OPTIMAL AND PRACTICAL HANDOVER DECISION ALGORITHMS IN HETEREGENEOUS MACRO-FEMTO CELLULAR NETWORKS

by

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Abstract

Driven by the smart tablet/phone revolution and the proliferation of bandwidth hungry applications such as cloud computing and streaming video, the demand for high data rate wireless communication is increasing tremendously. In order to meet the increasing demand from subscribers, wireless operators are in the process of augmenting their macrocell network with supplemental infrastructure such as microcells, distributed antennas and relays. An alternative with lower upfront costs is to improve indoor coverage and capacity by using end-consumer installed femtocells. A femtocell is a low power, short range (up to 100 meters coverage radius) cellular wireless access point (AP), functioning in service provider owned licensed spectrum. Due to the proximity of end users to the femtocell access points, APs are able to provide higher end-user QoE and better spatial reuse of limited spectrum. Femtocells are useful in offloading the macro-cellular network as well as reducing the operating and capital expenditure costs for operators.

Femtocells coexist with legacy cellular networks consisting of macrocells. In this emerging combined architecture, large number of Femtocell Application Point (FAPs) is randomly deployed in the coverage area of macro BSs. However, several problems related to MM (mobility management) and RM (resource management) in this combined architecture still remain to be solved. The ad hoc deployment of FAPs and asymmetric radio communication and call processing capabilities between macro-femto networks are the primary causes of these problems. Uncoordinated deployment of FAPs providing indoor oriented wireless access service within the macro coverage may cause severe interference problems that need to be mitigated and handled by RM/MM schemes. The MM decisions should take into account the resource constraints and UE mobility in order to prevent unnecessary or undesirable handovers towards femtocells. Ignoring these factors in MM decisions may lead to low customer

satisfaction due to mismanagement of handover events in the combined macro-femto network, delayed signaling traffic and unsatisfactory call/connection quality.

In order to address all of the aforementioned issues, the handover decision problem in combined femto-macro networks has been formulated as a multi-objective non-linear optimization problem. Since there are no known analytical solution to this problem, an MDP (Markov Decision Process) based heuristic has been proposed as a practical and optimal HO (handover) decision making scheme. This heuristic has been updated and improved in an iterative manner and has also been supported by a dynamic SON (Self Organizing Networks) algorithms that is based on heuristic's components. The performance results show that the final version of MDP based heuristic has significantly superior performance in terms offloading the macro network, minimizing the undesirable network events (e.g. outage and admission rejection) when compared to state-of-art handover algorithms.

Özet

Akıllı telefon/tablet devriminin etkisi ve yüksek bantgenişliğine ihtiyaç duyan bulut bilişim ve duraksız video gibi uygulamaların yaygınlaşmasıyla beraber yüksek hızlı kablosuz iletişime duyulan talep yıldan yıla ciddi oranda artmaktadır. Abonelerden gelen bu talep artışını karşılamak için kablosuz şebeke operatörleri klasik makro erişim sistemlerini microcell, dağıtık antenler ve atlama noktaları gibi ilave ekipmanlarla zenginleştirme yoluna gitmektedir. Düşük maliyetli, alternatif bir şebeke genişletme aracı ise iç mekanlardaki erişim kapasitesi ve kapsamasını iyileştiren, son kullanıcı tarafından kurulan femtocell yapılarıdır. Femtocell'ler düşük yayın gücüne sahip, dar kapsama alanlı (100 metreye kadar) ve operatörün lisanslı bandını kullanan hücresel kablosuz erişim noktalarıdır. Femtocell erişim noktaları son kullanıcıya fiziksel yakınlıkları sayesinde daha üst seviyede servis kalitesi ve uzamsal tayf geri kullanımı sağlamaktadırlar. Ayrıca sözkonusu sistemler, makro hücresel şebekesinin çağrı/oturum iletme yükünü hafifletmek ve operasyonel/yatırım maliyetlerini azaltmak noktasında da faydalı olmaktadır.

Femtocell'ler makro düğümlerden oluşan standart hücresel şebekeyle aynı ortamda ve etkileşim halinde çalışmaktadır. Oluşan kombine yapıda yüksek sayıda femtocell erişim noktası (FAP) makro baz istasyonlarının kapsama alanında rasgele denilebilecek şekilde devreye alınmaktadır. Bununla birlikte makro-femto birleşik yapısının kaynak ve hareketlilik yönetimi açısından halen çözülmeyi bekleyen sorunlara yolaçtığı gözlenmiştir. FAP cihazlarının merkezi kontrol/planlama olmadan devreye alınması ile makro-femto şebekeleri arasındaki asimetrik şekilde yapılanmış radyo haberleşmesi ve çağrı işleme yetenekleri bu sorunların başlıca nedenleridir. FAP sistemlerinin kapalı mekana özel olarak ve makro hücresel yapıyla koordine olmadan yayın yapması kaynak/hareketlilik yönetimi yapıları tarafından yönetilmesi gereken ciddi girişim sorunları ortaya çıkarmaktadır. Ayrıca hareketlilik yönetimi kararlarının

femtocell'lerdeki kaynak kısıtlarını ve aktif son kullanıcıların hareketlilik durumunu dikkate alması gerekmektedir. Bahsedilen faktörlerin ihmal edilmesi, makro-femto birleşik şebekesindeki geçiş (handover) olaylarının iyi yönetilmemesine, sinyalleşme trafiğinin gecikmesine ve çağrı/bağlantı kalitesinin düşmesine neden olacak, dolayısıyla müşteri tatmininde azalmaya yolaçacaktır.

Yukarıda bahsedilen potansiyel sorunları çözmek için makro-femto şebekelerindeki geçiş karar yapısı, çok-hedefli doğrusal olmayan bir eniyileme problemi olarak formüle edilmiştir. Sözkonusu problemin bilinen bir analitik çözümü bulunmadığından, kolay gerçeklenebilen MKS (Markov Karar Süreci) bazlı bir buluşsal yöntem (heuristic), pratik ve eniyilenmiş geçiş karar yapısı olarak önerilmiştir. Bu buluşsal yöntem döngülü şekilde güncellenmiş ve iyileştirilmiş ayrıca buluşsal yöntemin bazı bileşenlerini kullanan bir dinamik SON algoritması tarafından da desteklenmiştir. Benzetimle elde edilen deneysel sonuçlar MKS bazlı algoritmaya dayanan geçis kararlarının makro şebekesinin yükünü azaltmakta ve istenmeyen şebeke olaylarını en aza indirmede literatürde mevcut geçiş karar algoritmalarına göre belirgin şekilde daha başarılı olduğunu göstermektedir.

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3G	3rd Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation
AMR	Adaptive Multi-Rate
AP	Access Point
BHCA	Busy Hour Call Attempt
BS	Base Station
BW	Bandwidth
CAC	Call Admission Control
CAPEX	Capital Expenditure
CDMA	Code Division Multiple Access
CPICH	Common Pilot Channel
CS	Circuit Switched
CSG	Closed Subscriber Group
DL	Downlink
DSL	Digital Subscriber Line
eNB	Evolved NodeB
FAP	Femtocell Access Point

HCS	Hierarchical Cell Structure
HeNB	Home Evolved NodeB
HMS	HNB Management System
HNB	Home NodeB
HO	Handover
HSDPA	High-Speed Downlink Packet Access
HSUPA	High-Speed Uplink Packet Access
HW	Hardware
IP	Internet Protocol
ITU	International Telecommunications Union
LoS	Line of Sight
LTE	Long Term Evolution
MCT	Mean Connection Time
MDP	Markov Decision Process
MHT	Mean Holding Time
MM	Mobility Management
MS	Mobile Station
MSC/VLR	Mobile Switching Center/Visitor Location Register
MU-MIMO	Multi-User Multi Input Multi Output

OAM	Operations Administration Maintenance
OFDMA	Orthogonal Frequency Division Multiple Access
PCI	Physical Cell Identity
PS	Packet Switched
PSC	Primary Scrambling Code
QoE	Quality Of Experience
QoS	Quality Of Service
RAN	Radio Access Network
RF	Radio Frequency
RM	Resource Management
RNC	Radio Network Controller
RRM	Radio Resource Management
RSCP	Received Signal Code Power
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RTP	Real Time Protocol
SeGW	Security Gateway
SGSN	Serving GPRS Support Node
SIB	System Information Block

SINR	Signal to Interference and Noise Ratio
SIR	Signal to Interference Ratio
SoC	System On Chip
SON	Self Organizing Networks
SW	Software
TDMA	Time Division Multiple Access
TX	Transmit
UDP	User Datagram Protocol
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UTRAN	UMTS Terrestrial Radio Access Network
WCDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network

1 INTRODUCTION

The demand for high data rate for wireless communication is increasing tremendously [1]. Existing wireless communication systems face many challenges to support high wide band data access. Both the coverage area and the capacity of existing cellular network systems are not sufficient to meet the expected demand of high speed data and multimedia traffic. In order to meet this increasing demand from subscribers, wireless operators are in the process of augmenting the macrocell network with supplemental infrastructure such as microcells, distributed antennas and relays [2]. An alternative with lower upfront costs is to improve indoor coverage and capacity using the concept of end-consumer installed femtocells or home base stations.

A femtocell is a low power, short range (10-200 meters) wireless data access point (AP) , functioning in service provider owned licensed spectrum, which provides in-building coverage to home/enterprise users and transports the user traffic over internet based backhaul such as cable modem or xDSL . Because of the proximity of users to their APs, femtocells provide higher spatial reuse of spectrum and cause less interference to other users. In addition to improved spatial reuse, small/femto cell technology has been proposed as one of the best approaches to diverse the load from the cellular networks as well as to reduce the operating and capital expenditure costs for operators.

Femtocells coexist and interwork with legacy cellular networks consisting of macrocells. This combined architecture that aims to provide better service quality for indoor mobile users [3] has been called as hierarchical macro/femto-cell networks. In these emerging networks, a hierarchical cell structure is formed as a large number of low-power femto base stations (femto BSs) are deployed in the coverage area of macro BSs. By implementing these femto BSs in a systematic manner, indoor mobile users are able to experience a higher signal to interference and noise ratio (SINR) from the femto BSs compared to that from the macro BSs. In addition, enhanced radio resource management can be performed by the macro BSs, because data traffic in the femto BSs is absorbed into wired backhaul links such as cable and DSL (digital subscriber line). As a result, network capacity, or equivalently, the total number of active users in the service area will be increased. However, several problems related to interference mitigation and handover/mobility management in the hierarchical cell structure are still remaining to be solved.

Two particular aspects of FAPs give rise to serious interference issues: 1) the co-channel spectrum sharing (or adjacent channel interaction) between femtocells and macrocells; 2) the "random" placement of FAPs (femtocell access point). First, unlike Wi-Fi access points, FAPs serve users in licensed spectrum, to guarantee Quality-of-Service (QoS) and because the devices they communicate with are developed for these frequencies. Compared to allocating separate channels inside the licensed spectrum exclusively to FAPs, sharing spectrum would be preferred from an operator perspective. Secondly, FAPs are installed by end-users in a "plug-and-play" manner, which translates into "randomness" in their locations: they can be deployed anywhere inside the macrocell area with no prior warning. For these two reasons, interference in two-tier networks is quite different than in conventional cellular networks, and endangers their successful co-existence. A typical scenario is the "Dead Zone" or "Loud Neighbor" problem, where mobile users transmit and receive signals at positions near FAPs but far from the macrocell BSs, causing significant macro-to-femto interference in the uplink. In the downlink, these users likewise suffer from low signal to interference ratios (SIRs) because of the strong interference from the

FAPs. These affects are akin to the well known near-far problem, but exacerbated by the de-centralization and lack of coordinated power control inherent in a two-tier network [4].

A typical mobility management problem is unneccessarily high HO attempts which is caused by the style of deployment of femtocells differing significantly from the deployment of the conventional underlay macrocells [5]. Femtocells are deployed by users and consequently little to no cell planning is taken into consideration during the deployment. This means that a femtocell may be deployed in unsuitable locations, where its pilot signals may radiate to areas outside of its intended area of coverage. This has the undesirable effect of triggering handovers from users outside that are passing by, who are not the intended users of the femtocell. Since the deployment of femtocells can be widespread, in dense urban areas this can cause a very large number of mobility events to occur. This, in turn, has an impact both on the network due to increased signaling load and on the battery life of user terminals.

In hierarchical macro/femtocell networks, there are two basic assumptions about mobility management. First, an MS (mobile station) gives higher priority to a femto BS (base station) over a macro BS when the MS selects its serving BS. A reason for this requirement is not only the high utilization of femtocells but also the usage of different billing models between two types of cells. (femto BS systems are expected to provide lower cost service to end-users) Thus, performing handoff from a macrocell to a femtocell efficiently can be seen as a way of increasing user satisfaction. Second, the deployment of femtocells should not cause drastic changes on mobility management procedures used in conventional macrocell networks. It means that conventional methods, such as cell scanning and handoff, can also be applied to the hierarchical macro/femto-cell networks. Based on these observations, it is possible to deduce that mobility events towards a femtocell coverage area have greater potential to create interference and increased signaling problems.

Other important issues that need to be addressed are scalability and fast-moving, correlated end-user communication. As femtocell deployments becomes dense with increasing number of end-users using these services, handover management will become a harder task as there will be more femtocells as HO (handover) candidates for each end-user. In the case of overlapping coverage regions (that is not possible to prevent in femtocell deployments), it is perfectly possible that end-user terminal jumps between alternate femto BS's in a cyclic and recurrent way creating artificially inflated signaling traffic. Apart from this scalability issue, serious timing and coordination issues might arise in fast-moving/correlated end-user communication cases due to very low sojourn times of end-users in small femtocell coverage areas. Therefore, there might be instances where HO towards femtocell zones is not desirable even if the radio environment situation overwhelmingly suggest a macro-to-femto or femto-to-femto handover decision.

Handover problem in femtocells is also closely related to user access policies namely the way end-users will be allowed to access femtocell services. There are three alternate methods in this respect [6].

1. Open access: all subscribers of an operator have the right to connect to any of the femtocells of the operator.

2. Closed access also referred to as Closed Subscriber Group (CSG) method: only certain preregistered subscribers of an operator (which are members of CSG) are allowed to connect to the given femtocell. The list of these clients is regulated by the femtocell owner.

3. Hybrid access: part of the femtocell resources is operated in open access, while the remaining follow a CSG approach. This translates into a preferential access

for CSG subscribers and a limited access for other non-CSG users.

These three different modes of subscriber access to femtocells leads to varying solutions for handover decisions. For example in closed access mode, macro-to-femto HO is only limited to registered users and femto-to-femto HO is normally not possible unless the user is simultaneously registered in two neighboring femtocell zones. In open access though, femtocells operate in a similar way to macrocells from HO support point of view and all HO variations (inter-femto, macro-to-femto etc) are supported as long as network resources are available. However both open and closed access modes bring extra complications to the HO problem. Open access method increases signaling in the network due to the elevated number of handovers that mobile users have to perform and may not be so desirable by subscribers who would like have some guaranteed amount of resources from their privately owned femtocell. On the other hand, closed access mode does not have privacy and service level degradation issues caused by non-registered users. The main problem in this mode of operation is increasing levels of radio interference between macro and femto networks. Closed access is the root cause of cross-tier interference of two-tier networks (i.e., macrocells and femtocells). Further, the effect of this problem is remarkably serious in the downlink of outdoor users not subscribed to any femtocell. Macrocell users inside the building perimeters that are covered by femtocells experience severe dead-zone problems while trying to get service from a physically distant macrocell BS whose signal is heavily attenuated. A hybrid access solution associated with an appropriate HO policy brings the advantages of two policies and it is possible to find examples from the literature that the disadvantages brought forward by open/closed access methods can be mitigated by carefully managing and integrating HO and hybrid access policies.

Considering all potential problem areas stated in above paragraphs, we can see that uncontrolled handover attempts towards femtocells will lead to low customer satisfaction due to excessive/delayed signaling traffic, frequent call drops, unsatisfactory call quality and connection speeds. This is the primary reason why this work aims to design a special handover decision algorithm that can be utilized in macro-to-femto, femto-to-femto and femto-to-macro mobility cases. These three cases cover all possible mobility management events towards a femtocell coverage area. The handover algorithm that will be designed should jointly consider

- End-user travel speeds and densities
- Femtocell deployment density and coverage overlaps between femtocells/macrocells
- Control signaling level generated by handover decisions towards between femtocell-macrocell networks
- Interference mitigation and transmit power control policies.
- Femtocell frequency spectrum, radio propagation environment characteristics.
- Femtocell resource limitations

so that a practical and optimal handover decision algorithm for hierarchical macro-femtocell network is designed.

Following design challenges are key to the success of the HO decision algorithm.

- Handling of QoS/signaling load trade-off in high-speed UE communications when a macro connected UE approaches to femtocell
- Limiting the number of femtocell handovers with marginal quality improvements

- Adaptation of SON (self organizing networks) algorithms providing low TX output power in general
- Integration of femtocell specific user access policies to MM (mobility management) decisions
- Consideration of residual BW, call processing and UL SIR limitations of femtocells
- Prevention of recurrent and undesirable handovers
- Management of femtocell bias in mobility management decisions
- Low complexity due to tight timing requirements
- Ease of implementation with no extra messaging/signaling outside the 3GPP specifications.

In subsequent chapters, this thesis document will thoroughly present the work carried out in order to meet above requirements for a practical and optimal handover decision algorithm specifically designed for macro-femto combined networks. The general thesis outline is as follows: Chapter 2 will provide the background and the state-of-art in mobility management for macro-femto networks. After this, the specific handover decision problem is mathematically formulated in chapter 3. Based on this formulation, chapter 4 explains the heuristic solution to the optimization problem based on Markov Decision Process approach. Chapter 5 presents detailed simulation based experimental results comparing the performance of the novel MDP based algorithm with respect to state-of-art methods. Chapter 6 provides the final discussion and conclusions based on the outcomes of experiments.

2 BACKGROUND

2.1 General aspects of femtocell systems

UMTS based Femtocell Access Point or FAP offers consumers quad-play services (voice, video, data, and mobile) while addressing the challenges of indoor 3G coverage by creating a small cell inside a residence, home office, or a small enterprise. Femtocell Access Point allows the consumer to use existing 3G UMTS handsets. Femtocell Access Point utilizes consumer's existing broadband backhaul to carry traffic back to the operator's core network. It also offers the mobile operator additional benefit of offloading macro network spectrum and avoiding CAPEX intensive 3G network upgrades required to support the exponential increase of mobile broadband data traffic over 3G.

Femtocells operate in licensed UMTS spectrum (for example band I in Europe). The maximum transmit power is usually between 10 dBm and 20 dBm depending on the customer deployment options such as residential or enterprise. The coverage cell radius is 200 m maximum in ideal radio propagation and LoS conditions. Femtocell Access Point devices are plug-and-play type devices that would be setup in customer premises without any technical assistance. That is why they are expected to support self-provisioning and self-configuring functionalities.

Femtocells are interworking with core network nodes and servers via broadband backhaul connections (in 3GPP jargon Femtocell Access Points are named as HNB). The FAP (HNB) seamlessly communicates with all standard UMTS user equipment (UE) via standard Uu (Air) interface. For privacy and security purposes the communication to the core network over the backhaul broadband connection is established over an IPSec tunnel. This IPSec tunnel is terminated in an operator owned/operated Security Gateway (SeGW). SeGW also acts as a firewall device gives access to only authorized HNB/FAP devices that are able to successfully establish end-to-end IPSec tunnel. Behind SeGW, we have Femto Gateway (or HNB GW in 3GPP jargon) that is acting as the main administrator/concentrator entity for femtocells.

FAP (HNB) nodes are supposed to register to HNB GW before providing UMTS access services. The interworking between HNB and HNB GW systems are achieved by Iu-h protocol as shown in below figure. HNB GW also implements signaling protocol conversion between Iu-h and Iu protocols and acts like a virtual RNC towards conventional core network nodes such as SGSN and MSC/VLR.

