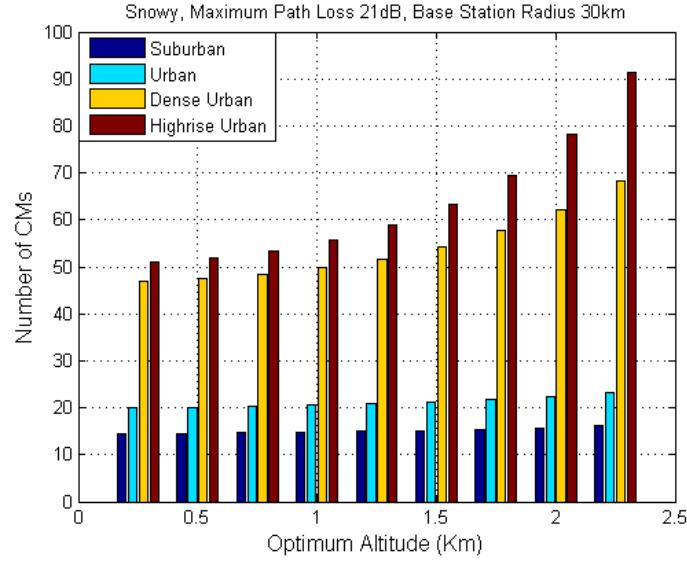


Figure 4.18 Optimum altitude vs number of CMs to cover the Macro cell area of 30 km radius for different cases in snowy environment.

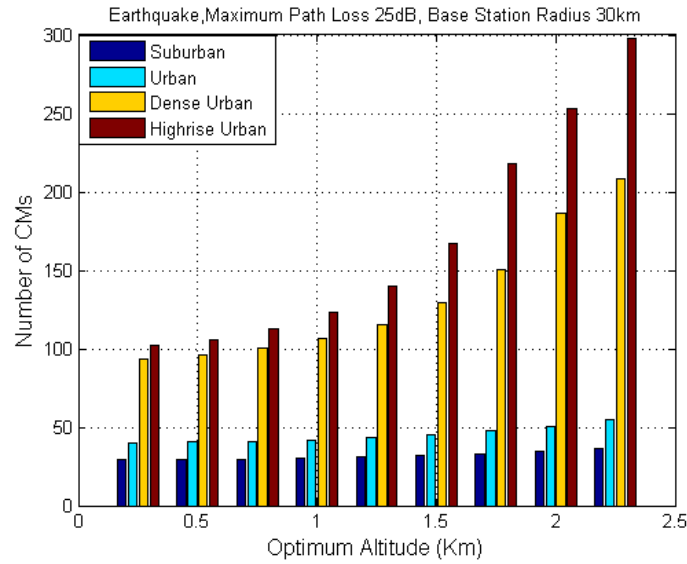


Figure 4.19 Optimum altitude vs number of CMs to cover the Macro cell area of 30 km radius for different cases in after earthquake environment.

coverage area per CM responses for different environmental cases. The optimal altitude increases and the maximum coverage area per CM decreases for all environmental cases. As earlier stated, when the optimal altitude is reduced, the maximum coverage radius is also shortened, resulting in a reduced coverage area per CM. Another factor is that when the density of buildings is lower, CMs can support higher coverage areas. In the case of the suburban area, the coverage area is more than 100km^2 when the optimal altitude is 3km. For the same reason, in the case of high-rise urban areas, the building densities are higher so the possibility of loss is greater therefore the coverage area is very much lower.

Table 4.3 Performance Comparison with Closely Related Work

Ref. No.	Max. Throughput(Mbps)	Max. Delay(ms)	PDR Max.
[8]	26	70	0.88
[9]	4	N/A	N/A
[38]	14	N/A	N/A
[14]	0.9(Normalized)	N/A	N/A
[78]	6.5	100	N/A
This work	33	30	0.69

Figure 4.16, Figure 4.17, Figure 4.18 and Figure 4.19 represent the number of CMs required to cover a 30km macro cell BS radius for different optimum altitudes of CMs in the case of different environmental cases and disaster situations. From the bar charts in the figures, it is observed that the required number of CMs to cover the macro cell area varies across different environmental cases. It is the reason of the fact that when the density of buildings is higher there are more possibilities of losses. Therefore, in the case of high-rise urban areas, covering the BS area requires the highest number of CMs. On the other side, for suburban areas, there are required very few numbers of CMs to cover the BS area. On the other hand, in different disaster situations, the maximum PL for maintaining a flexible connection varies. The PL values are 22 dB, 20.5 dB, 21 dB, and 25 dB, respectively. Due to varying environmental conditions during disasters, the level of obstruction changes, causing fluctuations in PL. When PL increases, the number of CMs required to cover a 30 km BS area also increases. For instance, during an earthquake, collapsed buildings create greater obstructions, resulting in higher PL compared to other scenarios. Consequently, the number of CMs needed to cover the 30 km BS area is greater during an earthquake than in other situations. Symbolically, this relationship can be represented as: $CM_{searthquake} > CM_{srain} > CM_{snow} > CM_{sfog}$

From the performance comparison Table 4.3 it is observed that the proposed work has performed noticeably better performance than the existing closely related works.

4.7 Conclusion

In this chapter, a cluster-based model is proposed for UAV-BS as an alternative to terrestrial BS. The core network is supported by FANETs, assisted by a MAC protocol. The MAC protocol is adapted to handle mobility, and transmission is managed using a 3D Markov chain CSMA/CA adaptive backoff process. Here is introduced an algorithm for movable CMs by adjusting the MAC protocol for transmission, which significantly improved system performance. In terms of

throughput, the model shows increasing results in 5 times for Nakagami- $m=1$ fading and 6 times for Nakagami- $m=2$ than the Shah's model. The comparison with existing studies is given in terms of maximum throughput, delay, and PDR, which shows the improvement done by the proposed mechanism. Regarding the number of CMs and throughput, the work shows increased values up to 30 CMs, whereas previous work only achieved this up to 15 CMs. In terms of PDR and delay, the work demonstrates lower PDR values and a delay of approximately 30ms for 30 CMs. To determine the optimal altitude, the maximum LoS PL is selected for achieving maximum coverage with the minimum number of CMs across various environmental scenarios, including suburban, urban, dense urban, and high-rise urban areas. An algorithm is developed for maximizing coverage with the minimum number of CMs to cover the macro cell BS area. By maintaining optimal altitudes up to 1.75, fewer than 100 CMs can cover a 30km radius BS area in high-rise urban areas.

MAD-MAC: Mobility Adaptive Dynamic MAC Protocol for FANETs

5.1 Introduction

Day by day the applications of UAVs known as drones are increasing proportionally [6]. Because UAV-based platform offers remotely flexible control and mobility [4]. To meet the growing demand of the next generation, devices are being connected to the Internet, which is known as the IoT [53]. UAVs support 5G networks by extending network coverage, enhancing capacity, and more. In 6G networks, UAVs enable technologies such as THz communication, ultra-massive MIMO, 3D wireless networks, and AI-driven network management, among others [53]. The existing terrestrial platforms are insufficient to support the increasing demand for services [79]. UAVs play a significant role by creating a network of terrestrial support using FANETs, which enable communication between UAVs without relying on fixed infrastructure. This is particularly useful in high-data-rate capacity areas and remote regions where terrestrial platforms are inaccessible [8]. Moreover, during a disaster, when TBSs are non-functional, UAV-based FANETs would be the ideal platform to support the TNs [3]. However, since UAVs are moving devices, frequent changes in network topology present a significant challenge [8]. Furthermore, if the packet transmission access points are not controlled efficiently, packet collisions occur, which reduces the performance of the network system [8]. Therefore, in this chapter, a FANET is proposed where the topology is managed using 3D mobility, and packet transmission is controlled through a 4D Markov chain-based backoff process. Additionally, cluster-based MIMO-OFDM is introduced for simultaneous packet transmissions using multiple subcarriers. In OFDM, synchronization is a major challenge; therefore, a fast backoff technique is established where the backoff time decreases with the number of subchannels [91]. By using MIMO antennas, it is possible to achieve simultaneous packet transmissions on multiple subchannels with appropriate synchronization. This means that, at the access point, multiple packets can successfully transmit

simultaneously [51].

