DELAY BASED HANDOVER ALGORITHM DESIGN FOR FEMTOCELL NETWORKS

by

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ABSTRACT

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Mobile communication systems have limited frequency resources and macrocellular architecture utilizes smaller one tier cells to gain frequency reuse. One approach to enhance the overall system capacity is to use two tier femtocell-macrocell systems. The introduction of femtocells has caused a great excitement in that the femtocell system can be a solution to poor indoor coverage for mobile communications. Since femtocells are plug-and-play devices and not deployed with central planning, the handover systems used in one tier macrocell infrastructure should be updated according to the needs of two tier femtocell-macrocell systems. Femtocell base stations utilize the broadband Internet connection to connect to the operator core network. Since the Internet is a lossy network incapable of guaranteeing the quality service requirements of real time voice communications over Internet Protocol (IP) networks, the handover systems based only on the wireless received signal strength are unable to provide a solution to the quality requirements of wired systems. The quality of service requirements for wireless and wired medium are both taken into account to maintain a better call quality in the novel handover algorithms in this study. The handover rate and the signal degradation rate are the key performance indicators of the handover system optimization. The simulation studies demonstrate that better results are achieved with the proposed algorithms compared to existing ones in the literature.

ÖZET

FEMTO HÜCRE AĞLARINDA GECİKME TABANLI AKTARIM ALGORİTMASI TASARIMI

Mobil iletişim sistemleri sınırlı frekans kaynağına sahiptir ve makrohücresel mimari daha küçük tek katmanlı hücreleri frekans kazanmak için kullanır. Sistem kapasitesini arttırmaya yönelik bir yaklaşım iki katmanlı femto ve makro hücre yapıları kullanmaktır. Femto hücrelerin sunulması, iç mekanlardaki kapsama problemlerine çözüm olacağı düşüncesiyle heyecanla karşılandı. Femto hücrelerin tak-çalıştır cihazlar olması ve merkezi planlamayla kurulmaması sebebiyle, tek katmanlı sistemlerde kullanılan aktarım sistemleri çift katmanlı mimarinin ihtiyaçlarına göre yeniden tasarlanmalıdır. Femto hücre baz istasyonları operatör merkezi sistemine bağlanmak için genişbant İnternet bağlantılarını kullanır. İnternetin kayıplı bir ağ olması ve anlık ses görüşmelerinin servis kalitesini garantileyebilecek özelliklere sahip olmaması nedeniyle, sadece alınan kablosuz sinyal gücüne dayalı aktarım yapıları kablolu sistemlerin servis ihtiyaçlarına yanıt oluşturamazlar. Bu çalışmada yeni tasarlanan aktarım algoritmalarıyla daha iyi bir ses kalitesi yakalamak için hem kablolu hem de kablosuz ortam servis kalitesine odaklanılmıştır. Performans kriterleri olarak aktarım ve sinyal gücünün zayıflaması oranları kullanılmıştır. Yapılan benzetim çalışmaları ile önerilen aktarım yöntemlerinde geleneksel aktarım yöntemlerine nazaran daha iyi sonuçlar alındığı gösterilmiştir.

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LIST OF SYMBOLS

c	The cost of handover
$\mathbf{C}$	Autocovariance Matrix
$\mathbf{C_L}$	Lower triangular matrix of $\mathbf{C}$
$\mathbf{C_U}$	Upper triangular matrix of $\mathbf{C}$
d_c	Effective correlation distance
d_f	Backhaul delay of FBS
d_m	Backhaul delay of MBS
K	The number of iterations
l_f	The distance between mobile station and FBS
l_m	The distance between mobile station and MBS
l_{mf}	The distance between FBS and MBS
m	The handover function of mobile station
n	Shape parameter of Erlang PDF
P_f	Output power of FBS
P_m	Output power of MBS
PL_f	Path-loss of femtocell signal
PL_m	Path-loss of macrocell signal
r	The state function of mobile station
$\mathbf{R}$	Autocorrelation Matrix
SD_f	Signal Degradation if served by FBS
SD_m	Signal Degradation if served by MBS
s_f	The RSS of femtocell signal
s_m	The RSS of macrocell signal
T_d	Delay threshold
t_s	Sampling rate
T_s	RSS threshold
v	The velocity of mobile station

α	Rate parameter of Erlang PDF
$\beta_t(i)$	Backward variable
η_f	Path-loss components for femtocell path-loss model
η_m	Path-loss components for macrocell path-loss model
ρ	Correlation coefficients of $\mathbf{C}$
σ_f	Standard deviation of log-normal shadowing for femtocell signal
σ_m	Standard deviation of log-normal shadowing for macrocell signal
Θ	Parameter set
$\triangle_d$	Delay shift

LIST OF ACRONYMS/ABBREVIATIONS

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	The 3rd Generation Partnership Project
4G	Fourth Generation
CAC	Call Admission Control
CAS	Centralized Antenna Systems
CDMA	Code Division Multiple Access
CPICH	Common Pilot Channel
CSG	Closed Subscriber Group
DAS	Distributed Antenna Systems
DCH	Dedicated Channel
DSL	Digital Subscriber Line
E-DCH	Enhanced Uplink Dedicated Channel
ETSI	European Telecommunications Standard Institute
FBS	Femtocell Base Station
FAP	Femto Access Point
FGW	Femtocell Gateways
HNB	Home NodeB
HSDPA	High-Speed Downlink Packet Access
GSM	Global System for Mobile Communications
IP	Internet Protocol
MBS	Macrocell Base Station
MOS	Mean Opinion Score
QoS	Quality of Service
RF	Radio Frequency
RNC	Radio Network Controllers
RSS	Received Signal Strength

SMS	Short Message Service
TCP	Transmission Control Protocol
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TTT	Time-to-Trigger
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Networks

1. INTRODUCTION

The cellular technologies have grown tremendously in the past 20 years since the introduction of mobile devices to the cellular market. Since First Generation (1G) cellular technology was introduced, mobile technologies have constituted a demanding cellular market. 1G technology refers to analog cellular communication that does not provide data services, but only offers speech services [1]. The wireless market has evolved from 1G analog technology to Second Generation (2G) digital cellular technology at the end of 1980s. 2G mobile systems not only carry speech communications but also data services. Data services provided by 2G are known as Short Message Service (SMS) and circuit-switched data services [2]. 2G mobile communications utilize Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) to maintain higher frequency efficiency and data rates. After 2G cellular systems, the introduction of Third Generation (3G) mobile telecommunication has made a great impact on cellular networks. It improved frequency allocation and data rates and combined Internet services with cellular technologies. With an extension to 3G systems, High-Speed Downlink Packet Access (HSDPA) has enhanced the data rates up to 14.4 Mbps on the downlink and 5.8 Mbps on the uplink. Current Fourth Generation (4G) systems that propose packet switching networks instead of circuit switching networks with an all Internet Protocol (IP) approach support up to 1 Gbit/s under proper conditions [2].

The increasing rate of mobile data traffic has led the cellular telecommunications to provide better indoor coverage. It is estimated that over 90% of wireless data transmission and approximately 65% of calls are generated indoors [3]. However, it is shown that 45% of households suffer from indoor coverage problems [4]. It gets very important for operators to offer high speed data services indoors to enhance end-user satisfaction.

Since most of the wireless transmission occurs indoors, the mobile infrastructure needs smaller cell sizes such as microcells and nanocells to increase indoor capacities.

The need for these smaller cell sizes is for frequency reuse. However for houses, small offices or home offices, installing these systems cost much than the revenue for operators. Higher coverage and lower cost of femtocell infrastructure lead the operator companies to use two-tier systems in order to overcome indoor coverage problems. Femtocell systems are regarded as one of the most probable solutions to the indoor coverage issue [3].

Femtocell topology drives a different architecture from one-layer cellular systems. One-tier networks compromise near to near neighbor cells, whereas femtocell two-layer networks consist of smaller cells within macrocells. This two-layer approach brings about challenging issues such as interference mitigation, self-organization and mobility management. One of these problems, mobility management, the design of handover decision algorithm for two-tier networks forms the subject of this study. Handovers from macrocell to femtocell and from femtocell to macrocell are crucial in terms of overall system capacity and call quality. Two tier systems have different aspects for handover decision algorithms than one tier systems:

- The transmit power of femtocell base stations (FBS) is low when compared to macrocell base stations (MBS).
- Femtocells are deployed in a distributed random manner however macrocells are installed with centralized planning. Femtocell handover parameters should change automatically to reach optimum efficiency based on the location and power levels of near femtocells and macrocells.
- Fast mobile stations passing near by femtocells may create undesired handovers that may result in ping-pong effect increasing overall system load.
- The backhaul line of femtocell base station is not capable of maintaining quality of service for real time voice communications, therefore handover decision algorithms should consider femtocell backhaul quality in order to increase user satisfaction.

1.1. Motivation of the Thesis

The femtocell architecture is quite different from the existing macrocell architectures. The handover schemes of existing macrocells are not adequate for macrocell to femtocell handover therefore the handover mechanisms used in 3G and 2G systems should be adapted to the new femtocell-macrocell two-tier networks in order to overcome mobility problems, i.e., a passing user equipment near a femtocell may be subject to undesired handovers and this may result in ping-pong effect.

There are many studies carried out for the design of handover algorithms on two-tier networks based on different concepts. The simplest algorithm is the one that the mobile equipment selects the base station with the strongest received signal strength (RSS) which leads to the ping-pong effect. Hysteresis is used in order to eliminate unnecessary handovers that may increase the instability of the whole system [5].

A femto access point (FAP) is a base station using the same frequencies with a macrocell and stationed at houses and offices. It connects to the core infrastructure via the wide area network connection, generally the digital subscriber lines (DSL) which are broadband Internet lines. The Internet network does not allow the user to maintain specific quality of service requirements that can be provided at leased lines. Telecommunication companies generally use the Time Division Multiplexing (TDM) at the line between the macrocell base station and the core network. These lines maintain the quality of service needs of real-time audio communications, which are especially the end-to-end delay, delay variance (jitter), packet loss rate and bandwidth. The quality of service aspect of the communication served by a macrocell is assessed by the signal to noise ratio. Conventional handover algorithms do not take into account the quality of service aspect of the wired line between the macrocell and the core network.

The wired line of the femtocell to the core network is an Internet broadband line in femtocell networks and the Internet network system does not guarantee the delay, jitter, packet loss and bandwidth requirements of real-time voice communications. To provide a good quality of service for voice communications, both the wireless medium between the mobile station and the femtocell, and the wired medium between the femtocell and the core network of the telecommunication companies should be considered in handover algorithm designs. Based on the wired and wireless quality of service aspects of femtocells, the handover mechanisms should utilize both the received signal strength of the mobile station and the quality of service requirements of a voice over IP communications namely delay, jitter, packet loss and bandwidth.

1.2. Scope of the Thesis

An overview of femtocell networks is given in Chapter 2. Femtocell technology is introduced as an alternate solution to the indoor coverage issues. Indoor coverage techniques and the difference between indoor coverage technologies and femtocell are sketched and the quality of service aspects of a femtocell backhaul wired line is depicted.

Handover systems are described in Chapter 3. Handover types are sketched, The 3rd Generation Partnership Project (3GPP) standards on handover decision for two tier and one tier systems are presented and related studies in literature on one tier and two tier handover systems are given.

The conventional handover algorithm and the proposed handover algorithms are presented in Chapter 4. This study introduces novel handover decision algorithms considering both the wireless medium signal degradation and femtocell backhaul wired medium signal degradation.

In Chapter 5, the comparison of the traditional handover algorithm and the proposed handover algorithms is provided and the simulation results are depicted.

Chapter 6 concludes this thesis.

2. FEMTOCELL NETWORKS

In this chapter, femtocell technology is covered briefly. Femtocell architecture and indoor coverage technologies are described in general. The service quality of real-time voice applications on femtocell backhaul wired line is given.

The need for femtocells is simply the poor indoor coverage issue of the existing macrocell infrastructure. Since calls are mostly generated indoors, the operator telecommunications companies aim to find a solution to the poor indoor capacities by using microcells, indoor base stations, picocells, repeaters [3]. However, installation and maintenance of these indoor stations generate some additional costs to the operator companies. By comparison, femtocell is a small cellular base station installed generally by subscribers at homes and offices and it helps to combine the mobile and the Internet technologies inside homes [6]. The installation, maintenance and operation costs are lower than other indoor coverage systems and mostly met by the customers. Hence with its low cost it provides a great opportunity for operator companies to overcome the indoor coverage problem.

Mobile data traffic has been growing tremendously in the past years. It is estimated that by 2014, 1.6 EB of data will have been circulated each month [7]. The wireless data growth may lead to spectrum surplus in the next years (See Figure 2.1) [8]. Since wireless transmission mostly occurs indoors, the mobile infrastructure needs smaller cell sizes such as microcells and nanocells to increase the capacity in crowded hotspots like shopping malls. The need for these smaller cell sizes is for frequency reuse. But for houses, small offices or home offices, installing these systems costs much than the revenue for operators. Therefore, lower cost of femtocell infrastructure lead the operator companies to use two-tier systems in order to overcome indoor coverage problems. And that's why femtocell systems are regarded as one of the most probable solutions to the indoor coverage issue [3].

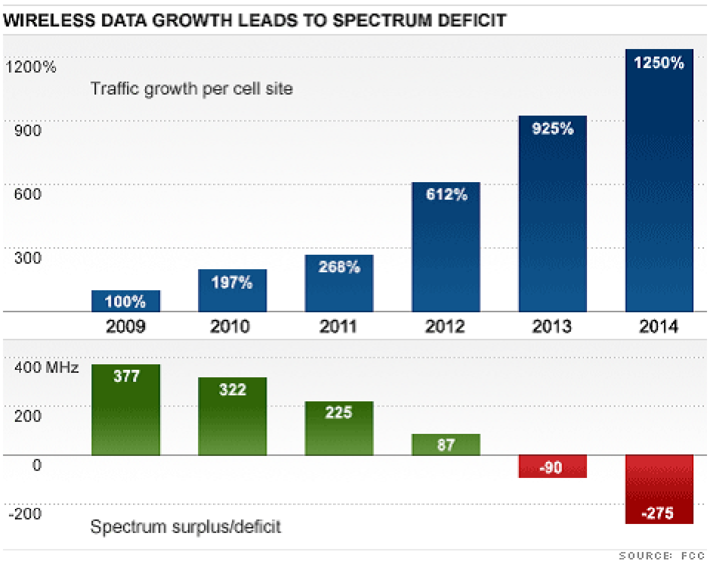

Figure 2.1. Wireless Data Growth [8].

Femtocells are very small and low cost home base stations. As they are designed to serve indoors, their transmit power is very low compared to macrocells. The transmit power needed for mobile stations is also lower at femtocell systems than at macrocell systems. Thus, it increases the battery life of mobile stations.

These devices are integrated to small plastic desktops and wall mounts cases that are powered from the customer's electricity sockets. Femtocell connects to the core network via the customer's Internet connection that can be DSL, or cable or any other broadband connection [9].

2.1. Overview of Indoor Coverage Techniques

In this section, indoor coverage technologies are briefly reviewed. The indoor coverage of wireless telecommunications is increasingly getting important with the widespread use of cellular telecommunications. Over 90% of wireless data –mostly video- transmission and approximately 65% of calls are generated indoors and the penetration of macrocell signal to indoors is poor with respect to the indoor coverage techniques [3]. On the other hand, the revenue growth of data services over-weigh the revenue growth of voice services in large telecommunications companies [4].

Indoor coverage is generally provided by macrocell base stations (MBS) that are planned by telecommunications companies according to city planning rules, health regulations and transmission power. The macrocell coverage planning is a delicate subject; an increase in the number of macrocells can generate interference which lowers the quality of service and increase the cost, on the other hand a decrease in the number of macrocells may result in coverage issues. Telecommunication companies desire to enhance the quality of service at indoor coverage with low cost. Therefore, the increasing rate of the usage of indoor communications leads the companies to solve the issue with indoor coverage technologies such as microcells, picocells, distributed antenna systems, repeaters and femtocells [2].

2.1.1. Distributed Antenna Systems

A distributed antenna system (DAS) that uses geographically distributed multiple antennas with low transmission power instead of a centralized antenna system (CAS) with high transmission power, is a method for acquiring diversity on the number of base stations. The distributed antenna systems model tries to eliminate large-scale fading by reducing the distances between the mobile stations and the antennas. The lower the distance is, the higher the received signal strength is. The difference can be seen in Figure 2.2 [10]. Besides, the distributed antenna systems model can only be planned, implemented and installed by telecommunications companies whereas femtocell installations are done by the end user. Another approach shall be using distributed antenna systems in conjunction with relays, picocells, femtocells or other indoor coverage techniques.