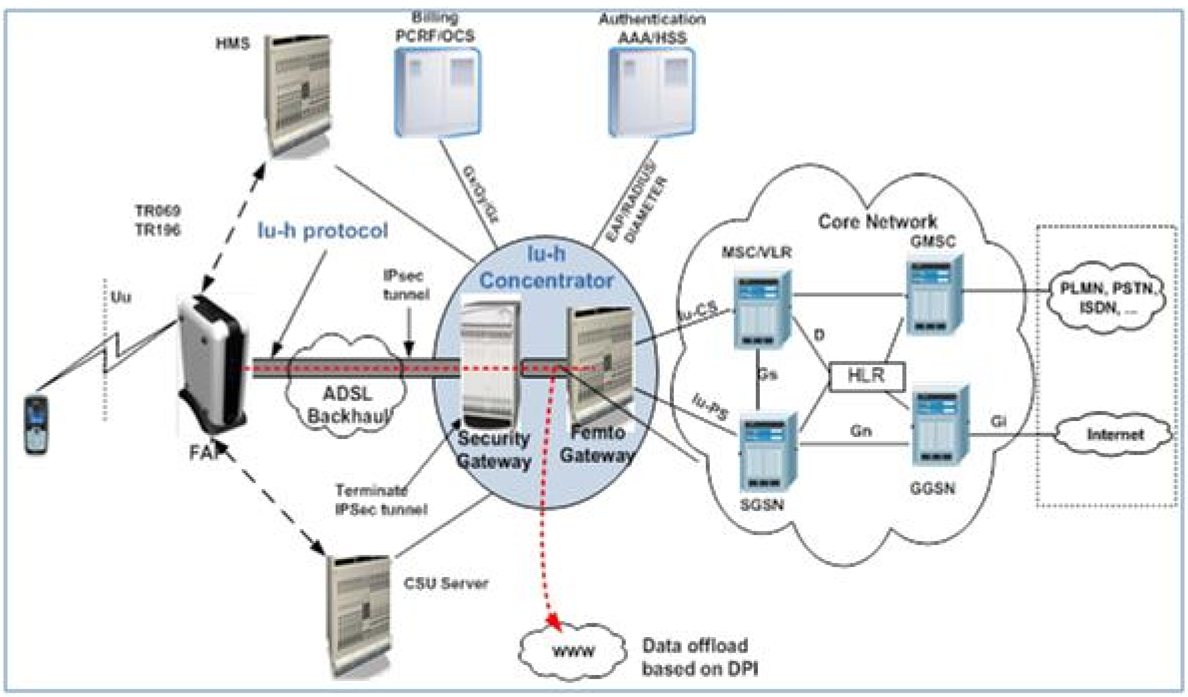

Figure 2.1: Femtocell solution architecture

In addition to these systems, a fundamental component in a femtocell network is called as HMS (HNB Management System) that provides OAM (Operations, Administration, Maintenance) functionality to FAP/HNB nodes. HMS system is crucially important in provisioning of FAP nodes and supports femtocell specific plug-and-play functionalities.

Femtocells support CS voice, video and PS data services for end-users. In current implementations, CS voice service is provided with full rate narrow-band AMR codec with maximum rate of 12.2 kbps. In the near future wide-band AMR functionality will also be supported providing better voice quality and QoS for femtocell end-users. CS video service supports native rates of 64 kbps or 128 kbps. Femtocell supports PS data services, HSDPA and HSUPA. For HSxPA services, the data rate could be restricted by the residual backhaul connection bandwidth.

2.2 Capacity limitations of Femtocells

Femtocells have limited capability in terms of simultaneous number of connected and idle mode user support. A typical femtocell node supports 4-16 simultaneous CS+PS calls depending on HW and SW implementation. The number of registered idle mode UEs is also limited to 32-64 users. These limitations stem from the fact that FAP nodes have small size, SoC (system on chip) based HW architectures implemented via embedded SW structures.

Another limitation of FAP device comes from its shared broadband backhaul connection. In typical deployment based on xDSL technologies, backhaul BW could be a limiting factor especially in the uplink side. One should also consider that backhaul BW is subject to fluctuations from shared usage of broadband service provider's network utilization. If the backhaul connection BW is also utilized by other entities that are outside the femtocell platforms control such as wi-fi (802.11) access points, this will bring an additional risk in terms of residual backhaul BW. The availability of backhaul BW is more critical for CS voice and video services as the amount of BW consumption for these real-time interactive services becomes significant even at low service rates. For example, in 12.2 narrowband AMR, the BW consumption for a single CS voice call become around 80 kbps due to considerable size of RTP , IPSec, UDP, IP and L2 headers.

Since femtocell typically operates in an indoor environment with UEs in close proximity, a special consideration should be given to limitations that might arouse from uplink radio channel utilization. Uplink Signal-to-interference ratio is normally used as an indication of heavy usage of uplink channel. Femtocells are expected to operate with uplink SIR values above 3 dB.

2.3 Self Organizing Network functionality in Femtocells

As far femtocell installation is concerned, there are likely to be two alternative use cases [7]. Firstly the femtocell can be deployed completely under the control of the operator; this would most likely be the case in rural and certain outdoor metropolitan scenarios. Alternatively the femtocell could be installed by an end-user rather than an operator.

For operator-controlled deployments it is possible that a centralized cell-planning approach is taken, where the exact location of the femtocell and its neighbors are known and modeled within an RF propagation analysis tool to allow for OAM configuration of the cells. While this may be applicable to rural deployments, it is likely that in metropolitan cases the localized propagation conditions at the scale of these small cells, coupled with the restricted availability of suitable installation sites, could mean that such an approach is unfeasible. The (hopefully) very large numbers of femtocells involved in an operator's network also makes centralized cell-planning an unattractive if not intractable. Clearly in the case of end-user installations, there is no opportunity for centralized operator OAM to provide deployment-specific configuration of the femtocell.

This leads us somewhat inevitably to the conclusion that femtocells will derive great benefit from self-configuration and other SON (Self Organizing Networks) techniques to mitigate against unwanted interference to and from neighboring cells. There are a wide range of SON practices that would apply in a deployment, including:

- self-configuration of physical cell identifier to be not only collision-free (i.e. different from immediate neighbors) but also confusion-free (i.e. different from neighbors of neighbors) amongst a cluster of femtocells;

- self-configuration of transmit power to provide a continuous archipelago of coverage from one femto island to the next;

- self-optimization of PSC/PCI and transmit power as new cells are added to the cluster;

- self-optimization of cell (re-)selection thresholds within a cluster of femtocells, making a femto more or less attractive or štickyäccording to its loading (aka Mobility Load Balancing);

- Self-healing within a cluster of femtocell, automatically detecting the failure of a neighbor cell and accommodating with an increase in coverage.

These SON techniques can be supported by the use of a Network Monitor Mode in the femtocell, sniffing for surrounding cells then collecting and recording measurements and broadcast System Information from them. The enabler for many of these techniques is the ability for a femtocell to be able to detect neighbors within its own cluster - i.e. other femtocells with which it should be co-operating to provide seamless coverage and quality of service.

The most relevant aspect of SON algorithm in terms of mobility management is self-configuration of RF transmit power that will directly shape the coverage area of femtocells. In current femtocell deployments, SON algorithm works independently of mobility management procedures so any MM algorithm should treat the resulting femtocell coverage areas (and their possible overlaps with other femtocells) as a given factor that should be carefully taken into account.

2.4 Literature Review

Many works have been done on the development of handover algorithms in wireless cellular networks. The main objective in these works is to decide an optimal connection with respect to user or system performance, while minimizing handoff latency and the number of handoffs. The most commonly used algorithm is based on the comparison of RSS's (Received Signal Strength) and the concept of hysteresis and threshold. [8] Note that the threshold sets the minimum level of the RSS from a serving BS and the hysteresis adds an extra margin to the RSS from a serving BS compared to that from a target BS. As applications of this algorithm, Moghaddam et al. [9] studied optimum combination of hysteresis and threshold to improve a handoff initiation phase. Moreover, Lee et al. [10] proposed an adaptive hysteresis algorithm to adjust the hysteresis according to user mobility and Zahran et al. [11] proposed a signal threshold adaptation algorithm where service requirements including RSS are reflected on determining the threshold. In addition to these handoff algorithms using RSS, various handoff criteria based on distance, bit error rate and achievable bandwidth, were suggested. Even though their efficiency was verified by both numerical and simulation results, the environment where a large number of femto BSs using extremely low transmit power are deployed in the coverage area of macro BSs was not taken into account.

One of the earliest work on handover and access control problem on multi-tiered, hierarchical cellular networks is presented in [12]. In this paper, the authors investigated a call-admission and handoff control framework for multi-tier cellular networks in which there are macrocell and microcell layers. The ultimate goal is to minimize handover traffic and to improve QoS by minimizing call drops while simultaneously taking advantage of the microcell layer by maximizing the number of users in the network. Various Call-Admission Control (CAC) algorithms are compared based on the cell-dwelling time by studying their impact on the handoff-call dropping and new-call blocking probabilities and the channel partitioning between the two tiers. As a result of their analysis, the authors have found that a simple uniform admission decision algorithm insensitive to cell dwelling duration performs optimally (in terms of call-blocking and handover failure rates) under various user mobility and call/service type scheme when compared to cell-dwell time based admission decision algorithm. Another significant result is that there is an optimal channel partition of the overall spectrum between the tiers which minimizes the dropping and blocking probabilities for the two different CAC algorithms studied in this paper. The second part of the paper concentrated on handover queuing strategies after the calls are admitted to the network. The authors show that implementing a queuing framework in one of the tiers (especially the upper, i.e., macrocellular tier), results in a significant reduction in the dropping probability. The results of this early paper are not exactly applicable to femtocell deployment though as call admission and handoff decision in the latter is less coordinated when compared to microcell based multi-tiered networks.

In order to handle this particular femtocell situation, more recent works proposed various alternatives. For example, the work in [3] proposes an efficient handoff decision algorithm that can be utilized in the situation where a user enters the coverage area of the femtocell. The main idea of the proposed algorithm is to combine the values of received signal strength from a serving macro BS and a target femto BS in the consideration of large asymmetry in their transmit powers.

Since the femtocell architecture is very different from the existing cellular networks, there are three issues in order to integrate femtocell/macrocell. First, if there exist many femtocells in a macrocell, they may cause interference. Second, due to many possible target femtocell candidates for macrocell to femtocell handover, communications with many femtocells in a large neighbor list may be required for the pre-handover procedure. Third, some modification of the existing network and protocol architecture is needed for the integration of femtocell networks with the existing macrocell. Since the coverage of a femtocell is very small, if a UE moves with high speed, the time duration it stays in the femtocell zone is very short, which causes two unnecessary handovers. In a wireless communication system, frequent and unnecessary handovers lower the service quality and decreases the capacity of the system. Therefore it is essential to minimize the number of unnecessary handovers to improve the service level of the users in a macrocell network coexisting with femtocells.

[13] specifically concentrates on the interference and mobility management relationship in LTE networks. They propose a mobility based inter-cell interference coordination technique in order to protect high-mobility UEs.

Based on all these observations a modified handover procedure for voice call service between 3GPP UMTS-based macrocell and femtocell networks has been proposed in [14] in order to minimize the number of unnecessary handovers, This novel procedure has been supplemented with special Call Admission Control (CAC) that is also contributing towards the goal of reducing the unnecessary handovers in the hybrid access mode.

The work in [15] approaches the femtocell mobility problem from an different framework in which an autonomous network optimization based on the method of cognitive interference management is utilized. This model assumes co-channel deployment. Instead of fully reusing %100 of the macrocellular resource, partial reuse is cognitively determined in femtocells based on their individual network environment. According to an interference signature perceived from the environment, a femtocell autonomously determines the appropriate channel allocation and minimizes the network interference. Upon the cognitive acquisition of the random infrastructure topology, base station pilot power is autonomously configured in order to maximize the cellular coverage. A series of network self-configuration procedures are discussed for automatic cell size adaptation and resource management. According to authors, the results of [15] show that the cognitive radio configuration facilitate the network optimization in terms of interference management, mobile handoff, pilot power control and network resource allocation. The proposed framework also offers a 4G vision for spectrum management in an autonomous self-managed cellular architecture.

When femtocells are overlaid on macrocells and they operate on the same RF channel, co-channel interference may occur. In particular, closed subscriber group femtocell BSs can only be accessed by a pre-defined set of MSs. Unauthorized users can not access a femtocell even if the received signal strength of the femtocell becomes much larger than that of the serving macro base station. In this case, severe interference can arise when a non-CSG MS operates near the femtocell BS. Because the MS is not allowed to handover to the femtocell BS, it has to be served by the distant macrocell base station. Therefore, the MS may cause large interference towards the femtocell BS in the uplink and receive large interference from the femtocell BS in the downlink. In order to tackle all these issues, [16] presents a simple method to perform access and handover management for femtocell systems, with the aim of reducing interference and enhancing service quality. This paper proposes a control mechanism to handle an incoming non-CSG (Closed Subscriber Group) mobile user entering the coverage of a CSG femtocell with efficient signaling and enables interference management to reduce interference, overhead and unnecessary handover in a femtocell deployment. For closed access, femtocell and macrocell base stations exchange CSG membership list so that unnecessary handover signalling can be avoided. Interference mitigation mechanisms such as MU-MIMO, beam-forming and resource scheduling are mentioned in order to reduce/cancel interference. Procedures for femtocell hybrid access have also been proposed, with femtocell initiated handover with adaptive threshold based on QoS.

In [17], Zhang et al again concentrated on QoS and UE speed criteria in what they names as SQ algorithm. The proposed method is shaped around LTE Femtocell deployment but handover decision process is equally applicable to UMTS femtocells as well. SQ algorithm works based on checking if two-levels of velocity thresholds have been exceeded by UE and if the type of service used in UE-HeNB connection is of real-time type of not. If the UE moves with an higher speed than threshold value, handover is avoided. Even at lower speeds, the handover is allowed if the service type is real-time (CS voice, CS video etc). The overall decision algorithm also calculates a special M parameter based on received signal strength from source and destination HeNB/eNB's and the handover decision is based on a combination of M value comparison, SQ algorithm criteria and HeNB's resource constraints.

Another work that emphasizes the role UE velocity in femtocell network handovers is [18]. Two handover algorithms specially designed for the two-level hierarchical networks composed of traditional macro cellular networks and embedded femtocell hotspots were proposed in this paper considering UE velocity as well as the received signal strength. Simulations were carried on the EV-DO Rev.A platform to evaluate the performance of the proposed algorithms compared with conventional soft handover. The results showed that handover probabilities of the two proposed schemes decreased to a large extent for high moving mobiles. With lower velocity threshold, the proposed schemes reacted on more moving mobiles and the macrocell's throughput was increased with high velocity mobiles holding a higher capacity.

All previous work proposing handover decision algorithms using UE speed as decision criteria assumes that HeNB/HNB system has an intrinsic capability to measure/deduce UE moving speed. A typical method on UE mobility estimation has been proposed in [19] under the domain of 802.16m networks.

[20] aims to develop asymptotic properties of the signal strength in cellular networks. This work approaches to the problem from an analytically tractable mathematical model on signal strength distribution originating from a base-station. It has been shown that the signal strength received at the center of a ring shaped domain B from a base station located in B belongs to the maximum domain of attraction of a Gumbel distribution. The paper then proves that the maximum signal strength and the interference received from n small/femto cells in B are asymptotically independent as n approaches to infinity. The above properties are proved under the assumption that sites are uniformly distributed in B and that shadowing is lognormal. Based on these results, Secondly, the distribution of the best signal quality is obtained. The authors propose a method to optimize scanning in small/femto cell networks so that mean user throughput is maximized.

[21] is another work that specifically deals with transmit power asymmetry between macrocells and femtocells. The authors of this work propose a special algorithm to be deployed in end-user equipment and aims to compensate the discrepancy in radio channel characteristics.

Another significant work in this area [4] aims to analyze the interference and mobility situation based on access modes of end-users. The paper compares the advantages and disadvantages of two approaches from a network operator and end-user perspectives. The general understanding is that this is a conflict of interest case where the network operator would prefer an open access deployment since this provides an inexpensive way to expand their network capabilities, whereas the femtocell owner would prefer closed access, in order to keep the femtocell's capacity and backhaul to himself. The analysis in [4] shows mathematically and through simulations that the reality is more complicated for both parties, and that the best approach depends heavily on whether the multiple access scheme is orthogonal (TDMA or OFDMA, per sub-band) or non-orthogonal (CDMA). According to this paper, in a TDMA/OFDMA network, closed-access is typically preferable at high user densities, whereas in CDMA, open access can provide gains of more than 200% for the home user by reducing the near-far problem experienced by the femtocell. The results of this paper suggest that the interests of the femtocell owner and the network operator are more compatible than typically believed, and that CDMA femtocells should be configured for open access whereas OFDMA or TDMA femtocells should adapt to the cellular user density.

Mobility management for femtocells is particularly challenging since femtocells have small size radio coverage. In busy indoor environments, prospective femtocell users would enter and leave femtocell zone quickly and handling this user mobility with limited resources is not straightforward. [22] aims to address this problem by proposing special algorithms for end-user mobility pattern prediction. So the overall mobility management scheme reduces the number of unnecessary or redundant handovers by predicting how much time femtocell users will spend in the femtocell zone. [23] is another similar work where user movement and target femtocell access point is predicted to eliminate frequent and unnecessary handovers.

[24] aims enhancement of handover procedure by taking advantage of low cell radius and considering FAP's backbone quality. Before performing handover to a FAP,

the FAP's backbone capacity and delay must be confronted with user's requirements. In this work, the handover is performed only if FAP's backbone is able to satisfy the user. Through the analysis of the time in cell, the authors have found that the variation of this parameter in femtocells is low. Thus, time in cell can be used as handover criteria towards FAPs.

As one of the most recent works in this area, [1] studies the details mobility management schemes for small and medium scale femtocell network deployment. Two different network architectures for small scale and medium scale WCDMA femtocell deployment are presented. The details of handover call flow for these two network architectures and CAC scheme to minimize the unnecessary handovers are proposed for the integrated femtocell/macrocell networks. In this work, the femtocell network is modeled as an M/M/N/N queue with each queue holding the number of active calls in each femtocell. The author propose a regulated M/M/N/N queuing scheme and they demonstrate its optimal behavior in terms of new call blocking probability, handover call blocking probability, and bandwidth utilization performance. A CAC algorithm is integrated to this queuing scheme in order to reduce the number of unnecessary handovers. However the queuing scheme regulation relies on calculating call admission thresholds through extensive computation whose parameters would be dependent on network characteristics.

[25] emphasizes one of the primary goals of this work that is the prolongation or maximization of femtocell connection time without causing low quality connection and/or outages. The conventional handover decision algorithm has been modified so that the handover towards femtocells is initiated as early as possible. The handover criterion in terms of SINR for handovers towards femtocells is relaxed to favor more connections coming to femtocells. In addition to this, the handovers from macro to femto is only possible if the connection quality in femtocell becomes equal to lowest

value without significant outage probability. [26] is a similar recent work that aims to achieve load balancing between femto and macro network via an energy efficient handover algorithm.

[27] proposes a load-balanced handover with adaptive hysteresis in an LTE femtocell system considering channel allocation status of target base station. The study results show that the proposed schemes reduce the ping-pong rate and improve the MSs handover-related performance in terms of handover failure probability compared with the conventional handover method in a femtocell system.

In recent years, MDP (Markov Decision Process) based methods have also become popular in handover decision algorithms for 4G wireless networks or cellular+WLAN heterogeneous networks [28]. Some of these approaches concentrate only on target cell's resource constraints and is combined with traditional methods in a limited way. Some other research is concentrated on transition decisions between cellular and WLAN based networks and thus remains outside the scope of this work [29]. MDP based methods have never been applied to handover decisions in UMTS networks or macrocell/femtocell hierarchical heterogeneous networks.

Concerning access policies in femtocells, [30] provides an extensive overview of general situation in femtocell access policies. The work in [31] concentrated on the interaction between mobile stations (MS) that are near to, but not necessarily communicating with, femtocells. It is shown that an adaptive femtocell access policy that takes specific account of the instantaneous loads on the network can lead to improved performance over a completely open, or completely closed approach

All above works are more or less partial solutions to the MM problem in femtocells by proposing rule-based hierarchical prioritization and/ decision tree algorithms to handle resource limitations. The approach in our work brings a holistic view of all factors involved in the decision process and aims to provided the most balanced and advantageous solution for an efficient and optimal decision.

2.5 Handover Decision Algorithms

2.5.1 Industry standards in femtocell mobility management

The control plane protocols and procedures for femtocell mobility management has been generally described in two 3GPP standards namely 3GPP 25.367 (Mobility procedures for Home Node B, Overall description; Stage 2) and 3GPP 25.467 (UTRAN architecture for 3G Home Node B). These state-of-art standards followed by all femtocell manufacturers define necessary base-line communications for macro-to-femto, femto-to-femto and femto-to-macro handovers but provide no description on specific handover decision algorithms. Consequently femtocell mobility management decisions are formed as similar to MM decisions in UMTS macrocell domain.