The simultaneous packet transmission process in cluster-based FANETs is illustrated in Figure 5.1.

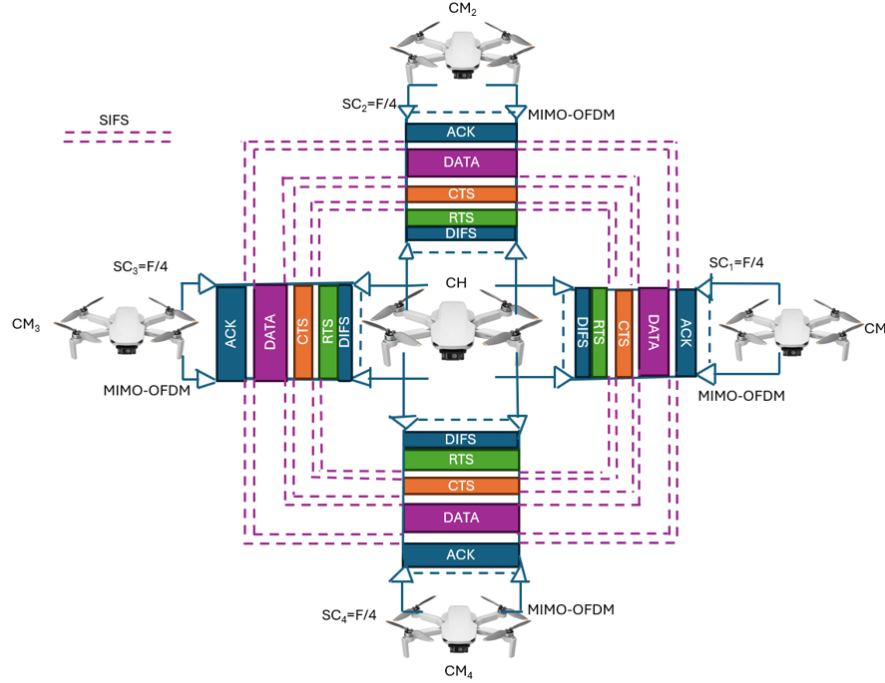


Figure 5.1 Cluster-based MIMO-OFDM simultaneous packet transmission by using multiple sub-carriers.

In this network, each cluster has one CH responsible for managing the cluster. For this reason, the CH communicates with other CMs in the same cluster through the transmission of SMs [8]. By dividing the carrier frequency into multiple subcarriers, the CH can send packets simultaneously using the request to send (RTS) and clear to send (CTS) data transmission processes [91]. During a disaster, when the BS is damaged, the proposed FANETs can support BS networks in emergency situations [3], [8]. The supporting coverage by cluster-based FANETs is illustrated in Figure 5.2, where the CMs in the FANET cover the damaged BS area, enabling mobile users to connect to the network.

The chapter is structured as follows: Section 5.2 covers MAD-MAC protocol, Section 5.3 describes physical layer analysis, Section 5.4 discusses simulation results and performance analysis, and Section 5.5 concludes the chapter.

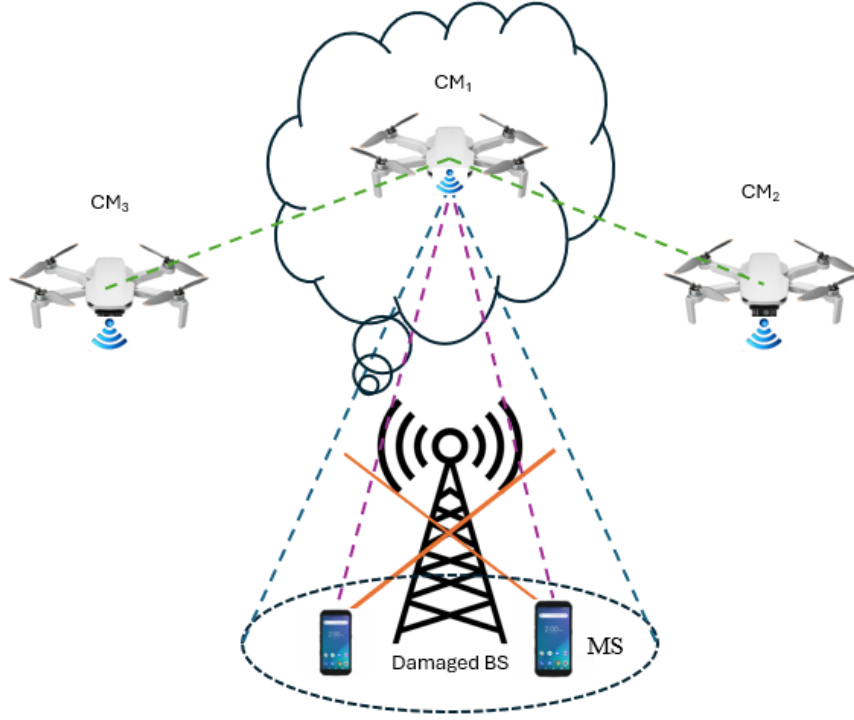


Figure 5.2 Damaged base station (BS) cellular emergency network coverage by using UAVs.

5.2 Proposed MAD-MAC Protocol

In this section, the detailed system model of the mobility adaptive dynamic (MAD-MAC) cluster-based protocol for FANETs has been presented. It is divided into three subsections: the MIMO-OFDM cluster-based fast backoff process, the 4D Markov chain model with mobility, and the simultaneous packet transmission algorithm with mobility.

5.2.1 MIMO-OFDM Cluster Based Fast Backoff Process

The simultaneous packet transmissions through the MIMO-OFDM based technique by dividing multiple sub-channels (n) is represented in Figure 5.3. The number of sub-channels is equal to the number of CMs in the cluster. Then after waiting for the DIFS time, the CH or CMs wait for the contention period. The CW time is reduced with $C_w - S_c$ instead of 1. When the contention time comes to zero the CH or CMs are sent RTS(n). Next time after waiting for SIFS time the CTS(n) is received. If the number of CTS is less than n then the remaining packets ($n - CTS(n)$) need to be sent again. Afterwards, 2nd time waiting SIFS the CH or CMs transmit the Data(n). Finally, at the last time waiting for SIFS time the ACK(n) is received through CH/CMs and the packet transmissions are completed. Suppose there are

