RESOURCE MANAGEMENT IN WIRELESS NETWORKS

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A local call admission control (CAC) algorithm for third generation wireless networks was designed and implemented, which allows for the simulation of network throughput for different spreading factors and various mobility scenarios. A global CAC algorithm is also implemented and used as a benchmark since it is inherently optimized; it yields the best possible performance but has an intensive computational complexity. Optimized local CAC algorithm achieves similar performance as global CAC algorithm at a fraction of the computational cost. Design of a dynamic channel assignment algorithm for IEEE 802.11 wireless systems is also presented. Channels are assigned dynamically depending on the minimal interference generated by the neighboring access points on a reference access point. Analysis of dynamic channel assignment algorithm shows an improvement by a factor of 4 over the default settings of having all access points use the same channel, resulting significantly higher network throughput.

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CHAPTER 1

INTRODUCTION

Mobile and wireless communications have become ubiquitous in the 21st century with the wide use of cell phones, personal digital assistants, and smart phones. The need for connectivity at any place and at any time is the defining feature for present and future wireless communications.The market for cell phone usage has seen a drastic increase in the last several years. These devices are needed not only to communicate voice but also send and receive text, video, and pictures.The third generation partnership project (3GPP) consisting of engineers, network operators, and service providers, has introduced new access techniques that could use the present infrastructure with a smooth transition from second generation (2G) systems to third generation (3G) systems.

The 1990s had seen the introduction of two access techniques: time division multiple access (TDMA) and code division multiple access (CDMA). Although TDMA has been a viable access technique for 2.5G with low speed data services, when it comes to 3G, systems should provide increased speeds and capacity for voice, video, and data calls simultaneously. CDMA was perceived as a much better technology than TDMA when it comes to providing higher capacity for cellular networks, so 3GPP introduced a new access technique known as wideband code division multiple access (WCDMA) for 3G networks based on CDMA [1].

In addition to cellular access, there is a growing need for mobile internet access. IEEE 802.11 series devices create high speed wireless local area networks (WLANs) that are comparable to wired LANs. Home and business users are switching from wired networks to wireless networks with decreasing costs of WLAN equipment.The committee on 802.11 introduced many types of wireless LANs, which operate in the frequency spectrum range of 2.4 GHz and 5 GHz. They are classified as IEEE 802.11a, b, and g. 802.11a works in the 5 GHz range at a maximum speed of 54 Mbps. Both 802.11b/g use the 2.4 GHz range at a maximum speed of 11 Mbps and 54 Mbps, respectively.

1.1. WCDMA Overview

WCDMA was proposed as a preferred access technique for universal mobile telecommunications system (UMTS) in 1998 by european telecommunications standards institute (ETSI) while submitting to the international telecommunications union's (ITU) international mobile telecommunications-2000 (IMT-2000) assuring backward compatibility with 2G global system for mobile communications. Before WCDMA was adopted, different groups were working on techniques like W-TDMA, orthogonal frequency division multiple access, and opportunity driven multiple access. The standardization organizations from Europe, Japan, Korea, the USA, and China agreed to create a partnership for 3G which became the 3GPP. The ETSI proposed UMTS terrestrial radio access now known as universal terrestrial radio access led to the use of WCDMA [1]. UMTS WCDMA has now been accepted as a world standard.

The main features for WCDMA are as follows:

- Based on Direct Sequence CDMA.
- Chip rate of 3.84 Mcps leads to a frequency spectrum of 5 MHz.
- Multiplexing is done both in frequency (FDD) and time (TDD).

In FDD, a pair of 5 MHz carriers are used for downlink and uplink with typical range for uplink from 1920 MHz to 1980 MHz, downlink from 2110 MHz to 2170 MHz with a separation of 190 MHz between the uplink and downlink frequencies. In TDD, a single 5 MHz carrier is used for uplink and downlink with typical range from 1900 MHz to 1920 MHz and from 2010 MHz to 2025 MHz with no separation for uplink and downlink bands.

In the year 2000 at ITU's world radio conference, three new frequency bands were added to the 3G spectrum in the frequency ranges of 2500-2690 MHz, 1710-1885 MHz, and 806-960 MHz. In USA a new band for IMT-2000 was introduced to efficiently use 3G services in the frequency range of 1710-1770 MHz and 2110-2170 MHz.

UMTS using WCDMA as the access technique will be the broadband for the cellular and mobile industry. The speeds for multimedia access on the downlink and uplink channels have seen a significant improvement over 2.5G. IMT-2000 proposed standards for downlink speeds for 3G of 2 Mbps for indoors, 384 Kbps for outdoor stationary, and 144 Kbps for vehicular. The 3GPP Release 5 introduced a new key feature called high speed downlink packet Access as the next generation of data access with increased download speeds. This changes the way UMTS offers data services with high speed download of services like high quality video, high resolution interactive gaming, and music. Another key feature includes changes to the core network from circuit switched to packet switched for all kinds of transmissions like voice and data [2]. Release 6, finalized in 2005, included support for broadcast services like mobile TV.

1.2. WLAN Overview

The IEEE 802.11 working group has played a major role in defining the standards for WLANs. The 802.11 standard uses the frequency spectrum in the 2.4 GHz range, which is designated by the federal communication commission (FCC) for use in industrial, scientific, and medical (ISM) purposes. The unlicensed ISM band frequencies are 915 MHz, 2.4 GHz, and 5 GHz, that can be used for consumer goods. The main technologies for data transmission in WLAN are direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS). The IEEE 802.11 medium access control uses the carrier sense multiple access with collision avoidance (CSMA/CA) as the access technique. The CSMA/CA protocol is designed to avoid collision before it starts to transmit data.

The 802.11a [3] introduced orthogonal frequency division multiplexing (OFDM) while 802.11b [4] used high range direct sequence spread spectrum for high data speeds. In 2003, the 802.11g [5] standard was approved, which used the OFDM modulation of 802.11a but operates in the narrow 2.4 GHz band of 802.11b. 802.11g is backward compatible with 802.11b making it a good alternative for users wanting high speeds without changing equipment.

1.3. Objectives

A local call admission control (CAC) algorithm for third generation wireless networks was designed and implemented, which allows for the simulation of network throughput for different spreading factors and various mobility scenarios. The design of the CAC algorithm uses global information; it incorporates the call arrival rates and the user mobilities across the network and guarantees the users quality of service as well as pre-specified blocking probabilities. On the other hand, its implementation in each cell uses local information; it only requires the number of calls currently active in that cell. A global CAC algorithm is also implemented and used as a benchmark since it is inherently optimized and uses global information in making every call admission decision; it yields the best possible performance but has an intensive computational complexity. Using simulation, the network throughput is determined, and show that optimized local CAC algorithm achieves almost the same performance as global CAC algorithm at a fraction of the computational cost for pre-specified blocking probabilities and quality of service requirements and spreading factor values of 256, 64, 16, and 4.

An algorithm is also designed for dynamic channel assignment of access points for 802.11 WLAN systems. Channels are assigned dynamically depending on the minimal interference generated by the neighboring access points on a reference access point. The use of this algorithm results in better transmission of data leading to higher throughput for networks. Implementation and analysis of algorithm was performed using simulation of a wireless LAN consisting of 4, 9, 16, and 25 APs.

The objectives of this work are as follows:

- UMTS/WCDMA 3G Networks:
  - Design, optimization, and simulation of local and global call admission control algorithms in 3G UMTS networks.

- IEEE 802.11 WLAN:

– Design, optimization, and simulation of a dynamic channel assignment algorithm in IEEE 802.11 networks.

1.4. Organization

In Chapter 2, a global CAC algorithm is presented for 3G UMTS systems using WCDMA as the access technique. The chapter discusses the advantages and disadvantages of using a global model in CAC while working with different services. Although, the global CAC algorithm is inherently optimized, it bears a huge computational complexity. However, it provides an excellent benchmark.