2.5.2 State-of-art in handover decision algorithms UMTS macrocell domain

Performance of inter-cell handover algorithms is critical to the overall mobility management performance of a cellular mobile communication system [32]. When an UE crosses a cell boundary between two base stations, handover is required to switch the unit from the departing base station to the approaching base station in order to maintain the connection. Channel fading causes fluctuations in the received signal strength which creates confusion in making an appropriate handover decision. This makes a call bounce back and forth between neighboring base stations jeopardizing voice quality and increasing the chance of a lost call. This phenomenon, i.e. repeated handovers between two base stations, is called a ping-pong effect. An improperly designed handover algorithm results in an unacceptably high level of bouncing (resulting in high signaling costs) and/or a high probability of forced termination. An optimal handover algorithm should reflect the optimal tradeoff between the call quality (i.e., higher signal strength) and the signaling cost. If the handovers could be accomplished without any signaling cost, the best algorithm is the one which connects the mobile station to a base station with higher signal strength at each instant. However, in the presence of non-zero signaling costs, a better handover algorithm is the one which also minimizes the number of unnecessary handovers.

A straightforward and frequently used method in decreasing the number of unnecessary handovers is called hysteresis margin. As a demonstration of application to hysteresis margin to Ec/Io based macro-to-femto handover decision making, Fig 1 provides a graph of Ec/Io values when UE travels from the macro-cell zone towards femto-zone. The downlink Ec/Io comparison constitutes the basis for handover decision but it is also subject to an hysteresis margin. In this particular case, Ec/Io_{femto} should be greater than Ec/Io_{macro} by an hysteresis margin so that back-and-forth, oscillatory handovers between macrocell coverage and femto-zone are prevented.

In above figure Ec/Io values intersect around -13 dBm but by also taking into account 1 dBm hysteresis margin macro to femto handover can only occur when Ec/Io_{macro} goes below -14 dBm. As it is possible to see from this figure, it is possible to decrease handover attempts by increasing the size of hysteresis region.

When an active UMTS connection is ongoing, the UE sends periodical measurement reports to radio system (NodeB, RNC etc) into which it is connected and getting service. These measurement reports contains the average values of DL RSCP (Received Signal Code Power) or Ec/Io values from serving and neighboring cells measured over an measurement averaging interval. The source RNC system evaluates these reports and decides to initiate a hard handover for this particular connection if some decision criteria is satisfied. Following discussion explains various handover decision criteria utilized in UMTS cellular systems [8]:

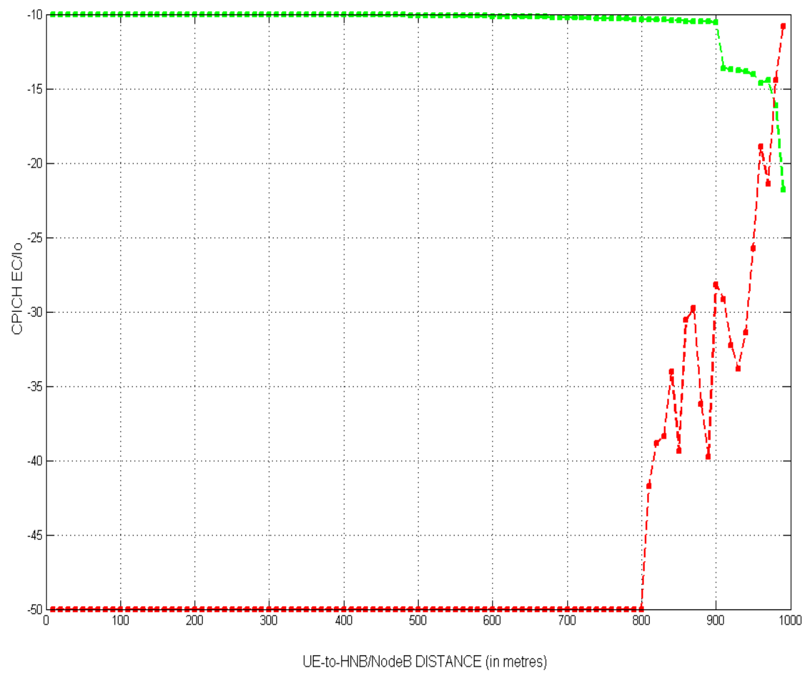

Figure 2.2: Sample diagram showing signal quality vs distance for HNB (red color) and NodeB (green color)

(a) **Relative signal strength:** Chooses the cell with strongest RSS or best Ec/Io at all times. The decision is based on an averaged measurement of the received signal. This method is shown to stimulate too many unnecessary handovers when the current base station signal is still adequate.

(b) **Relative signal strength with threshold:** allows a user to hand over only if the current signal is sufficiently weak (less than a threshold) and the other is the stronger of the two. The effect of the threshold depends on its value compared to the signal strengths of the two base stations at the point at which they are equal. If the threshold is higher than this value, say this scheme performs exactly like the relative signal strength scheme. If the threshold is lower than this value the mobile will delay handover until the current signal level crosses the threshold. If the threshold is way below the point where the signal strength or Ec/Io levels are equal, the delay may be so long that the mobile drifts far into the new cell. This reduces the quality of the communication link and may result in a dropped call. In addition, this causes additional interference to end-users. Thus, this scheme may create overlapping cell coverage areas. A threshold is not used alone in practice because its effectiveness depends on prior knowledge of the crossover signal strength between the current and candidate base stations.

(c) **Relative signal strength with hysteresis:** allows a user to handover only if the new base station is sufficiently stronger by a hysteresis margin than the current one. This technique prevents the so-called ping-pong effect, the repeated handover between two base stations caused by rapid fluctuations in the received signal strengths from both base stations. The first handover, however, may be unnecessary if the serving base is sufficiently strong.

(d) **Relative signal strength with hysteresis and threshold:** hands a user over to a new base-station only if the current signal level drops below a threshold and the target base station is stronger than the current one by a given hysteresis margin.

(e) **Prediction techniques:**base the handover decision on the expected future value of the received signal strength or Ec/Io.

As it is evident from above comparison, Ec/Io or relative signal strength with hysteresis and threshold method effective would handle interference and low quality problem of method (b) and also would prevent unnecessary first handovers brought by method (c). That is why Ec/Io with hysteresis and threshold has been taken as the one of the base-line state-of-art methods for this study and will be used as a benchmark for performance comparison purposes. Predictions techniques as handover decision criteria have been excluded from this study due to their increased complexity.

2.5.3 Advance Interference Management and Self Organizing Networks

Femtocells implement sophisticated interference management algorithms that extend the current 3GPP approach for SON. Current 3GPP approach for SON covers the initial installation phase and the ongoing network operation phase, whereas, advanced SON can also tackle interference problems created by dynamic nature of heterogeneous networks. These SON algorithms are architected and designed for real time operation and optimization and can support both distributed and hybrid network architectures. The optimization in SON algorithms is based on the radio environment measurements done by the small cell, UE measurement reports, and QoS requirements from the operator.

In co-channel deployment scenarios, on the downlink, small cell transmission can create a "dead-zone" for the Macrocell users which can result in poorer speech quality for voice calls and reduced data rates for HSDPA users. Small cells avoid dead-zones by implementing following algorithms:

1. Initial multi cell interference mitigation: This algorithm performs radio environment measurement and monitoring of the surrounding radio environment (Macrocells/Small cells) at power up and then at regular time intervals. It uses this information to minimize downlink interference to Macrocell UEs. It also provides uplink radio resource constraints for small cell UEs to minimize uplink interference to Macrocell UEs.

2. Dynamic real-time multi cell interference mitigation: Based on real time small cell interference measurements and UE measurement reports, this algorithm dy-

namically adjusts the downlink transmit power of the small cell and the uplink maximum power of the small cell UE to minimize downlink/uplink interference to Macrocell UEs. Algorithm supports flexibility and intelligence to give different QoS priorities to Macro cells UEs versus small cells UEs depending on operator requirements

In dedicated channel deployment scenarios, these algorithm optimizes and provides fair QoS for Small cell UEs in presence of other Small cell interference and it also optimizes the capacity of small cells. It is implemented in following two algorithms:

1. Initial multi cell interference mitigation: This algorithm performs radio environment measurement and monitoring of the surrounding radio environment (Macrocells/Small cells) at power up and then at regular time intervals. It uses the information to optimize uplink/downlink interference between small cells.

2. Dynamic real-time multi cell interference mitigation: Based on real time small cell interference measurements and UE measurement reports, this algorithm provides fairness in QoS between small cell UEs while optimizing the capacity of the small cell network. It again supports flexibility and intelligence to give different QoS priorities to different neighboring small cells depending on the operator requirements.

Within the scope of this work uplink femtocell UE power management part of above algorithms are omitted with the assumption that this type of UE enhancements are generally adopted in late stages of technology development. The dynamic SON algorithm implemented in this study will assume that femtocell UEs are not capable of performing special uplink power management while taking service from femto-zones.

2.5.4 Self Organizing Networks Algorithm

The SON implementation in this work is primarily based on adjusting the transmit power of FAP nodes. Since these nodes are deployed in an ad hoc manner, their transmit power should be carefully managed to minimize DL interference to non-femto UEs. For this purpose, all FAP perform a radio enviroment monitoring operation at the start-up and discover neighboring macrocells and femtocells. The received power from this transmitting nodes are fed into a SON algorithm that produces femtocell transmit power as output. The dynamic SON algorithm utilized in this work is the enhanced version of a so-called static state-of-art SON algorithm.

- **Static SON algorithm :** This algorithm is the standard carrier frequency and transmit output power selection scheme proposed in 3GPP RAN WG4 [33] for femtocells. It is workable and effective for both co-channel and dedicated channel deployments. It's main focus is about HNB/FAP output power and the trade-off between HNB downlink coverage and the downlink interference towards co-existing mobiles, which are not allowed to connect to the HNB. This algorithm is initiated at every FAP start-up.

  The primary inputs to the algorithm are RSCP values of all neighboring femtocells and macrocells. The femtocell is able to obtain these parameters with its WCDMA sniffing capability. At the first step, the femtocell measures interfering RSCP levels at all possible operating frequencies through sniffing operations and then selects the frequency with lowest interfering RSP level. At second step to maximum tranmit power levels are calculated namely P_{maxDZ} and $P_{maxQual}$. P_{maxDZ} is the maximum femtocell transmit power level beyon which macro UE not allowed to connect to HNB/FAP would experience non-tolerable DL interference from femtocell. Normally these type of interference creating dead-zone effect for Macro UEs should be minimized and can only occur if macro UE is in very close proximity of femtocell. The algorithm calculates P_{maxDZ} based on tolerated dead-zone radius (typically in the order of 20-100 cms) and macro signal RSCP. The other important maximum transmit power level $P_{maxQual}$ represents the output power required to sustain a given level of CPICH Ec/Io quality requirement for a femtocell connected UE located in the femto-zone boundary subject to interference from neighboring femtocells. $P_{maxQual}$ is calculated based on given level of CPICH Ec/Io quality requirement (typical value is between -16 and -18 dB), femto-zone boundary radius (varying between 20-50 metres based on deployment type) and total interfering RSCP from neighboring femtocells. At the third step, this static SON algorithm sets the transmit power to the $min(P_{maxQual}, P_{maxDZ}$ by following a conservative and risk averse approach for the resolution of the trade-off between two conflicting requirements. This is because any transmit power level greater than P_{maxDZ} would create dead-zone effect to macro UEs and will cause outages. When $P_{maxDZ} < P_{maxQual}$, the quality requirement is relaxed in order to meet the minimal dead-zone size requirement. When $P_{maxQual} < P_{maxDZ}$ both requirements are satisfied as the selected output power $P_{tx} = P_{maxQual}$ that is lower than P_{maxDZ} would meet both the minimal dead-zone size and DL CPICH Ec/Io quality requirement. Below figure provides the framework of the SON algorithm.

- **Dynamic SON algorithm:**

The dynamic SON algorithm is the improved version of the static SON algorithm. The primary enhancement is the dynamic selection of femtocell transmit power from $[P_{maxDZ}, P_{maxQual}]$ interval (in almost all cases P_{maxDZ} will be smaller than $P_{maxQual}$) based on femtocells' available call/session processing capacity, residual backhaul bandwith and UL SIR situation. As any given

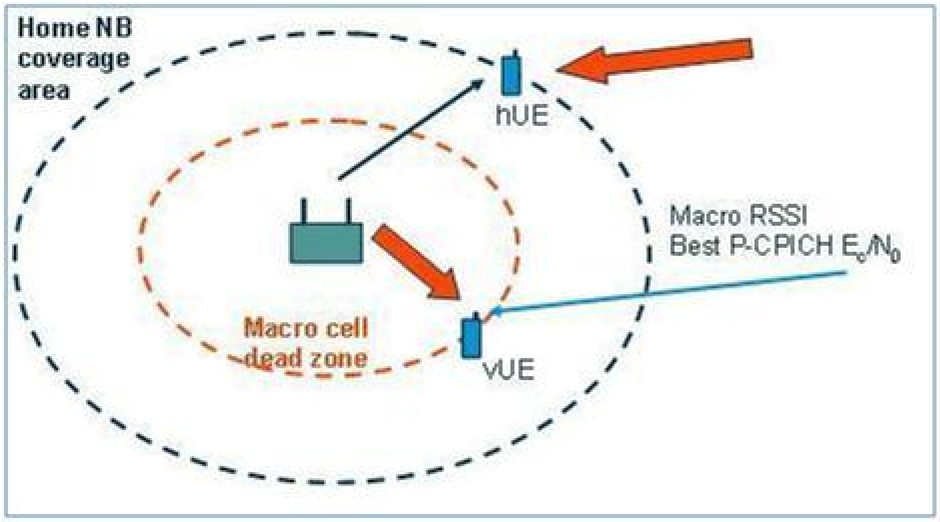

Figure 2.3: Femtocell SON algorithm operational criteria

femtocell has high available capacity and backhaul BW and favorable UL SIR situation, its transmit power would be selected as close to $P_{maxQual}$ in order to enforce handover of macro UEs to femto-zone. When the femtocell has limited or very low available capacity and backhaul BW and/or experiences unfavorable UL SIR situation, the transmit power should be set as close to P_{maxDZ}. The logic behind this is to minimize femto-zone radius and the possibility of disruptive DL interference to macro UEs that are unable to perform HO towards low/null resource femtocell. Varying levels of femtocell resources and UL SIR performance is represented as benefit parameters in MDP formulation. Below formula is utilized for the particular implementation in this work.

$$P_{tx} = P_{maxDZ} + (P_{maxQual} - P_{maxDZ}) min(f_{sir}, f_{res}) \tag{2.1}$$

2.5.5 Femtocell layer adaptations to state-of-art UMTS macrocell handover decision algorithms

According to prominent research work in this area, [32] [8] handover decision criteria needs to be adapted the special behavior of small/femtocell layer compared to macro cell layer. It is suggested that, in macrocellular systems with relatively gentle pathloss characteristics, the measurement averaging interval should be large enough to remove the variations due to fading. A large hysteresis value is never desirable though because it increases handover delay in cases of moderate fading. For femtocell (as similar to microcell systems) systems, a long averaging interval is not desirable due to the possibility of sudden path loss drops that requires prompt action in terms of mobility management. The hysteresis margin should be chosen high enough to avoid being fooled by the fading characteristics of the indoor radio environment.

In this work, asymmetrical hysteresis margin has been utilized as an adaptive policy in macro-femto network integration. In macro-to-femtocell handovers Ec/Io hysteresis margin has been taken as a negative value (-2 dB) whereas for femto-to-macrocell handovers Ec/Io hysteresis margin has been taken as a positive value (2 dB). So Ec/Io with asymmetrical hysteresis and threshold has been accepted as the third state-of-art and benchmark method. Measurement averaging intervals for femtocell and macrocell networks are accepted as the same for the initial stage of the research.

3 PROBLEM FORMULATION

Let T be the observation interval comprised of discrete time-steps $t \in 1, 2, , T..$ Let N be the number of active UE with UE index $i \in 1, 2, , N$ and K be the number of active femtocell nodes with index $j \in 1, 2, .., K..$ The index for single macrocell is accepted to be $K + 1$. All femtocell nodes operate on a single dedicated WCDMA frequency f_{femto}. It has been assumed that only one macro nodeB is present in the system that is operating in $f_{macro} = f_{femto}$. Therefore we have a typical co-channel femtocell deployment that needs to coexist and interwork with a classical UMTS Macro system by dealing with co-channel interference and smooth intra-frequency asymmetric handovers. Below figure depicts the configuration for this network.

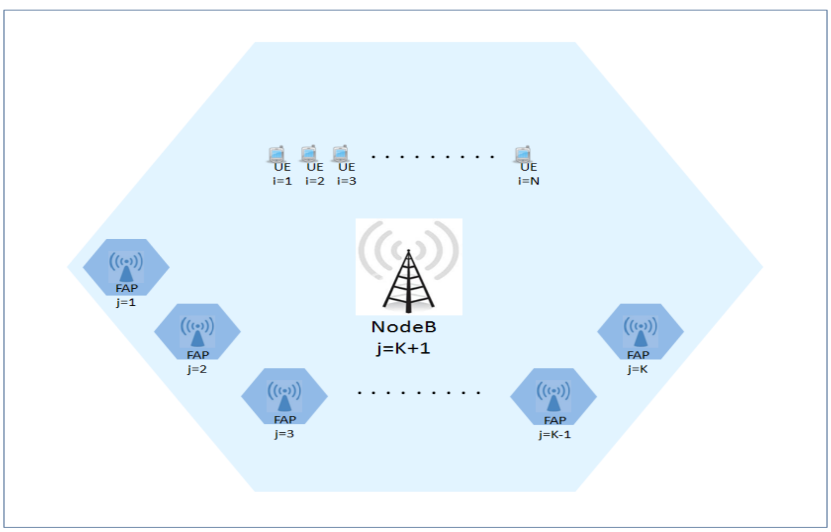

Figure 3.1: Network configuration representation

Following table summarizes the parameters used in the mathematical formulation of the problem

Table 3.1: List of variables and parameters used in problem formulation

Parameter name	Explanation
T	observation interval comprised of discrete time-steps $t \in 1, 2, , T$.
N	the number of active UEs with UE index $i \in 1, 2, , N$
K	the number of active femtocell nodes with index $j \in 1, 2, .., K$
V_i	speed of i'th UE
$G(i)$	the set of time indexes for which i'th UE is in CONNECTED state for an active CS connection
$J(i,t)$	the femtocell/macrocell index that i'th UE is getting active CS connection service at time t
X_j	successful CS call attempts process in femtocell j
T_{ia}	mean call interarrival time parameter
T_{mht}	mean holding time
Δ_{bw}	the minimum level of backhaul BW that will meet BW requirement of an additional CS call
$C(j,t)$	the set of UE indexes getting service from a particular femtocell j at time-step t
$L(j,t)$	the number of active CS voice connections served by femtocell j at time t
C_{sim}	the maximum number of UEs that are getting CS voice call service from a femtocell in a simultaneous way
$B(j,t)$	the residual backhaul BW for femtocell j at time t
$T_{femto}(i,j,t)$	indicator variable for a CS call initiated by i'th UE and getting CS call service from a femtocell j at time-step t.
$T^{\pi}_{femto}(i,j,t)$	the indicator variable $T_{femto}(i,j,t)$ under the HO attempt policy π
$CACF_{SIR,L,B}$	Call Admission Control function
η_{outage}	the minimum tolerable level of downlink Ec/Io ratio below which outage events start to occur
η_{sir}	the minimum tolerable level of uplink SIR ratio below which outage events start to occur
$HS^{\pi}(i)$	the overall number of HO success events for i'th UE under the HO attempt policy π
$HF^{\pi}(i)$	the overall number of HO failure events for i'th UE under the HO attempt policy π
$\rho(V_{i,t}, V_{lo}, V_{hi})$	the mobility related HO failure probability function depending on the speed of UE i at time t
ϵ_{ho}	maximum tolerable HO failure ratio
$A(i)$	the activity ratio during radio tranmission of a node i
$P(i)$	the transmit power of node i
$L(i,j)$	the pathloss between nodes i and j

All UEs are assumed to be moving with variable speed V_i (speed of i'th UE) according to Random waypoint mobility model. These UEs perform network registration or location update to the femtocell or macrocell system according to largest receive RSSI criteria. UE mobility is important in analyzing handover failures. In this work we define two UE speed thresholds such as V_{lo} and V_{hi} that respectively corresponds to low level of UE speed beyond which handover failure probability becomes non-negligible and high level of UE speed beyond which HO failure probability is large enough to deter any HO attempt

Let CPICH $EcIo_{i,t}$ be the ratio of received pilot energy per chip (Ec) to total received energy or the total power spectral density (Io) for i'th UE in time step t. This metric describes call connection quality in general and is usually measured in dB. Let $SIR_{i,j,t}$ be the Signal to Interference Ratio in the receiver of femtocell node j for uplink signals transmitted by i'th UE at time step t. This parameter will be used to describe connection quality on uplink channel.