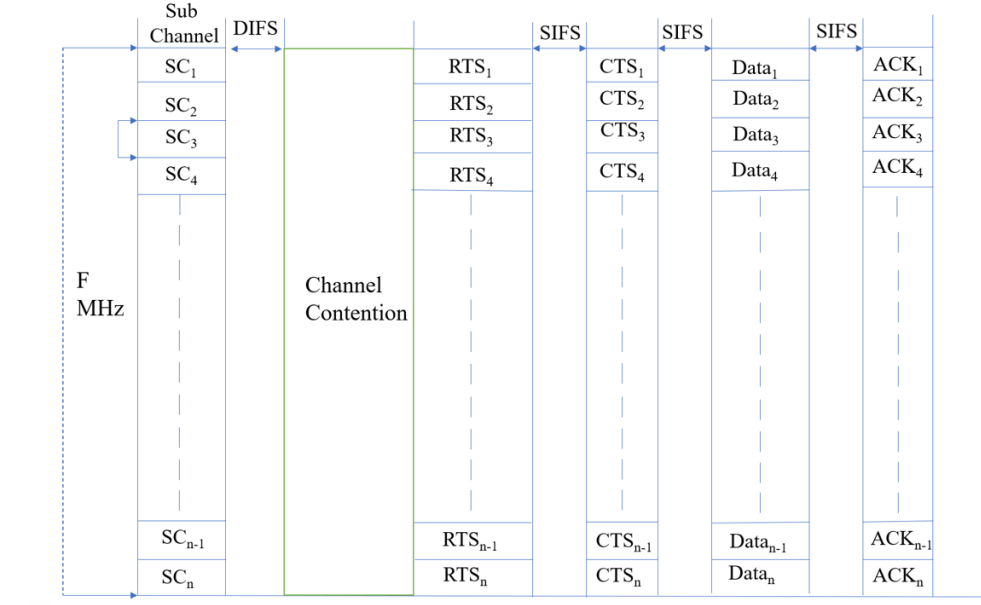


Figure 5.3 Simultaneous packets transmissions process by using multiple sub-channels.

N_{CM} number of CMs in total in the network and N_c number of clusters. Let the frequency F_{AL} be divided into S_c number of subchannels. So, the probability that the CMs in a cluster will send packets in a specific slot Γ can be calculated as:

$$\Gamma = \frac{S_c}{N_{CM}}. \quad (5.1)$$

The probability of channel idle, Φ can be illustrated by:

$$\Phi = (1 - \Gamma)^{M-S_c}. \quad (5.2)$$

ω is the probability that at least the S_c number of CMs are transmitted packets by S_c sub-channels at any slot. Therefore, $M - S_c$ CMs contending for the channel. Thus, ω can be given by [8]:

$$\omega = 1 - \Phi = 1 - (1 - \Gamma)^{M-S_c}. \quad (5.3)$$

ξ is the probability that the packet sent in the sub-channel and collided. When one of the remaining $M - S_c - 1$ CMs transmits a packet within the same time slot, a collision will occur. ξ can be given as [8]:

$$\xi = 1 - (1 - \Gamma)^{M-S_c-1}. \quad (5.4)$$

ρ is the probability that the existing packet delivery on the channel will be successful and it can be calculated as [8]:

$$\rho = \frac{(M - S_c)\Gamma(1 - \Gamma)^{M-S_c-1}}{1 - (1 - \Gamma)^{M-S_c}}. \quad (5.5)$$

The successful packet transmission time, channel idle and collision time can be represented by [59]:

$$T_{S(CMs-CH)} = T_{DIFS} + T_{RTS} + 3T_{SIFS} + T_{CTS} + \frac{S_c \times L_p + L_{hd}}{R_t} + T_{ACK} + T_{dl}, \quad (5.6)$$

$$T_{idle} = T_{SL}, \quad (5.7)$$

$$T_{col} = T_{DIFS} + T_{RTS} + T_{dl}. \quad (5.8)$$

Where, T_{DIFS} , T_{RTS} , T_{SIFS} , T_{CTS} , T_{ACK} , T_{dl} , and T_{SL} represent the DIFS, RTS, SIFS, CTS, ACK, delay and slot time period respectively. L_p symbolizes the packet size, L_h expresses the length of the MAC and PHY headers and finally R_t is the data transmission rate. According to our assumption, there are S_C number of sub-carriers therefore the counter K is started from $(0, C_{wi} - S_c)$. During the period of channel idle the counter is reduced by S_C and when it comes to 0 or less than zero the CMs attempt to transmit the packets. It is assumed that all the CMs reserved 1 packet to transmit, and the probability denoted by q . The backoff stage is denoted by $S_A(t)$. If $S_A(t) > 0$ that means collision occurs so needs to send again and the maximum backoff stage is denoted by $S_A(t) = S_m$. Let ψ be the transmission probability in the stationary distribution. The reduction of the stationary distribution is calculated by the probability distribution B . For the state of $(S_A(t), K)$ and $(0, K)_e$ the stationary probability is $B(S_A(t), K)$ and $B(0, K)_e$. Therefore, we can write [51]:

$$1 = \sum_{S_A(t)=0}^{S_m} \sum_{K=0}^{C_{wi}-S_c} B(S_A(t), K) + \sum_{K=0}^{C_w-S_c} b(0, K)_e. \quad (5.9)$$

The transmission probability would be calculated based on $B(0,0)$. We can calculate the $B(0,0)e$ as [51]:

$$\begin{aligned} \frac{1}{B(0,0)_e} &= 1 - q + \frac{q^2 C_{wi}(C_{wi} + 1)}{2(1 - (1 - q)^{C_{wi}})} + \frac{q(1 + C_{wi})}{2(1 - q)} \times \\ &\left(\frac{q^2 C_{wi}}{1 - (1 - q)^{C_{wi}}} + p(1 - q) - q(1 - p)^2 \right) + \frac{pq^2}{2(1 - p)(1 - q)} \\ &\left(\frac{C_{wi}}{1 - (1 - q)^{C_{wi}}} - (1 - p)^2 \right) \times (2C_{wi} \frac{1 - p - p(2p)^{S_m-1}}{1 - 2p} \\ &+ 1). \end{aligned} \quad (5.10)$$

Therefore, the transmission probability ψ can be calculated in terms of $B(0,0)e$ as [51]:

$$\psi = B(0,0)_e \frac{q^2}{(1 - q)} \times \left(\frac{C_{wi}}{(1 - p)(1 - (1 - q)^{C_{wi}})} - (1 - q)^{M-S_c} \right). \quad (5.11)$$

Therefore, the PAR q can be calculated by [51]:

$$q = 1 - e^{-\lambda_p T_{TP}}. \quad (5.12)$$

Now, the successful packet round probability R_p can be calculated by [51]:

$$\begin{aligned} R_p &= A_N \left(\frac{M\psi(1 - \psi)^{M-S_c}}{1 - (1 - \psi)^M} \times \frac{(M - S_c)\psi(1 - \psi)^{M-S_c-1}}{1 - (1 - \psi)^{M-S_c}} \times \right. \\ &\left. \dots \times \frac{(M - (K - 1))\psi(1 - \psi)^{M-K}}{1 - (1 - \psi)^{M-(K-1)}} \right). \end{aligned} \quad (5.13)$$

5.2.2 4D Markov Chain Model with Mobility

The 4D Markov chain-based fast backoff process is given in Figure 5.4. In the 4D Markov chain-based method the packet transmission is considered four parameters those are PAR, packet contention backoff time, packet retransmission stage and mobility of the CM. The cluster area dividing into smaller areas and adjusted CW with mobility in each Markov state is described elaborately in Chapter 4.