In Chapter 3, an optimized local CAC algorithm is proposed for 3G UMTS WCDMA networks. The network throughput is determined, and it is shown that the optimized local CAC algorithm achieves almost the same performance as the global CAC algorithm at a fraction of the computational cost. Calculations for the numerical results are performed using different mobility scenarios and spreading factors of 256, 64, 16, and 4.

In Chapter 4, a formulation and design of a dynamic channel assignment algorithm for IEEE 802.11 WLAN access points is presented. The algorithm assigns channels dynamically depending on the interference generated by the neighboring access points on a reference access point. This results in better transmission of data leading to higher throughput for networks.

In Chapter 5, details of the implementation and analysis of simulation results obtained from dynamic channel assignment algorithm are discussed. Numerical results are shown for WLAN consisting of 4, 9, 16, and 25 APs while using two versions for the algorithm.

Finally, in Chapter 6, the conclusions are presented, which summarize the contributions of this work.

CHAPTER 2

DESIGN AND ANALYSIS OF GLOBAL CALL ADMISSION CONTROL FOR UMTS 3G NETWORKS

2.1. Introduction

Universal mobile telecommunications system (UMTS) uses wideband code division multiple access (WCDMA) as the access technique for 3G systems, which introduces new capacity allocation problems with the availability of different classes of services like voice, data, and video. The need to manage resources and allow new calls and handoff calls to enter a cell while taking into consideration the calls in neighboring cells plays a major role in the capacity of the whole network. This leads to the design of call admission control (CAC) algorithms for better management of resources in wireless networks.

CAC algorithms address the issues related to quality of service (QoS), i.e., the probability of the loss of communication quality and grade of service (GoS), i.e., the call-blocking rate of handoff and new calls entering the network [6]. CAC algorithms usually fall under two general types: global and local. Global CAC takes into consideration all the calls in the network before allowing a handoff call or a new call into a cell. It calculates the interference that may be caused by a call to the whole network. The advantage of implementing this approach is that it gives the best possible solution to the network resource management problem. However, it has a large computational complexity and may be infeasible to implement in large networks. A local CAC algorithm looks only at a single cell for allowing handoff or new calls to enter the network.

CAC research in wireless communications has resulted in different approaches being proposed. Call admission control in second generation networks was concerned with only new or handoff *voice* calls entering a cell and affecting the QoS of the network. With 3G systems, calls include multiple services like voice, data, and video.

In this chapter, a global CAC algorithm is designed for multi-cell WCDMA networks and its complexity, implementation, and performance for different classes of services is analyzed.

2.2. Related Work

Resource management issues in 3G networks is an active research problem. The accommodation of new calls and handoff calls in each cell while considering the whole network is complex. Different models and approaches have been proposed to deal with this issue.

In the recent literature, there has been much discussion on the issues related to CAC in multimedia networks specifically UMTS WCDMA 3G networks. In [7], the authors introduce a new way of implementing CAC in WCDMA using fuzzy logic. This paper applies fuzzy logic for accepting a call while calculating the effective bandwidth and mobility information of the mobile station from the base station within a particular cell and its neighboring cells in a network. In [8], the authors propose a CAC scheme for CDMA systems supporting multimedia services evaluating their performance using Markov analysis. The numerical results show that their method can work for the international mobile telecommunications-2000 systems. In [9], the authors evaluate CAC for packet transmission in UMTS networks by setting an effective capacity threshold for uniform and non-uniform traffic scenarios in cells. In [10], the authors propose a search method for an optimal admission region for mobile systems supporting voice and data services. The voice and data calls share the same resources available while maintaining the QoS of the network.

In [11], a design for call admission control is proposed taking into consideration the effect of interference and power levels of the number of active calls in each cell. The authors compare the performance of two different classes of CAC for voice services, based on active calls present and online measures of base station power emission or total received interference. The simulations give results which keep the blocking probability low but do not consider any mobility scenarios. The optimal threshold value is determined taking into account the propagation environment. In [12], the authors discuss two CAC schemes uses fixed-dynamic and resource allocation criteria, while obtaining the performance results using simulations. Interference management is introduced which involves both the physical layer and some aspects of networking in WCDMA.

2.3. Mobility Model

There are several mobility models that have been discussed in the literature [13–23]. These models have ranged from general dwell times for calls to ones that have hyper-exponential and sub-exponential distributions. For the CAC problem investigated here, however, such assumptions makes the problem mathematically intractable. The mobility model used here is presented in [24] where a call stops occupying a cell either because user mobility has forced the call to be handed off to another cell, or because the call is completed.

The call arrival process to cell i with service g is assumed to be a Poisson process with rate $\lambda_{i,g}$ independent of other call arrival processes. The call dwell time is a random variable with exponential distribution having mean $1/\mu$, and it is independent of earlier arrival times, call durations and elapsed times of other calls. At the end of a dwell time a call may stay in the same cell, attempt a handoff to an adjacent cell, or leave the network. We define $q_{ii,g}$ as the probability that a call in progress in cell i (with service g) remains in cell i after completing its dwell time. In this case a new dwell time that is independent of the previous dwell time begins immediately. Let $q_{ij,g}$ be the probability that a call in progress in cell i after completing its dwell time moves to cell j. If cells i and j are not adjacent, then $q_{ij,g} = 0$. We denote by $q_{i,g}$ the probability that a call in progress in cell i leaves the network.

This mobility model is attractive because one can easily define different mobility scenarios by varying the values of these probability parameters [6]. For example, if $q_{i,g}$ is constant for all i, then the average dwell time of a call in the network will be constant regardless of where the call originates and what the values of $q_{ii,g}$ and $q_{ij,g}$ are. Thus in this case, by varying

$q_{ii,g}$'s and $q_{ij,g}$'s we can obtain low and high mobility scenarios and compare the effect of mobility on network throughput [25].

2.4. Global CAC Algorithm

First, the global CAC algorithm for multi-cell UMTS networks is presented and next details of its implementation using a simulator model is discussed.

Consider a multi-cell UMTS network with spread signal bandwidth of W, information rate of R_g bits/s, received signal S_g (at the serving base station assuming perfect power control), activity factor of v_g, and background noise spectral density of N_0. Assuming a total of G services and M cells, the bit energy to interference density ratio in cell i with service g is given by [26]

$$\left(\frac{E_b}{I_0}\right)_{i,g} = \frac{\frac{S_g}{R_g}}{N_0 + \frac{S_g}{W}\left[\sum_{g=1}^{G} n_{i,g} v_g + \sum_{j=1, j\neq i}^{M} \sum_{g=1}^{G} n_{j,g} v_g \kappa_{ji,g} - v_g\right]},$$

(1) $$\text{for} \quad i = 1, \dots, M, \qquad g = 1, \dots, G,$$

where $n_{i,g}$ is the number of calls in cell i (with service g) and $\kappa_{ji,g}$ is the per-call relative inter-cell interference factor from cell j to cell i. To achieve a required bit error rate, we must have $\left(\frac{E_b}{I_0}\right)_{i,g} \geq \tau_g$ for some constant τ_g. Thus, the number of simultaneous calls in each cell must satisfy

(2) $$\sum_{g=1}^{G} n_{i,g} v_g + \sum_{j=1, j\neq i}^{M} \sum_{g=1}^{G} n_{j,g} v_g \kappa_{ji,g} - v_g \leq c_{eff}^{(g)},$$

where

(3) $$c_{eff}^{(g)} = \frac{W}{R_g}\left[\frac{1}{\tau_g} - \frac{R_g}{S_g/N_0}\right].$$

A set of calls $\mathbf{n}$ satisfying the above equations is said to be a *feasible* call configuration, i.e., one that satisfies the $(\frac{E_b}{I_0})$ constraints. In this work, perfect power control is assumed and refer the reader to [27] for an extension to imperfect power control.