Let $C(j,t)$ be the set of UE indexes getting service (namely CS voice service in CONNECTED mode) from a particular HNB/FAP j at a particular time-step t. The maximum number of UEs that are getting CS voice call service from an HNB/FAP in a simultaneous way is C_{sim}. Based on above, the load of a femtocell $L_{j,t}$,has been defined as the number of active CS voice connections served by femtocell j at time t. Note that $L_{j,t} = |C(j,t)|$

Let $B(j,t)$ be the normalized residual backhaul BW of the broadband connection that is connecting to femtocell j to the managed IP network of the operator at time t. It will be assumed that each femtocell is able to measure this quantity by passive/active residual BW estimation methods with acceptable level of accuracy. Let Δ_{bw} be the minimum level of backhaul BW that will meet BW requirement of an additional CS call.

In order to guarantee an acceptable service quality with minimum outage and handover failures, above call/connection quality indicators such as $EcIo_{i,t}$ and $SIR_{i,j,t}$ should satisfy some benchmark quality thresholds. These are outlined in below

- Let η_{outage} be the minimum tolerable level of downlink Ec/Io ratio below which DL outage event would definitely occur

- Let η_{sir} be the minimum tolerable level of uplink SIR ratio below which UL outage event would definitely occur

- Let P^{th}_{outage} be the maximum tolerable outage probability due to outages occurring in unfavorable UL/DL radio conditions

Within this context, P^{ecio}_{outage} and P^{sir}_{outage} representing probabilities of Ec/Io and SIR outage events are defined as follows:

$$
\begin{aligned}
P_{outage}^{ecio} &= p(EcIo_{i,t} < \eta_{outage}) \; \forall i, t \\
P_{outage}^{sir} &= p(SIR_{i,j,t} < \eta_{sir}) \; \forall i, j, t
\end{aligned}
$$

The UEs generate active CS connections based on Poisson process that is governed by mean call interarrival time parameter T_{ia}. Holding time for generated active CS connections is taken T_{mht}. Let the X_j be the active CS call arrival process in femtocell j during $t \in 1, 2, , T$. according to CS call generation Poisson process governed by parameter T_{ia} and A_j^s be the successful CS call attempts process in femtocell j during $t \in 1, 2, , T$..

A CS call arrival becomes successful if it is approved by Call Admission Control function $CACF_{SIR,L,B}$. So we have $A^s = CACF_{SIR,L,B}(A^a)$. The call admission control function $CACF_{SIR,L,B}$ is deterministic in nature and the same function will be used in all femtocells. $CACF_{SIR,L,B}$ consists of following list of criteria that should simultaneously be satisfied for successful admission :

1. $SIR_{i,j,t} > \eta_{sir}$

2. $L_{j,t} < C_{sim}$

3. $B(j, t) > \Delta_{bw}$

When applied to a particular instance of i'th UE making a CS call admission attempt to j'th femtocell/macrocell at time t, $CACF(i, j, t) = A$ represents the case where call admission attempt is accepted and $CACF(i, j, t) = R$ represents the case where call admission attempt is rejected.

Let $T_{femto}(i, j, t)$ be the indicator variable for a CS call initiated by i'th UE and getting CS call service (in CONNECTED mode) from a femtocell j at time-step t. $T_{femto}(i, t)$ will take following values

$$T_{femto}(i,j,t) = 1$$

if i'th UE is getting active CS connection service from femtocell j at time-step t and

$$T_{femto}(i,j,t) = 0$$

if i'th UE is not getting an active CS connection service from femtocell j at time-step t

An active CS connection service at j'th femtocell may occur with inputs from two sources

1. X_j as successful CS call attempts process in femtocell j

2. success handovers event towards femtocell j from macro network of from other femtocells

Successful handover events (from femtocell network perspective) at time t for i'th UE in this heterogeneous network are defined as follows

- HO_{mf}^{succ} macro-to-femto Handover event: $T_{femto}(i,j,t) = 1$, $T_{femto}(i,j,t{+}1) = 1$, ...$T_{femto}(i,j,t+Tc) = 1$ where Tc denotes either call termination time or a femto-to-macro HO event time or femto-to-femto HO event time

- HO_{ff}^{succ} femto-to-femto Handover event : For source femtocell j_s and target femtocell j_t we have $T_{femto}(i,j_s,t) = 0$, $T_{femto}(i,j_s,t+1) = 0$, ...$T_{femto}(i,j,t+Tc) = 0$ and $T_{femto}(i,j_t,t) = 1$, $T_{femto}(i,j_t,t+1) = 1$, ...$T_{femto}(i,j,t+Tc) = 1$ where Tc denotes either call termination time or a femto-to-macro HO event time or femto-to-femto HO event time

- HO^{succ}_{fm} femto-to-macro Handover event : $T_{femto}(i,j,t) = 0$, $T_{femto}(i,j,t+1) = 0$, ...$T_{femto}(i,j,t+Tc) = 0$ where Tc denotes either call termination time or a macro-to-femto HO event time.

We define $HS_{mf}(i)$,$HS_{ff}(i)$ and $HS_{fm}(i)$ be the expected number of successful macro-to-femto, femto-to-femto and femto-to-macro HO events for i'th UE. (HO^{succ}_{mf},HO^{succ}_{ff} and HO^{succ}_{mf}). Successful macro-to-femto handovers play an important role in maximizing the amount of femtocell served CS traffic and offloading Macro network. Successful femto-to-femto HOs would contribute to sustaining connection quality while keeping the CS voice traffic in the femto system. Femto-to-macro HOs would not serve towards the goal of maximizing the amount of femtocell served CS traffic so in this study we aim to have them as little as possible and as a last resort to sustain call connection quality.

The primary and explicit objective of our optimization framework is to maximize average number of active CS connections served by Femtocell network. Our system has also an implicit goal of minimizing total number of handover events and this will be achieved my making sure that an HO attempt will be made only when it is necessary to fulfill connection quality requirements and back-and-forth oscillatory handover behavior is prevented. This goal will also serve to HO related signaling load and UE energy consumption minimization objectives.

There are two major impediments towards achieving the ultimate goal of maximizing the average number of active CS connections served by Femtocell network. These are outage and handover failure events. An outage occurs when an active CS connection experiences unacceptable level of connection quality in terms of DL EcIo or UL SIR. Handover failures may occur due a variety of reasons such as excessive HO latency, signalling message corruption, resource unavailability and abrupt/unpredictable changes in radio environment. However within the scope of this work, we assume that high latency and message corruption problems are properly handled so we concentrate on below reasons primarily (representing resource unavailability and abrupt/unpredictable changes in radio environment cases) as failure causes of handover attempts.

1. Handover attempt towards a target femtocell j_t is rejected by CAC (call admission control) function $CACF_{SIR,L,B}$ of target femtocell.

2. Handover attempt towards a macrocell is rejected by CAC function of macrocell. (which is assumed to admit all attempts towards macro)

3. The UE i is moving with high speed ($V_i > V_{lo}$) causing abrupt/unpredictable changes in radio environment and thus leading to HO failure towards a target femtocell j_t

Let $HF_{mf}(i)$,$HF_{ff}(i)$ and $HF_{fm}(i)$ be the expected number of macro-to-femto, femto-to-femto and femto-to-macro HO failures events for i'th UE. (HO_{mf}^{fail},HO_{ff}^{fail} and HO_{mf}^{fail})occurring while there is an HO attempt for the active CS connection serving i'th UE during $t \in 1, 2, , T..$ Let $\rho(V_{i,t}, V_{lo}, V_{hi})$ be the mobility related HO failure probability function depending on the speed of UE i at time t.This will be an increasing function of $V_{i,t}$ so HO failure probability will approach to one as $V_{i,t}$ increases. This will give us following HO failure event probabilities for an HO attempt by i'th UE towards femtocell with index j or towards macrocell with index $K + 1$ at time t.

$$P_{mf-fail}(i,j,t)=I(CACF(i,j,t)=R)+I(CACF(i,j,t)=A)\rho(V_{i,t})$$

$$P_{ff-fail}(i,j,t)=I(CACF(i,j,t)=R)+I(CACF(i,j,t)=A)\rho(V_{i,t})$$

$$P_{fm-fail}(i,K+1,t)=\rho(V_{i,t})$$

Let $G(i)$ be the set of time indexes for which i'th UE is in CONNECTED state for an active CS connection and $J(i,t)$ be the femtocell/macrocell index that i'th UE is getting active CS connection service at time t. Below equations provide expected number of HO failure events in terms of HO failure probabilities provided above.

$$\begin{aligned} HF_{mf}(i) &= \sum_{t\in G(i)} P_{mf-fail}(i,J(i,t),t) \\ HF_{ff}(i) &= \sum_{t\in G(i)} P_{ff-fail}(i,J(i,t),t) \\ HF_{fm}(i) &= \sum_{t\in G(i)} P_{fm-fail}(i,J(i,t),t) \end{aligned}$$

Under this framework, any HO attempt policy π for all UEs $i \in 1,2,,N$ and all femtocells/macrocell indexes $j \in 1,2,..,K,K+1$ during $t \in 1,2,,T$. will provide following outcome.

$$\pi(i,j,t) \Rightarrow \begin{cases} HO^{succ}_{mf} & \text{with probability } 1-P_{mf-fail} \\ HO^{fail}_{mf} & \text{with probability } P_{mf-fail} \\ HO^{succ}_{ff} & \text{with probability } 1-P_{ff-fail} \\ HO^{fail}_{ff} & \text{with probability } P_{ff-fail} \\ HO^{succ}_{fm} & \text{with probability } 1-P_{fm-fail} \\ HO^{fail}_{fm} & \text{with probability } P_{fm-fail} \end{cases}$$

3.1 Single objective optimization formulation without handover failure constraint

The optimal HO and access control decision policy π^* aims to achieve below objective function:

$$\max\left\{\frac{1}{T}\sum_{t\in(1,2,.,T)}\sum_{i=1}^{N}T^{\pi}_{femto}(i,J(i,t),t)\right\} \tag{3.1}$$

Where $T^{\pi}_{femto}(i,j,t)$ is the indicator variable $T_{femto}(i,j,t)$ under the HO attempt policy π. This objective serves towards maximization of the time-average of number of active CS connections served by femtocell network.

Subject to HO performance, quality and capacity constraints:

$$P^{ecio}_{outage} < P^{th}_{outage} \tag{3.2}$$

This quality constraint is there to ensure that actual Ec/Io outage probability is below quality threshold of outage probability.

$$P^{sir}_{outage} < P^{th}_{outage} \tag{3.3}$$

This quality constraint is there to ensure that actual SIR outage probability is below quality threshold of outage probability.

$$|C(j,t)| \leq C_{sim}\ \forall j,t \tag{3.4}$$

This is a capacity constraint that guarantees that maximum simultaneous CS call processing capacity of femtocells are not exceeded.

3.2 Single objective optimization formulation with handover failure constraint

The optimal HO and access control decision policy π^* aims to achieve below objective function:

$$\max \left\{ \frac{1}{T} \sum_{t \in (1,2,.,T)} \sum_{i=1}^{N} T^{\pi}_{femto}(i, J(i,t), t) \right\} \tag{3.5}$$

Where $T^{\pi}_{femto}(i,j,t)$ is the indicator variable $T_{femto}(i,j,t)$ under the HO attempt policy π. This objective serves towards maximization of the time-average of number of active CS connections served by femtocell network.

Subject to HO performance, quality and capacity constraints:

$$\frac{\sum_{i \in (1,.,N)} HF^{\pi}(i)}{\sum_{i \in (1,.,N)} HF^{\pi}(i) + HS^{\pi}(i)} \leq \epsilon_{ho} \tag{3.6}$$

Where $HF^{\pi}(i) = (HF_{mf}(i) + HF_{ff}(i) + HF_{fm}(i))$ is the overall number of HO failures for i'th UE under the HO attempt policy π. $HS^{\pi}(i) = (HS_{mf}(i) + HS_{ff}(i) + HS_{fm}(i))$ stands for the overall number of successful HO attempts for i'th UE under the HO attempt policy π and ϵ_{ho} represents maximum tolerable HO failure ratio. This constraint aims to keep overall HO failure ratio (left side of the constraint equation) below a certain user-defined performance threshold (such as 1% for example)

$$P^{ecio}_{outage} < P^{th}_{outage} \tag{3.7}$$

This quality constraint is there to ensure that actual Ec/Io outage probability is below quality threshold of outage probability.

$$P_{outage}^{sir} < P_{outage}^{th} \tag{3.8}$$

This quality constraint is there to ensure that actual SIR outage probability is below quality threshold of outage probability.

$$|C(j,t)| \leq C_{sim} \ \forall j, t \tag{3.9}$$

This a capacity constrain that guarantees that maximum simultaneous CS call processing capacity of femtocells are not exceeded.

3.3 Multiple objective optimization formulation without explicit handover failure constraint

The major difference between previous single objective optimization model is that HO failure ratio being lower than upper performance threshold is not included to the problem as a constraint. This time, we try to minimize the number of HO failure events as a second objective in addition to maximization of time-average of femtocell based active CS connections. This would give us an alternate optimization formulation of multi-objective nature.

The optimal HO and access control decision policy π^* should achieve below objectives simultaneously:

Following serves towards maximization of the time-average of number of active CS connections served by femtocell network.

$$\max \left\{ \frac{1}{T} \sum_{t \in (1,2,.,T)} \sum_{i=1}^{N} T^{\pi}_{femto}(i, J(i,t), t) \right\} \tag{3.10}$$

The other objective serves towards minimization of the total number of HO attempt events for all UEs.

$$\min \left\{ \sum_{i \in (1,.,N)} HF^{\pi}(i) + HS^{\pi}(i) \right\} \tag{3.11}$$

These two optimization problems could be merged under below multiobjective optimization problem with the introduction of coefficients $\alpha + \beta = 1$

$$\max \left\{ \alpha \frac{1}{T} \sum_{t \in (1,2,.,T)} \sum_{i=1}^{N} T^{\pi}_{femto}(i, J(i,t), t) \right. \tag{3.12}$$

$$\left. - \beta \sum_{i \in (1,.,N)} HF^{\pi}(i) + HS^{\pi}(i) \right\}$$

Subject to below quality and capacity constraints:

$$P^{ecio}_{outage} < P^{th}_{outage} \tag{3.13}$$

$$P^{sir}_{outage} < P^{th}_{outage} \tag{3.14}$$

$$|C(j,t)| \leq C_{sim} \ \forall j, t \tag{3.15}$$

In this method, determination of α and β that represents the weight or importance of each objective function remains challenging as minimizing handover attempts and maximizing the amount of CS connections served by femtocells are inherently conflicting (as the number of handovers are forced to decrease, all UEs will tend to remain in macro network and the number of femtocell CS calls will decline). A simplistic approach to manage this trade-off could come from the assumption that the service provider for femtocell network has a policy such as maximum M_{ho} number of handover attempts should occur during a CS call of standard length (meaning of duration equal to mean holding time). If such policy is available then these objective functions could be merged in such a way that marginal contribution to the first objective function by one CS call in femtocell network should be equal to the maximum allowable marginal cost that this one CS call would bring in terms of handover attempts. This brings us the equality of $\alpha = M\beta$. Combining this with $\alpha + \beta = 1$, we would obtain $\alpha = M_{ho}/(M_{ho}+1)$ and $\beta = 1/(M_{ho}+1)$.

3.4 Common quality parameters

For both single and multi-objective formulations, $EcIo$ for femtocell j_f, $EcIo$ for macrocell $M = K+1$ and uplink SIR for femtocell j_f are calculated with respective formula.

$$EcIo_{i,j_f} = \frac{\frac{A(j_f)P_{j_f}}{L(i,j_f)}}{\frac{P(j_f)}{L(i,j_f}) + \sum_{j\in(1,..,K)-j_f} \frac{P(j)}{L(i,j)} + \frac{P(M)}{L(i,M)ACIR}} \tag{3.16}$$

$$EcIo_{i,K+1} = \frac{\frac{A(M)P(M)}{L(i,M)}}{\frac{P(M)}{L(i,M)} + \sum_{j\in(1,..,K)} \frac{P(j)}{L(i,j)ACIR}} \tag{3.17}$$

$$SIR_{i,j(i)} = \frac{\frac{P(i)\times SG}{L(i,j(i))}}{\sum_{k\in(1,..,N)-C(j(f))-C(M)} \frac{P(k)}{L(k,j(i))} + \sum_{k\in C(M)} \frac{P(k)}{L(k,j(i))ACIR}} \tag{3.18}$$

Where $A(i)$ is the activity ratio during radio transmission of a node i, $P(i)$ is the transmit power of node i, $L(i, j)$ is the pathloss between nodes i and j. ACIR and SG stand for adjacent channel interference ratio and spreading gain respectively.

4 MARKOV DECISION PROCESS (MDP) APPROACH

In this section, we describe how the asymmetrical handoff decision problem in heterogeneous macro-femto networks can be formulated as a Markov decision process (MDP). A MDP model can be characterized by following elements: decision epochs, states, actions, transition probabilities, rewards. At each decision epoch, the decision process has to choose an action based on its current state. With this state and action, the system then evolves to a new state according to a transition probability function. This new state lasts for a period of time until the next decision epoch comes, and then there is a new decision again.

For any action that the system chooses at each state, there is a reward associated with the status of the CS connections (whether they are serving towards the goals of previous section's problem formulation). In this work, the goal is to maximize the expected total reward for all CS connections in the system.

4.1 States and actions

For each UE i We represent the decision epochs by $T_i = (T_{s,1}, T_{s,1}+1, .., T_{c,1}, T_{s,2}, T_{s,2}+1, ...T_{c,2}, ..., T_{s,q_q}, T_{s,q_i}+1, .., T_{c,q_i})$, where $T_{s,(1,2,...,q_i)}$ denotes CS call start time and $T_{c,(1,2,...,q)}$ denotes CS call termination time for q_i amount of CS calls made during observation time. We denote the state space of the system by the load and residual backhaul BW of each femtocell, connection status (CONNECTED to j th cell vs idle) and speed of all UEs, DL EcIo values of all UE with respect to femtocells/macrocell and UL SIR of all femtocells. All these parameters constitute state space S of the combined UE, femtocell and macrocell system.

At each decision epoch, based on the current state S, the system chooses an action $a \in A_s$, (A_s is the set of possible actions in state s) where the action a consists of HO attempt decisions for all UEs with UE index $i \in 1, 2, , N$ together with the the index of target cell they intend to perform HO. So the action a would be a vector of $[(i, j_t]$ parameter pairs indicating that there is an HO attempt for i'th UE towards target cell whose index is j_t if $j_t \neq J(i)$. If $j_t = J(i)$, this means that no HO attempt will be done (target cell is already connected cell index).

4.2 Rewards

When the system chooses an action a in state s, it receives an immediate reward $r(s, a)$. The reward function depends on the benefit and penalty functions explained below.

For the benefit function, we are considering 4 different aspects of active CS connections. These are independent benefit functions for DL EcIo performance, UL SIR performance, residual femtocell resources and femtocell usage preference.

We are starting to formulate benefit functions by populating two functions that would reflect the benefit coming from the satisfaction of performance constraints. Let the DL EcIo benefit function $f_{ecio}(s, a = (i, j_t))$ represent the benefit that the system can gain by selecting action $a = (i, j_t)$ (that is HO attempt for i'th UE towards target cell j_t) in state s:

$$f_{ecio}(s,a) = \begin{cases} \frac{-\eta_{outage} + EcIo^{dl}(a)}{-\eta_{outage} + (-10)} & \text{if } EcIo_{i,j_t} \geq \eta_{outage} \\ -\infty & \text{if } EcIo_{i,j_t} < \eta_{outage} \end{cases}$$

If there is no HO attempt, this means that the above expression will be re-used for $f_{ecio}(s,a)$ but this time j_t will be replaced by the femtocell/macrocell index that the UE i remains already connected, namely $J(i)$.