2.1.2. Repeaters

A repeater system is also one of the indoor coverage techniques used by telecommunication companies. Due to their lower cost and easy installation, they are used in order to cover the areas where the signal level of macro base stations is weak or

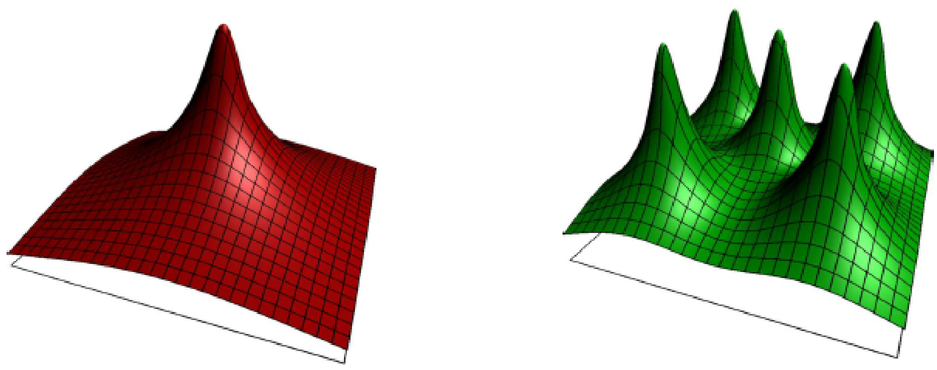

Figure 2.2. Geographical distribution of the average received signal strength for CAS (red) vs DAS (green) [10].

non-existing. Dead spots get signals via repeaters which broaden the coverage area both for indoors and outdoors [11].

Repeaters have two antennas: the donor antenna connects the repeater to the macro base station, and has to be isolated from the server antenna which serves the mobile stations. To achieve this goal, the donor antenna is directed towards the macro base station, whereas the server antenna uses beamforming to serve the dead spot.

There exist two types of repeaters: Regenerative (active) repeaters clean the received signal from noise, thus the process adds a delay to the transmission. After getting rid of the noise, the repeater amplifies the signal. Nonetheless, non-regenerative (passive) repeaters only amplify the received signal, thus the noise is also amplified. Non-regenerative repeaters are simpler and noisier but cheaper devices than regenerative repeaters. The installation and planning of using repeaters to extend the indoor coverage can only be done by telecommunication companies whereas the femtocells are installed by the end users [12].

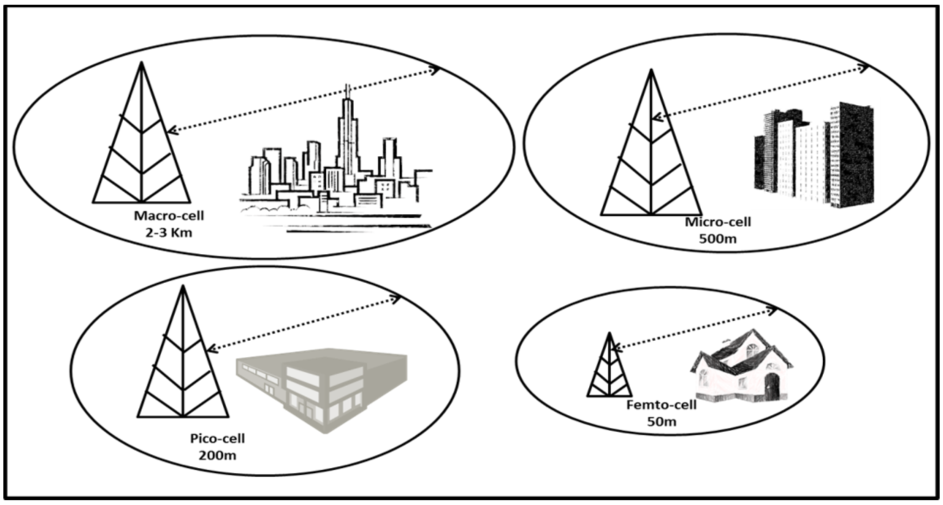

Figure 2.3. Macrocell, microcell, picocell and femtocell ranges [13].

2.1.3. Picocells

Microcells and particularly picocells are also considered to be a solution to the indoor coverage problem. Picocell base stations -like femtocells- operate at low transmission powers compared to the macrocell base stations. Picocells use the network of a telecommunication company whereas femtocells use the Internet network architecture that is owned by subscribers. Picocells have broader coverage up to 200m, whereas femtocells cover up to 50m shown in Figure 2.3 [13].

Picocells are installed by the operator likewise the distributed antenna systems and repeaters. The planning of the locations of the picocells is held by the operator, hence the interference issues can be solved via beamforming by the operator; whereas, the locations of femtocells can be installed beyond the knowledge of operator companies thus the interference issues of femtocells have to be handled within the system itself.

2.2. Femtocell Technology

In this section, femtocell features, advantages and issues are briefly discussed. Femtocell coverage area, integration of the current cellular technology, operation frequency, plug & play feature, access methods, the advantages and issues of femtocell technology are reviewed.

2.2.1. Coverage Area

Femtocell technology has been developed mainly to bring a solution to indoor coverage issues and aimed to operate indoors, particularly at households, small offices and malls. For this reason, the transmit power of femtocell base stations is low and therefore the coverage area is very small compared to macrocell base stations. Figure 2.3 provides a comparison of macrocells, microcells, picocells and femtocells and depicts the femtocell coverage range as less than 50 meters radius [13].

2.2.2. Integration to Cellular Technology

Femtocell technology aims to complement the current mobile technologies to indoors. Femtocell base stations integrate with the cellular technologies already used. Femtocells operate at the same frequencies with the macrocells. Unlike wireless local area networks, femtocells use the licensed spectrum like one tier cell systems. Operation of femtocells in licensed spectrum leads the user equipments to operate without dual-mode network cards. As dual-mode usage decreases battery life of user equipments, femtocell technology instead of Wireless Fidelity (Wi-Fi) increases battery life of mobile stations [3].

2.2.3. Plug & Play

Femtocell base stations are plug & play devices that the subscriber does not make any configuration on the device which brings ease of use for the subscriber. The operation parameters of femtocell base stations are given from the operator company. As it provides flexibility for the user, auto-configuration of femtocell base stations needs further research on self-organization, power control for interference cancellation, time synchronization and handover handling.

2.2.4. Access Methods

Three access methods are offered to femtocell networks: closed access, open access and hybrid access.

The closed access method, also called Closed Subscriber Group (CSG), allows only the user equipments in the CSG list to enter the femtocell network. The CSG list is specified by the subscriber to the operator. Since it allows only the subscriber decided users, the capacity of femtocell network is only utilized by these allowed ones. This may block optimum utilization of femtocell. Besides, the closed access method causes high cross-layer interference that is the interference between the macrocell and femtocell. The closed access method is generally preferred by home femtocell customers for individual property [14].

All users can access the femtocell network in the open access method. The open access method reduces the cross-layer interference, however it increases the number of handovers that brings a load to the overall system. The more the users join the network, the higher the network throughput it provides. The open access method targets enterprise companies, dense area sites and hotspot deployment, since most home users prefer the closed access to the open access.

Since the closed access and the open access methods have the mentioned drawbacks, an alternate, so-called the hybrid access method has been developed. Hybrid method allows the list determined by the subscriber with a preferential access, whereas it also permits others to join the network with limited access. If the network is available, anyone can join; otherwise the users in the list are preferred.

2.2.5. Femtocell Issues

Femtocell deployment creates changes in the one tier cellular topology. Introducing femtocells, one tier cellular topology becomes two tier cellular topology in which macrocells constitute the conventional planned layer and femtocells introduce the second layer that cover very small areas within macrocellular layer. Femtocell coverage areas are not planned and located by the customers, i.e., femtocells should have auto-configuration capabilities so that they can operate in different locations.

The two tier network brings about new challenges in comparison with the one tier network. Since femtocells and macrocells use the same frequency band, interference problems occur. Cross-layer interference -the interference caused by femtocell and macrocell signals operating at the same frequency- and co-layer interference -the interference caused by neighboring femtocells- should be mitigated by interference cancellation techniques. Power control, time-hopping and beam forming are popular research subjects on interference mitigation for two-tier cellular networks [3].

Mobility management is one of the most challenging issues for femtocells. Handovers from macrocell to femtocell and from femtocell to macrocell are very important for overall system capacity and call quality. Two tier systems have different aspects for handover decision algorithms as against to the one tier systems:

- The transmit power of femtocell base stations is quite low when compared to macrocell base stations.
- Femtocells are deployed in a distributed random manner whereas macrocells are installed with centralized planning. Femtocell handover parameters should change automatically to reach optimum efficiency based on the location and power levels of neighbor femtocells and macrocells.
- Fast mobile stations passing near by femtocells may create undesired handovers that may result in ping-pong effect increasing overall system load.
- The backhaul line of femtocell base station is not capable of maintaining quality of service for real time voice communications, therefore handover decision algorithms should consider femtocell backhaul quality in order to increase user satisfaction.

Since femtocells are located in a distributed manner, the operator does not plan the location and the number of femtocells in a macrocell area, therefore femtocells should have self-organization capabilities to integrate with the macrocellular base stations,

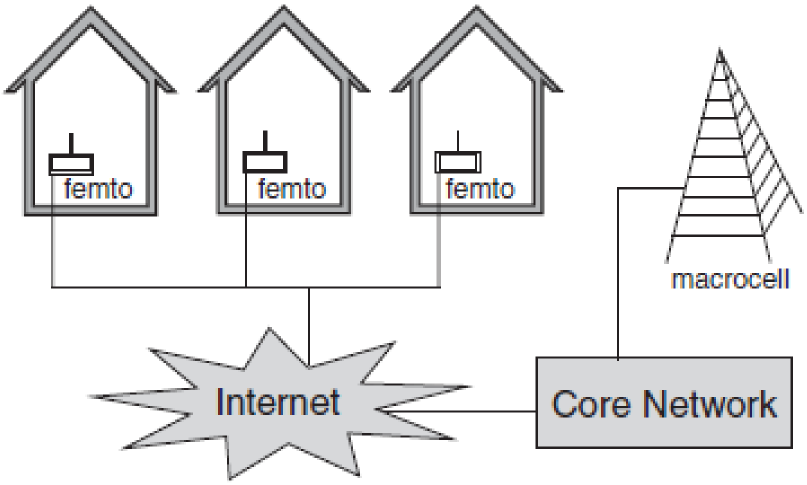

Figure 2.4. Typical Femtocell Connection [3].

and to learn about the neighbor femtocells and macrocells and to change the handover, power control and interference mitigation parameters accordingly [3].

2.2.6. Femtocell Backhaul

Femtocell base stations use the broadband Internet line to connect to the core operator network. Figure 2.4 depicts the connection to core network of femtocell base stations [3]. The backhaul line is one of the most important aspects of femtocells. Macrocells, picocells and microcells communicate the core network with the leased lines owned by operator companies whereas femtocells use broadband Internet lines in which packet prioritization is not implemented.

2.3. Quality of Service on Femtocell Backhaul

The femtocell base station facilitates the broadband wired line that is used by the subscriber for the Internet connection to connect to the core network of the operator company. Internet broadband networks are not capable of packet prioritization and differentiated queue mechanisms. Broadband Internet lines cannot guarantee the quality of service for real time voice communications over IP networks because Internet network routers that belong to different Local Internet Registries (LIR), clear the packet prioritization values stamped on voice packets. On the other hand, the leased lines owned and used by operator companies on the backhaul of macrocell base stations guarantee quality of service for real time voice communications with packet classification, bandwidth management, header compression, prioritization of relatively small voice packets over large data packets and queue management.

Qualifying real-time voice communications over IP networks needs measurable quantities to guarantee the quality of the communication [15]. There are many parameters that can be used to measure the quality of service but the most important ones are the one way delay, delay variance (jitter), packet loss and minimum bandwidth. These parameters measure the network performance based on the application. For instance, real time voice communications are sensitive to delay that should be less than 150 ms, packet loss should be less than 10^{-4}, and jitter should be less than 20 ms for good quality, whereas mail traffic is insensitive to delay or jitter or packet loss, because mail traffic uses Transmission Control Protocol (TCP) that can retransmit the lost packets and one way delay is not sensitive for non-real time applications [16].

Since the femtocell base stations use the broadband wired line which is not capable of guaranteeing the quality of service for delay, jitter, and packet loss sensitive real time applications, the quality of service for wireless signaling provided by handover mechanisms, based on RSS values of the serving and candidate base stations, does not maintain the quality of service for femtocell backhaul. For this reason, new parameters such as one way delay, delay variance, packet loss or a combination of these should be used in the handover algorithm designs in the two-tier networks.

In this study, the one way delay parameter affecting the real time voice communications is used as a parameter in handover decision for increasing the quality of service for femtocell backhaul. Other parameters such as jitter, packet loss or a combination of all are not in the scope of this study. Since one way delay parameter has been crucial to the real time applications, the delay dynamics of the Internet networks have been widely researched at different studies with different data sets [17–22].

In the Internet networks, a packet passes through a number of wired links connected via network routers and switches. The packet experiences different types of delays: the propagation delay related to the link distance and the queuing and processing delay at routers and retransmission delays for lost packets (only in applications using TCP), the retransmission delay does not occur in voice communications. The sum of propagation delay at links and the queuing and processing delays at routers can be modeled as an M/M/1 queue [22]. The probability distribution of an M/M/1 queue is modeled as an Erlang Probability Distribution Function (PDF). The model is also similar to the Internet delay at Oboe and Fiorini's work that uses a shifted exponential distribution for 150-km connection and a Erlang like probability density for 10000-km connection [21]. Since exponential probability distribution is Erlang-1 probability distribution, Erlang distribution is used for modeling delay in this study.

2.4. Summary of the Chapter

Femtocell technology increases the overall cellular capacity as a solution to the indoor coverage issue. Besides, since the distance between the femtocell base station and the mobile station is short, femtocells decrease the call drop rate caused by shadowing effects thus providing high spectrum efficiency.

Operator companies aim to tackle the indoor coverage problems by installing indoor base stations, picocells, distributed antenna systems but the costs of maintenance and installation of these systems increase churn. Due to the low cost of femtocells when compared to other indoor coverage technologies, femtocells are regarded as a beneficial solution to indoor coverage issue [3].

Femtocell base stations are plug & play devices, so the installation is not a burden for the customer. Besides, the auto-configuration of femtocell devices are handled by operators that leads rapid femtocell deployment. Additionally, it is possible for operators to offer combined pricing for the Internet broadband line and mobile phone with femtocell deployment or cheaper prices for calls generated from femtocells.

Femtocells should have self-organization capabilities; they should learn about the neighbor femtocells and macrocells and change the handover, power control and interference mitigation parameters accordingly in order to integrate into the cellular network [3].

Macrocells are interconnected via a backbone providing high quality in the one tier macrocellular networks. Nonetheless, the backhaul line of femtocell base station is generally connected to the core network via a connection of low rate, incapable of maintaining quality of service for real time voice communications, therefore handover decision algorithms should consider femtocell backhaul quality in order to maximize cellular capacity.

And last but not least, since the transmit power is low for mobile stations, femtocell use increases battery life of user equipments compared to macrocell use.

3. HANDOVER FOUNDATIONS

In this chapter, handover systems and handover types are briefly reviewed. 3GPP standards on handover decision algorithms for both one tier and two tier architecture are examined and related works on literature are given.

As the available frequency band is scarce, the increasing number of mobile stations worldwide requires efficient algorithms to utilize the limited spectrum. The technology providers seek ways to reuse this finite frequency band [3]. In order to increase frequency reuse, smaller cell structures are used and mobility among these smaller cells creates the problem of handover. When a mobile station starts to move closer to the neighbor macro base station and leaves the service area of registered base station or when the quality of service gets weaker, the mobile station should be transferred to another base station. This is accomplished by handover mechanisms.

3.1. Handover Types

Handover is defined as the process of reassigning a current call or data communication from a frequency of a cell to another. Handovers are categorized in terms of used access technologies, as vertical and horizontal handover; in terms of the system, as intra-system handover and inter-system handover, and in terms of the cell diversity, as hard handover and soft handover.

3.1.1. Vertical Handover

Vertical handover occurs between different access technologies. It is also called inter-technologies handover. Vertical handover is performed generally between a wireless local area network and a cellular technology [23]. It can also occur in between different cellular access networks, e.g., when a mobile station moves from Global System for Mobile Communications (GSM) network to Wireless Local Area Networks (WLAN) or Universal Mobile Telecommunications System (UMTS) based network as

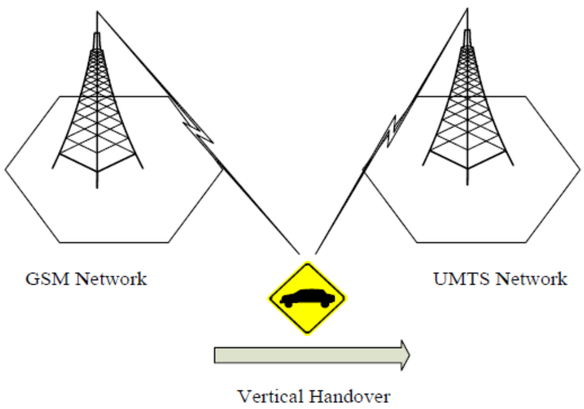

Figure 3.1. Vertical Handover [24].

depicted in Figure 3.1 [24].

3.1.2. Horizontal Handover

Horizontal handover occurs between same access technologies. When a mobile station moves from a GSM network to another GSM network or from a UMTS network to another UMTS network, it is called horizontal handover as shown in Figure 3.2 [24].