2.5. Simulator Model

The total simultaneous calls that guarantee the quality of service for call admission requirements must satisfy

$$C_{i,g}(t) = n_{i,g}(t) + I_{i,g}(t) \leq c_{eff}^{(g)},$$

$$\text{for} \quad i = 1, \ldots, M, \quad g = 1, \ldots, G. \tag{4}$$

for every time t where $I_{i,g}$ is the total relative inter-cell interference at cell i caused by every user in the network with service g. A new call or a handoff call arriving in cell i (with service g) is blocked if this call leads to a violation of any of the above inequalities, i.e., causing interference that no longer meets the $\left(\frac{E_b}{I_0}\right)$ constraints from (2).

The simulator is constructed as a sequential state machine running in a loop, where every loop cycle corresponds to a single time unit. It consists of two modules that are executed in sequential order – call arrival and admission module, and call removal module as shown in Fig. 2.1. The call arrival control is responsible for cell selection and determining arrival rates for each cell. The global CAC algorithm is implemented by call admission control, enforcing the conditions specified by (4). Finally, the call removal control relocates and removes calls depending on the mobility parameters.

2.5.1. *Call Arrival and Admission Module*

The module is comprised of two parts, call arrival control and call admission control. The call arrival control generates calls for the UMTS network whereas the call admission control processes these calls and tries to admit them depending on the total offered traffic for a particular cell while maintaining the QoS for the whole network. The total offered traffic $\rho_{i,g}(t)$ to cell i with service g for time t is calculated as

$$\rho_{i,g}(t) = \lambda_{i,g}(t) + \nu_{i,g}(t),$$

$$\text{for} \quad i = 1, \ldots, M, \quad g = 1, \ldots, G, \tag{5}$$

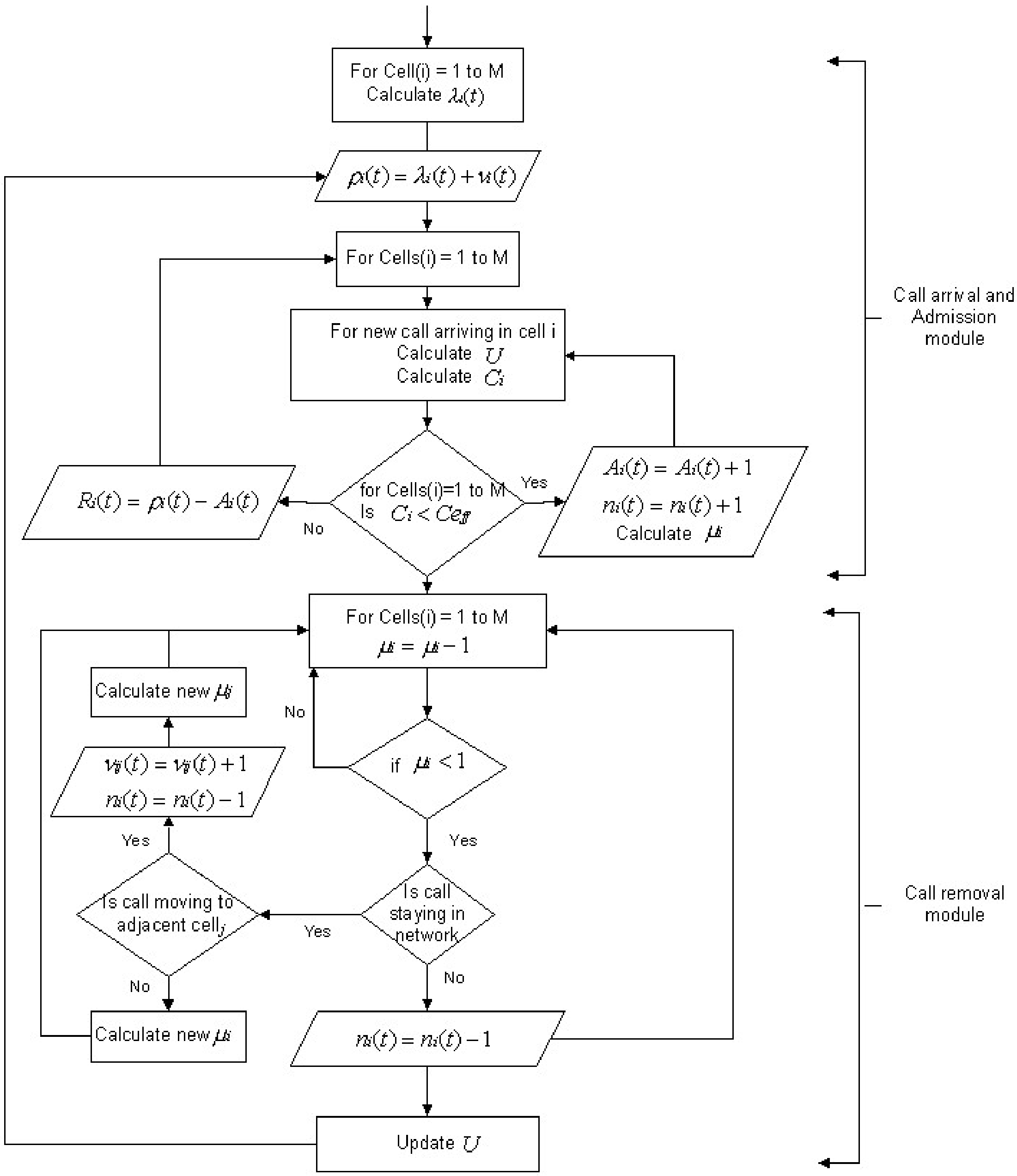

Figure 2.1. Flowchart of the network simulator for our global CAC algorithm (the subscript g is removed from the figure to enhance readability).

where $\nu_{i,g}(t)$ are the calls that moved to cell i with service g at time $t-1$. Note that $\nu_{i,g}(1) = 0$, for $i = 1, ..., M$ and $g = 1, ..., G$. The call arrival control then selects each call randomly for a randomly chosen cell, and passes it to the call admission control along with the location of this new call.

In order to determine if the call can be admitted, the call admission control computes $C_{i,g}$ to check if the conditions given by (4) will still hold if the call is allowed to enter the network. Traditionally, the total interference contributed by a cell has been viewed as an approximation, determined by simply multiplying the number of calls in that cell by the average per-call inter-cell interference factor offered by that cell [28]. In other words, a call placed anywhere within a cell generates the same amount of inter-cell interference. However, a second more realistic approach and calculation of the actual interference as a function of the actual distance of each user from each base station is presented. This approach is used in simulations.

2.5.1.1. *Average Interference* . If average interference is used (and a uniform user distribution is assumed), let $F_{ji,g}$ be the average per-call inter-cell interference factor with service g from cell j to cell i [29]. $F_{ji,g}$ are elements in a three dimensional matrix F with $i, j = 1, ..., M$ and $g = 1, ..., G$. Consequently, the total relative average inter-cell interference experienced by cell i is simply the summation of the product of number of calls $n_{j,g}$ in cell j with service g and their respective per-call interference factor $F_{ji,g}$

$$I_{i,g} = \sum_{j=1}^{M} n_{j,g} F_{ji,g},$$

$$\text{for} \quad i = 1, ..., M, \quad g = 1, ..., G. \tag{6}$$

Since the creation of matrix F, which has a computational complexity of $O(M^2 G)$, can be computed in advance, the above calculation is adequately fast since it requires only M lookups in the matrix. However, the interference caused by a user is independent of its location within a given cell. In this case, the new set of $C_{i,g}(t)$ is calculated as

$$C_{i,g}(t) = n_{i,g}(t) + \sum_{j=1}^{M} n_{j,g}(t) F[j, i, g],$$

$$\text{for} \quad i = 1, ..., M, \quad g = 1, ..., G. \tag{7}$$

The computational complexity for the implementation of the global CAC algorithm using average interference is $O(MG)$.