The UL SIR benefit function $f_{sir}(s, a = (i, j_t))$ represent the benefit that the system can gain by selecting action $a = (i, j_t)$ (that is HO attempt for i'th UE towards target cell j_t) in state s. Let SIR^{ul}_{max} and SIR^{ul}_{min} be maximum and minimum uplink SIR levels for femtocells in the target cell j's neighborhood

$$f_{sir}(s,a)=\begin{cases} \frac{SIR^{ul}(a)-SIR^{ul}_{min}}{SIR^{ul}_{max}-SIR^{ul}_{min}} & \text{if } SIR_{i,j_t} \geq \eta_{sir} \\ -\infty & \text{if } SIR_{i,j_t} < \eta_{sir} \end{cases}$$

Now, we are introducing the femtocell specific benefit function that describes how feasible and beneficial handovers towards a specific femtocell would be depending on its residual backhaul BW situation and current CS connection load. Logically, the system should favor femtocells with large residual backhaul BW and low CS connection load as suitable HO targets. In line with these principles femtocell resource benefit function $f_{res}(s, a = (i, j_t))$ is defined as follows:

$$f_{res}(s,a)=\begin{cases} 1 & \text{if } j_a = K+1 \text{ (macro)} \\ -\infty & \text{if } j_t \neq K+1 \text{ and } (L(j_a) \geq C_{sim}(j_a) \text{ or } B(a) < \Delta_{bw}\ ) \\ \text{for all other cases} & \\ \frac{min(\frac{B(a)}{B_{req}}, C_{sim}(a)-L(a))}{C_{sim}(a)} & \end{cases}$$

where B_{req} is the minimum residual backhaul requirement for a femtocall at full load (so there is C_{sim} number of active calls served by the femtocell) . Note that macrocell in the system is assumed to have no resource constraints in terms of backhaul BW and CS connection load so the benefit of making a HO attempt towards macrocell in these terms are always favored (through always unity resource benefit function) when compared to HO attempts towards femtocells.

As a last contribution to benefit part, we want to introduce femtocell preference benefit function $f_{pref}(s,a)$ that would encourage using femtocells as HO targets or keeeping active CS connections as sustained by femtocells. This benefit function will contribute to the objective of maximizing the number of active CS connections on femtocells. The main objective of femtocell preference benefit function is to make sure that a femto with average capacity and UL SIR situation would be considered as equal to macrocell in terms of these benefits. Thus the formulation has been constructed as follows

$$f_{pref}(s,a)=\begin{cases} 0 \\ \text{if } a=(i,j_t=K+1) \\ 1 \\ \text{if } a=(i,j_t=1,2,..,K) \text{ and} \\ EcIo^{dl}(a)>EcIo^{dl}(K+1)-2 \end{cases}$$

So $f_{pref}(s,a$ represents the equalizing benefit when an active CS connection remains served by a femtocell or an HO attempt towards a femtocell is realized.

Above benefit functions are combined as follows to provide the overall benefit function $f(s,a)$:

$$\begin{aligned} f(s,a)=&\kappa_{ecio}f_{ecio}(s,a)+\kappa_{sir}f_{sir}(s,a)+\kappa_{res}f_{res}(s,a) \\ &+\kappa_{pref}f_{pref}(s,a) \end{aligned} \tag{4.1}$$

Where κ_{ecio}, κ_{sir}, κ_{res} and κ_{pref} are related benefit function weights that could be used to adjust the effects of each seperate benefit on the aggregate function.

On the penalty side, the system is penalizing fast moving UE behavior through penalty function $h_{speed}(s,a)$ described below.

$$h_{speed}(s,a)=\begin{cases} 0 & \text{if } j_t = J(i) \text{ (no HO)} \\ 0 & \text{if } j_t \neq J(i) \text{ (HO) and } V_i \leq V_{lo} \\ \frac{V_i - V_{lo}}{V_{hi} - V_{lo}} & \text{if } j_t \neq J(i) \text{ (HO) and } V_{lo} < V_i \leq V_{lo} \\ 1 & \text{if } j_t \neq J(i) \text{ (HO) and } V_i > V_{hi} \end{cases}$$

It could be seen that if any i'th UE's speed (V_i) is below V_{lo}, there is no penalty for HO attempts. For the UE speeds between V_{lo} and V_{hi} that constitutes an intermediary zone, a linear increase in the penalty value is devised. Finally if $V_i > V_{hi}$, HO attempts are fully penalized.

The handover attempt penalty function $h_{ho}(s,a)$ is formulated to serve towards HO attempt minimization goal. Let $N_{ho}(i,t)$ be the number of handovers user i has performed during the CS call he/she is performing at time t and M_{ho} be the maximum tolerable number of handovers per call as per UMTS operators policy. HO attempts are penalized through following function using $N_{ho}(i,t)$ as parameter.

$$h_{ho}(s,a)=\begin{cases} 0 & \text{if } a = (i, j_t = J(i)) \\ \frac{e^{N_{ho}(i,t)}}{e^{M_{ho}}} & \text{if } a \neq (i, j_t = J(i)) \\ 1 & \text{if } \frac{e^{N_{ho}}}{e^{M_{ho}}} \geq 1 \end{cases}$$

Here $h_{ho}(s,a)$ represents the extra penalty when the action a in state s embodies an HO attempt decision for i'th UE.

Since there is no other penalty functions, the overall penalty function is $h(s,a) = \kappa_{speed} h_{speed}(s,a) + \kappa_{ho} h_{ho}(s,a)$ where κ_{speed}, κ_{ho} are related penalty function weights. The reward function that will be used in the HO attempt decision process at each decision epoch is thus based on following reward function $r(s,a)$.

The partial benefit and penalty function coefficients are shaped according to below principles

1. κ_{ecio} is chosen as 3 times greater than κ_{sir} and κ_{res} : Since the greater portion

of the outage events are caused by high DL interference leading to low Ec/Io, more weight is given to choose the target cells with good Ec/Io values and outage events would decrease considerably

2. $\kappa_{sir} = \kappa_{res}$: This gives balanced results as both factors (uplink SIR and network resource situation) seems to be equally effective in lowering undesirable call admission and HO attempt rejection events.

3. $\kappa_{pref} = \kappa_{sir} + \kappa_{res}$: Femtocell bias benefit function should be able to bridge the gap between the benefit function for a non-resource constrained macrocell ($\kappa_{sir} f_{sir}(s,a) + \kappa_{res} f_{res}(s,a) = \kappa_{sir} + \kappa_{res}$) and for a femtocell with scarce but still sufficient resource constraints (assume $f_{sir}(s,a) = \epsilon_{sir}$ and $f_{res}(s,a) = \epsilon_{res}$ (where $\epsilon_{sir}, \epsilon_{res} > 0$ but is marginally close to 0). In this case $\kappa_{sir} f_{sir}(s,a) + \kappa_{res} f_{res}(s,a)$ will also be marginally close to zero. Therefore the femtocell bias benefit function coefficient should satisfy $\kappa_{pref} = \kappa_{sir} + \kappa_{res}$ equality so that femtocells are still favored in this most asymmetric resource situation between macrocell and femtocell.

4. $\kappa_{ho} = \frac{\kappa_{pref}}{2}$: This equality comes from the worst case analysis when HO attempt penalty function takes the maximum amount of 1. This is the situation where any subsequent HO attempts in not desirable and should be performed only if it is absolutely necessary. In this situation, it is desirable that handover penalty κ_{ho} at least partially cancels κ_{pref}, the maximum possible value of femtocell bias benefit function.

5. $\kappa_{speed} = \kappa_{ecio} + \kappa_{sir} + \kappa_{res}$: This equality makes sure that the speed penalty remains effective even if all partial benefit functions encouraging HO attempt have their maximum value as 1 and the partial HO attempt penalty function is 0. In this most favorable HO attempt situation, the benefit function value

will be equal to $\kappa_{ecio} + \kappa_{sir} + \kappa_{res}$. The partial speed penalty function should be able to cancel this maximum benefit situation if the UE speed is high and HO attempt for this UE is not favorable. This is achieved by having $\kappa_{speed} = \kappa_{ecio} + \kappa_{sir} + \kappa_{res}$ equality satisfied

When all above equalities are combined, it is possible to propose the coefficient values in below table as a set of most balanced and optimal set of partial benefit and penalty function coefficients (the value of κ_{sir} is taken as k as a reference value, the choice of k as any positive number will not influence the way the algorithm functions)

Below benefit and penalty functions coefficients have been chosen for deployment.

Table 4.1: Benefit and penalty function coefficients

Coefficient	**Value**
κ_{ecio}	3k
κ_{sir}	k
κ_{res}	k
κ_{pref}	2k
κ_{ho}	k
κ_{speed}	5k

The reward function that will be used in the HO attempt decision process at each decision epoch is thus based on following reward function $r(s, a)$.

$$r(s, a) = f(s, a) - h(s, a)$$

4.3 MDP formulation

A decision rule $\delta_{t,i}$ for all $t \in T_i = (T_{s,1}, T_{s,1}{+}1, .., T_{c,1}, T_{s,2}, T_{s,2}{+}1, ...T_{c,2}, ..., T_{s,q_q}, T_{s,q_i}+1, .., T_{c,q_i})$ is used to specify the action at a particular decision epoch based on system state at that epoch. A policy would be a sequence of decision rules $\delta_{i,t}$ for all i and all $t \in T_i$. Let $v^{\pi}(s)$ the expected discounted total reward obtained for all CS connections that are serving to all UEs at all decision epoch given that policy π is used with an initial system state of s. We can state MDP optimization problem as follows.

$$\text{maximize } v^{\pi}(s) = E^{\pi}(s) \left\{ \sum_{t=1}^{T} \lambda^{t-1} r(s_t, a_t) \right\}$$

Since there is no constraint in this MDP formulation and the structure of decision epochs that are based on CS connection generation pattern could be accepted as independent from HO attempt decisions in terms of the positive reward contribution, it is possible to propose a static step-wise reward maximization rule that will also maximize overall expected reward in above equation. The underlying logic behind independence of decision epoch structure and HO attempt decision could be explained as follows. Let's assume that the HO attempted according to the decision taken at any decision epoch is successful. Then reward for this particular connection will still be contributing towards overall reward in the maximum possible amount. If the HO is not successful, CS connection will be dropped and the reward from this connection will be negatively effected. So if the static step-wise reward maximization rule achieves to minimize HO failure probability while implicitly limiting the number of HO attempts to the necessary minimum level then it is possible to assume that it will achieve an optimal or near optimal solution to above MDP optimization problem.

Based on these principles, the following decision rule $\delta_{i,t}$ is proposed that will also define the stationary and deterministic policy π since at every decision epoch and for all i's the same decision rule will be applied and it will choose an action with certainty at each decision epoch.

$$\delta_{t,i} \Rightarrow a^*(i,t) = \underset{a \in A_s}{argmax}\ r(s,a) \tag{4.2}$$

According to above rule, the action providing highest reward should be chosen at each decision epoch. So the decision rule can be summarized as there will be an HO attempt towards the cell that provides the highest reward for every active CS connection at all decision epochs. If the maximum reward through the action $a^*(i,t)$ consists of remaining in the same cell, no HO attempt is made. In above MDP formulation, the reward function explained in previous section is expected to provide as much near-optimal behavior as possible while minimizing unnecessary handovers.

5 PERFORMANCE ANALYSIS

5.1 Simulation platform and femtocell deployment models

In order to simulate macrocell-femtocell interaction in combined heterogeneous network, the simulations were based on femtocells being randomly deployed in the coverage area of a single macrocell. For this purpose, an UMTS NodeB transmitting at 46 dBm omnidirectional TX power has been placed at the centre of a square area representing the typical macrocell coverage zone. The macrocell coverage has been assumed to accommodate a fixed number of end-users for the duration of the simulation. The size of the square are representing macrocell coverage zone and the number of end-users depend on the deployment mode.

There are four deployment modes namely dense urban, urban, suburban and rural settings. The macrocell cell size and end-user densities for these deployment modes are taken from IMT report No. 6 issued by UMTS forum in 1998 as generic planning guide for UMTS networks [34]. The number of femtocells is obtained with the assumption that %3.33 market penetration rate for femtocells (so there will be one femtocell operational per 30 subscribers of the femtocell operator). These femtocells have been deployed randomly within the indoor areas of the buildings. There are three types of buildings namely residential and public hotspot types. The buildings have been modeled to have square-based rectangular prism geometry with specific edge lengths and heights that reflects the average sizes of these buildings. The buildings have been populated in perturbed grid method in which each grid line has been separated by a distance that is handling perturbation effects and still guaranteeing a realistic inter-building distance. The ratio of residential/enterprise buildings and the concentration ratio (the probability of having a building populated in each grid intersection point) can be customized according to the deployment style. For example, by defining a high residential/enterprise building ratio and a low concentration ratio, it is possible to model rural/suburban settings whereas a low residential/enterprise building ratio with high concentration ratio could be used to model an urban/dense-urban settings. Each building has multiple floors and physical obstacles within the same floor are crudely included to the simulation for complexity reduction purposes.

The simulation covers UMTS CS voice calls generated by UEs towards outgoing destinations. Each CS voice call utilizes narrowband 12.2 kbps AMR codec and occupies a backhaul BW of 80 kbps with IPSec/RTP/UDP/IP/L2 headers. CS voice calls are generated according to Poisson process and goes through an admission process if the UE is getting service from femtocells. The femtocell call admission scheme is simplistic and takes into account residual call handling capacity, residual backhaul BW and uplink SIR status. If any of these femtocell metric does not satisfy required criteria, the CS call is rejected. PS calls are omitted from the simulation since mobility management is considered as much more critical for real-time services such as voice and video calls. No admission control procedure is applied if the UE initiates the CS call through macrocell. Cell selection and reselection has been carried out based on standard RSSI based methods. However cell selection and reselection in idle mode have been biased towards femtocells by using 3GPP standard based HCS (Hierarchical Cell Structure) method.

The femtocells are assumed to operate under hybrid or open user access control scheme. Closed access scheme is excluded from the analysis due to unfeasibility of this mode in co-channel deployments and the limitations it would bring to mobility management (only CSG member UEs are allowed to hand-in to femtocells). Dynamic

SON algorithm has been implemented in FAP nodes for all deployment scenarios and HO decision algorithm options. The femtocells in the simulated network are deployed within the buildings in a constrained randomized way. The main physical deployment constraint for each femtocell is the assumption of having a minimum inter-FAP distance of 10 meters. Therefore, it is assumed that the end-users will not deploy femtocells in close vicinity of each other. This constraint aims to bring some level of realism to the deployment style as femtocell localization will be made in independent/discrete units (aka flats) for residential buildings and inter-femtocell distances in business building deployments will be made according to coverage requirements of each enterprise.

5.1.1 Simulated deployment scenarios

The characteristics of femtocell deployment scenarios are as follows

5.1.1.1 Dense urban deployment

This deployment is characterized by populated densely business and public hotspot buildings with no residential establishments. The radio propagation characteristics in business and public hotspot buildings are shaped with the assumption of more open spaces and low number of intra-building flats as compared to residential. Typical users tend to be more mobile in public hotspot buildings as compared to business and residential buildings. The macrocell coverage radius is expected to be around 300-400 metres with very high number of UMTS subscribers per sq km.

5.1.1.2 Urban deployment

This deployment is characterized by moderately populated business and public hotspot buildings with few residential establishments. The radio propagation characteristics and end-user mobility patterns will be similar to dense-urban setting. The macrocell coverage radius is expected to be around 400-600 metres with high number of UMTS subscribers per sq km.

5.1.1.3 Suburban deployment

This deployment is characterized by moderately densely populated residential buildings with few business and public hotspot buildings. The macrocell coverage radius is expected to be around 1000 metres with moderate number of UMTS subscribers per sq km. The number of CS calls per subscriber in busy hour will be lower but close to the average. User mobility will also be lower as compared to urban deployment modes.

5.1.1.4 Rural deployment

This deployment is characterized by sparsely populated small size residential buildings with few public hotspot buildings. The macrocell coverage radius is expected to be around 1-2 kms with low number of UMTS subscribers per sq km. The number of CS calls per subscriber in busy hour will be low as well as user mobility.

Below tables provide an overview of deployment specific parameters used in the simulation.

Table 5.1: Deployment mode specific simulation parameters

Parameter	**D.Urban**	**Urban**	**Suburban**	**Rural**
Building concentration percentage	% 10	% 5	% 1	% 0.25
Residential building ratio	% 5	% 20	% 60	% 80
Business building ratio	% 65	% 50	% 20	% 10
P. hotpot building ratio	% 30	% 30	% 20	% 10
Simulation area width (m)	800	1000	2000	3000
Average Indoor UE ratio	% 80	% 80	% 80	% 80
Population density per sq.km	45000	27000	1800	108
Market penetration percentage	% 2.5	% 2.5	% 2.5	% 2.5

Table 5.2: Building specific simulation parameters

Parameter	Residential	Business	P. Hotspot
Square base edge length (m)	20	30	50
Building height (m)	20	48.5	13.5
Per floor height (m)	3.5	3.5	3.5
ITUP.1238 Pathloss Coeff.	28	30	22
Mean distance per wall (m)	5	10	10
Shadowing Loss (dB)	8	10	10
External Wall Loss (dB)	15	15	15

5.1.2 User mobility models

The UEs in the simulation are implemented in a simplistic way but according to UMTS industry standards and conventions in terms of uplink power management, cell camping/reselection behavior and other relevant mobility management principles. The logical and physical RF channels between UE and UMTS NodeB/FAPs are not implemented as the emphasis of the simulation is on handover decision algorithm's effectiveness. The UEs move around the simulation zone according to Markov mobility model. However maximum UE speed and the mobility pattern is somewhat different based on UEs being indoor or outdoor. In the simulation, UE starts to move inside a building towards its designated target with constant speed randomly selected over the range of minimum and maximum indoor UE speed. Once the UE reaches to its target, the decision is made on whether to move towards another target point within the same building (in a 3 dimensional way) or to move towards a target point in another building within the simulation zone. The decision is made in a probabilistic way according to some user-defined remain-in-the-building probability. If the UE decides to leave the building towards another target, the outdoor part of UE movement on the ground level (2-dimensional) is implemented until the UE reaches the designated building. Outdoor movement speed is also randomly selected over the range of minimum and maximum outdoor UE speed. As expected maximum outdoor

UE speed is considerably higher than indoor speed in order to simulate high-speed vehicular mobility. Therefore the simulation covers a wide range of UE speeds and mobility patterns.

5.1.3 Wireless propagation and channel modeling

The femtocell network in the simulation is a single, shared frequency system. The UMTS frequency used by femtocells is one of the macrocell frequencies in the operators' radio spectrum. Thus, co-channel interference is expected to occur concerning macro-to-femto RF interaction as well as femto-to-femto RF interaction. The downlink transmit power of femtocells is controlled by the dynamic SON algorithm. The uplink transmit power of UEs are adjusted according to an approximate model based on RSS [35].

ITU P1238-6 radio propagation model [36] has been utilized for all indoor pathloss and fading calculations of femtocell transmissions. Following formula and parameters have been utilized for path-loss calculation.

$$L_{total} = 20log_{10}(f) + Nlog_{10}(d) + L_f(n) + L_{shadow} - 28$$

where L_{total} is the total pathloss, N is distance based power loss coefficient, f is the transmit frequency in MHz, d is the separation distance between the base station and portable terminal, $L_f(n)$ is the floor penetration loss factor in dB, L_{shadow} is the shadow fading based loss and n is the number of floors between base station and portable terminal.

Typical parameter values for N and L_f, based on various measurement results, are given in below tables

In our work, f is taken as 2100 Mhz as compliant to UMTS standards. Based on this f value, residential, office and commercial power loss coefficients (N) corre-

Table 5.3: Power Loss Coefficient for different building types

Frequency	**Residential**	**Office**	**Commercial**
1.8-2Ghz	28	30	22

Table 5.4: Power Loss Coefficient for different building types

Frequency	**Residential**	**Office**	**Commercial**
1.8-2Ghz	4n	15+4(n-1)	6+3(n-1)

sponding to 1.8-2Ghz range in ITU P.1238 model have been utilized as residential, business and public hotspot pathloss coefficients as depicted in table 4. In a similar vein, the corresponding ITU P.1238 formulation for L_f has also been reutilized in residential, business and public hotspot deployments of femtocells..