The transition probability when the CM moves from area A_{S_1} to A_{S_2} in the slot backoff time in 4D Markov chain can be illustrated as [7]:

$$\begin{aligned} P_{SLOT}(A_{S_2}, S_A, B_A | A_{S_2}, S_A, B_A + 1) &= \left(\frac{E[T_{MSL}]}{t_{A2}} \right), \\ A_S &\in [1, n], S_A \in [0, S_m], B_A \in [0, W_A - S_c]. \end{aligned} \quad (5.14)$$

The transition probability when the CM transmits successfully with a successful

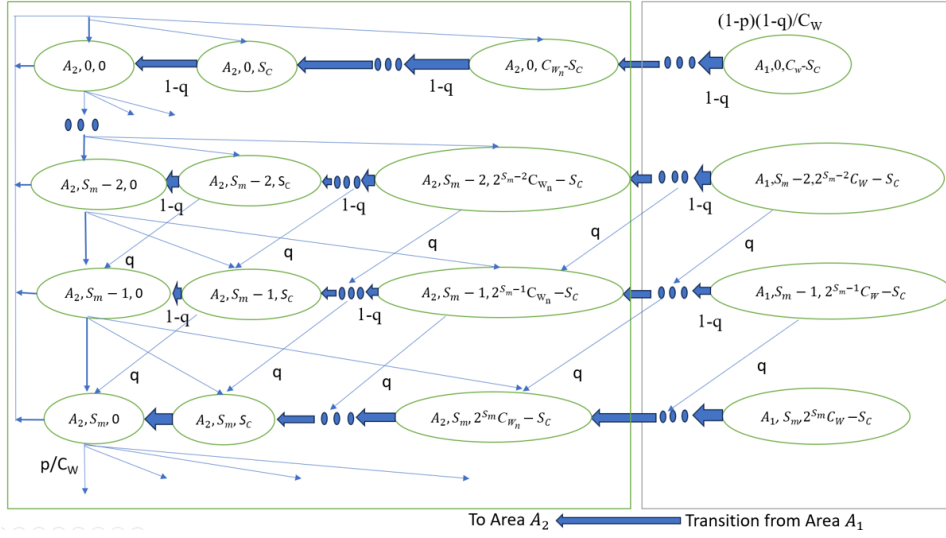


Figure 5.4 4D Markov chain-based fast backoff process.

round can be calculated by [7], [80]:

$$P_{Succ}(A_{S_2}, 0, B_A | A_{S_2}, S_A, 0) = \left(\frac{R_p E[T_S]}{W_A t_{A2}} \right), \quad (5.15)$$

$$A_S \in [2, n], S_A \in [0, S_m], B_A \in [0, W_A - S_c].$$

Now, when the CM falls on collision of the maximum number of retransmissions, then the transition probability comes into as [7]:

$$P_{coll}(A_{S_2}, S_m, B_A | A_{S_1}, S_m, 0) = \left(\frac{\xi T_{col}}{2^{S_m} W_A t_{A2}} \right), \quad (5.16)$$

$$A_S \in [2, n], S_A \in [0, S_m], B_A \in [0, W_A - S_c].$$

The norm distribution of the slot time can be found by [7]:

$$E[T_{MSL}] = T_{SL} + \rho T_S + \xi T_{col}. \quad (5.17)$$

The total passage time T_{TP} in the 4D Markov chain can be calculated by [7], [61]:

$$T_{TP} = \Phi T_{SL} P_{SLOT} + \omega \rho P_{Succ} T_S + \omega (1 - \rho) T_{col} P_{coll}. \quad (5.18)$$

Therefore, the throughput T_{hd} can be calculated as total data transmission per time, which can be found by [8]:

$$T_{hd} = \frac{(1 - P_e) \omega p L_p S_c}{T_{TP}}. \quad (5.19)$$

When the packet is sent but ACKs are unable to receive that means the PDR Δ_{PDR}

can be calculated by [8]:

$$\Delta_{PDR} = [(1 - p)P_{coll}]^{S_m}. \quad (5.20)$$

Finally, the packet transmission delay ϵ_d can be illustrated by [8]:

$$\epsilon_d = T_{TP} \left(N - \frac{F}{1 - F} \times \frac{2}{1 + C_w + \frac{S_m C_w}{2}} \right). \quad (5.21)$$

Where F is the packet-dropping probability.

Algorithm 6 Simultaneous Packet Transmission with Mobility.

1. Select the frequency F_{AL}
 2. Divide frequency F_{AL} into multiple sub-channels
 3. **If** sense $CN = CN_{idle}$
 4. Set $\vec{d}_A = d_{NC}$
 5. **If** $\vec{d}_A = d_{NC}$
 6. $A_S = 1, 2, 3, \dots, n$
 7. $C_{wi} = \text{Renew } C_{wi}$
 8. **If** in slot period $P(trs) = P_{SLOT}$, $A_S \in [1, n]$, $S_A \in [0, S_m]$, $B_A \in [0, C_{wi} - S_c]$
 9. **End**
 10. **If** in successful transmission period $P(trs) = P_{succ}$, $A \in [2, n]$, $S_A \in [0, S_m]$, $B_A \in [0, C_{wi} - S_c]$
 11. **End**
 12. **If** in collision period $P(trs) = P_{coll}$, $A_S \in [2, n]$, $S_A \in [0, S_m]$, $B_A \in [0, C_{wi} - S_c]$
 13. **End**
 14. **Else** $C_{wi} = C_{wi}$
 15. **End**
 16. $T_{W1} = T_{DIFS}$, sense $CN = CN_{idle}$, $T_{W2} = T_B[0, C_{wi} - S_c]$
 17. **If** $T_B = 0$ send RTS(n), $T_{W3} = T_{SIFS}$
 18. **If** received CTS(n), $T_{W4} = T_{SIFS}$, send Data(n)
 19. **Else** return step 16
 20. **If** $T_{W5} = T_{SIFS}$, received ACK(n), Data(n) succesful transmission
 21. **Else** return step 14
 22. **End**
 23. **End**
 24. **End**
 25. **End**
-

5.2.3 Simultaneous Packet Transmission Algorithm with Mobility

The MIMO-OFDM packet transmissions algorithm is presented in algorithm 6 with the flowchart in Figure 5.5. First of all, need to select the packet transmission

channel frequency range F_{AL} . Then based on the number of CMs in the cluster divide the frequency into multiple sub-channels. CN and CN_{idle} symbolize the channels and idle channels respectively. $P(trs)$ expresses the transition probability in different case slots, successful and collision periods. $T_W(1, 2, \dots, 5)$ and T_B represent the waiting times required for packet transmission and backoff time respectively. $(\vec{d}_A)$ is the vector distance and d_{NC} represents the distance where the throughput changes noticeably.