2.5.1.2. *Actual Interference* . If the actual distance of each user k from its serving base station is used to calculate interference, the matrix F cannot be used. Instead, a new matrix U is computed and updated in order to account for the actual increase in interference due to admitting a new call:

$$U[j,i,g](t) = U[j,i,g](t-1) + (U_{ji,g})_k\,,$$

$$\text{for} \quad ij = 1,\ldots,M, \quad g = 1,\ldots,G, \tag{8}$$

where, $U[j,i,g](t)$ contains the current total relative actual inter-cell interference exerted by cell j to cell i and $(U_{ji,g})_k$ is the relative actual interference offered by user k in cell j to cell i with service g. Now, the new set of $C_{i,g}(t)$ is calculated as

$$C_{i,g}(t) = n_{i,g}(t) + \sum_{j=1, j\neq i}^{M} U[j,i,g](t),$$

$$\text{for} \quad i = 1,\ldots,M, \quad g = 1,\ldots,G. \tag{9}$$

The computational complexity for the implementation of the global CAC algorithm using actual interference is $O(M^2G)$.

If the inequalities in (4) still hold for the new $C_{i,g}$'s, then the call is allowed to enter the network, otherwise the call is rejected. A point to be noted is that the simulator does not incorporate an intra-cell mobility model, hence the simulator places users randomly in a cell. At the end of dwell time, if there is no handoff then the call is placed again randomly in the cell and it's new interference is updated which may result in the call being dropped.

In Fig. 2.1, $A_{i,g}(t)$ is the number of calls *admitted* in cell i with service g during time t. If a call is admitted, $A_{i,g}(t)$ and $n_{i,g}(t)$ (the *total* number of calls in cell i with service g at time t) are increased by one, the call's dwell time is calculated, and control is passed back to the call arrival control. The cycle continues until all the arriving calls for this time unit have been processed. The number of rejected calls $R_{i,g}(t)$ for cell i with service g during this time unit is calculated by subtracting $A_{i,g}(t)$ from the total offered traffic $\rho_{i,g}(t)$. In current implementation, if multiple calls are seeking admission of which some will need to be rejected, those calls are chosen randomly. Future work might be to extend the algorithm and give priority to handoff calls if possible over new calls .

2.5.2. *Call Removal Module*

The module starts by reducing the dwell time of every call present in the network by one time unit for various services available. Then, for every call whose dwell time is less than one time unit, the following decision is made depending on the probability parameters: $q_{i,g}$, $q_{ii,g}$, and $q_{ij,g}$. The call can either leave the network, or stay in the network. If it is staying in the network, then it can either stay in the same cell with a new dwell time without being considered a new call, or it can move to one of its randomly selected adjacent cells. The handoff calls are processed again through the call arrival and admission control module.

2.6. Summary

Design and implementation of a global CAC algorithm for UMTS networks is discussed, which is used as a benchmark since it is inherently optimized and uses global information in making every call admission decision. Global CAC yields the best possible performance but has an intensive computational complexity. Calculation of the interference taking into consideration the average and actual interferences for calls entering the network and individual cells is performed. The computational complexity of the implementation of the global CAC algorithm using average interference is $O(MG)$ and using actual interference is $O(M^2G)$ where M is the total number of cells and G is the total number of services.

CHAPTER 3

OPTIMIZED LOCAL CALL ADMISSION CONTROL FOR UMTS 3G NETWORKS

3.1. Introduction

Wideband code division multiple access (WCDMA) is an enhancement to the code division multiple access (CDMA) technology with an increase in the voice capacity and high speed data transfer (up to 2 Mbps) for third generation (3G) cellular systems. The heterogeneous nature of calls combined with intracell and intercell interferences drastically affects the capacity of a universal mobile telecommunications system (UMTS) network, which leads to designing call admission control (CAC) algorithms to maintain the quality of service (QoS) and optimize resource utilization [7].

3.2. Related Work

In [30], the authors propose a new method for reserving resources for service specific CAC in WCDMA systems. Two types of reservation: code and power are employed depending on the data rate services. The system performance is analyzed using a Markov model. The results obtained meet the design objectives of their study.

In [31], an analytical model for adaptive CAC in UMTS systems is introduced and compared with wideband power based (WPB) and throughput based (TB) CAC schemes. This new scheme gives better performance than WPB and TB, which have their own limitations as both are preferential to certain services of UMTS-WCDMA. Simulations were conducted in OPNET.

In this chapter, design and implementation of an optimized local CAC algorithm using different mobility scenarios and spreading factor values of 256, 64, 16, and 4 is presented.

Using simulation, the performance of algorithm is calculated and compared with a global CAC, which is inherently optimized.

3.3. Optimized Local CAC Algorithm

3.3.1. *Admissible Call Configuration*

Recall that in the global CAC algorithm, a call arriving in cell i with service g is accepted if and only if the new state is a *feasible* state. Clearly that CAC algorithm requires global state, i.e., the number of calls in progress in all the cells of the network. In order to simplify the CAC algorithm, only those CAC algorithms which utilize local state, i.e., the number of calls in progress in the current cell, are considered. To this end a state $\mathbf{n}$ is defined to be *admissible* if

$$n_{i,g} \leq N_{i,g} \quad \text{for} \quad i = 1, ..., M \text{ and } g = 1, ..., G, \tag{10}$$

where $N_{i,g}$ is a parameter which denotes the maximum number of calls with service g allowed to be admitted in cell i. Clearly the set of admissible states is a subset of the set of feasible states. The blocking probability for cell i with service g is then given by

$$B_{i,g} = B(T_{i,g}, N_{i,g}) = \frac{T_{i,g}^{N_{i,g}}/N_{i,g}!}{\sum_{k=0}^{N_{i,g}} T_{i,g}^{k}/k!}, \tag{11}$$

where $T_i = \rho_{i,g}/\mu_{i,g} = \rho_{i,g}/\mu(1 - q_{ii,g})$ is the Erlang traffic in cell i with service g. Note that the complexity to calculate the blocking probabilities in (11) is $O(MG)$.

Once the maximum number of calls (for different services) that are allowed to be admitted in each cell, $\mathbf{N}$, is calculated (this is done offline and described in the next section), the local CAC algorithm for cell i will simply compare the number of calls with service g currently active in cell i to $N_{i,g}$ in order to accept or reject a new arriving call. Thus local CAC algorithm is implemented with a computational complexity that is $O(1)$.

3.3.2. *Calculation of* **N**

The local CAC algorithm is constructed as follows. A constrained optimization problem is formulated in order to maximize the throughput subject to upper bounds on the blocking probabilities and a lower bound on the signal-to-interference constraints in (2). The goal is to optimize the utilization of network resources and provide consistent GoS while at the same time maintaining the QoS, β_g, for all the calls for different services g. This approach for designing the CAC also allows different thresholds for blocking to be set in individual cells.

The throughput of cell i consists of two components: the new calls that are accepted in cell i minus the forced termination due to handoff failure of the handoff calls into cell i for all services g. Hence the total throughput, H, of the network is

$$H(\mathbf{B}, \rho, \lambda) = \sum_{i=1}^{M} \sum_{g=1}^{G} \{\lambda_{i,g}(1 - B_{i,g}) - B_{i,g}(\rho_{i,g} - \lambda_{i,g})\}, \tag{12}$$

where **B** is the vector of blocking probabilities and λ is the matrix of call arrival rates.

In this optimization problem the arrival rates are given and the maximum number of calls that can be admitted in all the cells are the independent variables. This is given in the following

$$\begin{aligned} \max_{\mathrm{N}} \quad & H(\mathbf{B}, \rho, \lambda), \\ \text{subject to} \quad & B(T_{i,g}, N_{i,g}) \leq \beta_g, \\ & \sum_{g=1}^{G} N_{i,g} v_g + \sum_{j=1, j \neq i}^{M} \sum_{g=1}^{G} N_{j,g} v_g \kappa_{ji,g} - v_g \leq c_{eff}^{(g)}, \\ & \text{for} \quad i = 1, \ldots, M. \end{aligned} \tag{13}$$

The optimization problem in (13) is solved offline to obtain the values of **N**.