Concerning fading characteristics in ITU P1238, the indoor shadow fading statistics are accepted to comply to zero mean log-normal distribution and standard deviation values (dB) utilized in the simulation are given in below table

Table 5.5: Standard deviation for log-normal shadow fading

Frequency	**Residential**	**Office**	**Commercial**
1.8-2Ghz	8	10	10

COST 231 Hata radio propagation model has been utilized for all outdoor and indoor pathloss calculations of macrocell transmissions [37]. The model details are as follows.

$$L_{total} = 46.3 + 33.9log_{10}(f) - 13.82log_{10}(h_B) - a(h_R) + [44.9 - 6.55log_{10}(h_B)]log_{10}(d) + C$$

where L_{total} is the total pathloss, f is the transmit frequency in MHz, d is the separation distance between the base station and portable terminal, h_B is the base-station effective height, h_R is the mobile station device effective height, $a(h_R)$ is the mobile station correction factor and C is the additional urban clutter correction factor. According to this model $a(h_R)$ is calculated as follows:

$$a(h_R) = (1.1log_{10}(f) - 0.7)h_R - (1.56log_{10}(f) - 0.8)$$

5.2 Implemented handover decision algorithms

- **Algorithm 1: Ec/Io with hysteresis-threshold** If DL CPICH Ec/Io drops below -18 dB (quality threshold) and any neighbor cell's CPICH Ec/Io is greater than current cell's Ec/Io by a margin of Ec/Io hysteresis, then perform handover to this cell. If there are multiple neighbor cells satisfying this criteria, perform handover to the cell with maximum Ec/Io value. This is standard handover decision criteria in cellular UMTS systems

- **Algorithm 2: Ec/Io with hysteresis-threshold with femtocell resource consideration** If DL CPICH Ec/Io drops below -18 dB (quality threshold) and any neighbor cell's CPICH Ec/Io is greater than current cell's Ec/Io by a margin of Ec/Io hysteresis (standard Ec/Io hysteresis margin= 2dB)include this neighbor cell to the handover candidate list. If any member of the target cell list is a macrocell, perform handover towards macrocell. If there is no macrocell in the list, check femtocell resources (backhaul, call processing and UL SIR) for every cell in the handover candidate list by starting from the femtocell with highest Ec/Io value.Also check if UE speed is below some speed threshold. Perform handover to the femtocell if resources are able to handle the handed over CS call and if UE speed is below speed threshold. This method and its slightly different variants have been proposed in the literature as femtocell specific handover decision criteria.

- **Algorithm 3: Ec/Io with asymmetric/biased hysteresis-threshold with femtocell resource consideration** If DL CPICH Ec/Io drops below -18 dB (quality threshold) and any neighbor cell's CPICH Ec/Io is greater than current cell's Ec/Io by a margin of Ec/Io hysteresis include this neighbor cell to the handover candidate list. However in this option, Ec/Io hysteresis is asymmetrical with femtocell bias. So if the serving cell is macrocell, Ec/Io hysteresis margin is -2 dB for all femtocell handover candidates as long as their CPICH Ec/Io is greater than quality threshold. So if the serving cell is femtocell, Ec/Io hysteresis margin is 2 dB as in the normal hysteresis case. If any member of the target cell list is a macrocell, perform handover towards macrocell. If there is no macrocell in the list, check femtocell resources (backhaul, call processing and UL SIR) for every cell in the handover candidate list by starting from the femtocell with highest Ec/Io value. Perform handover to the femtocell if resources are able to handle the handed over CS call and if UE speed is below speed threshold. Biased/asymmetric hysteresis margin have also been proposed in the literature and is hereby combined with state-of-art femtocell specific handover criteria

- **Algorithm 4: MDP based handover decision criteria** This novel method has been explained in previous chapter.

5.3 Matlab Implementation

Matlab simulation implements all aspects of the simulated environment depicted in previous section. However the simulation does not model individual network nodes and packet exchanges. The handovers are occurring in an implicit way according to specific decision algorithm (aka algorithm 1,2,3 or 4). While being quite accurate mathematically, the simulation is not real-time event based.

Following figure depicts dense-urban deployment scenario through a drawing in Matlab environment. Green dots represent NodeB and HNBs and red dots represent moving UE. There different types of building are also drawn as rectangular prisms

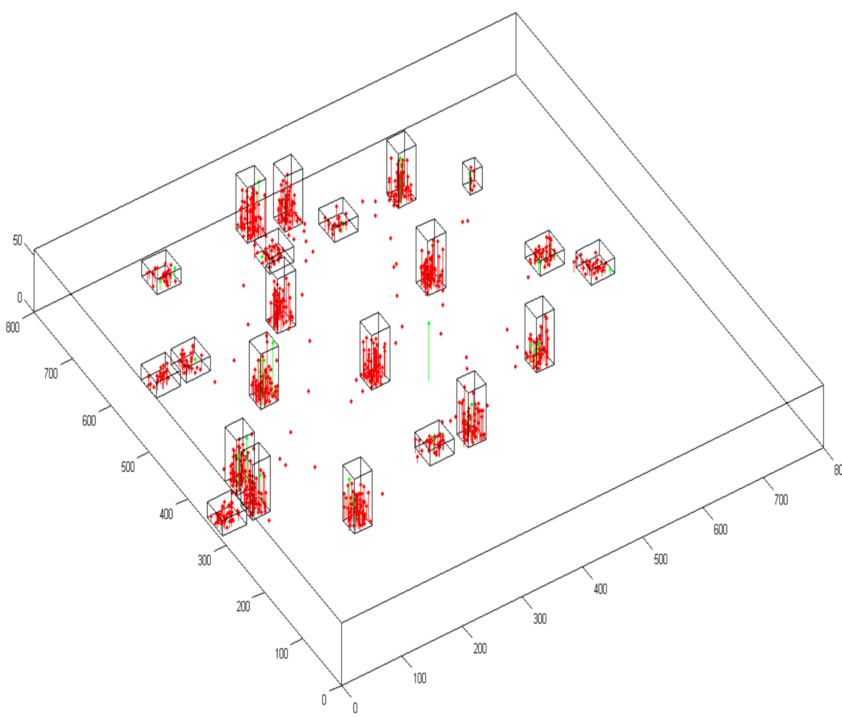

Figure 5.1: Matlab drawing for dense urban simulation

Parameters in below table are used in Matlab simulation.

Table 5.6: List of variables and parameters used in Matlab simulation

Parameter name	**Value**
Simulation time (in seconds)	270
Mean holding time (in seconds)	60
Call inter arrival time (in seconds)	30
HO decision interval (in seconds)	0.5
Maximum tolerable number of HOs per call	5
HO time hysteresis (in seconds)	2
V_{lo} (in m/s)	2
V_{hi} (in m/s)	15
η_{outage} (in dB)	-20
η_{sir} (in dB)	3
Spreading factor	256

5.3.1 Matlab results

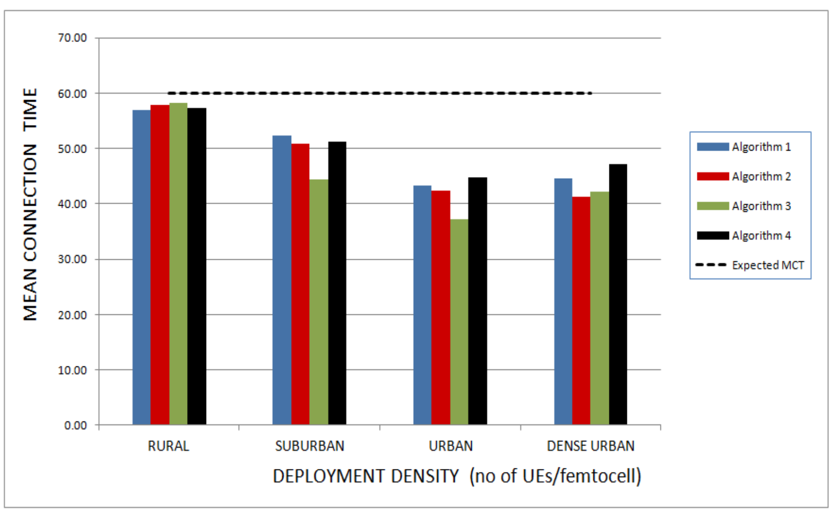

Figure 5.2: Mean Connection Time values across different deployment options

Mean Connection Time (MCT) reflects the success of the network in terms of call completion. From 5.2, it is possible to observe that the macro-femto combined network underperforms in dense deployment scenarios ($MCT < 60sec = MHT$) due to high admission reject ratio of femtocells in loaded conditions. Especially in denser deployments, MDP based HO decision method is able to increase overall network traffic up to %3-10 through lower outage and admission reject events. According

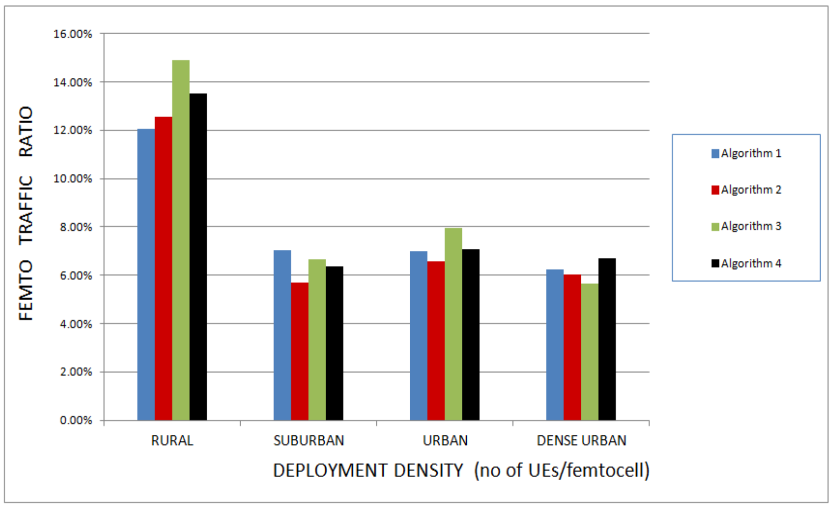

Figure 5.3: The ratio of CS traffic handled by femtocell network

to figure 5.3, algorithm 4 achieves acceptable performance in increasing the femto quality coverage ratio at all deployment modes. The traffic capturing capability of MDP method becomes more prominent in higher deployment densities. Asymmetric hysteresis based HO decision (Algorithm 3) scheme is the best method to transfer generated circuit-switched (CS) traffic to femtocells.

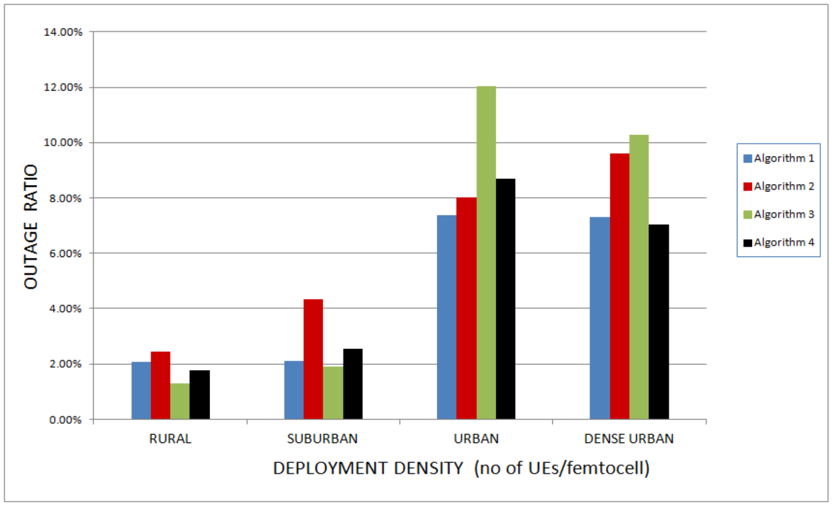

Figure 5.4: Outage percentage

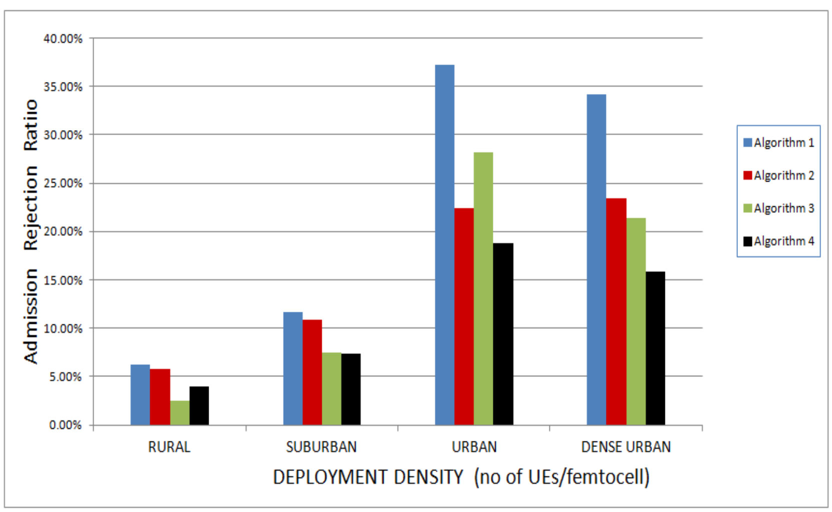

Figure 5.5: The percentage of non-admitted CS call attempts by UEs camped to femtocells

As seen in figures 5.4 and 5.5, MDP based HO decision algorithm (Algorithm 4) has the best performance (in terms of minimizing outage and admission reject events) with better load sharing between femtocells and joint consideration of all MM related criteria. In urban and suburban deployment scenarios, MDP method (algorithm 4)

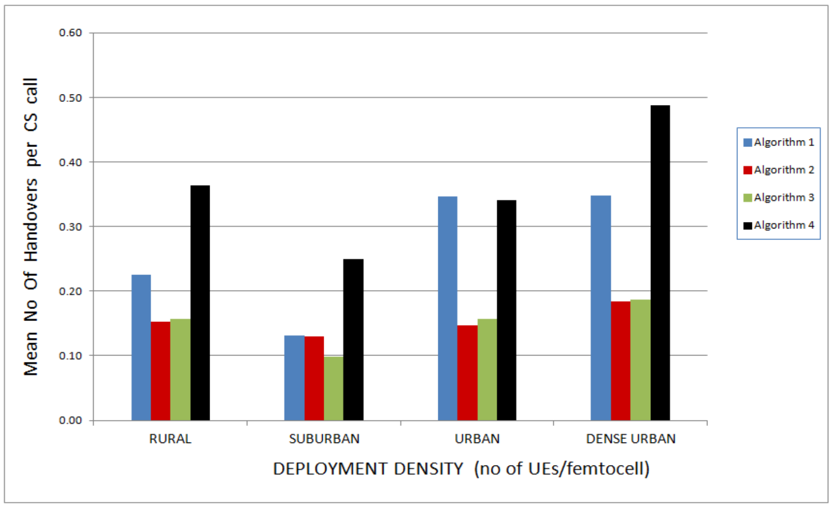

Figure 5.6: Average number of HO attempts per CS call

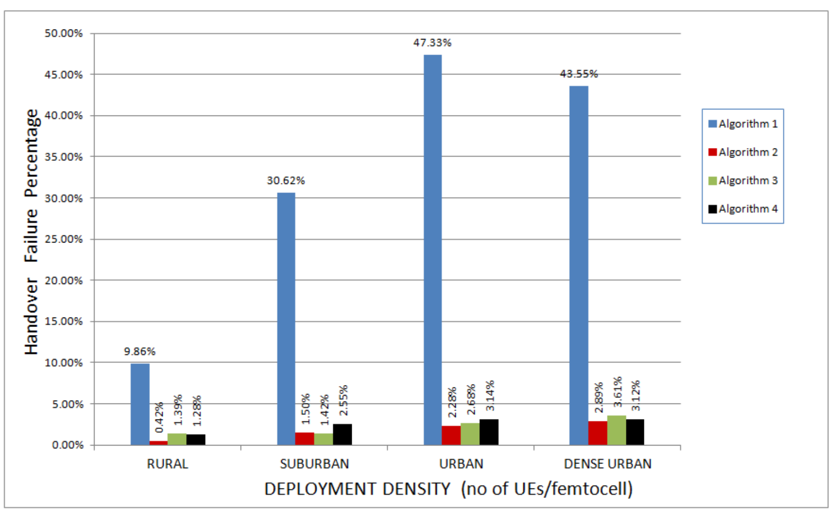

Figure 5.7: The percentage of HO failures

increases the number of HO attempts around 1.5-2 times as compared to state-of-art methods (as seen in figure 5.6). In dense urban scenario, MDP method has same level of HO attempts as compared to other algorithms. Standard hysteresis and threshold method (algorithm 1) has worst HO failure ratio as it does not take into consideration the resource constraints of femtocells. All other methods have very low HO failure ratio (refer to figure 5.7) MDP method (algorithm 4) achieves .3 to 1 point increase

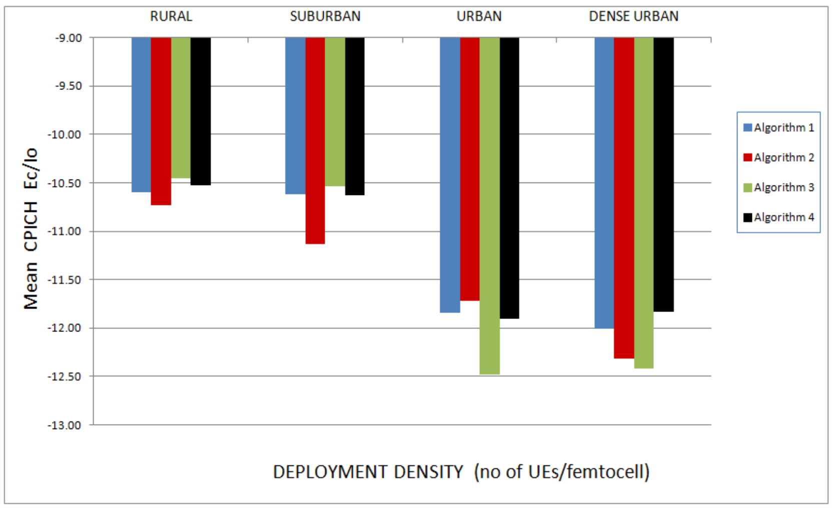

Figure 5.8: Mean Ec/Io experienced by macro-femto network UEs

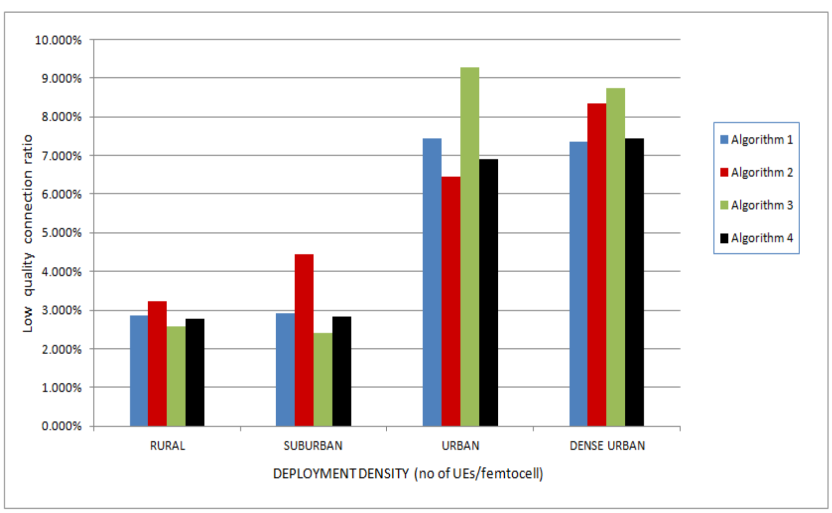

Figure 5.9: The ratio of active connections below Ec/Io quality threshold of -18 dB

in mean CPICH Ec/Io ratio for all scenarios (refer to figure 5.8). This considerable QoS improvement would help cellular network operators in deploying macro-femto combined networks since end-user quality perception will increase. MDP method also decreases low quality connection ratio and thus increases customer satisfaction significantly especially in denser deployment scenarios.

5.4 OPNET Implementation

OPNET simulation implements all major aspects of the simulated environment with the exception of RSS based cell selection/reselection and multi-floor buildings. In OPNET simulation all buildings are assumed to have single floors with identical square sized basement. Cell selection/reselection in idle mode is not implemented as the UE selects the appropriate HNB/NodeB when the call arrival occurs. These simplifications ensure that the simulations computational load remains low. In OPNET simulation all network nodes are individually modeled with packet exchanges occurring in user plane. The femtocells would produce SIB based broadcast packets to inform the UEs about the residual resource status. All the mechanisms and state transition diagrams required for dynamic SON algorithm and network measurements are implemented within relevant node and process models. The simulation operates in real-time event based manner.

Table 5.7: List of variables and parameters used in OPNET simulation

Parameter name	**Value**
Simulation time (in seconds)	180
Mean holding time (in seconds)	60
Call inter arrival time (in seconds)	30
HO decision interval (in seconds)	0.5
Maximum tolerable number of HOs per call	5
HO time hysteresis (in seconds)	2
V_{lo} (in m/s)	2
V_{hi} (in m/s)	15
η_{outage} (in dB)	-20
η_{sir} (in dB)	3
Spreading factor	256
Building size	30x30 m

Following developments have been done in the wireless suite of OPNET modeler.