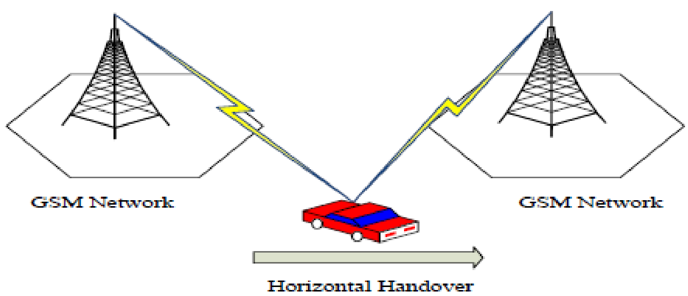

Figure 3.2. Horizontal Handover [24].

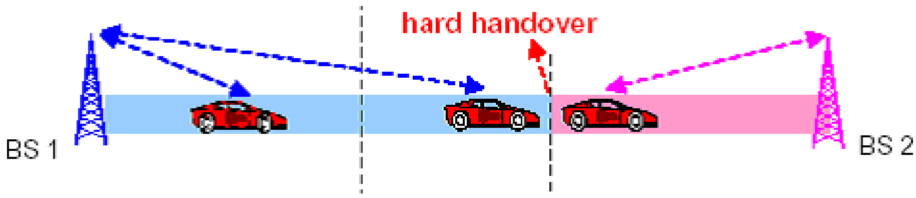

Figure 3.3. Hard Handover [25].

3.1.3. Intra-System Handover

Intra-System handover occurs between the cells in a single system. There are two types of intra-system handovers: Intra-Frequency Handover and Inter-Frequency Handover. The former occurs among the cells of the same frequency carrier and the latter is among the cells of different frequency carriers.

3.1.4. Inter-System Handover

If a mobile station is transfered from one cellular system to a different cellular system, it is referred as an Inter-System handover. Unlike Intra-System handovers, the serving base station and the target base station belong to different systems.

3.1.5. Hard Handover

Hard handover is the handover mechanism known as break-before-make. The radio link between the mobile station and serving base station is removed before making the radio link between the target base station and the mobile station (See Figure 3.3 [25]). Hard handover can be an intra-frequency or inter-frequency handover. The handover process time is designed to be lower than the time of breaking a call. If the handover time is less than the breaking of a call, the handover appears to be seamless which means that the mobile station is not affected by the handover process.

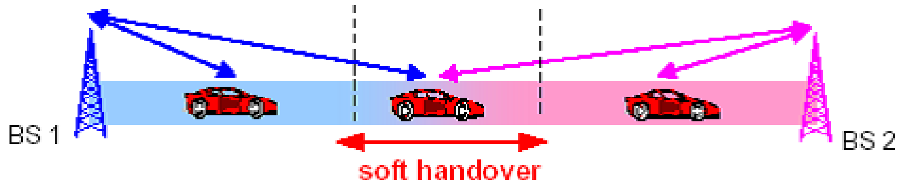

Figure 3.4. Soft Handover [24].

3.1.6. Soft Handover

Soft handover is the handover mechanism known as make-before-break. The mobile station makes the connection of the target base station before breaking the connection of the serving base station. In the event of soft handover, the mobile station communicates simultaneously with two or more cells that are in the active set. Therefore, in order to get signals from multiple base stations the soft handover is performed on the same carrier frequency. All soft handovers are intra-frequency handovers. Figure 3.4 depicts the soft handover [24].

If the active set size is configured as equal to one, then hard handover is initiated; if the active set size is configured as more than one, then soft handover is performed.

3.2. ETSI Mobility Standards

A Home NodeB (HNB), the European Telecommunications Standard Institute (ETSI) abbreviation of femtocell base station, works in the form of the closed access method. The standards of handovers from a macrocell to a femtocell, from a femtocell to a macrocell and between femtocells are specified in ETSI technical specification [26]. The handover from a macrocell to a femtocell uses the same handover architecture of one tier macrocellular networks [27, 28]. It differs the standard handover procedure in three ways: proximity estimation, PSC/PCI Confusion, access control. The proximity estimation can be used in determining mobility actions. The PSC/PCI Confusion occurs when a macrocell is unable to choose the defined correct femtocell, since there may be multiple femtocells in the coverage area of the macrocell. The access control is used when a femtocell is working in the form of the hybrid access method. The messaging structure of handovers in femtocell systems is same as in the handover structure in the macrocell systems.

3.2.1. Inter-Frequency Mobility Measurements

Inter-frequency handover occurs between the cells of different frequency carriers. Initiation of all inter-frequency handovers and active set updates are triggered by measurement events in ETSI specification. One of the measurement events is the change of best frequency, event 2A [27]. The quality estimates of the candidate frequency and the serving frequency are compared and the event is triggered if Equation 3.1 holds for a time period so called Time-to-Trigger (TTT):

$$Q_c \geq Q_s + H_{2a}/2. \tag{3.1}$$

In Equation 3.1, Q_c and Q_s denote the quality estimates of the candidate and the serving frequency, respectively; H_{2a} represents the hysteresis value for event 2A. The measurement report generated in event 2A is based on the hysteresis parameter. Event 2B refers to the event that the estimated quality of currently used frequency is below a certain threshold and the estimated quality of a non-used frequency is above a certain threshold. This event occurs if Equations 3.2 and 3.3 are satisfied for the TTT period,

$$Q_{Nonused} \geq T_{Nonused} + H_{2b}/2, \tag{3.2}$$

$$Q_{Used} \leq T_{Used} - H_{2b}/2, \tag{3.3}$$

where $Q_{Nonused}$ and Q_{Used} denote the quality estimate of the non-used and used frequency, respectively; $T_{Nonused}$ and T_{Used} represent the threshold values used in event 2B for non-used and used frequency, respectively; and H_{2b} symbolizes the hysteresis value for event 2B. The measurement report generated in event 2B combines the threshold and hysteresis parameters.

If the threshold parameters are chosen as shown in Equation 3.4,

$$T_{Used} = T_{Nonused}, \tag{3.4}$$

Equations 3.2 and 3.3 yield to a hysteresis and threshold based handover algorithm presented as

$$Q_{Used} + H_{2b} \leq Q_{Nonused} \text{ and } Q_{Used} \leq T_{Used} - H_{2b}/2. \tag{3.5}$$

If the threshold parameters are chosen as

$$T_{Used} = T_{Nonused} + H_{2b}, \tag{3.6}$$

Equations 3.2 and 3.3 yield to a threshold based handover algorithm expressed as

$$Q_{Used} \leq T_{Nonused} + H_{2b}/2 \leq Q_{Nonused}. \tag{3.7}$$

3.2.2. Intra-Frequency Mobility Measurements

Intra-frequency handover occurs among the cells of the same frequency carrier. An intra-frequency handover may be a soft handover or a hard handover. The measurements for intra-frequency quality estimates are used in the decisions of intra-frequency hard handover or active set update.

The intra-frequency reporting events in the 3GPP technical specification [27] are triggered if

- a Primary Common Pilot Channel (CPICH) enters the reporting range (Reporting event 1A),
- a Primary CPICH leaves the reporting range (Reporting event 1B),
- a non-active primary CPICH becomes better than an active primary CPICH (Reporting event 1C),
- the change of best cell occurs (Reporting event 1D),
- a Primary CPICH becomes better than an absolute threshold (Reporting event 1E),
- a Primary CPICH becomes worse than an absolute threshold (Reporting event 1F),
- a non-active Enhanced Uplink Dedicated Channel (E-DCH) but active Dedicated Channel (DCH) primary CPICH becomes better than an active E-DCH primary CPICH (Reporting event 1J).

When a primary CPICH enters the reporting range, Event 1A is triggered. Event 1A indicates that the cell entering the reporting range should be added to the active set. It is triggered if Equation 3.8 is satisfied for TTT period:

$$10logM_{New} + CIO_{New} \geq W10log\left(\sum_{i=1}^{N}(\frac{1}{M_i})\right) + (1-W)10logM_{Best} - (R_{1a} + H_{1a}/2), \tag{3.8}$$

where M_{New} and M_i and M_{Best} denote the measured quantity for the new cell, the cells in the active set and the highest measured quantity, respectively. The number of cells in the active set is represented as N. R_{1a} is the reporting range constant, H_{1a} is the hysteresis value for event 1A and CIO_{New} is the cell individual offset for the new cell. W symbolizes the normalization parameter. Equation 3.8 shows that the cell addition occurs if the measured quantity of the new cell is higher than the weighed sum of the measured quantities of the cells in the active set with a hysteresis value for the Time-to-Trigger period and if the active set size is not full. Figure 3.5 depicts the update of the active set with measurement event 1A [29].

When a primary CPICH leaves the reporting range, Event 1B is triggered. Event

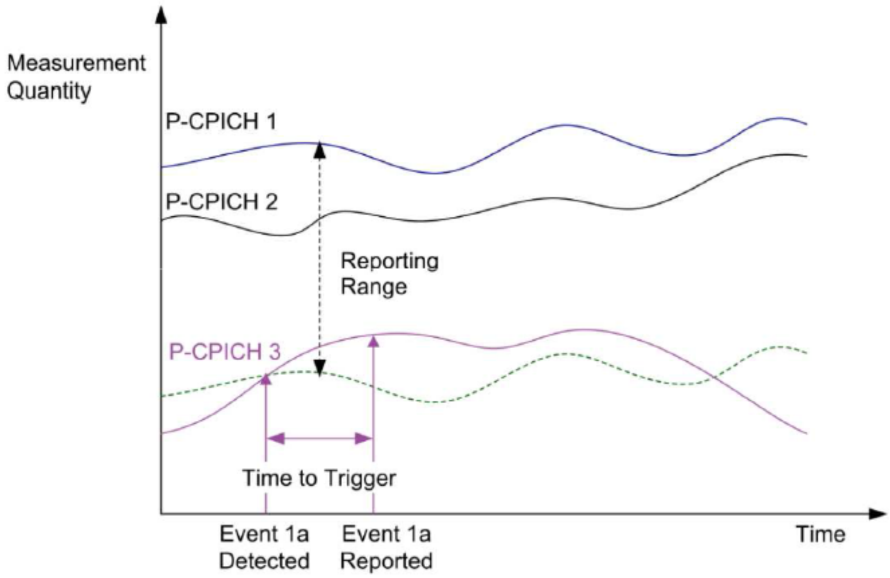

Figure 3.5. New cell enters the reporting range [29].

1B indicates that the cell leaving the reporting range should be removed from the active set. It is triggered if Equation 3.9 is fulfilled for TTT period:

$$10logM_{Old}+CIO_{Old} \leq W10log\left(\sum_{i=1}^{N}(\frac{1}{M_i})\right)+(1-W)10logM_{Best}-(R_{1b}+H_{1b}/2), \quad (3.9)$$

where M_{Old}, M_i and M_{Best} denote the measured quantity for the cell to be removed, the cells in the active set and the highest measured quantity, respectively. CIO_{Old} represents the cell individual offset and the number of cells in the active set is referred as N. R_{1b} is the reporting range constant, H_{1b} is the hysteresis value and W is the normalization parameter. Equation 3.9 shows that the cell removal event occurs if the measured quantity of the cell to be removed is less than the weighed sum of the measured quantities of the cells in the active set with a hysteresis value for TTT period.

When a non-active primary CPICH becomes better than an active primary CPICH, event 1C is reported. Event 1C refers that the active set is full and the weakest cell in the active set is removed and a new cell is added. It is triggered if Equation 3.10 is

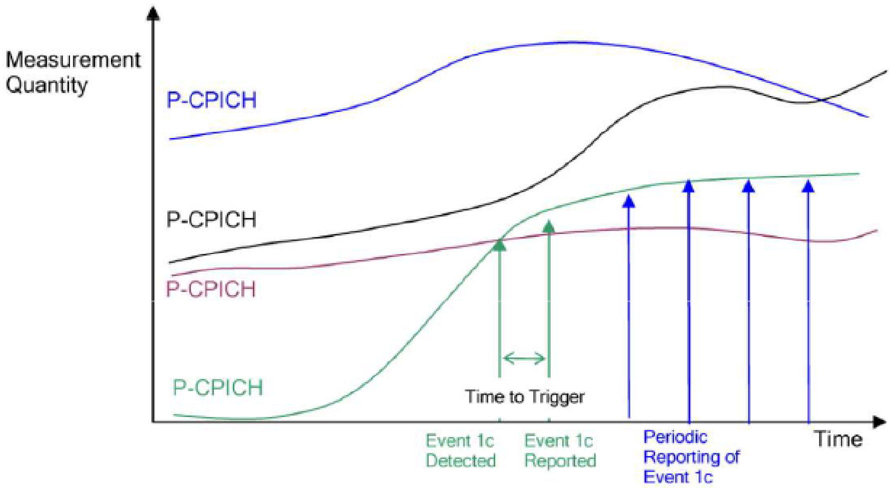

Figure 3.6. Addition of the new cell to the active set and removal of the weakest cell [29].

satisfied for TTT period:

$$10LogM_{New} + CIO_{New} \geq 10LogM_{InAS} + CIO_{InAS} + H_{1c}/2, \tag{3.10}$$

where M_{New} and M_{InAS} denote the measurement result of the new cell and the weakest cell in the active set, respectively; CIO_{New} and CIO_{InAS} are the individual cell offsets of the new cell and the weakest cell, respectively; and is H_{1c} is the hysteresis parameter. When the active set is full, a new cell cannot be added to the active set, therefore the cell with the weakest cell in the active set should be removed to make room for the better cell. Figure 3.6 depicts the addition of the new cell to the active set and removal of the weakest cell from the active set with the measurement event 1C [29].

Reporting event 1D is generated when the best cell changes in the active set. It generally initiates a hard handover in HSDPA. The change of best cell event is triggered if Equation 3.11 is fulfilled for TTT period:

$$10LogM_{NotBest} + CIO_{NotBest} \geq 10LogM_{Best} + CIO_{Best} + H_{1d}/2, \tag{3.11}$$

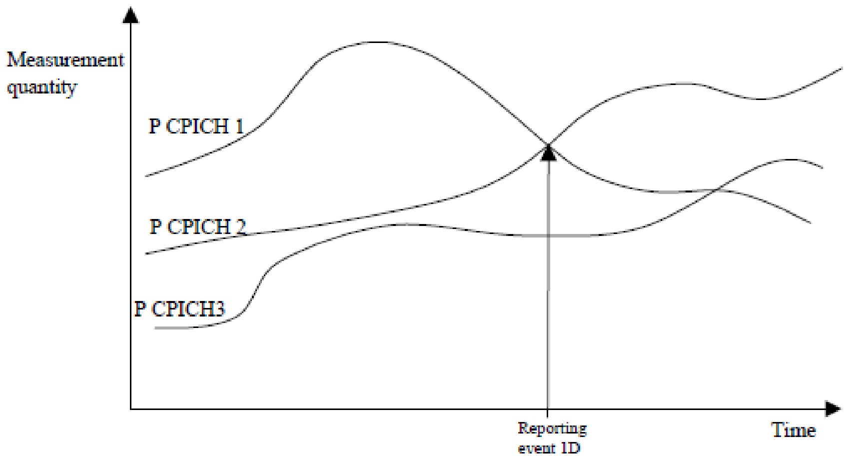

Figure 3.7. Change of best cell [27].

where M_{Best} and $M_{NotBest}$ denote the measurement result of the best cell and the cell that will be the best cell after the 1D event, respectively; $CIO_{NotBest}$ and CIO_{Best} are the cell individual offsets of the cells and H_{1d} is the hysteresis parameter. Figure 3.7 depicts the change of best cell with the measurement event 1D [27]. Hysteresis, TTT and the cell individual offsets are not included in the figure.

Reporting event 1E occurs when a new cell exceeds an absolute threshold. After event 1E is generated, a new cell is added to the active set as after the event 1A. However event 1E is based on the threshold method. It is triggered if Equation 3.12 is satisfied for TTT period:

$$10LogM_{New} + CIO_{New} \geq T_{1e} + H_{1e}/2, \tag{3.12}$$

where M_{New} denotes the measurement result of the new cell and CIO_{New}, T_{1e} and H_{1e} are the cell individual offset, the threshold and the hysteresis values for the event, respectively. The cell addition occurs if the measured quantity of the new cell is higher than an absolute threshold with a hysteresis value for TTT period and the active set size is not full. Figure 3.8 depicts the cell addition to with measurement event 1E [27]. Hysteresis, TTT and the cell individual offsets are not included in the figure.