In a network's coverage area the call arrival rate profile, λ, will change from time to time. By solving the optimization problem in (13), one can compute the values of **N** for different call arrival rate profiles and store these in the mobile switching center along with the time periods of the corresponding profiles. A dynamic local CAC algorithm can then be implemented whereby the optimized values of **N** are used during each corresponding time period. This is reminiscent of the dynamic nonhierarchical routing which was introduced in the mid 1980's in the long distance AT&T network [32].

3.3.3. *Theoretical Throughput*

A second optimization problem can be formulated in which the arrival rates and the maximum number of calls that can be admitted in all the cells are the independent variables and the objective function is the throughput. This is given in the following

$$
\begin{aligned}
\max_{\lambda,\ N} \quad & H(\mathbf{B}, \rho, \lambda), \\
\text{subject to} \quad & B(T_{i,g}, N_{i,g}) \le \beta_g, \\
& \sum_{g=1}^{G} N_{i,g} v_g + \sum_{j=1, j\neq i}^{M} \sum_{g=1}^{G} N_{j,g} v_g \kappa_{ji,g} - v_g \le c_{eff}^{(g)}, \\
& \text{for} \quad i = 1, \ldots, M.
\end{aligned}
\tag{14}
$$

The optimized objective function of (14) provides an upper bound on the total throughput that the network can carry. This is the *theoretical throughput* for the given GoS and QoS requirements.

The optimization problem in (13) is an integer programming (IP) problem. The optimization problem in (14) is a mixed integer programming (MIP) problem. One technique to solve the IP/MIP problem is based on dividing the problem into a number of smaller problems in a method called branch and bound [33]. Branch and bound is a systematic method for implicitly enumerating all possible combinations of the integer variables in a model. In this approach, the number of subproblems and branches required can become extremely large.

By relaxing the integer variables **N** to continuous variables, the optimizations in (13)-(14) are solved using a Sequential Quadratic Programming (SQP) method [34]. In this method, a Quadratic Programming subproblem is solved at each iteration. An estimate of the Hessian of the Lagrangian is updated at each iteration using the Broyden-Fletcher-Goldfarb-Shanno

(BFGS) formula [35]. A line search is performed using a merit function [36]. The Quadratic Programming subproblem is solved using an active set strategy [37].

The optimization problems in (13)-(14) are not convex optimization problems, and so it may be possible for the approaches described above not to converge to a global optimal solution. In order to ensure that this did not occur we verified the results of the SQP optimizations for a few select cases by using simulated annealing (SA) [38]. Simulated annealing is an optimization method that has many attractive features. In particular, it can statistically guarantee finding a globally optimal solution [39]. However, SA can be quite time consuming to find an optimal solution. Details on our SA parameters and implementation are given [40]. For computational speed, we have used the SQP optimization method for all the results presented in this work.

3.3.4. *Simulator Model*

The functional flow and modular structure of our local CAC algorithm simulator is shown in Fig. 3.1.

3.3.4.1. *Call Arrival and Admission Module.* The module is comprised of two parts, call arrival control and call admission control. The call arrival control generates actual arrival rates for each cell as input to the network and computes the total offered traffic to each cell using (5) and passes control to the call admission module.

The call admission module for our local CAC algorithm is much simpler to implement than our global CAC algorithm. Since **N** is known in advance (as a result of the optimization (13)) there is no need to calculate the inter-cell interference of each call. Thus the number of calls that can be admitted in cell i with service g, $A_{i,g}(t)$, for time t is determined by comparing the total offered traffic, $\rho_{i,g}(t)$, to the maximum number of calls that can be admitted in cell i with service g, $N_{i,g}$.

3.3.4.2. *Call Removal Module.* The call removal module for our local CAC algorithm is similar to the call removal module of our global CAC simulator model.

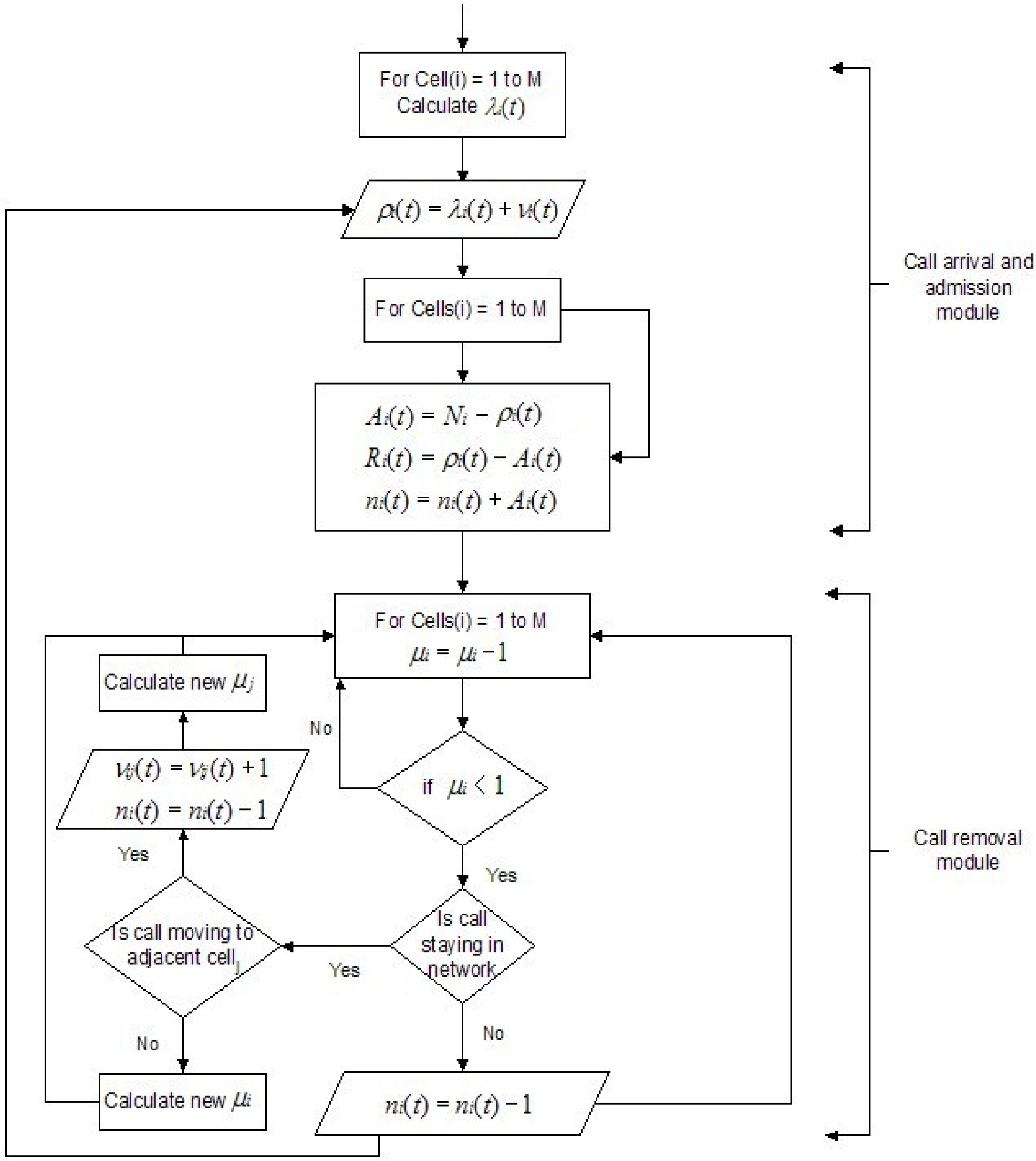

Figure 3.1. Flowchart of the network simulator model for our local CAC algorithm (the subscript g is removed from the figure to enhance readability).