5.4.1 Wireless communication modules

- ITU P.1238 and COST 231 Hata propagation model have been implemented in OPNET's pathloss related SW modules.

- CPICH Ec/Io has been implemented in SNR and interference/noise modeling SW modules

- Closure SW module has been updated so that femtocell transmissions have no reach to remote UEs.

- Transmit gain related modules have been adapted so that transmit power of FAPs are adjustable through processing of a special field in transmitted packets.

5.4.2 UE mobility modules

- Random waypoint mobility module have been updated to support inbuilding as well as intra-building randomized mobility

- The UE speed in indoor environment has been decreased accordingly by changing the random waypoint module. So UEs would move in normal walking speed inside the buildings

5.4.3 Nodes and process models

- Three new node models for NodeB, HNB and UE has been generated with new or customized process models that would implement scrambling code based wireless communication in UMTS networks. (each scrambling code have been implemented with a different transmitter/receiver pair in UE)

- UE node model can process SIB information (carrying residual resource and UL SIR information) from NodeB/FAPs and extract received power and DL SINR information from received packets. Based on this information handover decision algorithms have been implemented in the new UE stream processing process model. UE node model is also responsible of generating speech calls, producing user plane packets and sending them to NodeB/FAP that UE is getting service from.

- FAP/HNB node models have broadcast SIB packet generator and dynamic SON algorithm implementation. HNB/NodeB models measure uplink SINR and uplink backhaul BW consumption that would be inserted to SIB packets.

Figure 5.10,5.11 and 5.12 depict some of node and process models designed for OPNET simulations.

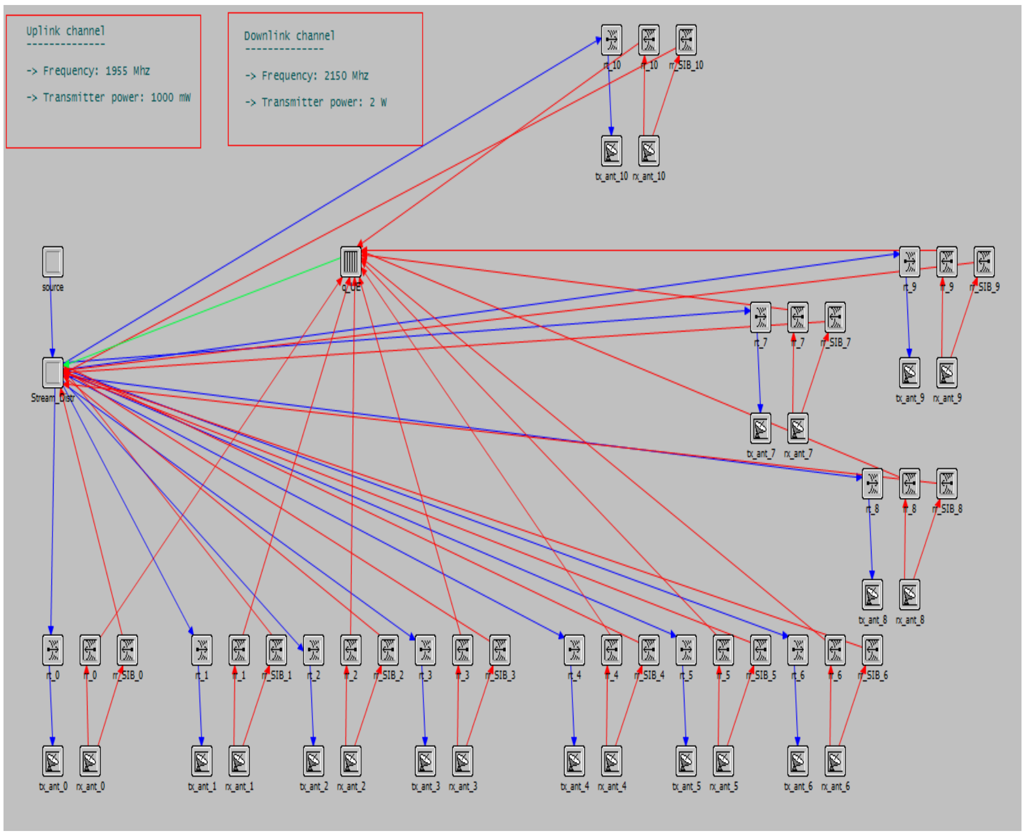

Figure 5.10: UE model in opnet that can support upto 10 scrambling codes

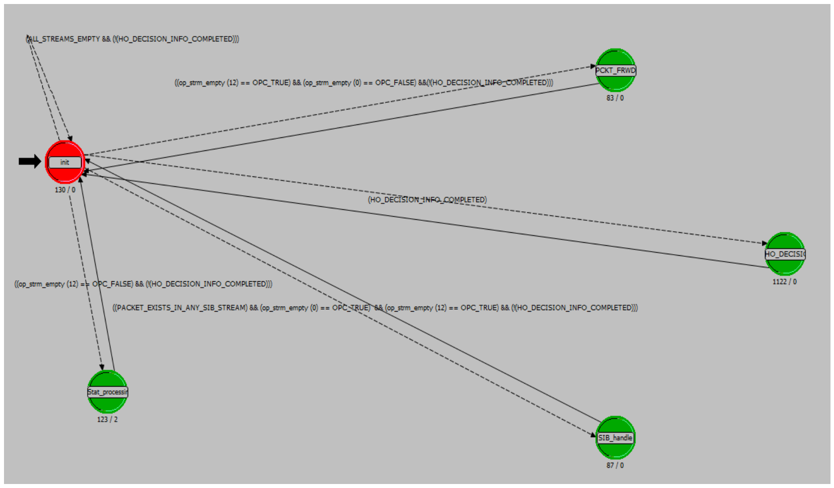

Figure 5.11: The streaming processing process model handling handover decisions and packet streaming

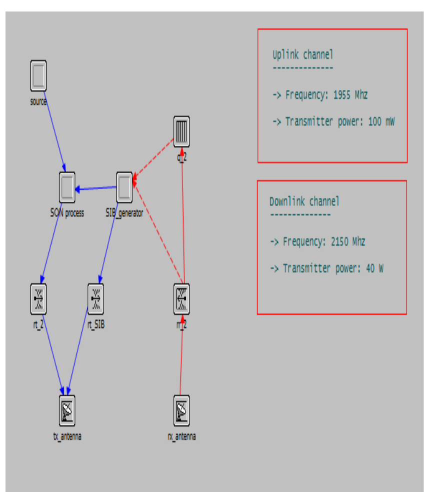

Figure 5.12: HNB/NodeB node model with SON processor and SIB packet generator

5.4.4 Statistic generation

- New global statistics have been defined for femto traffic ratio, mean connection time, handover failure ratio, outage ratio, mean number of HO per call and low quality connection ratio
- All above statistics are generated on-the-fly by explicitly recording network events

5.4.5 OPNET results

Figure 5.13 gives an example for statistic collection in OPNET. Collected statistics are updated in real-time as the simulation progresses.

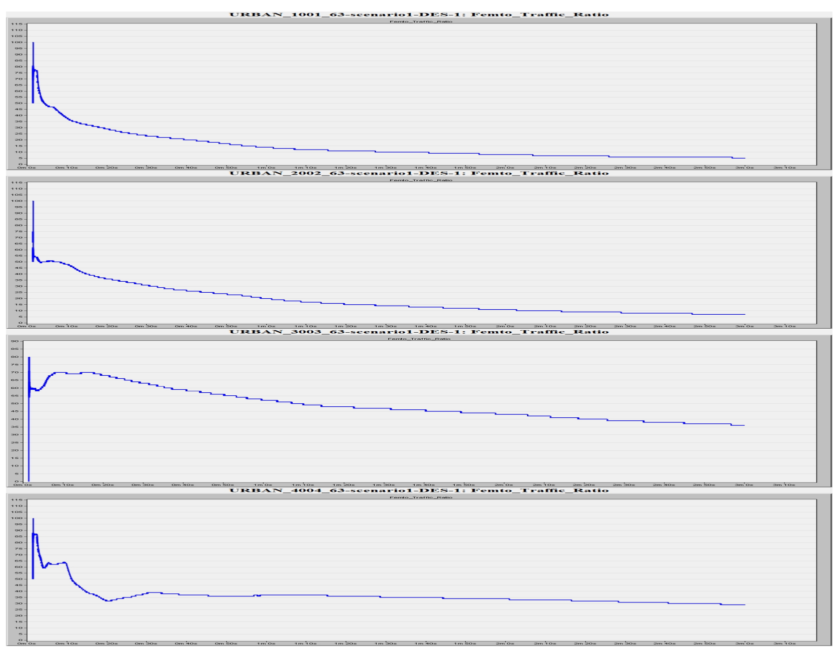

Figure 5.13: Femto traffic ratio statistic collection example from OPNET urban deployment scenario

Following figures provide summarized performance results. As similar to Matlab

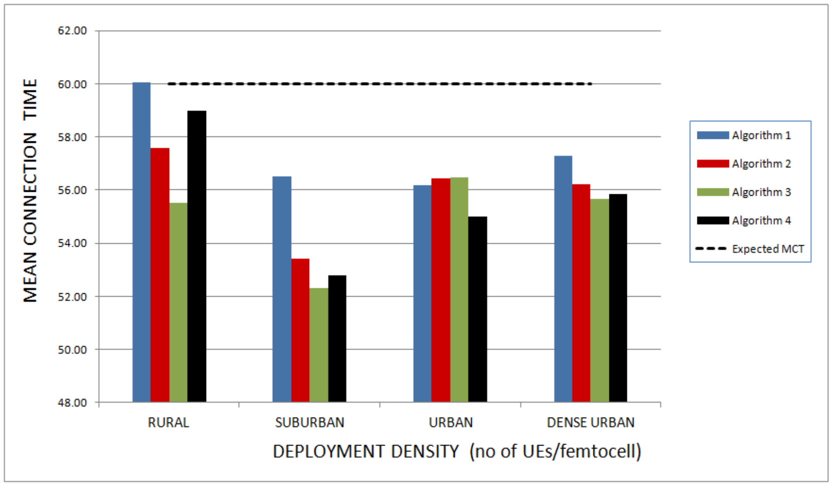

Figure 5.14: Mean Connection Time values accross different deployment options

simulations, the macro-femto combined network underperforms in dense deployment scenarios ($MCT < 60sec = MHT$) due to high admission reject ratio of femtocells in loaded conditions. Algorithm 1 achieves the best MCT performance in all deployment scenarios. Algorithm 4 performs as comparable to other methods (refer to figure 5.14) Algorithm 4 achieves superior performance in increasing the femto quality coverage

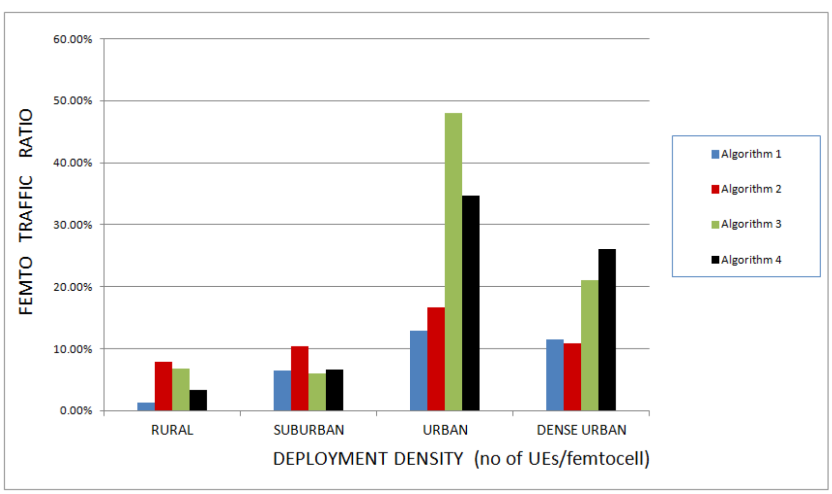

Figure 5.15: The ratio of CS traffic handled by femtocell network

ratio in suburban, urban and dense urban scenarios. Asymmetric hysteresis based HO decision method is the second best method to transfer generated circuit-switched (CS) traffic to femtocells. This is also a similar result to Matlab simulations of the same scenarios. In terms of outage ratio MDP based HO decision algorithm has the

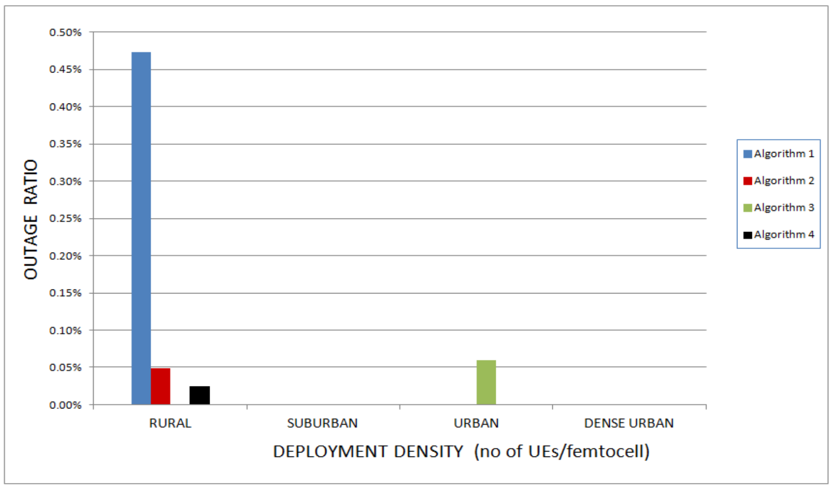

Figure 5.16: Outage percentage

best performance with better load sharing between femtocells and joint consideration of all MM related criteria. Algorithm 3 causes outage in urban deployment scenario in contrast to newly proposed Algorithm 4. In urban and suburban deployment scenarios, MDP method (algorithm 4) increases the number of HO attempts around 1.5-2 times as compared to state-of-art methods (refer to figure 5.17. This is the only disadvantageous aspect of Algorithm 4. As expected, standard hysteresis and threshold method (algorithm 1) has worst HO failure ratio as it does not take into consideration the resource constraints of femtocells. All other methods have very low HO failure ratio as it was the case in Matlab simulations As it was the case in Matlab simulations of previous section, MDP method (algorithm 4) significantly decreases low quality connection ratio and thus increases customer experience significantly especially in denser deployment scenarios (refer to 5.19).

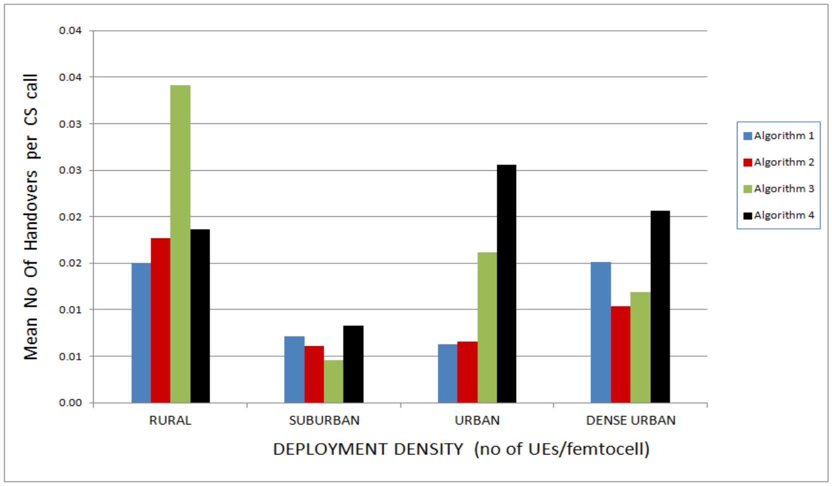

Figure 5.17: Average number of HO attempts per CS call

The analysis of simulation results in a combined fashion shows that Algorithm 4 increases the femto traffic ratio up to %30-40 while decreasing the low quality connection percentage to %1 range. Algorithm 4 performs as comparable to state-of-art methods in all other criteria except mean number of HO attempts per call. Increased number of HO attempts under MDP scheme seems inevitable since Algorithm 4 produces extra handovers for better load sharing between femtocells and interference minimization.

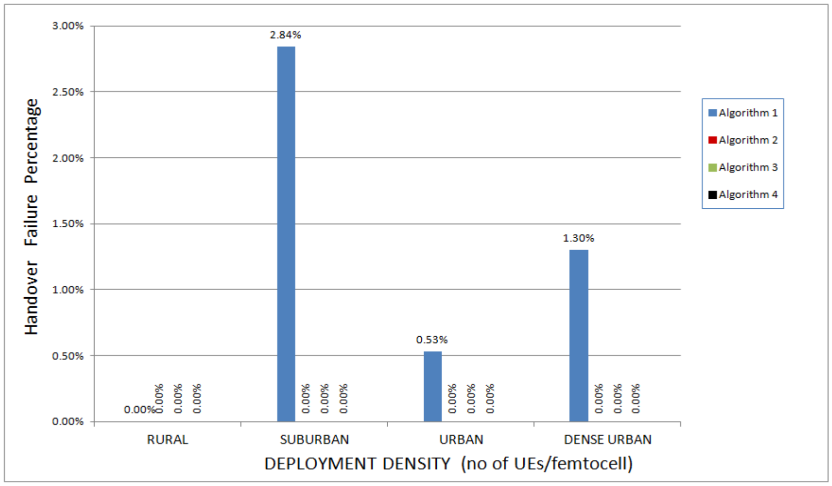

Figure 5.18: The percentage of HO failures

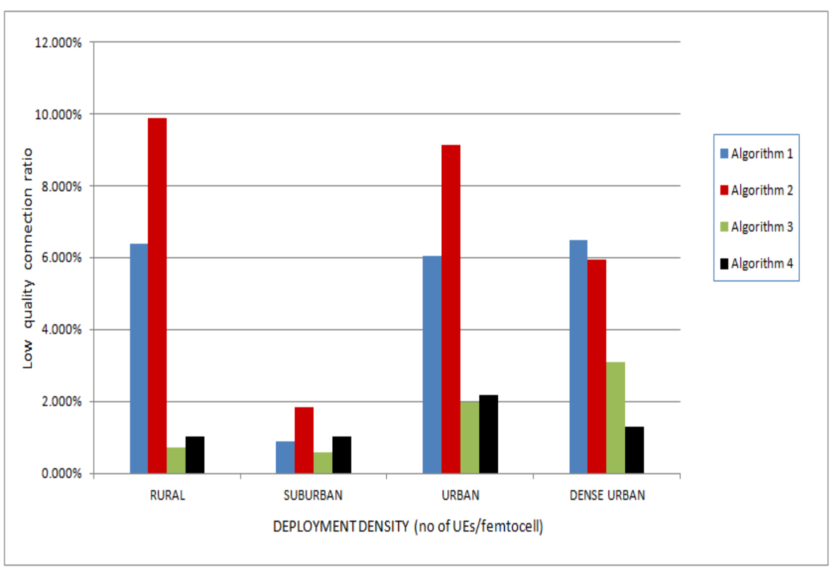

Figure 5.19: The ratio of active connections below Ec/Io quality threshold of -18 dB

5.4.5.1 High end-user density results

In order to test Algorithm 4's performance under different network scenarios, rural deployment scenarios have been altered to obtain an unusually large number of end-users with same configuration of femtocells and macrocell. Simulation results show