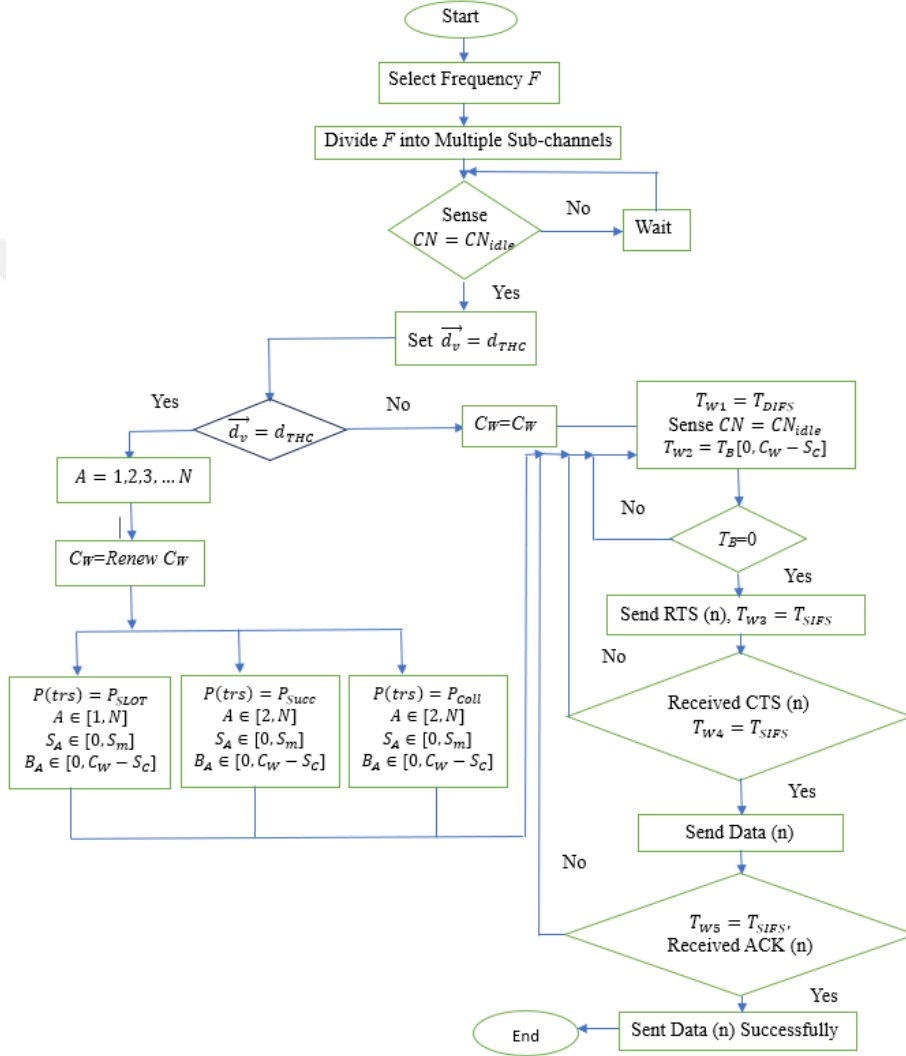


Figure 5.5 Multiple sub-channels simultaneous packet transmission flow chart.

5.3 Physical Layer Analysis

In the case of MIMO-OFDMA, it is difficult to receive signals accurately from the multiple transmitted signals from the multiple sub-carriers. To overcome this problem, the time orthogonal cyclic prefix is used which is the length of $2N_p$ and a number of subcarrier S_c . Therefore, according to IEEE 802.11 standards the length

of training sequence $N_t = 2(N_p + S_c)$ for every transmitter antenna. 8×8 time orthogonal preamble for MIMO configuration is given in Figure 5.6.

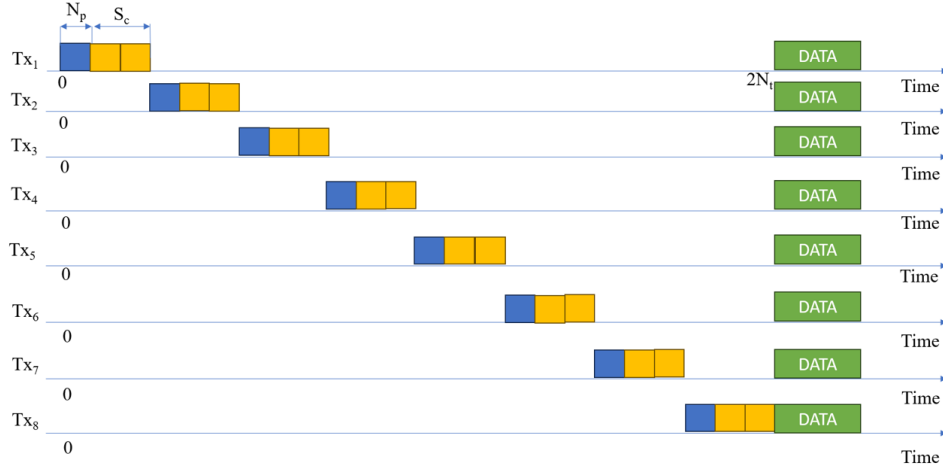


Figure 5.6 8x8 time orthogonal preamble for MIMO configuration.

Let s be symbolized as the transmitter antenna ($s = 1, 2, 3, \dots, A_{NT}$) where A_{NT} is the number of transmitter antennas. On the other side, r_A is symbolized as the receiver antenna ($r = 1, 2, 3, \dots, A_{NR}$) where A_{NR} is the number of receiver antennas. $i_n = [i_1, i_2, i_3, \dots, i_{A_{NT}}]^T$ are expressed the transmitted signal vectors with $N_n = [N_1, N_2, \dots, N_{A_{NR}}]^T$ noises. Therefore, the received signal vector can be expressed as $o = [o_1, o_2, \dots, o_{A_{NR}}]^T$. The received signals equations can be illustrated as [38], [92]:

$$o = M_H i + N_n = \sum_{r=1}^{A_{NR}} K_{s,r} i^r + N_n^s. \quad (5.22)$$

$$M_H = \begin{bmatrix} k_{1,1} & \cdots & k_{1,A_{NT}} \\ \vdots & \ddots & \vdots \\ k_{A_{NR},1} & \cdots & k_{A_{NR},A_{NT}} \end{bmatrix} \quad (5.23)$$

We have considered every transmitted and received signal as a FIR. Therefore, the coefficient can be represented as $k_{s,r}(g)$ where $g = 0, \dots, M_{p-1}$, M_p is the number of multipath. So, the DFT of x_{th} frequency subcarrier can be illustrated as [38], [93]:

$$K_{s,r}(x) = \frac{1}{\sqrt{S_c}} \sum_g^{S_c-1} k_{s,r}(g) e^{-j2\pi g/S_c}, \quad 0 \leq x \leq S_c - 1. \quad (5.24)$$

There is no relation between one antenna to another, total SNR can be calculated by [18], [34], [93]:

$$u_x = \frac{1}{A_{NT}} \sum_{s=0}^{A_{NT}} \sum_{r=0}^{A_{NR}} \frac{A_s}{\delta} |K_{s,r}(x)|^2. \quad (5.25)$$

When there is no relation between the receiver antenna, the moment generating function can be calculated by [38]:

$$\begin{aligned}\omega_{u_x}(z) &= \mathbb{E}[e^{zu_x}] = \int_0^\infty e^{zu_x} f_{u_x}(u_x) du_x \\ &= \sum_{r=1}^{A_{NT}} \sum_{s=1}^{A_{NR}} \left(1 - \frac{A_s \mu_f}{\delta A_{NT} A_{NR} \sin^2 \theta} \right)^{-A_{NR}}.\end{aligned}\quad (5.26)$$

Here, $f_{u_x}(u_x)$ is expressed as the PDF of u_x . In the case of binary phase shift keying (BPSK), BER can be calculated by [51], [94]:

$$P_{\text{BER}}(u_x) = Q(\sqrt{2u_x}). \quad (5.27)$$

Q expresses the Gaussian function, and it can be found by [93]:

$$Q(y) = \frac{1}{\pi} \int_0^{\pi/2} e^{-\frac{y^2}{2 \sin^2 \theta}} d\theta. \quad (5.28)$$

In the instance of M-PSK the BER can be calculated by [51]:

$$P_{\text{BER}}(u_x) = \frac{a_c Q(\sqrt{2b_c u_x})}{\log_2^{M_{th}}}. \quad (5.29)$$

Here, $a_c = 2$ and $b_c = \sin^2 \pi/2$ generally. Finally, regarding M-QAM the BER can be illustrated as [51], [94]:

$$P_{\text{BER}}(u_x) = \frac{4a_c}{\log_2^{M_{th}}} \sum_{e=0}^{\sqrt{M_{th}}/2} (2e-1) \sqrt{2b_c u_x \log_2^{M_{th}}} \quad (5.30)$$