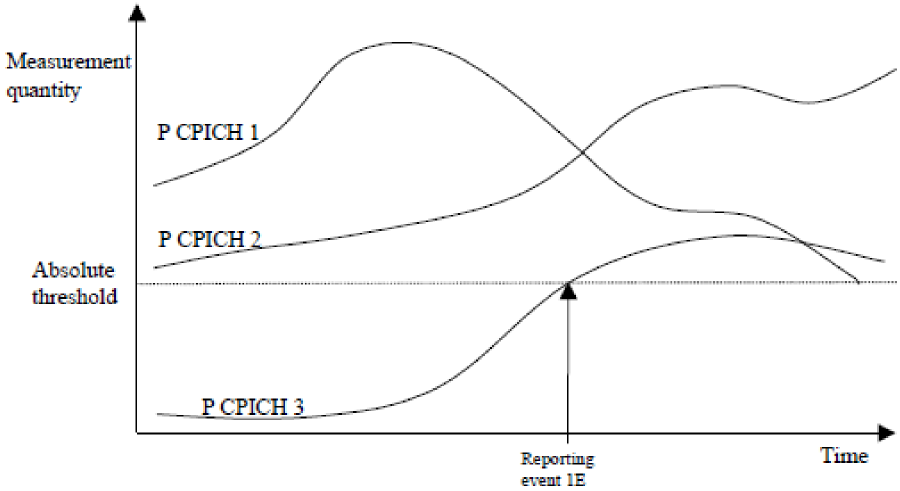

Figure 3.8. Addition a new cell to active set with threshold method [27].

Reporting event 1F occurs when a cell in the active set is less than an absolute threshold. Event 1F refers to the removal of a cell from the active set as in the event 1B. However event 1F is based on threshold method. It is triggered if Equation 3.13 is satisfied for TTT period:

$$10LogM_{Old} + CIO_{Old} \leq T_{1f} - H_{1f}/2, \tag{3.13}$$

where M_{Old} denotes the measurement result of the cell to be removed from the active set and CIO_{Old}, T_{1f} and H_{1f} are the cell individual offset, the threshold and the hysteresis values for the event, respectively. The cell removal occurs if the measured quantity of the cell is less than an absolute threshold with a hysteresis value for TTT period as shown in Figure 3.9 [27]. Hysteresis, TTT and the cell individual offsets are not included in the figure.

When a non-active Enhanced uplink DCH (E-DCH) but active DCH primary CPICH becomes better than an active E-DCH primary CPICH, event 1J is reported. Event 1J generally indicates that the active set is full and the weakest cell in the E-DCH active set is removed from the E-DCH active set and a new cell that is already in the DCH active set but not in the E-DCH active set is added to the E-DCH active

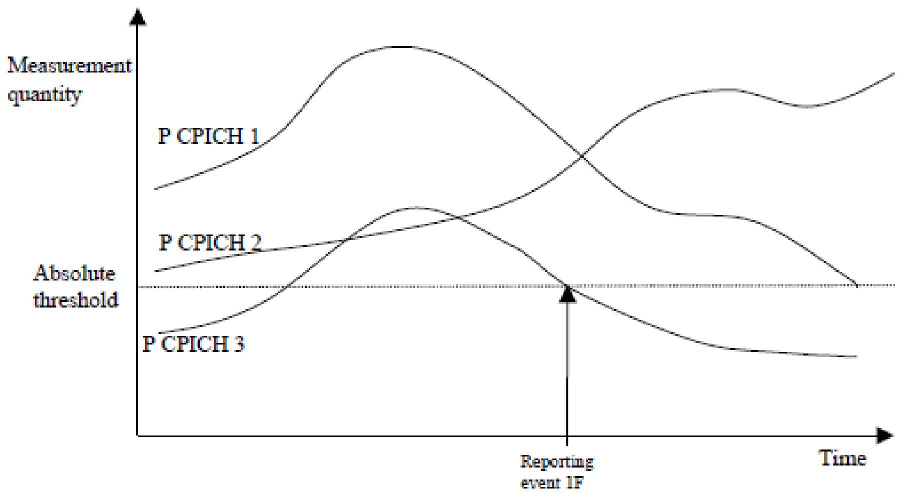

Figure 3.9. Removal of a cell from active set with threshold method [27].

set. It is triggered if Equation 3.14 is fulfilled for TTT period:

$$10LogM_{New} + CIO_{New} \geq 10LogM_{InAS} + CIO_{InAS} + H_{1j}/2, \qquad (3.14)$$

where M_{New} and M_{InAS} denote the measurement result of the new cell and the weakest cell in the E-DCH active set, respectively; CIO_{New} and CIO_{InAS} are the individual cell offsets of the new cell and the weakest cell, respectively; and H_{1j} is the hysteresis parameter of event 1J. When the E-DCH active set is full, even a new cell that is already in DCH active set cannot be added to the E-DCH active set, therefore the cell with the weakest cell in the E-DCH active set should be removed from the E-DCH active set in order to make room for the better cell. Figure 3.10 depicts the addition of the new cell to the E-DCH active set and removal of the weakest cell from the E-DCH active set with the measurement event 1J [27].

When events 1A and 1E are triggered, a new cell is added to the active set. Event 1A is reported when the new cell exceeds the weighed sum of the cells in the active set, whereas Event 1E is reported when the new cell exceeds a certain threshold. When events 1B and 1F occur, a cell is removed from the active set. Event 1B is reported when the quality of a cell in the active set is less than the weighed sum of the measured

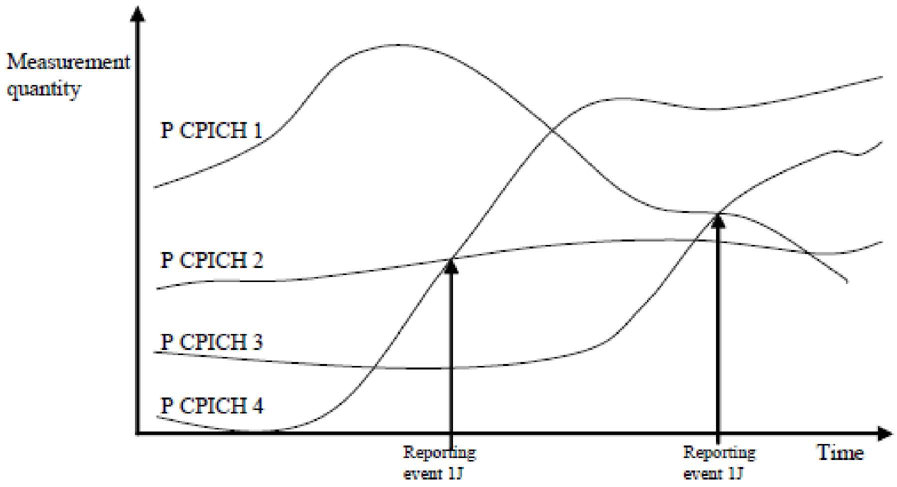

Figure 3.10. A non-active E-DCH but active DCH cell becomes better than an active E-DCH cell [27].

qualities of the cells in the active set, whereas Event 1F is reported when the measured quality of a cell in the active set is less than a certain threshold. When events 1C and 1J are triggered, a better cell is replaced with the weakest cell in the active set. The quality of the new cell should be better than the removed cell. Event 1D is the change of best cell, generally used in the hard handover in HSDPA [27].

3.2.3. Hysteresis

In order to limit ping-pong effects caused by successive handovers or to restrict the excessive amount of triggered reports, a hysteresis value is used in each reporting criterion Equations 3.1-3.3, 3.8-3.14. The usage of hysteresis to decrease the number of unnecessary handovers or active set updates is supported in 3GPP technical specification as depicted in Figure 3.11 [27]. Since the cell exceeds the best cell with the hysteresis value, reporting event is generated first; however after a period even if the cell becomes better than the best cell the report is not generated because it does not exceed the best cell with the hysteresis value.

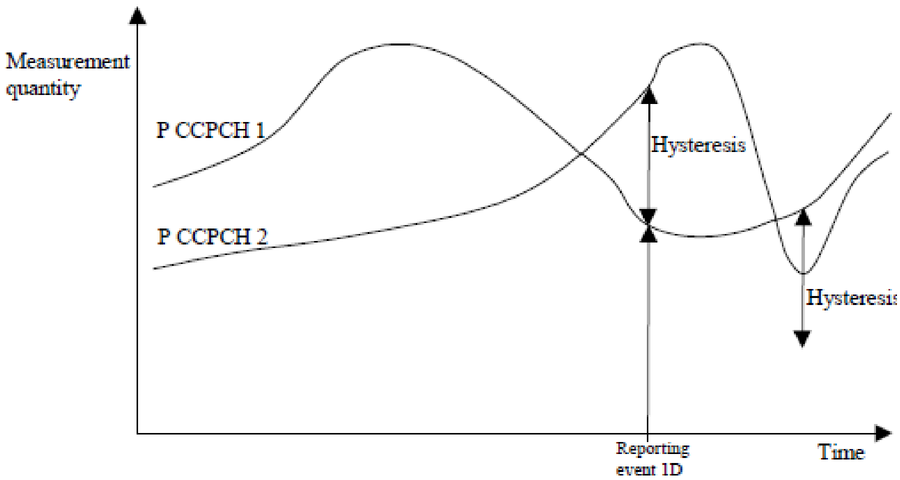

Figure 3.11. Hysteresis limits the amount of measurement reports [27].

3.2.4. Time-to-Trigger

Time-to-Trigger is used in each reporting criterion Equations 3.1-3.3, 3.8-3.14 similar to the hysteresis parameter in order to limit excessive amount of triggered reports. Each reporting event is triggered only if the criterion is fulfilled for Time-to-Trigger period. The usage of Time-to-Trigger to decrease the number of unnecessary handovers or active set updates is supported in 3GPP technical specification as shown in Figure 3.12 [27]. Even if the cell is within the reporting range, the measurement report is not generated since it leaves the reporting range within the Time-to-Trigger period. When only the new cell is in the reporting range for Time-to-Trigger period, the report is generated and the cell is added to the active set.

3.3. One-Tier Handover Decision Algorithms

Handover algorithms aim to optimize handover decisions in order to minimize the call drop rate and the number of unnecessary handovers. A variety of parameters have been suggested in the field of handover decision algorithms. The wireless link quality between an user equipment and a macrocell base station is evaluated by the following parameters: Bit error rate, signal to noise ratio, distance, traffic load, received signal

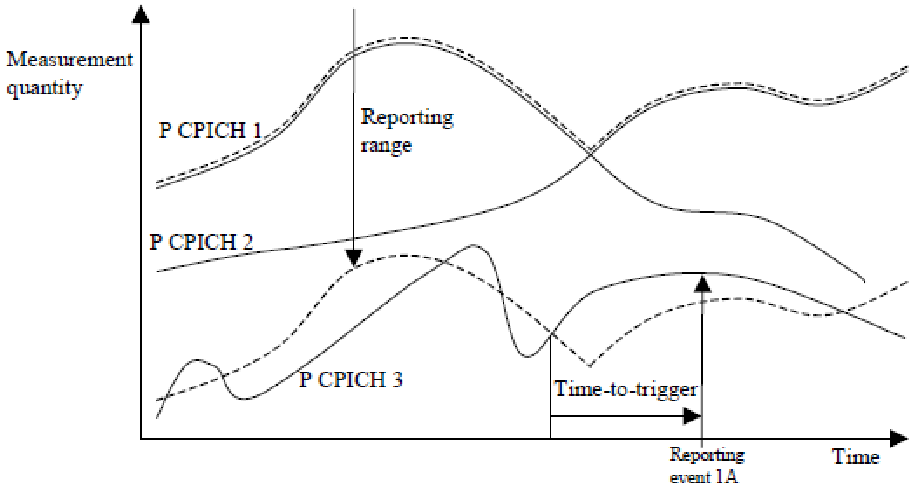

Figure 3.12. Time-to-Trigger limits the amount of measurement reports [27].

strength, and different combinations of these parameters [5, 30–37]. Received signal strength based algorithms are simple to simulate and give satisfactory results, therefore they have received considerable attention [5, 30–37].

The simplest handover algorithm based on the received signal strength is the one that the mobile equipment selects the base station with the highest RSS. However, this simplest algorithm leads to unnecessary handovers when the serving base station signal can provide call continuity [30]. Gudmundson analyzed handover algorithms with three performance measures: the probability of lost calls, the probability of unnecessary handover and the probability of handover [30]. These performance criteria achieved a tradeoff in analyzing handover algorithms. It is shown that when the serving station signal is sufficient to maintain call quality, switching to another station creates the problem of unnecessary handovers.

Introducing a hysteresis margin can block unnecessary successive handovers caused by shadowing effects. Vijayan and Holtzman proposed a model for evaluating handover algorithms that tends to minimize the handover delay and the number of handovers as the performance criteria achieved a tradeoff by changing the values of handover algorithm design parameters: hysteresis and the size of averaging interval [5]. They studied the hysteresis margin effect in a shadow fading environment and showed that hysteresis can eliminate the unnecessary handovers and the absolute value of RSS from the serving base station can be considered to avoid handovers when the weaker signal is strong enough.

Zhang and Holtzman extended the hysteresis algorithm analyzed in [5] by introducing an additional criterion based on absolute signal strength constituting a hysteresis and threshold based algorithm [31]. In this handover decision algorithm, the mobile station performs a handover if the absolute signal strength from the serving base station falls below the threshold and the relative signal strength between the candidate and the serving base stations reaches the hysteresis level.

Zonoozi, Dassanayake and Faulkner introduced a hysteresis model to find optimum a hysteresis level to achieve a tradeoff in the minimization of the performance criteria: unnecessary handovers and handover delay [32]. It is shown that for optimal handover in microcells, it is preferred to have longer averaging period and smaller hysteresis level. However, in macrocells, it is suggested to use smaller averaging period and higher hysteresis level.

Moghaddam, Vakili and Falahati proposed handover algorithms using combinations of threshold and hysteresis parameters based on RSS values [33]. In hysteresis-and-threshold method, a mobile user performs a handover if the RSS of the serving station drops below the threshold level and if the RSS of the target station is stronger than the serving station with a given hysteresis margin and if the RSS of the target station is higher than the threshold level. In hysteresis-or-threshold method [33], a mobile user performs a handover if the RSS of the serving station drops below the threshold level and the RSS of the target station is stronger than the serving station with a given hysteresis margin or the RSS of the target station is higher than the threshold level.

Kumar and Holtzman introduced a handover algorithm based on received signal strength and bit error rate [34]. The proposed algorithm performs a handover when the bit error rate of the serving station is not adequate and the RSS of target base station is stronger than the RSS of serving base station by a certain hysteresis level.

Wang, Green and Malkawi suggested an adaptive handover method based on mobile location information, cell Radio Frequency (RF) propagation statistics and signal strength [35]. Another study considering the location information as a handover decision parameter is carried out by Itoh, Watanabe, Shih and Sato [36]. The authors proposed a handover algorithm based on distance and RSS.

Akar proposed a joint power control and handover mechanism achieving a tradeoff between the performance criteria: the number of signal degradations, the number of handovers and the total power consumption [37]. The number of signal degradations criterion measures the quality of calls and the number of handovers criterion refers to the switching load to the network and total power consumption criterion reduces both the total power consumption and the interference.

3.4. Two-Tier Handover Decision Algorithms

Two tier systems approach differently to the handover decision algorithms:

- The transmit power of femtocell base stations is very low compared to macrocell base stations. In case when the distance between the MBS and FBS is very short, femtocells may not be used efficiently due to the gap between the power levels of FBS and MBS. Studies proposed an offset for femtocell signal or adding a combination of macrocell and femtocell signal strength to the femtocell received signal strength to utilize the femtocells [38, 39].
- Femtocells are deployed in a distributed random manner however macrocells are installed with centralized planning. Femtocell handover parameters should change automatically to reach optimum efficiency based on the location and the power levels of neighbor femtocells and macrocells.
- Fast mobile stations passing near by femtocells may create unwanted handovers that may result in ping-pong effect increasing overall system load. Time-to-Trigger parameter is proposed in some studies in order to reduce extensive han-

dovers [40, 41].

- The backhaul line of femtocell base station is not capable of maintaining quality of service for real time voice communications, so handover decision algorithms should consider femtocell backhaul quality in order to increase user satisfaction [42–45].

Chowdhury, Ryu, Rhee, and Jang introduced a handover mechanism designed for UMTS networks [40]. The authors propose a Call Admission Control (CAC) for the minimization of unnecessary handovers caused by fast mobile users. The CAC algorithm observes the signal strength for a specific time interval (Time-to-Trigger) for the mitigation of unnecessary handover of a fast moving mobile station.

Kim and Lee offered a handover procedure and a Call Admission Control mechanism for the hybrid access mode to reduce the number of unnecessary handovers and to improve the handover performance [41]. Besides, the CAC algorithm involves user authentication.

Moon and Cho adapted the RSS-based handover algorithms to the two tier networks [39]. The handover criterion for macrocell to femtocell handover is that received signal strength from macrocell base station drops below threshold level and the relative strength between femtocell signal and macrocell signal reaches hysteresis level. As the RSS from the macrocell is generally stronger than the RSS from the femtocell, the RSS of the macrocell is factored with a number between zero and one. The factorization is used in order to overcome the handover issue when the distance between the femtocell base station and macrocell base station is short. Since the RSS value of the macrocell signal does not fall below the threshold, the handover to femtocell does not occur without factorization. Therefore, the overall system capacity is not enhanced. By using factorization, the area spectral efficiency is enhanced via increasing the femtocell network usage.

Handover from macrocell to femtocell is generally designed with received signal strength based algorithms. A different approach is proposed by Mahmoud, Guvenc and Watanabe [46]. It is suggested to choose the target femtocell according to the channel capacity.