3.4. Spreading Factors

In UMTS networks, just like CDMA networks, communication from a single source is separated by channelization codes, i.e., the dedicated physical channel in the uplink and the

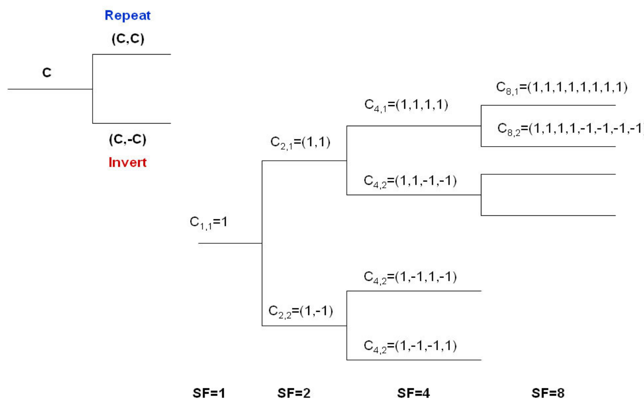

Figure 3.2. Generation of OVSF codes for different Spreading Factors.

downlink connections within one sector from one mobile station (MS) to a base station (BS). The orthogonal variable spreading factor (OVSF) codes, which were originally introduced in [41], were used to be channelization codes for UMTS. The use of OVSF codes allows the orthogonality and spreading factor (SF) to be changed between different spreading codes of different lengths. Fig. 3.2 depicts the generation of different OVSF codes for different SF values.

The data signal after spreading is then scrambled with a scrambling code to separate MSs and BSs from each other. Scrambling is used on top of spreading, thus it only makes the signals from different sources distinguishable from each other. The typical required data rate or dedicated traffic channel (DTCH) for a voice call is 12.2 Kbps. However, the dedicated physical data channel (DPDCH), which is the actual transmitted data rate, is dramatically increased due to the incorporated dedicated control channel (DCCH) information, and the processes of channel coding, rate matching, and radio frame alignment. Fig. 3.3 depicts the process of creating the actual transmitted signal for a voice call. Fig. 3.4 shows the DPDCH data rate requirement for 64 Kbps data call. Table 3.1 shows the approximation of the maximum call data rate with $\frac{1}{2}$ rate coding for different values of DPDCH. The simulation results for network throughput are for spreading factor values of 256, 64, 16, and 4.

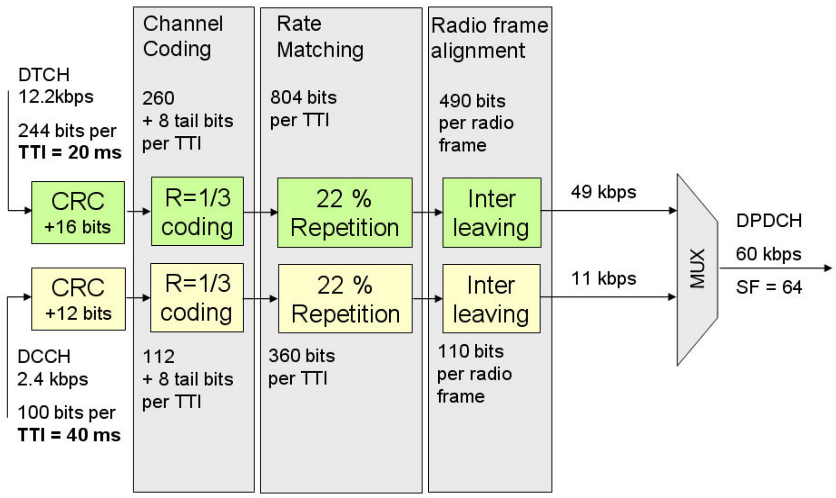

Figure 3.3. 12.2 Kbps Uplink Reference channel.

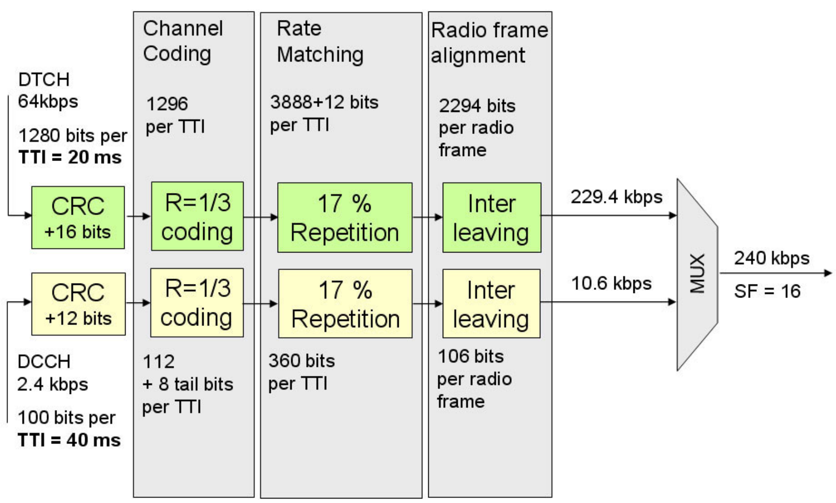

Figure 3.4. 64 Kbps Uplink Reference channel.

3.5. Simulation Results

The following results have been obtained for the twenty-seven cell UMTS network shown in Fig. 3.5. The base stations are located at the centers of a hexagonal grid whose radius is 1732 meters. Base station 1 is located at the center. The base stations are numbered consecutively in a spiral pattern. The COST-231 propagation model [1] with a carrier frequency of 1800 MHz, average base station height of 30 meters, and average mobile height of 1.5 meters is

Table 3.1. Uplink DPDCH data rates.

DPDCH Spreading Factor	Channel bit rate (Kbps)	Maximum call data rate
256	15	7.5 Kbps
128	30	15 Kbps
64	60	30 Kbps
32	120	60 Kbps
16	240	120 Kbps
8	480	240 Kbps
4	960	480 Kbps
4, with 6 parallel codes	5740	2.8 Mbps

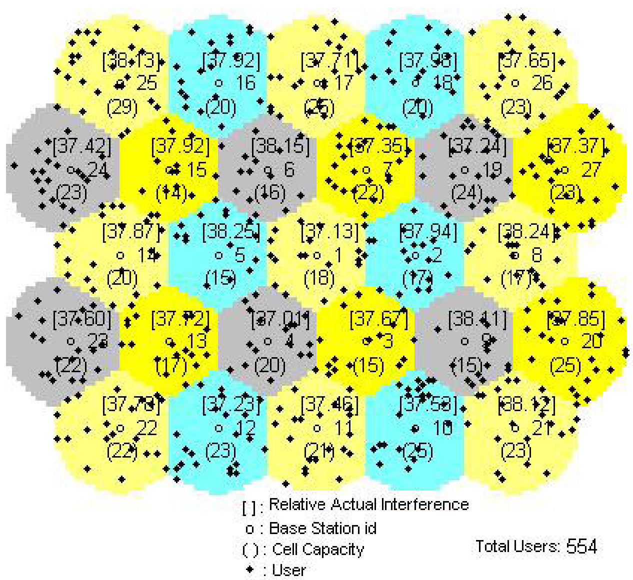

Figure 3.5. Simulated network capacity where users are uniformly distributed in the cells.

used to determine the coverage region. The following is assumed for the analysis. The bit energy to interference ratio threshold is 7.5 dB. The activity factor is 0.375. The processing gain $\frac{W}{R_g}$ is 6.02 dB, 12.04 dB, 18.06 dB, 24.08 dB for Spreading Factor (SF) of 4, 16, 64, and 256, respectively.

Three mobility scenarios: no mobility, low mobility, and high mobility of users are considered. The following parameters are used for the no mobility case: $q_{ij,g} = 0$, $q_{ii,g} = 0.3$

Table 3.2. The low mobility probabilities.