Here, $a_c = 1 - \frac{1}{\sqrt{M_{th}}}$ and $b_c = \frac{3}{2(M_{th}-1)}$ for the calculation of BER. Mean BER for x_{th} frequency sub-carrier can be calculated by [51]:

$$\begin{aligned}P_{\text{BER},x} &= \int_0^\infty P_{\text{BER}}(u_x) f_{u_x}(u_x) du_x \\ &= \frac{1}{\pi} \int_0^\infty \int_0^{\pi/2} e^{-\frac{u_x^2}{2 \sin^2 \theta}} f_{u_x}(u_x) du_x d\theta \\ &= \frac{1}{\pi} \int_0^{\pi/2} \omega \left(z = -\frac{1}{\sin^2 \theta} \right) d\theta \\ &= \frac{1}{\pi A_{NT}} \int_0^{\pi/2} \left(1 + \frac{u_x}{A_{NT} A_{NR} \sin^2 \theta} \right)^{-A_{NT} A_{NR}} d\theta.\end{aligned}\quad (5.31)$$

To sum up, the overall BER can be found by [51], [77]:

$$P_{\text{BER, overall}} = 1 - (1 - P_{\text{BER},x})^{S_c}. \quad (5.32)$$

Table 5.1 Constant Values for Simulations

Parameters	Value
Maximum number of sub-channels, S_c	20
Maximum number of antennas, A_N	20
$T_{SL}, T_{DIFS}, T_{SIFS}, T_{dl}, T_{RTS}, T_{CTS}$ (μs)	20, 50, 15, 1, 112, 92
L_p, L_h, T_{ACK} (bytes)	512, 50, 14
$R_t, V, f, u_{th}(SNR)$	11, 1-35m/s, 5GHz, 5(dB)
$G_r, G_t, C_{wi}, S_m, l, \sigma_n$	1, 1, 64, 7, 3, -50
$P(rt), N_{CM}, N_c, \vec{d}_A$	10, 110, 11, 20-30m

5.4 Simulation Results and Performance Analysis

This section discusses the simulation results and performance analysis of the proposed network system based on Algorithm 6. The main focus of the performance analysis is the number of sub-channels and throughput responses between the CH and CMs, the number of CMs, the CW size, and the PAR. Additionally, the performance was also analyzed based on delay, PDR, and BER for different channel models and modulation techniques. All simulations were performed in the MATLAB software environment. The simulation parameters are provided in Table 5.1.

The throughput variation with distance changes is represented in Figure 5.7. When the distance between the CH and CMs is shorter, the throughput is very high. As the distance increases, the throughput decreases because greater distances require more time for data transmission and lead to higher data loss. Additionally, since the system operates in the high-frequency GHz range, the throughput declines with increasing distance. In other cases, increasing the number of sub-channels divides the frequency F_{AL} into multiple sub-channels, creating multiple paths. This enables simultaneous data transmissions, thereby increasing throughput as the number of sub-channels rises.

The throughput fluctuations with changes in the number of CMs are presented in Figure 5.8. As the number of CMs increases, the throughput decreases because a greater number of CMs leads to more packet transmissions, resulting in more collisions and therefore reduced throughput. In another case, when the number of sub-channels increases, more data paths are created, which reduces collisions and therefore enhances throughput.

The throughput variations with respect to the number of sub-channels under different channel fading conditions are illustrated in Figure 5.9. As the number

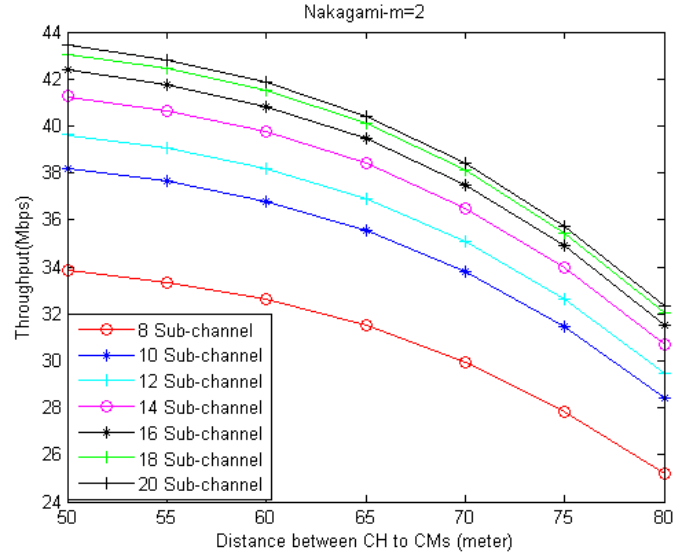


Figure 5.7 Throughput variation with distance between CH to CMs under Nakagami-m=2 fading condition.

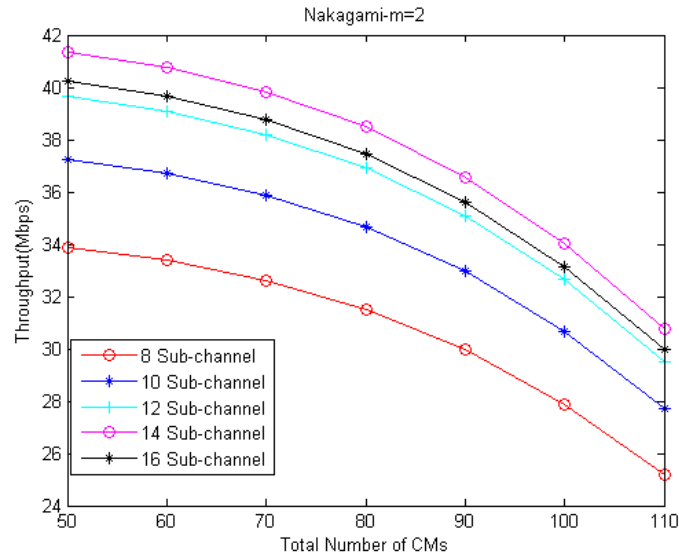


Figure 5.8 Throughput variation with number of CMs under Nakagami-m=2 condition.

of sub-channels increases, the throughput also increases across all channels, fading conditions. As described earlier, an increase in the number of sub-channels creates more multiple paths, resulting in higher throughput. However, until the number of sub-channels reaches 20, the throughput increases; beyond this point, it decreases. Dividing frequency F_{AL} into too many sub-channels leads to interference, causing packet collisions at the receiver side. Moreover, the Nakagami-m=4 channel fading shows better performance compared to $m = 2$ and Rayleigh fading ($m = 1$). When the shape parameter m increases, it reduces the BER and frame transmission errors, leading to higher throughput and lower OP.

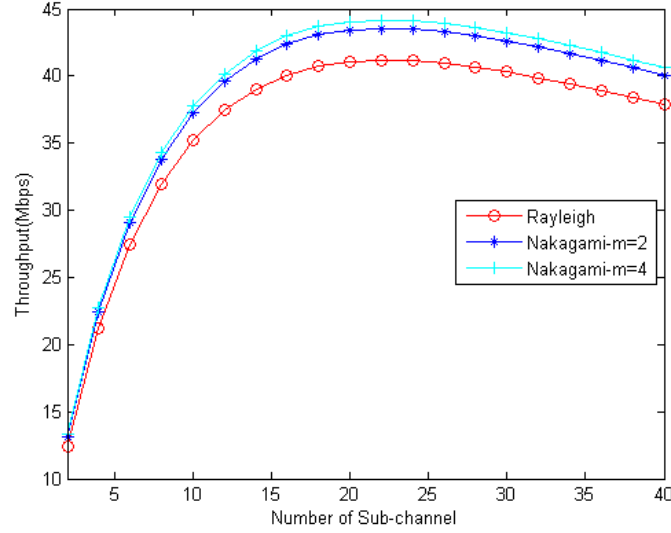


Figure 5.9 Throughput variations with number of sub-channels for different channels fading conditions.