Taleb and Ksentini introduced an admission control system for femtocells considering the predicted QoS for femtocell backhaul [42]. Their proposed solution concentrate on the handover from macrocell to femtocell via an admission control system occurring before handover. The suggested admission control is based on the collected user satisfaction levels by asking customers to rate the quality of service levels. The collected MOS values are updated via the available bandwidth and total number of users connected to the femtocell base station. The continuously updated MOS values are used as the call admission control parameter.

Another QoS based call admission control system is proposed by Olariu, Fitzpatrick, Perry and Murphy [44]. Unlike Taleb and Ksentini's work [42], the admission control mechanism calculates its MOS without asking customers. By limiting the number of calls from femtocell network, the CAC algorithm provides call quality. However, it does not initiate a handover when a call is generated first with good quality then degraded within a call.

Mase and Toyama focus on packet loss for measuring the QoS for VoIP communications [43]. The designed CAC algorithm provides a guarantee that average packet loss rate is lower than a certain threshold, if the packet loss rate passes the threshold value, the call generation is not permitted via the proposed CAC. The CAC systems work at the admittance of call generation. If the QoS degrades during a call, the CAC does not initiate handover.

An important improvement of handover decision algorithm is introduced by Becvar and Mach [45]. The proposed model focuses on handing in the femtocell network, namely macrocell to femtocell handover. The capacity and the delay of the femtocell backhaul is considered during the decision of handover. The handover is initiated if the femtocell backbone capacity and delay satisfy the requirements. The proposed model brings an important enhancement for handovers from macrocell to femtocell however it does not provide handover decisions from femtocell to macrocell.

3.5. The Summary of the Chapter

Handover is defined as the process of transferring a current call or data communication from one cell to another in order to achieve call continuation. Handovers are categorized in terms of used access technologies, as vertical and horizontal handover; in terms of the system, as intra-system handover and inter-system handover, and in terms of the cell diversity, as hard handover and soft handover.

Two tier femtocell-macrocell systems have different issues for handover decision algorithms. The transmit power of femtocell base stations is low when compared to macrocell base stations. In case when the distance between the MBS and FBS is very short, femtocells may not increase the area spectral efficiency due to the gap between the power levels of FBS and MBS. Using an offset for femtocells can be a solution in these cases. Fast mobile stations passing near by femtocells may create undesired handovers that may result in ping-pong effect increasing overall system load. Using Time-to-Trigger as a handover decision algorithm parameter can decrease extensive handovers in such cases.

In 3GPP mobility standards, handovers from macrocell to femtocell or from femtocell to macrocell in two tier cellular networks use the same messaging architecture and handover decision algorithms of one tier macrocellular networks [27,28]. The handover decision algorithms in the standards do not take into account the backbone quality of femtocells, however real-time voice communications over IP networks are sensitive to delay and backhaul line of femtocell base station is incapable of maintaining quality of service for real time voice communications, therefore poor femtocell backhaul quality can result in signal degradations.

In the following chapter, we propose three novel handover decision algorithms considering the quality of femtocell backhaul, introducing the delay at femtocell backbone as an algorithm parameter.

4. HANDOVER ALGORITHM DESIGN

The problem definition, the system model and proposed handover methods are described in this chapter. The parameters used in the novel algorithm and the performance metrics for evaluation of the algorithms are given.

Consider a two-tier network, one femtocell layer and one macrocell layer. The femtocell layer resides in the macrocell layer. Macrocell has long range and installed with a planning strategy whereas femtocell has short range and lower power output and is deployed without central planning. Both femtocell and macrocell base stations serve the user mobile stations at same frequency. The frequency reuse enlarges the capacity of the cellular network. Handover from a serving base station to a candidate base station has to be designed optimally to increase the overall capacity of the two tier system. A wrong handover strategy may increase the call drop probability and result in decreasing user satisfaction.

In this study, the handover decision model is designed in order to minimize the handover rate and the signal degradation rate. These parameters are chosen as performance metrics. The handover rate and the signal degradation rate are inversely proportional, therefore the parameter optimization in the handover decision model is crucial for the trade-off between the performance metrics.

4.1. The System Setup

The experimental setup used in the design and comparison of the traditional handover algorithm and the proposed algorithms contains one femtocell base station and one macrocell base station. The mobile station walks with a constant speed from the start point to the end point. The received signal strength of mobile station for both the base stations are simulated according to the system model given in Section 4.1.1.

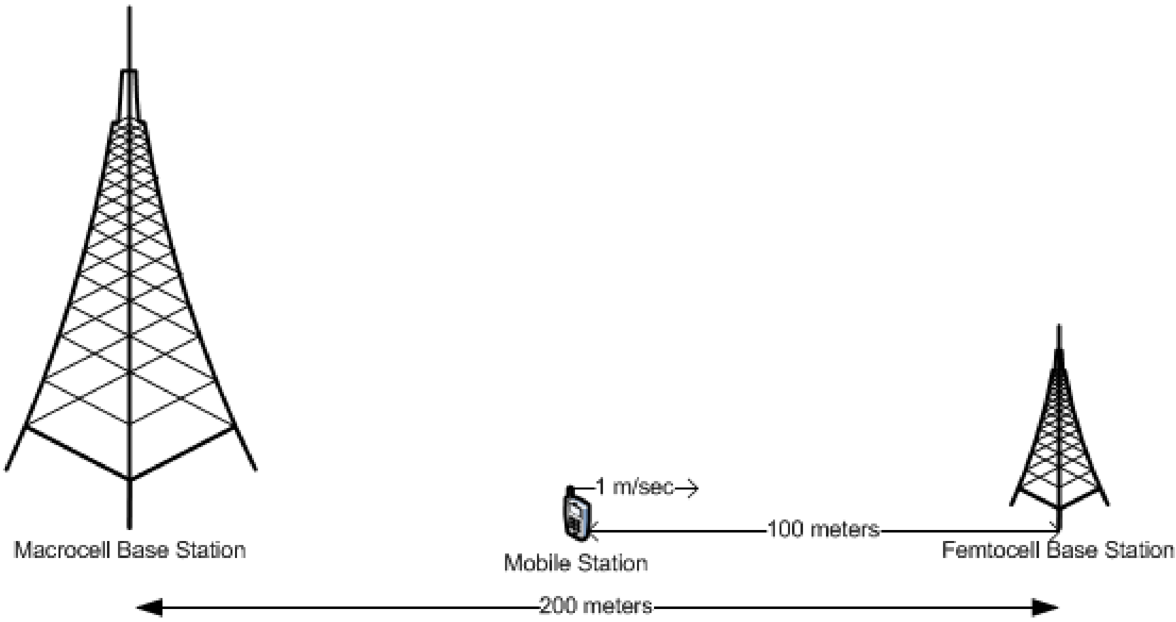

Figure 4.1. Experimental Setup.

The system setup is depicted in Figure 4.1. The distance between the macrocell base station and the femtocell base station is chosen as 200 meters and the distance from the start point of the mobile station to the femtocell base station and to the macrocell base station is 100 meters. The mobile station starts to move from its start point towards the end point with a constant velocity taken to be 1 m/sec in the simulations.

4.1.1. The Signal Model

In the signal model, the received signal strengths from macrocell and femtocell base stations are equal to the output powers of MBS and FBS minus the pathloss of macrocell and femtocell signals, respectively; that are described as

$$s_m = P_m - PL_m, \tag{4.1}$$

$$s_f = P_f - PL_f, \tag{4.2}$$

where s_m and s_f denote the RSS from MBS and FBS, respectively; P_m and P_f represent the fixed output powers of the MBS and FBS, respectively; and PL_m and PL_f refer to the pathloss for macrocell and femtocell signals, respectively. The pathloss models of macrocell and femtocell signals contain three parts given as

$$PL_m = PL_{0m} + \eta_m 10log(l_m/l_{0m}) + PL_{sm}, \tag{4.3}$$

$$PL_f = PL_{0f} + \eta_f 10log(l_f/l_{0f}) + PL_{sf}, \tag{4.4}$$

where PL_{0m} and PL_{0f} refer to the pathloss of the macrocell and femtocell signal at reference distances, l_{0m} and l_{0f}, respectively. The second part in the model is logarithmic scaling with the distance from the mobile station to the macro and femto base stations, l_m and l_f, respectively; factored with the so-called the pathloss exponents, η_m and η_f, for macrocell and femtocell signals, respectively. PL_{sm} and PL_{sf} comprise the log-normal shadowing for macrocell signal and femtocell signal, respectively. PL_{sm} and PL_{sf} are auto-correlated Gaussian random variables with zero mean in decibel unit for macrocell signal and femtocell signal, respectively [47–49]. The mobile station moving from x_i to x_j has the shadowing correlation coefficient $C(x_i, x_j)$ described as

$$C(x_i, x_j) = \rho_{l_{ij}} = \sigma^2 e^{-\frac{l_{ij}}{D_c}} \text{ where } l_{ij} = \parallel x_i - x_j \parallel, \tag{4.5}$$

where $\rho_{l_{ij}}$ denotes the correlation coefficient, and σ is the standard deviation of the Gaussian random variables and D_c is the effective correlation distance at which correlation coefficient reduces to 0.5 [50, 51]. The effective correlation distance for suburban areas is higher than the effective correlation distance for urban areas.

We can represent the correlation coefficients stated in Equation 4.5 in matrix form as

$$C = \sigma^2 \begin{bmatrix} 1 & \rho_1 & \rho_2 & \dots & \rho_{l-1} \\ \rho_1 & 1 & \rho_1 & \dots & \rho_{l-2} \\ \rho_2 & \rho_1 & 1 & \dots & \rho_{l-3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_{l-1} & \rho_{l-2} & \rho_{l-3} & \dots & 1 \end{bmatrix}, \tag{4.6}$$

where C denotes the autocovariance matrix. Since C is a positive definite symmetric matrix, it can be decomposed using Cholesky decomposition as

$$C = C_L C_U, \tag{4.7}$$

where C_L is the lower triangular matrix and C_U is the upper triangular C_U. The correlated log-normal shadowing is constituted as

$$PL_s = \alpha C_U \text{ where } \alpha_i,\ i = 1, 2, 3, \dots, l, \tag{4.8}$$

where PL_s denotes the correlated log-normal shadowing part of path-loss for macrocell signal in Equation 4.3 and femtocell signal in Equation 4.4; α is an $1 \times l$ array that is composed of normally distributed random numbers with zero mean and unit variance [50].

4.1.2. The Delay Model

In the delay model for femtocell backhaul line, two different delay probability distributions are used in order to classify the subscribers with "stable" delay at femtocell broadband lines and the subscribers with "unstable" delay at femtocell backhaul. For the subscribers who own a stable Internet broadband line, the one way delay is modeled as a shifted exponential function [21]. The delay in this backhaul does not change much in time and therefore the line does not suffer from jitter. For good Internet delay, in the simulations, random variables are used that are distributed according to the shifted exponential probability distribution (d_g) expressed as

$$d_g(x, \lambda) = \begin{cases} \lambda e^{-\lambda x} & x \geq \triangle_d \\ 0 & x < \triangle_d \end{cases}, \tag{4.9}$$

where λ and $\triangle_d$ denote the rate parameter and the shift of delay, respectively. As expected, the delay of femtocell backhaul with stable Internet conditions does not result in signal degradations. The probability of the occurrence of the event that the delay (d_f) at stable femtocell backbone exceeds the maximum acceptable delay level for voice over IP communication (T_d) can be defined as a complementary cumulative distribution function ($F(T_d; \lambda)$) as

$$F(T_d; \lambda) = \begin{cases} e^{-\lambda T_d} & T_d \geq \triangle_d \\ 0 & T_d < \triangle_d \end{cases}. \tag{4.10}$$

Since the delay threshold (T_d) exceeds the defined delay shift ($\triangle_d$), Equation 4.10 can be simplified as

$$F(T_d; \lambda) = e^{-\lambda T_d}. \tag{4.11}$$

The delay at "unstable" Internet connection is modeled as an Erlang-n probability distribution function given as

$$d_b(x, n, \lambda) = \frac{\lambda^n x^{n-1} e^{-\lambda x}}{(n-1)!} \text{ for } x, \lambda > 0, \tag{4.12}$$

where d_b denotes the Erlang-n probability distribution, and n is the number of routers the communication packets pass through [22]. The delay at femtocell backbone can be unstable, i.e., it can change rapidly in the communication duration. The real-time communications suffer from rapid increase in delay which creates jitter. The probability of the occurrence of the event that the delay (d_f) at unstable femtocell backhaul exceeds the maximum acceptable delay level for voice over IP communication

(T_d) can be defined as a complementary cumulative distribution function $(F(T_d; n, \lambda))$ as

$$F(T_d; n, \lambda) = \sum_{k=0}^{n-1} \frac{1}{k!} e^{-\lambda T_d} (\lambda T_d)^k. \tag{4.13}$$

4.2. Performance Criteria of Interest

The objective of the proposed handover algorithms is to minimize the number of handovers and the number of signal degradations as performance indicators. These performance indicators depend on the received signal strength and delay of the backhaul femtocell station broadband wired line. The tradeoff between the performance criteria leads us to achieve optimal algorithm parameters in order to minimize the performance indicators: Total number of signal degradations N_{SD} and total number of handovers N_H [37].

Total number of signal degradations can be expressed as

$$N_{SD} = \sum_{k=1}^{K} \mathbb{I}\{(d_k > T_d) \vee (s_k < T_s)\}, \tag{4.14}$$

where $\mathbb{I}\{.\}$ denotes the indicator function and K is the total number of iterations. A signal degradation is said to occur when the delay at iteration k (d_k) is more than the delay threshold (T_d) or when the RSS at iteration k (s_k) is less than the RSS threshold (T_s). Total number of signal degradations is obtained by counting each signal degradation from the start point to the end point. A signal degradation does not necessarily imply that the call is dropped since the RSS threshold level (T_s) can be chosen higher than the minimum acceptable signal level and the delay threshold (T_d) can be picked lower than the maximum acceptable delay level. Hence, the total number of signal degradations criterion (N_{SD}) can measure the call quality from the point of human user perspective. The degradations that occur when the delay exceeds the delay threshold (T_d), show the quality of service level for wired backhaul line of femtocell base station; whereas the degradations that occur when the RSS falls below the RSS threshold (T_s), assess the quality of service of the wireless link.

Total number of handovers can be described as

$$N_H = \sum_{k=1}^{K} \mathbb{I}\{M(k) = 1\}, \tag{4.15}$$

where $M(k)$ denotes the handover function that can be defined as

$$M(t) = \begin{cases} 1 & \text{if } |r(t) - r(t-1)| = 1, \\ 0 & \text{otherwise.} \end{cases} \tag{4.16}$$

In Equation 4.16, “1” is the handover state of mobile station from FBS to MBS or from MBS to FBS and “0” is the state that the mobile station stays at the serving station and the state function ($r(t)$) of the mobile station can be written as

$$r(t) = \begin{cases} 1 & \text{MS served by MBS at time } t, \\ 0 & \text{MS served by FBS at time } t. \end{cases} \tag{4.17}$$

In Equation 4.17, “1” is the state of mobile station if served by MBS and “0” is the state of mobile station if served by FBS.

The total number of handovers (N_H) criterion indicates the burden of the handovers to the cellular network since it is crucial to prevent excessive switching between the femtocell and the macrocell base stations.

4.3. Traditional Handover Algorithm

In this section, the conventional handover decision design based on threshold and hysteresis parameters are given briefly in mathematical formulation and in algorithmic form.

Traditional handover algorithm tends to achieve a tradeoff between the total number of signal degradations (N_{SD}) and the total number of handovers (N_H), where N_{SD} and N_H are described in Equations 4.14 and 4.15, respectively.

The probability of signal degradation ($Pr[SD]$) is the probability of the occurrence of the event that the received signal strength from the serving base station (s) falls below a threshold (T_s). It can be described as

$$Pr[SD] = Pr[s < T_s]. \tag{4.18}$$

The probability of signal degradation when the mobile station is served by MBS ($Pr[SD_m]$) can be described as

$$Pr[SD_m] = Pr[s_m < T_s]. \tag{4.19}$$

If the received signal strength of macrocell signal (s_m) defined in Equation 4.1 is combined in Equation 4.19, $Pr[SD_m]$ can be written as

$$Pr[SD_m] = Pr[P_m - PL_m < T_s]. \tag{4.20}$$

The pathloss of macrocell signal (PL_m) defined in Equation 4.3 can be put in Equation 4.20 as

$$Pr[SD_m] = Pr[P_m - PL_{0m} - \eta_m 10log(\frac{l_m}{l_{0m}}) - PL_{sm} < T_s]. \tag{4.21}$$

The probability of signal degradation when the mobile station is served by MBS ($Pr[SD_m]$) can be given as

$$Pr[SD_m] = Q\left(\frac{-T_s + m(l_m)}{\bar{\sigma_m}}\right), \tag{4.22}$$

where $m(l_m)$, $\bar{\sigma}$ and Q are described as

$$m(l_m) = P_m - PL_{0m} - \eta_m 10log(l_m/l_{0m}), \tag{4.23}$$

$$\bar{\sigma_m}^2 = \sigma_m^2(1 - a^2), \text{ where } a = e^{-d_s/D_c}, \tag{4.24}$$

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \mathrm{e}^{-t^2/2}\,\mathrm{d}t. \tag{4.25}$$

In Equation 4.24, d_s denotes the sampling distance used in the correlation coefficients described in Equation 4.5.