$\|A_i\|$	$q_{ij,g}$	$q_{ii,g}$	$q_{i,g}$
3	0.020	0.240	0.700
4	0.015	0.240	0.700
5	0.012	0.240	0.700
6	0.010	0.240	0.700

Table 3.3. The high mobility probabilities.

$\|A_i\|$	$q_{ij,g}$	$q_{ii,g}$	$q_{i,g}$
3	0.100	0.000	0.700
4	0.075	0.000	0.700
5	0.060	0.000	0.700
6	0.050	0.000	0.700

- $\|A_i\|$ is the number of cells adjacent to cell i.
- $q_{ij,g}$ is the probability of a call with service g in cell i goes to cell j.
- $q_{ii,g}$ is the probability of a call with service g in cell i stays in cell i.
- $q_{i,g}$ is the probability of a call with service g in cell i leaves the network.

and $q_{i,g} = 0.7$ for all cells i and j. Tables 3.2 and 3.3 show respectively the mobility characteristics and parameters for the low and high mobility cases. In all three mobility scenarios, the probability that a call leaves the network after completing its dwell time is 0.7. Thus, regardless of where the call originates and mobility scenario used, the average dwell time of a call in the network is constant. In the numerical results below, for each SF value, the average throughput per cell is analyzed by dividing the results from (13) and (14) by the total number of cells in the network and multiplying by the maximum data rate in Table 3.1.

3.5.1. *UMTS Throughput Optimization with SF of 256*

First, setting SF to 256, which is used to carry data for the control channels. The instantaneous and average throughput from simulation of optimized local CAC are compared with theoretical throughput (obtained from (14)) over a period of 100 time units for blocking probability of 10%. The results for no mobility, low mobility, and high mobility scenarios are

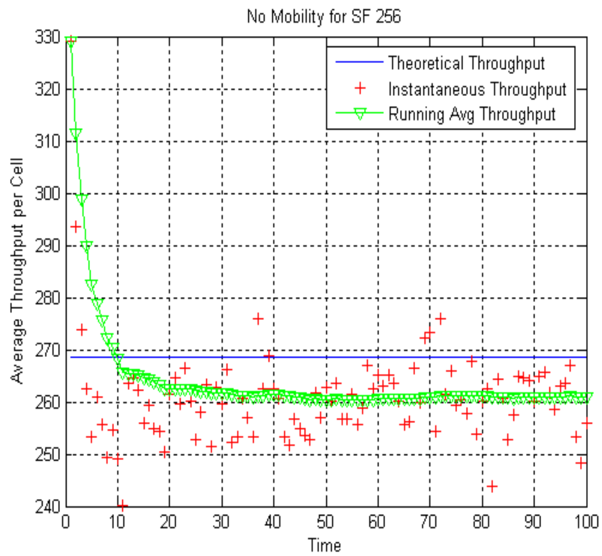

Figure 3.6. Throughput for local CAC algorithm for SF 256 for no mobility case with blocking probability equal to 10%.

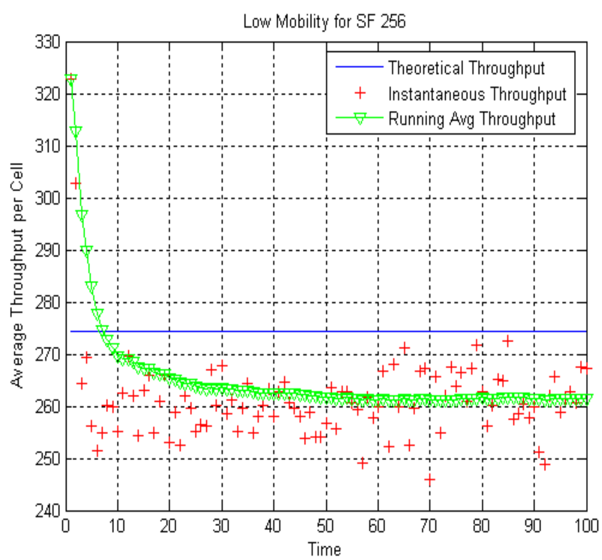

Figure 3.7. Throughput for local CAC algorithm for SF 256 for low mobility case with blocking probability equal to 10%.

shown in Figures 3.6, 3.7, and 3.8, respectively. The average throughput for local CAC is between 2.5% and 5% of the theoretical throughput.

Table 3.4 shows the optimized values of **N** for each cell for all three mobility models and 2% blocking probability. Fig. 3.9 shows the throughput per cell for a blocking probability

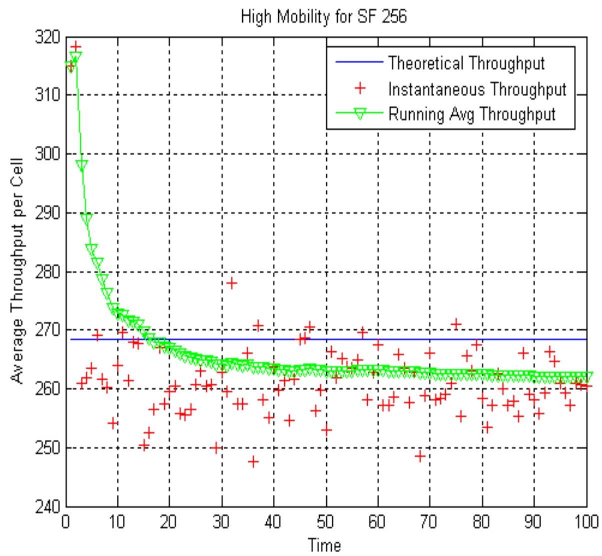

Figure 3.8. Throughput for local CAC algorithm for SF 256 for high mobility case with blocking probability equal to 10%.

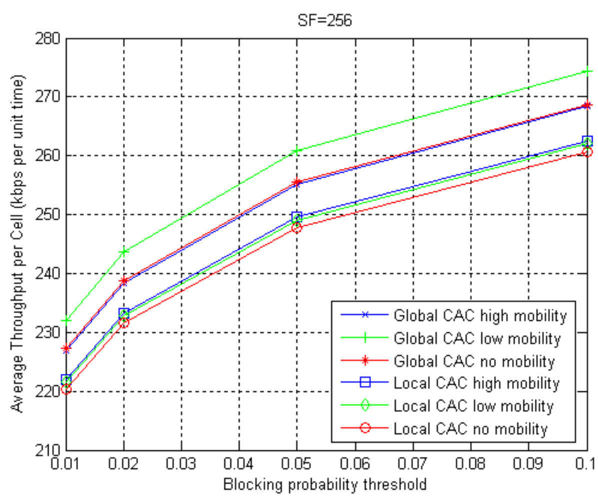

Figure 3.9. Average throughput in each cell for SF = 256.

from 1% to 10%. The throughput for local CAC is within 5% of the throughput for the global CAC algorithm for SF equal to 256.

3.5.2. *UMTS Throughput Optimization with SF of 64*

Next, setting SF to 64, which is used for voice communication. The results for the throughput of optimized local CAC algorithm for no mobility, low mobility, and high mobility

Table 3.4. Calculation of **N** for uniform user distribution with SF = 256 and blocking probability = 0.02.