Figure 5.10 shows the throughput variations with the CW size. As the CW size increases, the throughput decreases because a larger CW means a longer waiting time for packet transmission, resulting in lower throughput. In contrast, increasing the number of sub-channels increases the number of multi-paths for simultaneous packet transmission, enhancing throughput for the same CW size. The network system achieves optimal results with a CW size of 64 and 20 sub-channels, showing favorable throughput.

Figure 5.11 shows the throughput responses as a function of the PAR. From the figure, it is observed that varying the PAR does not affect the throughput value, which remains constant. This is because the 4D Markov chain takes the PAR into account, ensuring that throughput values stay stable. In contrast, increasing the number of sub-channels leads to higher throughput. This occurs because adding sub-channels creates multiple paths for the simultaneous transmission of packets, thereby increasing throughput. Figure 5.12 represents the delay characteristics curve as a function of the number of CMs. As the number of CMs increases, the delay rises proportionally. This is because increasing the number of CMs raises the packet transmission probability, leading to more collisions and higher delays. In other cases, when the frequency F_{AL} is divided into multiple sub-channels, multiple paths are created, allowing packets to be transmitted simultaneously, which reduces delay. For instance, with 20 sub-channels and 100 CMs, the network system exhibits a delay of only 15ms. PDR is a critical parameter in network performance analysis. Figure 5.13 shows that as the number of CMs increases, the PDR value also increases proportionally. This is due to a higher number of CMs leading to a

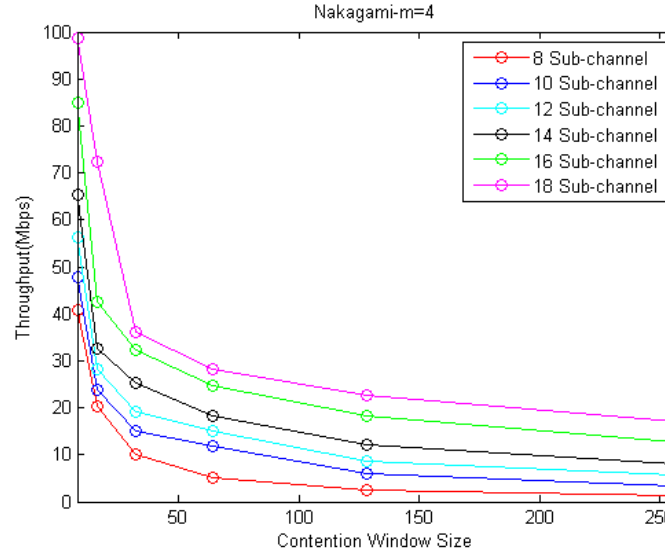


Figure 5.10 Throughput variations with contention window size for different number of sub-channels.

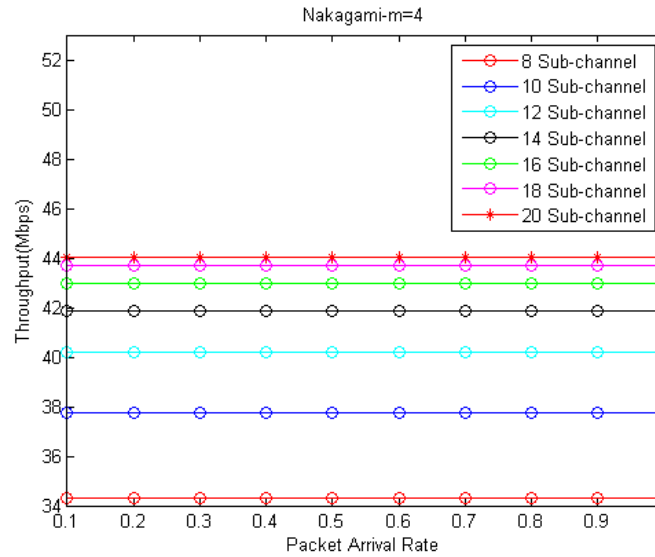


Figure 5.11 Throughput response with packet arrival rate for different number of sub-channels.

greater probability of packet collisions, resulting in more packet drops. Conversely, increasing the number of sub-channels reduces PDR values. This is owing to additional sub-channels creating more favorable multi-paths, which decreases PDR values. For instance, in network systems with 20 sub-channels and 100 CMs, the PDR is nearly zero. Figure 5.14 illustrates the BER vs. SNR characteristics curve for various modulation techniques. From the figure, it is observed that increasing the SNR reduces the BER. This occurs because a higher SNR improves the signal reception capability at the receiver, thus reducing the BER. Additionally, changing the modulation techniques causes fluctuations in BER values. BPSK modulation

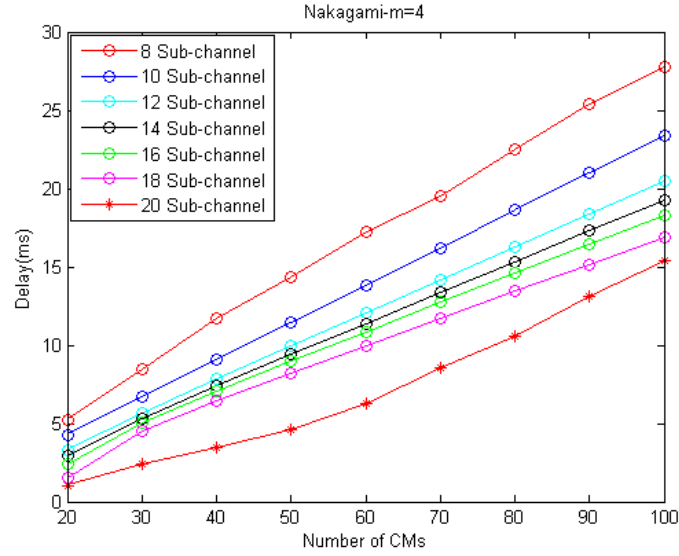


Figure 5.12 Delay characteristics curve with different number of CMs for various number of sub-channels.

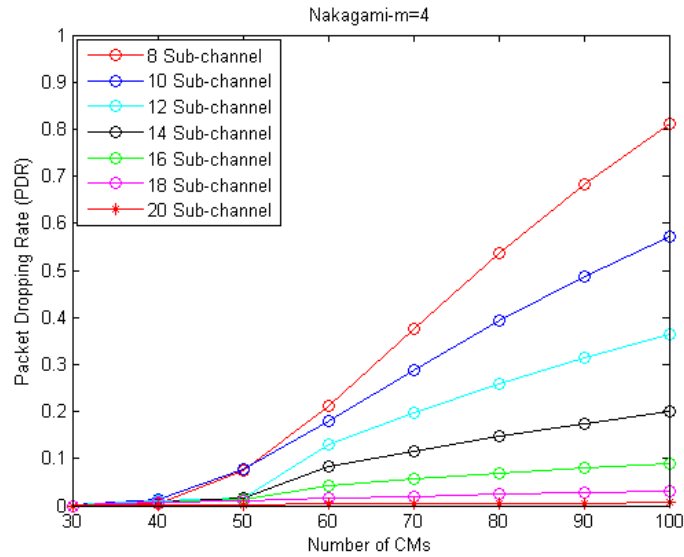


Figure 5.13 Packet dropping rate (PDR) vs number of CMs for different number of sub-channels.

shows lower BER than QPSK and QAM, respectively. Furthermore, with the same modulation technique, increasing the number of antennas reduces the BER. This is attributable to adding MIMO antennas enhances the packet reception capacity at the receiver, resulting in a lower BER.

Table 5.2 presents the performance comparison. It is observed that the proposed work has performed noticeably better performance than the existing closely related work.