The probability of signal degradation when the mobile station is served by FBS ($Pr[SD_f]$) can be expressed as

$$Pr[SD_f] = Pr[s_f < T_s]. \tag{4.26}$$

If the received signal strength of femtocell signal (s_f) defined in Equation 4.2 is combined in Equation 4.26, $Pr[SD_f]$ can be written as

$$Pr[SD_f] = Pr[P_f - PL_f < T_s]. \tag{4.27}$$

The pathloss of femtocell signal (PL_m) defined in Equation 4.4 can be rewritten in Equation 4.27 as

$$Pr[SD_f] = Pr[P_f - PL_{0f} - \eta_f 10log(\frac{l_f}{l_{0f}}) - PL_{sf} < T_s]. \tag{4.28}$$

The probability of signal degradation when the mobile station is served by FBS ($Pr[SD_f]$)

can be given as

$$Pr[SD_f] = Q\left(\frac{-T_s + m(l_f)}{\bar{\sigma_f}}\right), \tag{4.29}$$

where $m(l_f)$ and $\bar{\sigma_f}$ are described as

$$m(l_f) = P_f - PL_{0f} - \eta_f 10log(l_f/l_{0f}), \tag{4.30}$$

$$\bar{\sigma_f}^2 = \sigma_f^2(1 - a^2). \tag{4.31}$$

The probabilities of signal degradation if the mobile station is served by MBS or if the mobile station is served by FBS are given in Equations 4.22 and 4.29, respectively.

The handover function $(M(t))$ for the conventional handover algorithm can be given as

$$M(t) = \begin{cases} 1 & \text{if } r(t) = 1 \text{ and } \mathbb{I}\{(s_m + h < s_f) \wedge (s_m < T_s)\}, \\ & \text{or } r(t) = 0 \text{ and } \mathbb{I}\{(s_f + h < s_m) \wedge (s_f < T_s)\}, \\ 0 & \text{otherwise.} \end{cases} \tag{4.32}$$

where $r(t)$ denotes the state function of the mobile station defined in Equation 4.17. In Equation 4.32, "1" is the handover state of mobile station from FBS to MBS or from MBS to FBS and "0" is the state that the mobile station stays at the serving station.

Traditional handover algorithm design utilizes the received signal strength from MBS and FBS as a measure of signal quality. Handover from a macrocell to a femtocell occurs only when the signal quality of the candidate base station is higher than the signal quality of the serving base station with a hysteresis value and the signal level of the serving base station is lower than a threshold value. The hysteresis test is used in order to reduce unnecessary handovers. The RSS threshold and hysteresis parameters are optimized in the traditional handover algorithm in order to minimize a weighted sum of the total number of handovers and the total number of signal degradations.

The conventional handover algorithm does not take into account the quality of service aspects of the wired broadband line. Handover decision algorithms in two tier networks are similar to the algorithms in one tier network in 3GPP mobility standards as given in Section 3.2 [27, 28]. The backbone quality of FBS should be considered in the handover decision algorithms in order to decrease the number of signal degradations that can be rooted from the low quality of wired broadband line properties. One of these properties, explicitly the delay property is used to increase the signal level quality at the novel handover methods.

4.4. Proposed Handover Algorithms

The handover model proposed in this study is based on not only the received signal strength from the serving and candidate base stations but also the delay of the backhaul broadband wired connection to the core network of the operator. The received signal strength demonstrates the wireless signal quality and the delay at femtocell backbone measures the quality of service level of the wired medium of the femtocell backhaul. Similar to the traditional handover model, the proposed handover decision models aim to decrease the signal degradation and the unnecessary handover rates. However the suggested algorithms differ from the conventional algorithm in the definition of the signal degradation. The signal degradation in two tier networks consists of both the wireless signal degradation and the wired signal degradation.

Given Equations 4.14 and 4.15, the objective is to derive handover decision algorithms in order to minimize a weighted sum of the performance criteria, N_{SD} and N_H. The received signal strength of the serving base station is compared to the received signal strength of the candidate base station and besides the delay at the femtocell backhaul connection to the core network is taken into account. The parameters used in the handover decisions are the received signal strength level and the delay at femtocell backbone. In order to decrease the number of undesired handovers and forestall the ping-pong effect, the hysteresis test and the threshold method are used and these parameters are optimized to minimize the rate of handovers and signal degradations.

Three different handover algorithms are proposed in this study. All three algorithms consider the delay at femtocell backbone as well as the received signal strength as algorithm metrics.

4.4.1. Proposed Handover Algorithm I

The first handover algorithm proposed in this study endeavors to achieve a trade-off between the total number of signal degradations (N_{SD}) and the total number of handovers (N_H), where N_{SD} and N_H are described in Equations 4.14 and 4.15, respectively.

The handover function suggested in this handover decision algorithm is defined as

$$M(t) = \begin{cases} 1 & \text{if } r(t) = 1 \text{ and } \mathbb{I}\{(s_m + h < s_f) \wedge (s_m < T_s) \wedge (d_f < T_d)\} \\ & \text{or } r(t) = 0 \text{ and } \mathbb{I}\{(s_f + h < s_m) \wedge ((s_f < T_s) \vee (d_f > T_d))\}, \\ 0 & \text{otherwise,} \end{cases} \quad (4.33)$$

where $r(t)$ denotes the state function of the mobile station defined in Equation 4.17. The first proposed handover decision algorithm represented in Equation 4.33 performs a handover from macrocell to femtocell or from femtocell to macrocell based on the algorithm metrics: the received signal strength (s) and femtocell backhaul delay (d_f) and the algorithm variables: delay threshold (T_d), RSS threshold (T_s) and hysteresis (h).

If the serving cell is a macrocell base station, handover occurs only if the received signal strength of femtocell (s_f) is higher than the received signal strength of macrocell

(s_m) with a hysteresis (h), and if the received signal strength of the serving macrocell base station (s_m) falls below the RSS threshold (T_s), and if the femtocell backhaul delay (d_f) is less than the delay threshold (T_d). That's to say, in order to perform a handover from macrocell to femtocell both the wired quality of service and the wireless signal quality should be maintained, otherwise mobile station stays at the serving macrocell.

The algorithm performs a handover from femtocell to macrocell if the received signal strength of macrocell (s_m) is higher than the received signal strength of femtocell (s_f) with a hysteresis (h) and if either the received signal strength of femtocell (s_f) falls below the RSS threshold (T_s) or the delay at femtocell backhaul (d_f) exceeds the delay threshold (T_d); i.e., the mobile station initiates a handover from femtocell to macrocell if wired or wireless signal degradation is about to occur at femtocell serving station and if the macrocell signal quality is better than the femtocell signal quality with a hysteresis. Hysteresis test is performed in order to prevent excessive switching.

The proposed algorithm utilizes the delay at femtocell backbone as an algorithm metric that is not taken into account in the handover decision algorithms of 3GPP standards.

4.4.2. Proposed Handover Algorithm II

The second handover algorithm proposed in this study tends to achieve a trade-off between the total number of signal degradations (N_{SD}) and the total number of handovers (N_H), where N_{SD} and N_H are described in Equations 4.14 and 4.15, respectively.

The handover function suggested in this handover decision algorithm is defined as

$$M(t) = \begin{cases} 1 & \text{if } r(t) = 1 \text{ and } \mathbb{I}\{(s_m + h < s_f) \wedge (s_m < T_s) \wedge (d_f < T_d)\} \\ & \text{or } r(t) = 0 \text{ and } \mathbb{I}\{((s_f + h < s_m) \wedge (s_f < T_s)) \vee ((s_m > T_s) \wedge (d_f > T_d))\}, \\ 0 & \text{otherwise,} \end{cases} \tag{4.34}$$

where $r(t)$ denotes the state function of the mobile station defined in Equation 4.17. The handover decision algorithm represented in Equation 4.34 performs a handover from macrocell to femtocell or from femtocell to macrocell based on the algorithm metrics: the received signal strength (s) and femtocell backhaul delay (d_f) and the algorithm variables: delay threshold (T_d), RSS threshold (T_s) and hysteresis (h).The second proposed algorithm utilizes the same metrics as in the first proposed algorithm in Equation 4.33.

If the serving cell is a macrocell base station, the handover decision algorithm from macrocell to femtocell is the same as in the first algorithm. A handover occurs only if the received signal strength of femtocell (s_f) is higher than the received signal strength of macrocell (s_m) with a hysteresis (h), and if the received signal strength of the serving macrocell base station (s_m) falls below the RSS threshold (T_s), and if the femtocell backhaul delay (d_f) is less than the delay threshold (T_d).

If the serving cell is a femtocell base station, handover is performed only if either the received signal strength of macrocell (s_m) is higher than the received signal strength of femtocell (s_f) with a hysteresis (h) and if the received signal strength of femtocell (s_f) falls below the RSS threshold (T_s); or if the received signal strength of macrocell (s_m) is higher than the RSS threshold (T_s) and the delay of femtocell backhaul (d_f) exceeds the delay threshold (T_d). Femtocell to macrocell handover in the second algorithm is handled if the wireless signal quality or the quality of service of femtocell backbone is about to degrade.

The second proposed algorithm differs from the first suggested algorithm at handovers from femtocell to macrocell. If the signal degradations rooted from low wireless signal quality and poor femtocell backbone are separately analyzed; handover decision based on the wireless (RSS based) signal degradation is the same in first and second algorithms, both algorithms use hysteresis and threshold tests. Handover decision rooted from the femtocell backbone (delay based) signal degradation is made if the delay at femtocell backhaul line exceeds the delay threshold. However, the wireless signal quality of the candidate macrocell should be tested in order to prevent excessive switching. In the first algorithm the wireless signal quality of the candidate base station is checked by hysteresis test; whereas in the second algorithm it is based on threshold test.

4.4.3. Proposed Handover Algorithm III

The third handover algorithm proposed in this study endeavors to achieve a tradeoff between the total number of signal degradations (N_{SD}) and the total number of handovers (N_H), where N_{SD} and N_H are described in Equations 4.14 and 4.15, respectively. The tradeoff between N_{SD} and N_H can be reached via the minimization of a weighed sum of the probability of signal degradation and the probability of handover that can be given as

$$\text{Minimize } Pr[\text{Signal Degradation}] + cPr[\text{Handover}], \tag{4.35}$$

where c denotes the cost of handover.

The probability of signal degradation ($Pr[SD]$) is defined as the probability of occurrence of the event that the delay at serving station backbone (d) exceeds the maximum acceptable delay level for voice over IP communications (T_d) or the received signal strength (s) falls below the minimum acceptable received signal strength level (T_s). $Pr[SD]$ can be formulated as

$$Pr[SD] = Pr[(d > T_d) \mid\mid (s < T_s)] \tag{4.36}$$

$$= 1 - Pr[(d \leq T_d) \,\&\, (s \geq T_s)]. \tag{4.37}$$

Since the delay of the wired backhaul is independent of the received signal level of the mobile station, Equation 4.37 can be simplified as

$$Pr[SD] = 1 - Pr[d \leq T_d] \; Pr[s \geq T_s]. \tag{4.38}$$

The probability of signal degradation when the mobile station is served by MBS ($Pr[SD_m]$) can be described as

$$Pr[SD_m] = 1 - Pr[d_m \leq T_d] \; Pr[s_m \geq T_s]. \tag{4.39}$$

Since the backhaul connection to the core network of the macrocell is capable of guaranteed quality of service for real time voice communications and the delay at macrocell backbone (d_m) is very low compared to the maximum acceptable delay level (T_d), the signal degradation rooted from macrocell backhaul is negligible. Therefore, Equation 4.39 can be simplified as

$$Pr[SD_m] = Pr[s_m < T_s]. \tag{4.40}$$

If the received signal strength of macrocell signal (s_m) defined in Equation 4.1 is combined in Equation 4.40, $Pr[SD_m]$ can be written as

$$Pr[SD_m] = Pr[P_m - PL_m < T_s]. \tag{4.41}$$

The pathloss of macrocell signal (PL_m) defined in Equation 4.3 can be put in Equation 4.41 as

$$Pr[SD_m] = Pr[P_m - PL_{0m} - \eta_m 10log(\frac{l_m}{l_{0m}}) - PL_{sm} < T_s]. \tag{4.42}$$

The probability of signal degradation when the mobile station is served by MBS

$(Pr[SD_m])$ can be given as

$$Pr[SD_m] = Q\left(\frac{-T_s + m(l_m)}{\bar{\sigma_m}}\right), \tag{4.43}$$

where $m(l_m)$, $\bar{\sigma}$ and Q are described as

$$m(l_m) = P_m - PL_{0m} - \eta_m 10log(l_m/l_{0m}), \tag{4.44}$$

$$\bar{\sigma_m}^2 = \sigma_m^2(1 - a^2), \text{ where } a = e^{-d_s/D_c}, \tag{4.45}$$

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \mathrm{e}^{-t^2/2}\,\mathrm{d}t. \tag{4.46}$$

The probability of signal degradation when the mobile station is served by FBS $(Pr[SD_f])$ can be expressed using Equation 4.38 as

$$Pr[SD_f] = 1 - Pr[d_f \leq T_d]\ Pr[s_f \geq T_s]. \tag{4.47}$$

If the received signal strength of femtocell signal (s_f) defined in Equation 4.2 is combined in Equation 4.47, $Pr[SD_f]$ can be written as

$$Pr[SD_f] = 1 - Pr[d_f \leq T_d]\ Pr[P_f - PL_f \geq T_s]. \tag{4.48}$$

The pathloss of femtocell signal (PL_f) defined in Equation 4.4 can be rewritten in Equation 4.48 as

$$Pr[SD_f] = 1 - Pr[d_f \leq T_d]\ Pr[P_f - PL_{0f} - \eta_f 10log(\frac{l_f}{l_{0f}}) - PL_{sf} \geq T_s]. \tag{4.49}$$

The probability of signal degradation when the mobile station is served by FBS $(Pr[SD_f])$

given in Equation 4.49 can be written as

$$Pr[SD_f] = 1 - Q\left(\frac{T_s - m(l_f)}{\bar{\sigma_f}}\right)(1 - F(T_d)), \tag{4.50}$$

where the complementary cumulative distribution functions $(F(T_d))$ for stable delay and unstable delay at femtocell backbone are defined in Equations 4.11 and 4.13, respectively; Q is given in Equation 4.46; and $m(l_f)$ and $\bar{\sigma_f}$ are described as

$$m(l_f) = P_f - PL_{0f} - \eta_f 10log(l_f/l_{0f}), \tag{4.51}$$

$$\bar{\sigma_f}^2 = \sigma_f^2(1 - a^2). \tag{4.52}$$

The handover function $(M(t))$ suggested in this handover decision algorithm is given as

$$M(t) = \begin{cases} 1 & \text{if } r(t) = 1 \text{ and } Pr(SD_m) > c + Pr(SD_f), \\ & \text{or } r(t) = 0 \text{ and } Pr(SD_f) > c + Pr(SD_m), \\ 0 & \text{otherwise.} \end{cases} \tag{4.53}$$

The third proposed algorithm is based on the probability of signal degradation and the cost of handover. The probability of signal degradation consists of both the wired and the wireless medium degradations. If the signal degradation probability at time $t + t_s$ of the serving cell is more than the signal degradation probability at time $t + t_s$ of the candidate cell with the cost of handover, the mobile station performs handover to the candidate cell. The probability of signal degradation at time $t + t_s$ is calculated at time t.

If the serving cell is macrocell, the probability of degradation is the probability that the macrocell received signal strength falls below the RSS threshold at time $t + t_s$ based on the measured RSS value at time t. If the serving cell is femtocell, the probability of degradation is the probability that the femtocell received signal strength is less than the RSS threshold or the delay at femtocell backhaul line exceeds the delay threshold at time $t + t_s$ based on the measured values of RSS and delay at time t.

4.5. The Summary of the Chapter

The system setup, the signal model, the delay model, the performance criteria of interest and proposed handover methods are described in this chapter. The parameters used in the novel algorithms and the performance metrics for evaluation of the algorithms are given.

The experimental setup used in the design and comparison of the traditional handover algorithm and the proposed algorithms contains one femtocell base station and one macrocell base station. The mobile station walks with a constant speed from the start point to the end point. The received signal strength of mobile station from both the base stations are simulated according to the system model given in Section 4.1.1.

In the delay model for femtocell backhaul line, two different delay probability distributions are used in order to classify the subscribers with "stable" delay at femtocell broadband lines and the subscribers with "unstable" delay at femtocell backhaul. The delay at stable femtocell backhaul is modeled as a shifted exponential function given in Equation 4.9. The delay at "unstable" Internet connection is modeled as an Erlang-n probability distribution function expressed in Equation 4.12.