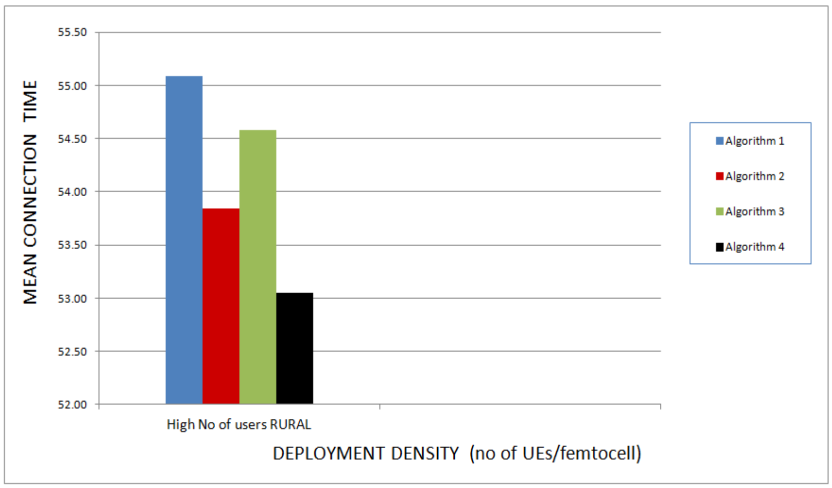

Figure 5.20: Mean Connection Time values accross different deployment options

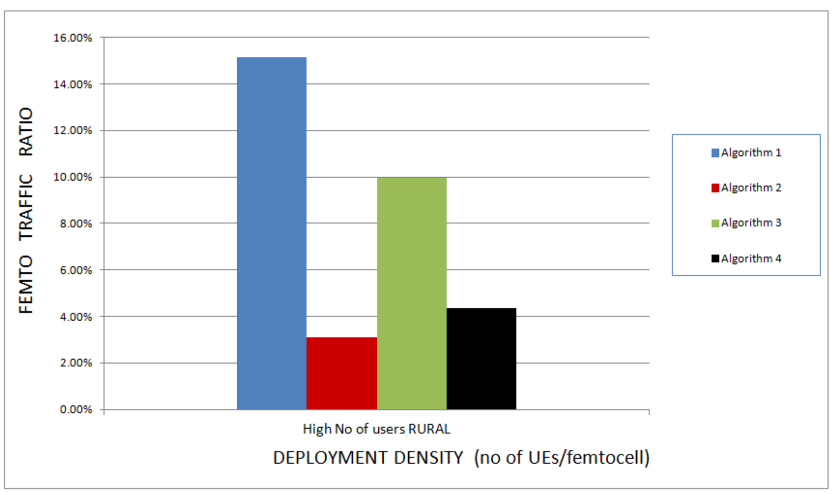

Figure 5.21: The ratio of CS traffic handled by femtocell network

that in overloaded conditions algorithm 4 does not produce any outages (refer to

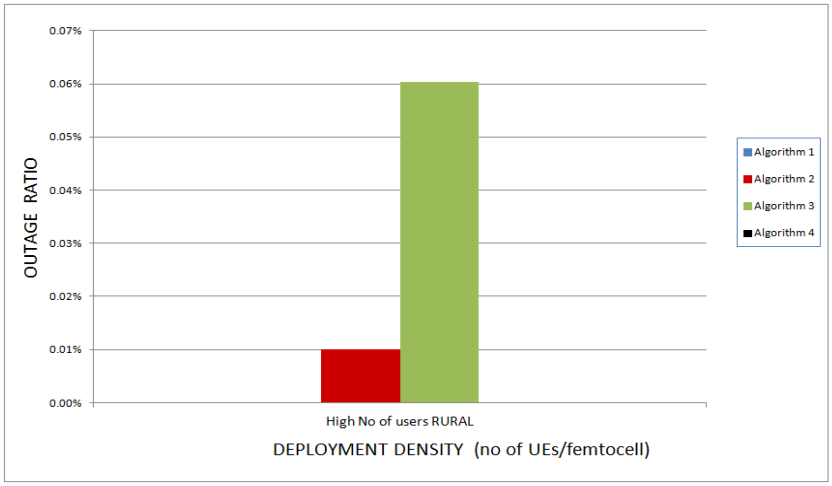

Figure 5.22: Outage percentage

5.22) and increase connection quality while performing comparably with respect to other algorithms (refer to 5.24).

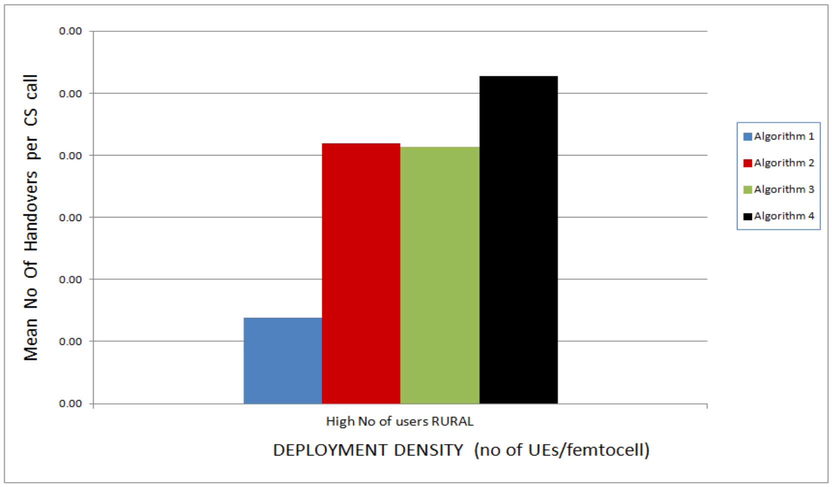

Figure 5.23: Average number of HO attempts per CS call

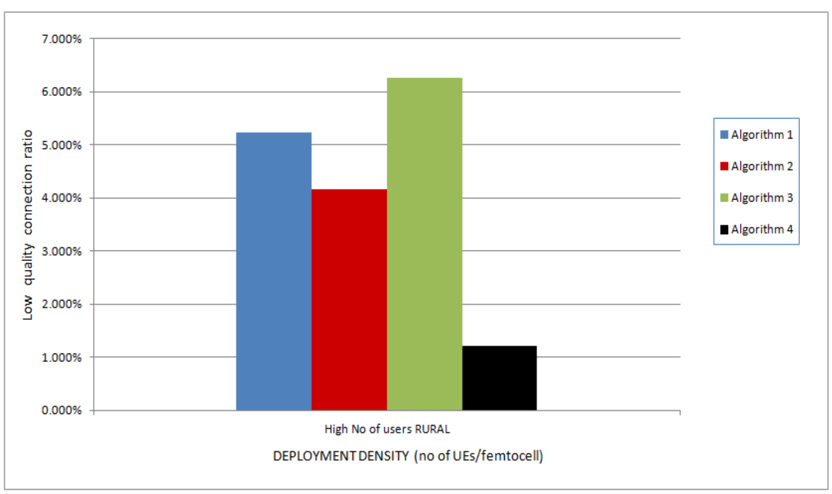

Figure 5.24: The ratio of active connections below Ec/Io quality threshold of -18 dB

5.4.5.2 Different HO decision interval results

In this section, all algorithms are implemented in two alternate HO decision intervals such as 0.25 and 1 seconds.

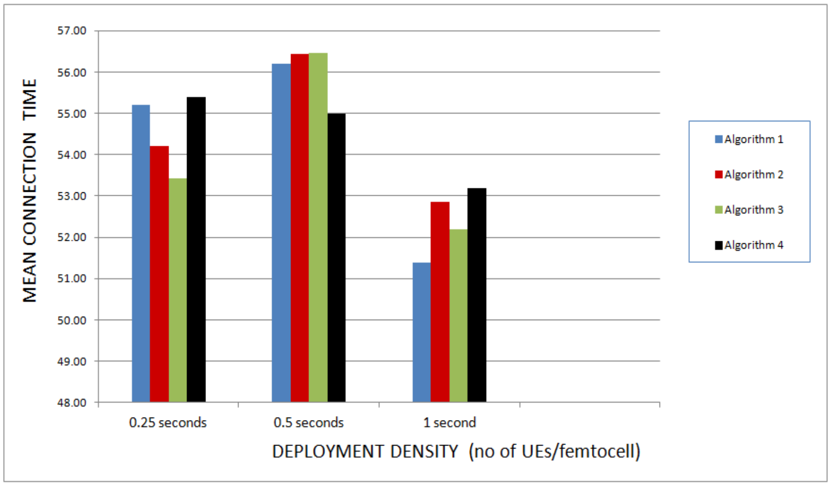

Figure 5.25: Mean Connection Time values accross different deployment options

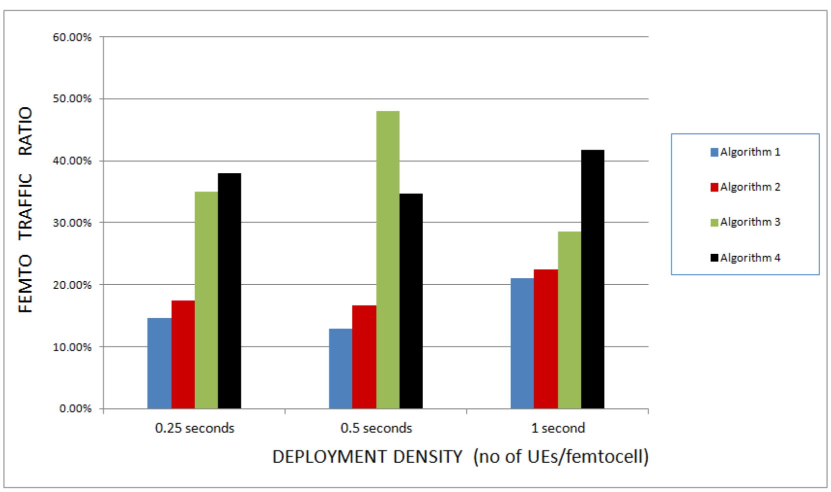

Figure 5.26: The ratio of CS traffic handled by femtocell network

Simulation results show that algorithm 4 is successful in maintaining its superiority on better traffic offloading to femtocells and better connection quality even if the HO decision intervals are changed.

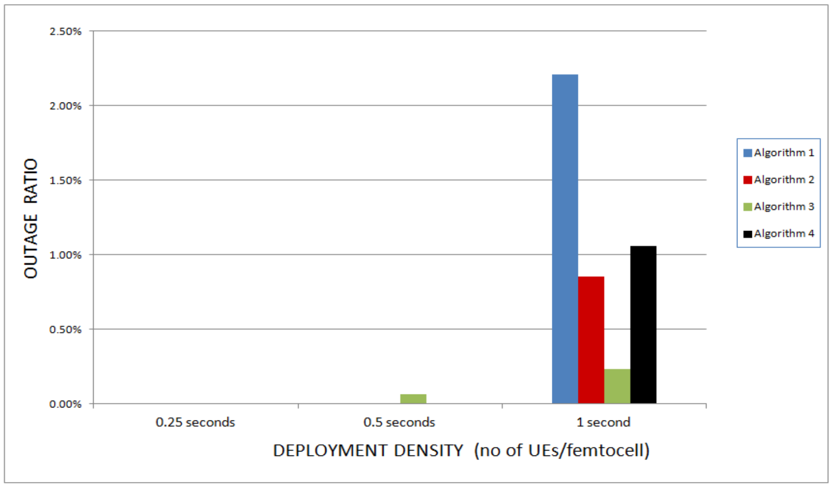

Figure 5.27: Outage percentage

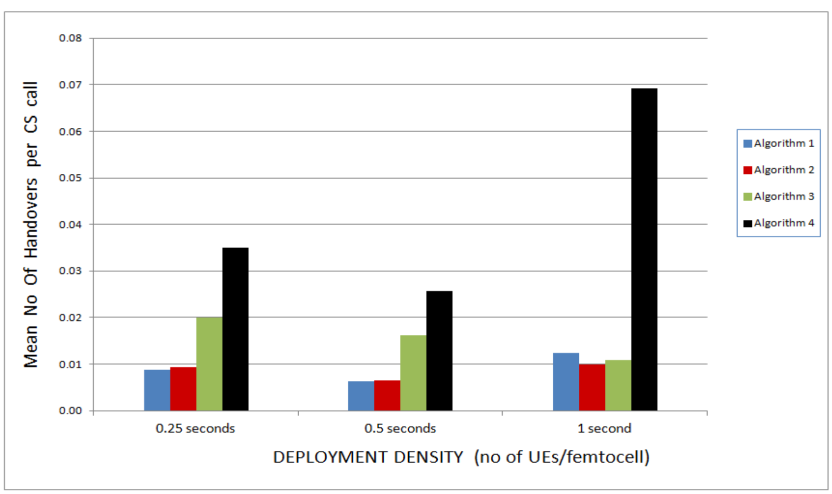

Figure 5.28: Average number of HO attempts per CS call

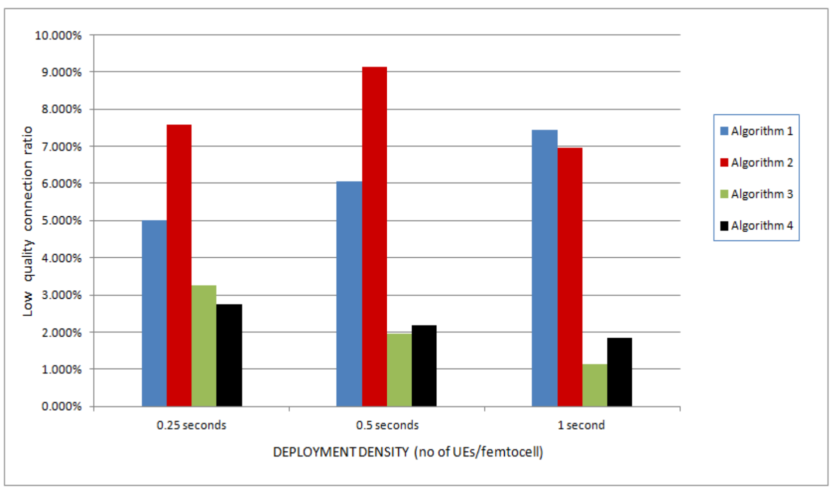

Figure 5.29: The ratio of active connections below Ec/Io quality threshold of -18 dB

5.4.5.3 Low busy hour call attempt scenario

In this section, all algorithms are implemented in a deployment scenario of BHCA=0.01 per end-user. The objective of this experiment is to investigate algorithm 4's and state-of-art HO decision algorithm's performance in very low CS traffic conditions.

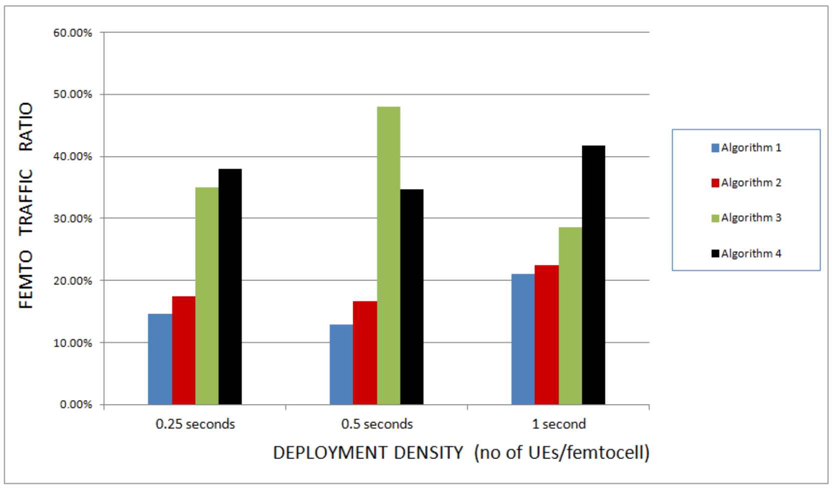

Figure 5.30: The ratio of CS traffic handled by femtocell network

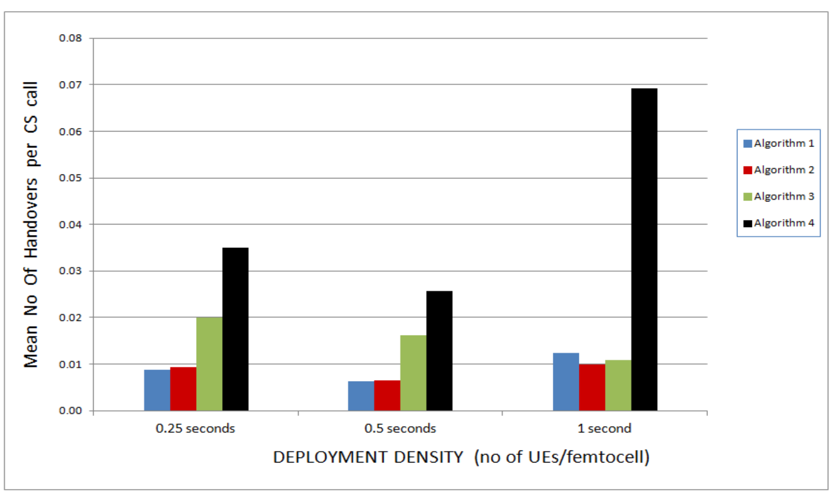

Figure 5.31: Average number of HO attempts per CS call

Simulation results show that algorithm 3 and 4 remain as the most successful schemes

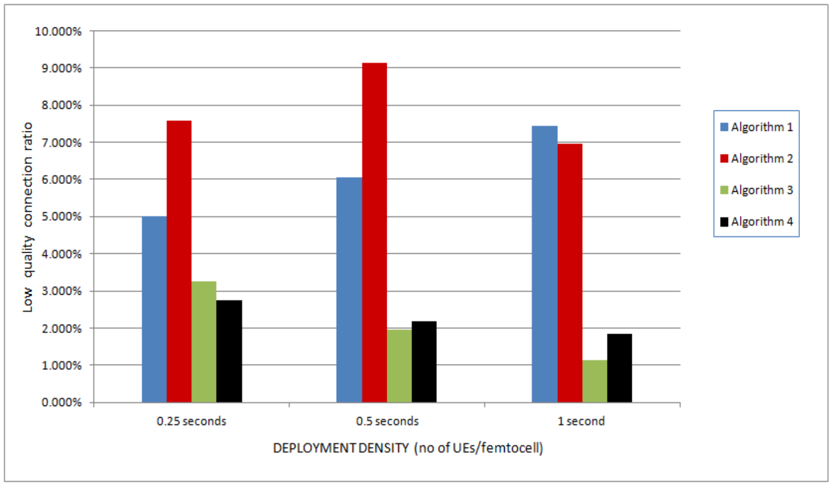

Figure 5.32: The ratio of active connections below Ec/Io quality threshold of -18 dB

for traffic retention/forwarding in femtocell network. As expected the mean number of HO attempts is higher in algorithm 4 as compared to state-of-art methods.

6 CONCLUSIONS

The main problem that has been addressed in this research work was to design a practical and optimal handover decision algorithm for hierarchical macro-femtocell networks. The most important requirement was improved interference mitigation and maximization of femtocell network utilization while satisfying QoE criteria and staying adaptive to network capacity constraints.

We had following key design challenges:

- Handling of QoS/signaling load trade-off in high-speed UE communications when a macro connected UE approaches to femtocell
- Improving the performance of static SON algorithm providing low TX output power in general
- Handling of asymmetric radio conditions occurring while end-users transition between femtocell and macrocell networks
- Consideration of residual BW, call processing and UL SIR limitations of femtocells :
- Prevention of recurrent and undesirable handovers
- Not producing high number of femtocell handovers with marginal quality improvements

In order to address all above issues, the handover decision problem has been formulated as a multi-objective non-linear optimization problem. Since there are no known analytical solution to the problem, an MDP based heuristic has been proposed as a practical and optimal HO decision making scheme. This heuristic has been updated and improved in an iterative manner and has also been supported by a dynamic SON algorithms that is re-utilizing some of the heuristic components.

The proposed HO decision algorithm has been subject to extensive simulations both in non-realtime (Matlab) and real-time event based (OPNET) environments. Multiple realistic deployment scenarios were experimented with various traffic profiles, HO decision intervals and user density fluctuations. Simulation results from both platforms confirm each other's outcomes to a great extent. The results show that MDP based heuristic has superior performance in terms offloading the macro network, minimizing the undesirable network events (e.g. outage and admission rejection) and increasing end-user QoS when compared to state-of-art handover algorithms. The performance gap is wider in dense urban and urban deployment scenarios since the conventional and state-of-art UMTS handover decision algorithms perform poorly in more resource constrained and high interference macro-femto combined network. MDP based heuristic is easy to implement with minor additional requirements being the insertion of femtocell resource information to SIB packets already broadcasted by femtocells and forwarding of UE speed estimation information from physical layer to RRM layer of femtocells. Therefore femtocell operators would easily benefit from this new mobility management scheme in providing greater quality of service to their customers as well as in utilizing femtocells with greater efficiency.

As continuation of this work, following future improvements are planned as beneficial enhancements.

- Enhancing the existing dynamic SON algorithm with FAP nodes being capable of performing real-time radio network sniffing. By this way, the SON algorithm would be more adaptive to changing radio channel conditions

- Integrating the MDP based mobility management algorithm with uplink interference management schemes that would be important in high end-user density environments

- Shaping the MDP algorithm's benefit/penalty coefficients in such a way that they are dynamically updated according to mobility and resource management statistics gathered from real networks.
- Adapting the proposed HO decision algorithms to outdoor LTE/UMTS based smallcell networks.
- Implementing the proposed HO decision algorithm on physical femtocell system SW and validating the performance improvements shown in simulations in real heterogeneous cellular networks.

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