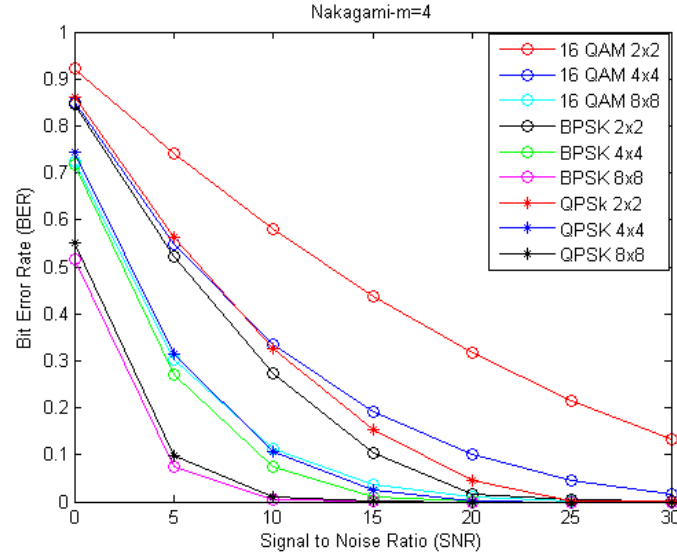


Figure 5.14 Bit error rate (BER) vs SNR characteristics curve for different modulation techniques.

Table 5.2 Performance Comparison with Closely Related Work

Ref. No.	Limitation	Max. Throughput (Mbps)
[8]	Fixed Height	26
[3]	Single UAV	N/A
[33]	Missing MAC	N/A
[38]	Lower Throughput	14
[41]	Missing MAC	N/A
[9]	Missing Mobility	4
[14]	Consumes Extra UAVs	0.9 (Normalized)
[78]	Lower Throughput	6.8
This work	Complex Structure	44

Ref. No.	Max. Delay (ms)	Max. PDR	Max. BER
[8]	70	0.88	N/A
[3]	N/A	N/A	0.1
[33]	N/A	N/A	0.6
[38]	N/A	N/A	0.9
[41]	N/A	N/A	0.8
[9]	N/A	N/A	N/A
[14]	N/A	N/A	N/A
[78]	100	N/A	N/A
This work	27	0.8	0.9

5.5 Conclusion

In this chapter, a cluster-based FANET model is proposed in which the CMs or CH transmit packets simultaneously using the MIMO-OFDMA technique. In the OFDMA technique, the packet transmission channel is divided into multiple

sub-channels. Consequently, the network system performance improves noticeably in terms of throughput, delay, PDR, BER, and so forth. However, number of sub-channels after a certain level of 20 the system performance reduced monotonously because of interference. Thanks to the advantages of MIMO on the receiver side, the packet receiving capacity increases, resulting in a reduction in BER. The packet transmission is controlled using a 4D Markov chain-based fast backoff process considering PAR, mobility, backoff time and stage. Therefore, the network topology was efficiently controlled and noticeably improved. For 20 sub-channels and 100 CMs, the delay was only 15 ms, with a maximum throughput of 44 Mbps, lower PDR, and reduced BER.



6

CONCLUSION

6.1 Result and Discussion

Firstly, cluster-based FANET with a 3D mobility platform is considered. An efficient cluster build-up process and control mechanism are designed that demonstrates better throughput value and lower delay compared to existing work. The network system is analyzed on an efficient 3D mobility model so the system performs properly even when the UAVs are moving. All the analytical studies, such as throughput, OP, SNR, packet transmission and collision probability, PDR, delay, etcetera, are performed by using the Markov chain model while considering the different types of channels, such as Rayleigh, Nakagami-m, and Rician channels. Under the Rician channel environment. The simulation results are analyzed by considering randomly taking values for 1000 Monte Carlo simulations.

Secondly, the work represents the cluster-based FANETs MAC protocol with MIMO-OFDM in the 3D Mobility platform. A 3D Markov chain-based backoff method is introduced to improve the performance. The simulation results are analyzed by special throughput with the function of the range between two UAVs, the relative velocity of the two UAVs, and the quantity of UAVs for several types of channels and MIMO-OFDM criteria. The performance analysis is also investigated regarding BER, OP, and delay.

Thirdly, a cluster-based model is proposed for UAV-BS as an alternative to terrestrial BS. The core network is supported by FANETs, assisted by a MAC protocol. The MAC protocol is adapted to handle mobility, and transmission is managed using a 3D Markov chain CSMA/CA adaptive backoff process. An algorithm for movable CMs by adjusting the MAC protocol for transmission, significantly improved system performance. In terms of throughput, the model shows increasing results in 5 times for Nakagami-m=1 fading and 6 times for Nakagami-m=2 than the Shah's model. The comparison with existing studies is given in terms of maximum throughput, delay, and PDR, which shows the improvement done by the

proposed mechanism. Regarding the number of CMs and throughput, the work shows increased values up to 30 CMs, whereas previous work only achieved this up to 15 CMs. In terms of PDR and delay, the work demonstrates lower PDR values and a delay of approximately 30ms for 30 CMs. To determine the optimal altitude, the maximum LoS PL is selected for achieving maximum coverage with the minimum number of CMs across various environmental scenarios, including suburban, urban, dense urban, and high-rise urban areas. An algorithm is developed for maximizing coverage with the minimum number of CMs to cover the macro cell BS area. By maintaining optimal altitudes up to 1.75, fewer than 100 CMs can cover a 30km radius BS area in high-rise urban areas.

Finally, mobility adaptive dynamic (MAD-MAC) has been developed with the integration of the MIMO-OFDMA technique. In the OFDMA technique, the packet transmission channel is divided into multiple sub-channels. Consequently, the network system performance improves noticeably in terms of throughput, delay, PDR, BER, and so forth. However, the number of sub-channels after a certain level of 20 the system performance reduced monotonously because of interference. The packet transmission is controlled using a 4D Markov chain-based fast backoff process considering PAR, mobility, backoff time and stage. Therefore, the network topology was efficiently controlled and noticeably improved.

6.2 Future Works

Based on the findings of this thesis, future work will focus on designing an AI-based model for optimal CH selection to ensure efficient and stable cluster management in UAV networks. An adaptive AI-driven MAC protocol will be developed to manage dynamic channel access, reduce collisions, and improve communication efficiency in rapidly changing aerial environments. A hybrid communication architecture integrating UAVs and satellites as NTN will be designed to enhance the coverage and reliability of TNs, especially during emergencies. All proposed systems will be practically implemented using real UAV platforms to validate performance and identify real-world challenges. Finally, key network parameters and UAV configurations will be optimized based on practical deployment results to ensure energy efficiency, scalability, and robust system performance.

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PUBLICATIONS FROM THE THESIS

Papers

1. M. T. Rahman, A. F. M. S. Shah, M. A. Karabulut, and H. Ilhan, "Cluster based emergency communication systems using UAVs with 3D mobility in 5G and beyond," Status: Under Review, IEEE Transactions on Communications, no. TCOM-TLS-25-0454, March, 2025.
2. M. T. Rahman, and A. F. M. S. Shah, "Adaptive cluster-based MAC with mobility and coverage optimization in FANETs for emergency disaster communication," Status: Under Review, IEEE Transaction on Wireless Communication, no. TW-Feb-25-0393, March, 2025.
3. M. T. Rahman, and A. F. M. S. Shah, "MAD-MAC:mobility adaptive dynamic MAC protocol for FANETs," Status: Under Review, IEEE Transaction on Intelligent Transportation Systems, no. T-ITS-25-04-1847, April, 2025.

Conference Papers

1. M. T. Rahman, A. F. M. S. Shah, M. A. Karabulut, and H. Ilhan, "Cluster-based FANETs with MIMO-OFDM under 3D Mobility in 5G and beyond," Status: Accepted, IEEE IEMCON 2024 at University of California, Berkeley USA.