The objective of the proposed handover algorithm is to achieve a tradeoff between the performance indicators: the number of handovers and the number of signal degradations. These performance indicators depend on the received signal strength and the delay at femtocell backbone. The handover model proposed in this study is based on not only the received signal strength from the serving and candidate base stations but also the delay of the backhaul broadband wired connection to the core network of the operator. The received signal strength demonstrates the wireless signal quality and the delay at femtocell backbone measures the quality of service level of the wired medium of the femtocell backhaul.

Three different handover algorithms are proposed in this study. The simulation results of these algorithms are demonstrated in the following chapter.

5. SIMULATION STUDIES

In this chapter, the proposed algorithms are tested numerically and the numerical results are given in order to demonstrate the gains and tradeoffs achievable by using delay parameter as a metric in handover decision algorithms in two tier femtocell networks.

5.1. Simulation Environment and Parameters

Table 5.1. Simulation Parameters.

	Parameter Values
P_m	43 dBm
P_f	10 dBm
PL_{0m}	28
PL_{0f}	38.5
η_m	3.5
η_f	2
v	1 m/s
σ_m	8
σ_f	6
l_{mf}	200 m
l_{m0}	100 m
l_{f0}	100 m
T_f	150 ms
T_s	-70 dBm
D_c	5 m
$\triangle_d$	10 ms
n	5
λ	0.05

The simulation parameters used in the system setup are depicted in Table 5.1.

The comparison of the traditional handover algorithm and the proposed handover algorithms, and the experiment setup are made by Matlab simulation. Because of the uncertain parameters presented in the system model given in Section 4.1, the Monte Carlo simulation with 10000 cycles is used to normalize the performance criteria of the algorithms.

The performance criteria described in Section 4.2 are the total number of handovers and the total number of signal degradations. The normalized number of handovers is located in the x axis and the normalized number of signal degradations is located in the y axis in the figures depicted in this chapter for comparison purposes and to demonstrate the tradeoff between the performance criteria.

Each point shown in Figures 5.1 - 5.6 generated by the simulations of the traditional and the first two proposed algorithms given in Sections 4.3, 4.4.1, 4.4.2, respectively; corresponds to the result of the simulation run with different combinations of the algorithm parameters: the delay threshold (T_d), the RSS threshold (T_s) and hysteresis (h). The algorithm parameters used in the simulations are as follows:

h= [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15] in dB,

T_s= [-90, -86, -82, -78, -74, -70, -66, -62] in dBm,

T_d= [150, 165, 180, 195, 210, 225, 240, 255, 270, 285, 300] in ms.

Each point depicted in Figures 5.1 - 5.6 generated by the simulation of the third proposed algorithm described in Section 4.4.3, corresponds to the result of the simulation run with different values of the algorithm parameter: the cost of handover (c). The algorithm parameter tested for the third algorithm in the simulations are as follows:

c= [0:0.05:1].

The performance evaluation of the proposed algorithms are categorized in two sections: stable delay at femtocell backhaul and unstable delay at femtocell backhaul. In the delay model for femtocell backhaul line described in Section 4.1.2, two different delay probability distributions are used in order to classify the subscribers with stable delay at femtocell broadband lines and the subscribers with unstable delay at femtocell backhaul. Algorithms demonstrate different characteristics in stable and unstable delay conditions at femtocell backbone, therefore the performance of algorithms are separately analyzed with respect to the delay properties of the femtocell backhaul.

5.2. Stable Delay at Femtocell Backhaul

The one way delay is modeled as a shifted exponential function in Equation 4.9 for stable delay conditions at femtocell backbone [21]. The delay in femtocell backhaul resists change and therefore the line does not suffer from jitter.

The simulation results of the traditional algorithm and the proposed algorithms are depicted according to the stable delay characteristics at femtocell backbone in Figure 5.1.

As it is expected, the simulation results of conventional algorithm and the first two proposed algorithms do not show a significant difference. Signal degradations described in Equation 4.14 occur when the received signal strength of the serving base station falls below the minimum acceptable RSS level or when the delay at femtocell backbone exceeds the maximum acceptable delay level.

Since the probability of the occurrence of the event that the delay at stable femtocell backbone exceeds the maximum acceptable delay level for voice over IP communication is very low, most of the signal degradations in Figure 5.1 occur when wireless signal quality gets poor at femtocell and macrocell boundaries, i.e., when the received signal strength of the serving base station falls below the minimum acceptable RSS level. This behavior of the proposed algorithms shows that the subscribers with clear channel and enough bandwidth on Internet broadband lines, can use femtocell

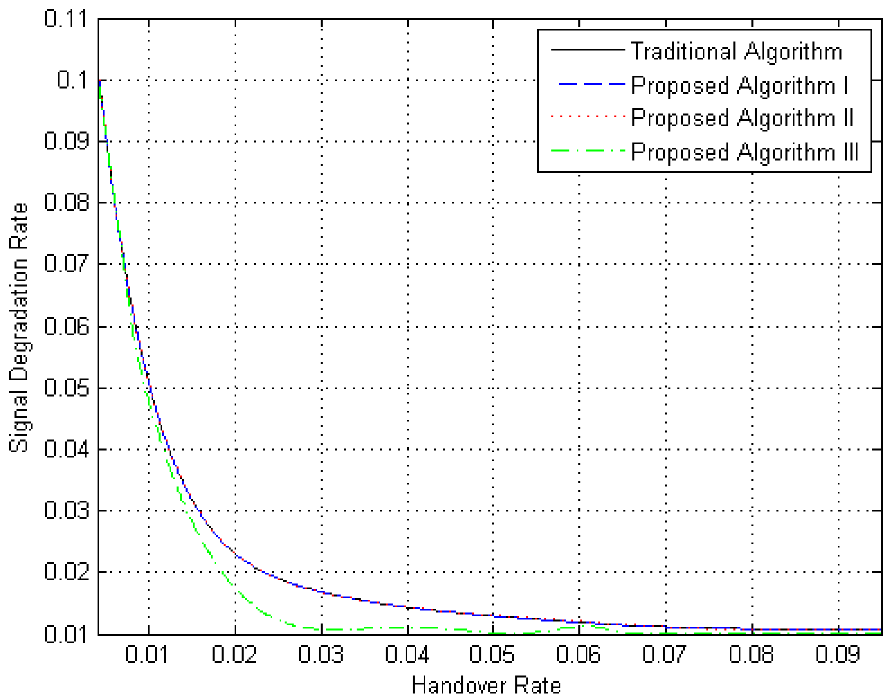

Figure 5.1. Comparison of Handover Rates vs Degradation Rates of the Algorithms at Stable Delay.

architecture readily.

The simulation of the third proposed algorithm give better results in terms of the signal degradation rate per the same handover rate than the other proposed algorithms. Besides, this algorithm reduces three algorithm parameters into one parameter. The results show that the third proposed algorithm can also be used in one tier macrocellular networks.

The tradeoff between the handover and signal degradation rates is achieved as shown in Figure 5.1. As hysteresis increases, the number of handovers is lowered and the number of signal degradations is raised expectedly. The hysteresis parameter is introduced to act as an agent that blocks ping-pong effect. If the hysteresis is kept too low, extensive unnecessary handovers occur resulting in system signaling overload and undesired use of system resources. If hysteresis is appointed too high, unnecessary han-

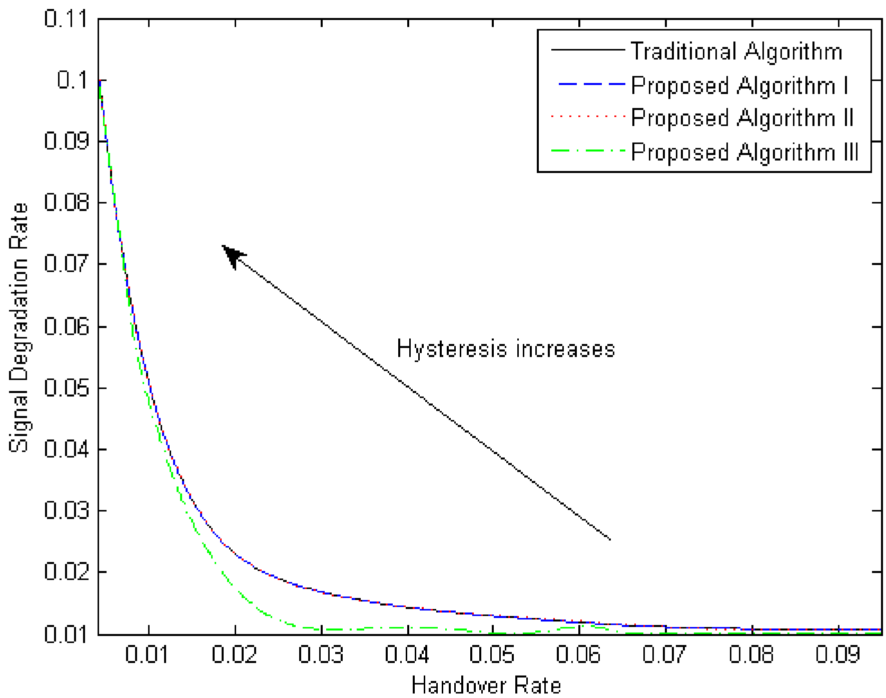

Figure 5.2. The Behavior of the Performance Criteria as Hysteresis Increases.

dovers are not performed however the number of signal degradations increases causing subscriber dissatisfaction and call drops. The behavior of the performance criteria as hysteresis increases is depicted in Figure 5.2.

RSS threshold parameter affects the performance criteria of the traditional algorithm and the proposed algorithms in case that as RSS threshold increases; the number of signal degradations decreases however the number of handovers raises. If the RSS threshold is chosen too high, the number of unnecessary handovers increases resulting in system signaling overload. If RSS threshold is picked too low, the number of signal degradations raises ending up user discontent on service quality. The behavior of the performance criteria as RSS threshold increases is shown in Figure 5.3.

The minimum value of delay threshold in the simulations is chosen as the recommended delay level for voice over IP communications [16]. The delay level of femtocell backhaul is inconsiderable to the minimum delay threshold value; therefore delay

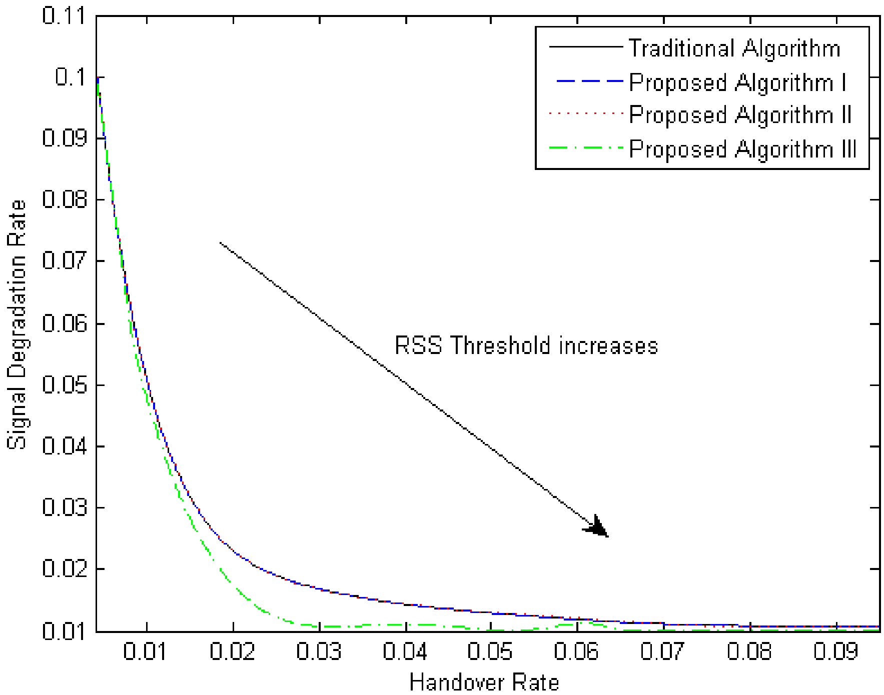

Figure 5.3. The Behavior of the Performance Criteria as RSS Threshold Increases.

threshold parameter becomes unnecessary for subscribers with stable femtocell backbone.

The cost of handover parameter used in the third algorithm affects as hysteresis. The cost of handover parameter should be picked as high to decrease the number of handovers in the areas where system signaling is overloaded; whereas it should be chosen as low as possible in areas where the cost of call drops is high. The behavior of the performance criteria as cost of handover increases is shown in Figure 5.4.

5.3. Unstable Delay at Femtocell Backhaul

The unstable delay at femtocell backbone is modeled as an Erlang-n probability distribution function given in Equation 4.12. The delay at femtocell backbone can be unstable, i.e., it can change rapidly during communication. The real-time communications suffer from rapid increase in delay which creates jitter. The probability of the

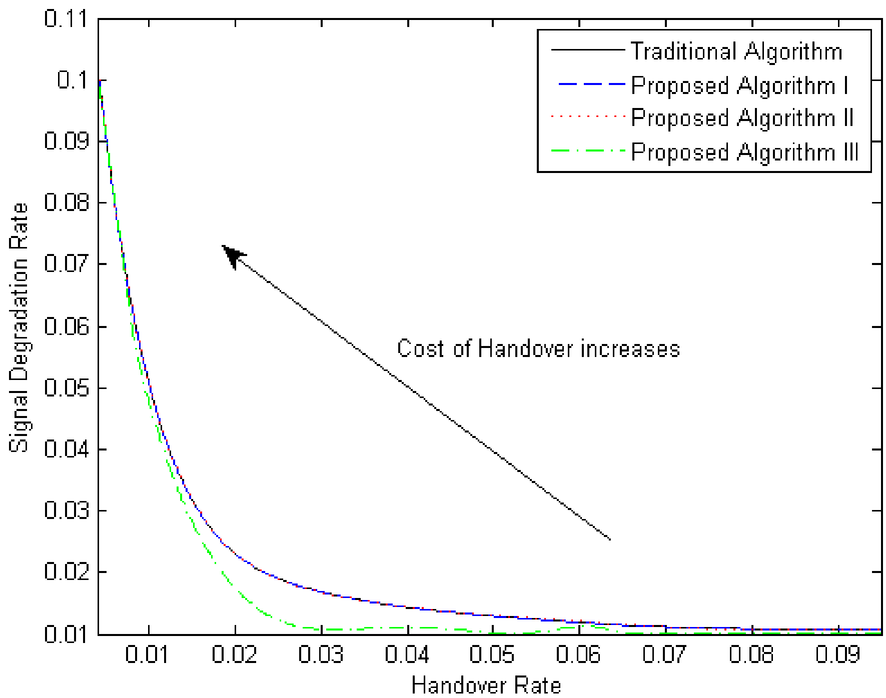

Figure 5.4. The Behavior of the Performance Criteria as Cost of Handover Increases.

occurrence of the event that the delay at unstable femtocell backhaul exceeds the maximum acceptable delay level for voice over IP communication is described in Equation 4.13.

The traditional algorithm and the proposed algorithms are simulated according to the unstable delay characteristics at femtocell backbone and the results are depicted in Figure 5.5.

If we compare the first proposed algorithm with the traditional algorithm, lower signal degradation rates per the same number of handovers are obtained. For instance, an operator that seeks at most 0.04 handover rate for this scenario, gets at least 0.075 signal degradation rate with the traditional algorithm but gets 0.058 signal degradation rate with the first proposed algorithm which implies a more than 20% enhancement in the signal degradation rate.

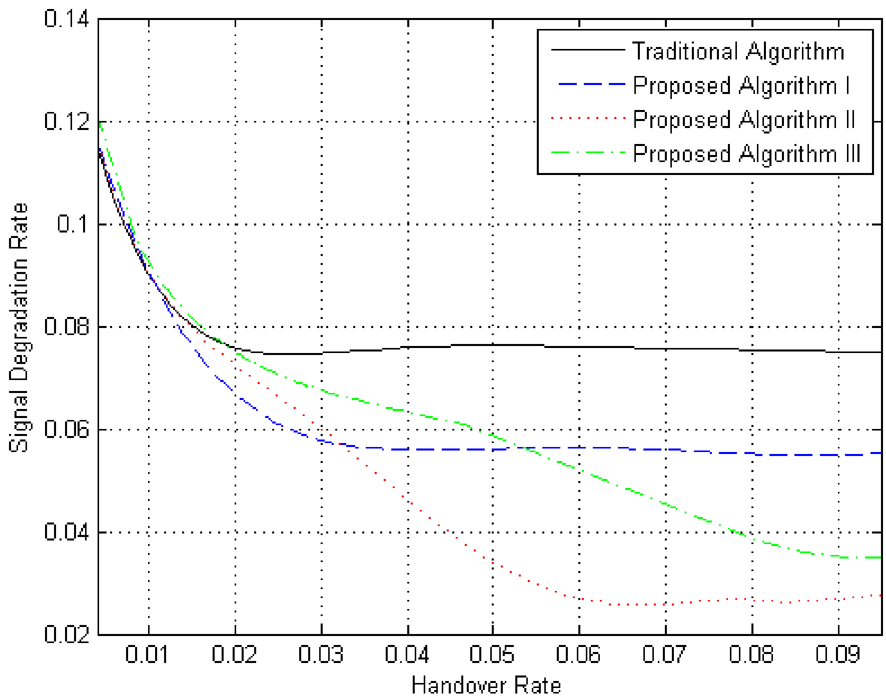

Figure 5.5. Comparison of Handover Rates vs Degradation Rates of the Algorithms at Unstable Delay.

The second proposed algorithm behaves better than the traditional algorithm in terms of signal degradation performance criterion. For instance, an operator that seeks a handover rate of 0.04, gets a signal degradation rate of at least 0.075 with the traditional algorithm however with the second proposed algorithm a signal degradation rate of 0.05 can be achieved which implies 33% advance in the signal degradation rate. The second proposed algorithm performs better than the first proposed algorithm at signal degradation rates for the same handover rates higher than 0.03 as far as the average number of signal degradations per the same number of handovers is concerned. However, the first proposed algorithm slightly outperforms the second proposed algorithm in between 0.015-0.03 handover rates on the same concern.

The performance of the third proposed algorithm against the traditional algorithm shows considerable enhancements as far as the average number of signal degradations per the same handover rates is concerned.

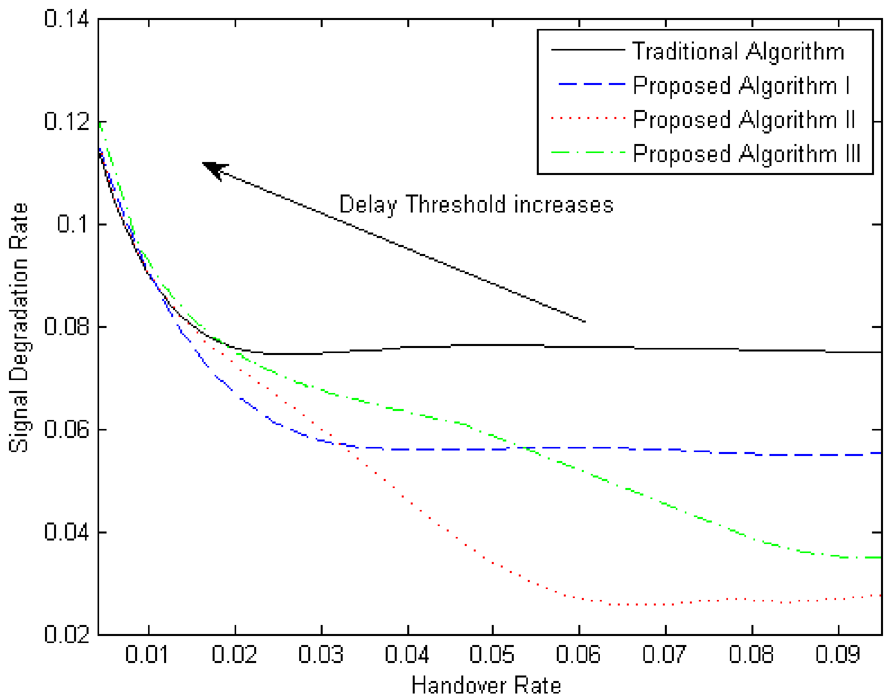

Figure 5.6. The Behavior of the Performance Criteria as Delay Threshold Increases.

The behavior of the performance criteria as delay threshold increases is depicted in Figure 5.6. Delay threshold parameter is used to prevent the signal degradations rooted from the femtocell backhaul. When the broadband backhaul of FBS is lossy and unstable, the delay threshold parameter grants action and decreases the number of signal degradations.

RSS threshold and hysteresis metrics behave the same way as explained in Section 5.2. If there is an increase in hysteresis, while the signal degradation rate raises, handover rate decreases. Conversely, the higher the RSS threshold is, the higher the handover rate but the lower the signal degradation rate is.

6. CONCLUSION

Femtocells are considered to be a solution to the indoor coverage problem, with its short range, low output power and low cost properties. Femtocell base stations connect to the core network via subscribers' broadband Internet lines. Due to the low capabilities of the Internet networks guaranteeing the service quality requirements of real-time voice communications, the fluctuations in the femtocell backhaul result in signal degradations. Therefore, the backbone quality of femtocells should be considered for an advanced handover decision algorithm. In this study, three different handover decision algorithms are designed. The proposed algorithms are numerically tested and the results show considerable enhancements as far as the number of signal degradations per the same number of handovers is concerned.

The number of handovers and the number of signal degradations are the two conflicting performance criteria in the design of handover decision algorithms. In the tradeoff between these performance criteria, when the number of handovers increases, the number of signal degradations decreases. Conversely, decreasing the number of handovers yields an increase in the number of signal degradations. Each handover has a cost to the network, that an optimum point in the tradeoff between the number of signal degradations and the number of handovers can be found by manipulating the handover algorithm parameters: hysteresis, the RSS threshold, the delay threshold and the cost of handover.

An increase in hysteresis yields an increase in the number of signal degradations yet a decrease in the number of handovers. If the cost of handover is high in a cellular network, hysteresis parameter can be chosen accordingly to decrease the number of handovers. If the system burden is low, then hysteresis parameter should be chosen as low as possible to decrease the number of signal degradations that enhances subscriber satisfaction.

RSS threshold is an essential parameter in the proposed algorithms. If the RSS threshold is chosen as too low, then handover from the serving cell to the candidate cell may not occur in time causing call drops. If it is chosen as too high, on the other hand, extensive handovers can occur in the cellular network. The optimum point of the RSS threshold is bounded to the handover cost of the system. Besides, if the RSS threshold is at the call drop level, each signal degradation refers to a call drop; whereas in case the RSS threshold is chosen as higher than the call drop level, signal degradation presents signal quality, resulting in an increase in user complacency, as well.

The proposed algorithms take into account the service quality of femtocell backhaul. One of the properties that can measure the quality of femtocell backbone is the delay parameter. The real-time voice communications over IP networks are sensitive to delay. The proposed algorithms utilize delay parameter as a measure of the quality of femtocell backbone. The signal degradation caused by the exceed of delay threshold refers to deterioration in voice calls. If delay threshold is chosen as too high, the signal degradation means not only deterioration but also call drop. However most of shattered calls in Voice over IP networks are hanged down by the subscriber. Real-time voice communications are very sensitive to delay, and that's why the delay threshold level should be picked accordingly. On the contrary, non-real time applications are not sensitive to delay, and therefore the delay threshold should be chosen as higher values in order to block extensive handovers. In this study, real-time voice communications is simulated. In future studies, the optimization of delay threshold parameter for non-real time applications can be considered for the advancement of the algorithms.

Three handover decision algorithms are proposed based on the received signal strength and delay parameters. The simulation results of the suggested algorithms indicate significant improvement in the optimization of the number of signal degradations and the number of handovers. The second algorithm demonstrates the best results as far as signal degradation rates per the same handover rates at high degrees are considered. In case that the cost of handover is very essential to the network, one can manipulate the parameters of the second proposed algorithm or else prefer either the first or the third algorithm that gives decreased number of handovers.

In future studies, other parameters such as delay variance (jitter), packet loss rate and bandwidth as measures of the femtocell backhaul can be considered to be used in handover decision algorithms. Besides, the use of Time-to-Trigger in handover decision algorithms can be an alternative solution to unnecessary handovers for faster mobile stations.

REFERENCES

1. Kumar, A., Y. Liu, J. Sengupta and D. Khurana, "Evolution of Mobile Wireless Communication Networks: 1G to 4G", *The International Journal on Electronics & Communication Technology*, Vol. 1, pp. 68–72, 2010.

2. Ouda, M., *Interference-Optimal Frequency Allocation in Femtocellular Networks*, M.S. Thesis, Queen's University, 2012.

3. Zhang, J. and G. Roche, *Femtocell: Technologies and Deployment*, John Wiley & Sons, Inc., West Sussex, UK, 2010.

4. Cullen, J., *Radioframe Presentation*, Femtocells Europe, 2008.

5. Vijayan, R. and J. M. Holtzman, "A Model for Analyzing Handoff Algorithms", *Proceedings of Vehicular Technology Conference*, Vol. 42, pp. 351–356, 1993.

6. *Wireless in Home & Office, the Need for Both 3G Femtocells and Wi-Fi Access Points*, 2010, `http://www.femtoforum.org`, accessed at January 2010.

7. Kumar, A., D. Khurana, T. Singh and S. S. Khurmi, "Femtocell – A Review", *The International Journal on Electronics & Communication Technology*, Vol. 2, pp. 16–18.

8. Goldman, D., *4G Won't Solve 3G's Problems*, 2011, `http://money.cnn.com/2011/03/29/technology/4g_lte/index.htm`, accessed at June 2011.

9. Jarvinen, M., *Femtocell Deployment in 3rd Generation Networks*, M.S. Thesis, Helsinki University of Technology, 2009.

10. Starr, J. K., *Interference Alignment with Distributed Antenna Systems*, M.S. The-

sis, The University of Texas at Austin, 2011.

11. Araújo, J. F., *Analysis of Radio Repeaters in UMTS*, M.S. Thesis, Universidade Técnica de Lisboa, 2009.

12. Laiho, J., A. Wacker and T. Novosad, *Radio Network Planning and Optimisation for UMTS*, John Wiley & Sons, Chichester, UK, 2006.

13. Bare, J. K., *Comparison of the Performance and Capabilities of Femtocell vs Wi-Fi Networks*, M.S. Thesis, Naval Postgraduate School, 2012.

14. Carlaw, S., *IPR and the Potential Effect on Femtocell Markets*, FemtoCells Europe, 2008.

15. Cole, R. G. and J. H. Rosenbluth, "Voice over IP Performance Monitoring", *ACM SIGCOMM Computer Communication Review*, Vol. 31, pp. 9–24, 2001.

16. Cicconetti, C., G. G. de Blas, X. Masip, J. S. Silva, G. Santoro, G. Stea and H. Tarasiuk, "Simulation Model for End-to-End QoS across Heterogeneous Networks", *Proceedings of 3rd IPS MoMe*, pp. 79–89, 2005.

17. Bolot, J., "Characterizing End-to-End Packet Delay and Loss in the Internet", *Journal of High Speed Networks*, Vol. 2, pp. 305–323, 1993.

18. Paxson, V., *Measurements and Analysis of End-to-End Internet Dynamics*, Ph.D. Thesis, University of California, Berkeley, 1997.

19. Fei, A., G. Pei, R. Liu and L. Zhang, "Measurements on Delay and Hop-Count of the Internet", *Proceedings of the IEEE Global Internet*, pp. 1–8, 1998.

20. Hooghiemstra, G. and P. V. Mieghem, *Delay Distributions on Fixed Internet Paths*, 2001, `http://www.nas.ewi.tudelft.nl`, accessed at May 2013.

21. Fiorini, P. and R. Oboe, "A Design and Control Environment for Internet-Based

Telerobotics", *The International Journal of Robotics Research*, Vol. 17, pp. 433–449, 1998.

22. Wee, S., W. Tan, J. Apostolopoulos and M. Etoh, "Optimized Video Streaming for Networks with Varying Delay", *Proceedings of IEEE International Conference on Multimedia and Expo*, Vol. 2, pp. 89–92, 2002.

23. *3GPP TS 23.234 3GPP System to Wireless Local Area Network Interworking*, 2012, http://www.3gpp.org/ftp/Specs/html-info/23234.htm, accessed at September 2012.

24. Khan, M. M. and M. S. Khan, *Investigation of Handovers in 3G UMTS Traffic Classes*, M.S. Thesis, Blekinge Institute of Technology, 2010.

25. Cheema, R. A. and M. J. Irshad, *Issues and Optimization of UMTS Handover*, M.S. Thesis, Blekinge Institute of Technology, 2008.

26. *3GPP TS 25.367 UMTS Mobility Procedures for Home NodeB*, 2013, http://www.3gpp.org/ftp/Specs/html-info/25367.htm, accessed at April 2013.

27. *3GPP TS 25.331 Radio Resource Control Protocol Specification*, 2013, http://www.3gpp.org/ftp/Specs/html-info/25331.htm, accessed at April 2013.

28. *3GPP TS 25.467 UTRAN Architecture for 3G Home Node B*, 2013, http://www.3gpp.org/ftp/Specs/html-info/25467.htm, accessed at April 2013.

29. Brück, S., *3G/4G Mobile Communications Systems*, 2012, http://www.ant.uni-bremen.de, accessed at May 2012.

30. Gudmundson, M., "Analysis of Handover Algorithms", *Proceedings of Vehicular*

Technology Conference, pp. 537–542, 1991.

31. Zhang, N. and J. M. Holtzman, "Analysis of Handoff Algorithms Using Both Absolute and Relative Measurements", *Proceedings of Vehicular Technology Conference*, Vol. 45, pp. 174–179, 1996.

32. Zonoozi, M., P. Dassanayake and M. Faulkner, "Optimum Hysteresis Level, Signal Averaging Time and Handover Delay", *Proceedings of IEEE Vehicular Technology Conference*, Vol. 1, pp. 310–313, 1997.

33. Moghaddam, S., V. T. Vakili and A. Falahati, "New Handoff Initiation Algorithm (Optimum Combination of Hysteresis & Threshold Based Methods)", *IEEE Vehicular Technology Conference*, pp. 1567–1574, 2000.

34. Kumar, P. and J. M. Holtzman, "Analysis of Handoff Algorithms Using Both Bit Error Rate and Relative Signal Strength", *International Conference on Universal Personal Communications*, pp. 1–5, 1994.

35. Wang, S., A. Rajendran and M. Wylie-Green, "Adaptive Handoff Method Using Location Information", *Proceedings of IEEE Personal, Indoor and Mobile Radio Communications*, Vol. 1, pp. D43–D47, 2001.

36. Itoh, K., S. Watanabe, J. Shih and T. Sato, "Performance of Handoff Algorithm Based on Distance and RSSI Measurements", *IEEE Transactions on Vehicular Technology*, Vol. 51, pp. 1460–1468, 2002.

37. Akar, M., "Integrated Power and Handoff Control for Next Generation Wireless Networks", *Wireless Networks*, Vol. 15, pp. 691–708, 2007.

38. Moon, J. M. and D. H. Cho, "Novel Handoff Decision Algorithm in Hierarchical Macro/Femtocell Networks", *Proceedings of Wireless Communications and Networking Conference*, pp. 1–6, 2010.

39. Moon, J. M. and D. H. Cho, "Efficient Handoff Algorithm for Inbound Mobility in Hierarchical Macro/Femto Cell Networks", *IEEE Communication Letters*, Vol. 13, pp. 755–757, 2009.

40. Chowdhury, M., W. Ryu, E. Rhee and Y. M. Jang, "Handover Between Macrocell and Femtocell for Umts Based Networks", *Proceedings of International Conference on Advanced Communication Technology*, pp. 237–241, 2009.

41. Kim, J. S. and T. J. Lee, "Handover in UMTS Networks with Hybrid Access Femtocells", *Proceedings of International Conference on Advanced Communication Technology*, pp. 904–908, 2010.

42. Taleb, T. and A. Ksentini, "QoS/QoE Predictions-based Admission Control for Femto Communications", *Proceedings of IEEE International Conference of Communications*, pp. 5146–5150, 2012.

43. Mase, K. and Y. Toyama, "End-to-end Measurement Based Admission Control for VoIP Networks", *Proceedings of IEEE International Conference on Communications*, Vol. 2, pp. 1194–1198, 2002.

44. Olariu, C., J. Fitzpatrick, P. Perry and L. Murphy, "A QoS Based Call Admission Control and Resource Allocation Mechanism for LTE Femtocell Deployment", *Proceedings of Consumer Communications and Networking Conference*, pp. 884–888, 2012.

45. Becvar, Z. and P. Mach, "On Enhancement of Handover Decision in Femtocells", *Proceedings of Wireless Days 2011*, pp. 1–3, 2011.

46. Mahmoud, H., I. Guvenc and F. Watanabe, "Performance of Open Access Femtocell Networks with Different Cell-Selection Methods", *Proceedings of IEEE Vehicular Technology Conference*, pp. 1–5, 2010.

47. Gudmundson, M., "Correlation Model for Shadow Fading in Mobile Radio Sys-

tems", *Electronics Letters*, Vol. 27, pp. 2145–2146, 1991.

48. Baum, D. S., J. Hansen, J. Salo, G. D. Galdo, M. Milojevic and P. Kyösti, "An Interim Channel Model for Beyond-3G Systems", *Proceedings of Vehicular Technology Conference*, Vol. 5, pp. 3132–3136, 2005.

49. Graziosi, F. and F. Santucci, "A General Correlation Model for Shadow Fading in Mobile Radio Systems", *IEEE Communication Letters*, Vol. 6, pp. 102–104, 2002.

50. Khan, A., C. Constantinou and I. Stojmenovic, "Realistic Physical Layer Modelling for Georouting Protocols in Wireless Ad-Hoc and Sensor Networks", *Proceedings of International Conference on Ultra Modern Telecommunications & Workshops*, pp. 1–8, 2009.

51. Agrawal, P. and N. Patwari, "Correlated Link Shadow Fading in Multi-hop Wireless Networks", *IEEE Transactions on Wireless Communications*, Vol. 8, pp. 4024–4036, 2009.