	No Mobility	Low Mobility	High Mobility
Cell ID	N_i	N_i	N_i
$Cell_1$	52.86	52.86	52.86
$Cell_2$	53.95	53.95	53.95
$Cell_3$	51.84	51.84	51.84
$Cell_4$	51.84	51.84	51.84
$Cell_5$	53.95	53.95	53.95
$Cell_6$	51.85	51.85	51.85
$Cell_7$	51.85	51.85	51.85
$Cell_8$	53.00	53.00	53.00
$Cell_9$	50.73	50.73	50.73
$Cell_{10}$	62.74	62.74	62.74
$Cell_{11}$	63.29	63.29	63.29
$Cell_{12}$	62.73	62.73	62.73
$Cell_{13}$	50.73	50.73	50.73
$Cell_{14}$	53.01	53.01	53.01
$Cell_{15}$	50.73	50.73	50.73
$Cell_{16}$	62.71	62.71	62.71
$Cell_{17}$	63.27	63.27	63.27
$Cell_{18}$	62.71	62.71	62.71
$Cell_{19}$	50.74	50.74	50.74
$Cell_{20}$	73.40	73.40	73.40
$Cell_{21}$	71.84	71.84	71.84
$Cell_{22}$	71.86	71.86	71.86
$Cell_{23}$	73.43	73.43	73.43
$Cell_{24}$	73.43	73.43	73.43
$Cell_{25}$	71.83	71.83	71.83
$Cell_{26}$	71.82	71.82	71.82
$Cell_{27}$	73.40	73.40	73.40

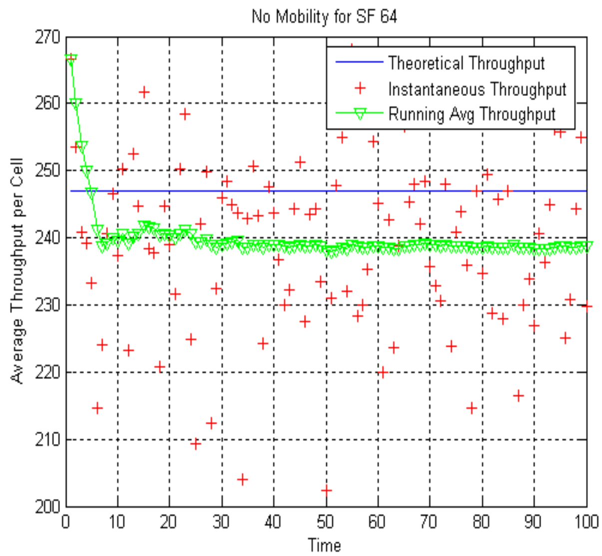

Figure 3.10. Throughput for local CAC algorithm for SF 64 for no mobility case with blocking probability equal to 10%.

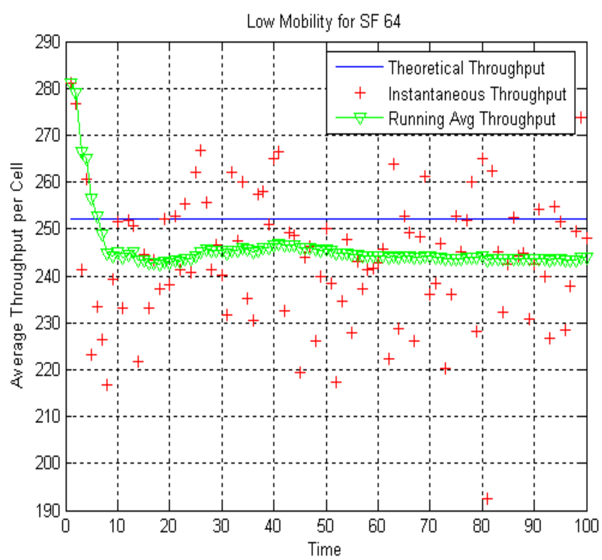

Figure 3.11. Throughput for local CAC algorithm for SF 64 for low mobility case with blocking probability equal to 10%.

scenarios are shown in Figures 3.10, 3.11, and 3.12, respectively. The average throughput for local CAC is between 2% and 4% of the theoretical throughput.

As a result of lowering the SF to 64, the number of possible concurrent connections within one cell is also decreased. Because the throughput is calculated based on the number

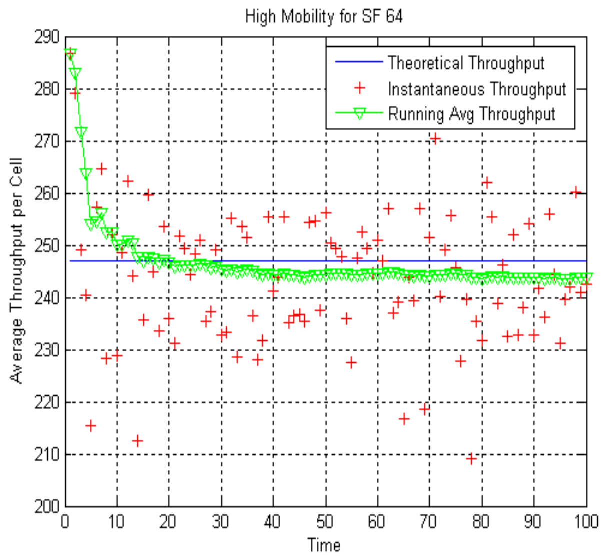

Figure 3.12. Throughput for local CAC algorithm for SF 64 for high mobility case with blocking probability equal to 10%.

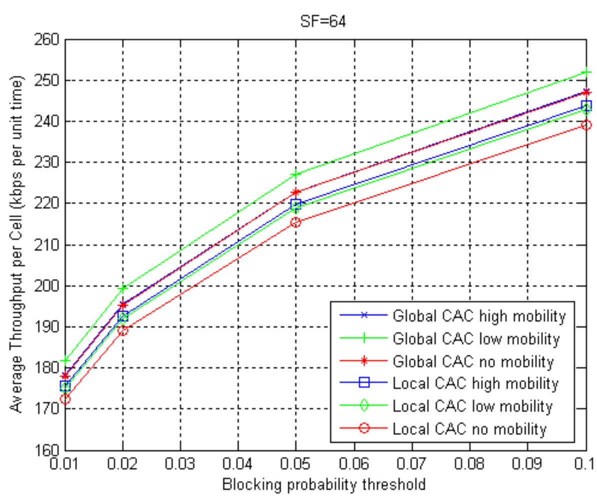

Figure 3.13. Average throughput in each cell for SF = 64.

of simultaneous connections between MSs and BSs, the lower trunking efficiency [1] leads to lower throughput as shown in Fig. 3.13. Table 3.5 shows the optimized values of **N** for each cell for all three mobility cases. The throughput for local CAC is within 4% of the throughput for the global CAC algorithm for SF equal to 64.

Table 3.5. Calculation of **N** for uniform user distribution with SF = 64 and blocking probability = 0.02.

	No Mobility	Low Mobility	High Mobility
Cell ID	N_i	N_i	N_i
$Cell_1$	13.58	13.58	13.58
$Cell_2$	13.86	13.86	13.86
$Cell_3$	13.32	13.32	13.32
$Cell_4$	13.32	13.32	13.32
$Cell_5$	13.86	13.86	13.86
$Cell_6$	13.32	13.32	13.32
$Cell_7$	13.32	13.32	13.32
$Cell_8$	13.61	13.61	13.61
$Cell_9$	13.03	13.03	13.03
$Cell_{10}$	16.11	16.11	16.11
$Cell_{11}$	16.26	16.26	16.26
$Cell_{12}$	16.11	16.11	16.11
$Cell_{13}$	13.03	13.03	13.03
$Cell_{14}$	13.62	13.62	13.62
$Cell_{15}$	13.03	13.03	13.03
$Cell_{16}$	16.11	16.11	16.11
$Cell_{17}$	16.25	16.25	16.25
$Cell_{18}$	16.11	16.11	16.11
$Cell_{19}$	13.03	13.03	13.03
$Cell_{20}$	18.85	18.85	18.85
$Cell_{21}$	18.45	18.45	18.45
$Cell_{22}$	18.46	18.46	18.46
$Cell_{23}$	18.86	18.86	18.86
$Cell_{24}$	18.86	18.86	18.86
$Cell_{25}$	18.45	18.45	18.45
$Cell_{26}$	18.45	18.45	18.45
$Cell_{27}$	18.85	18.85	18.85

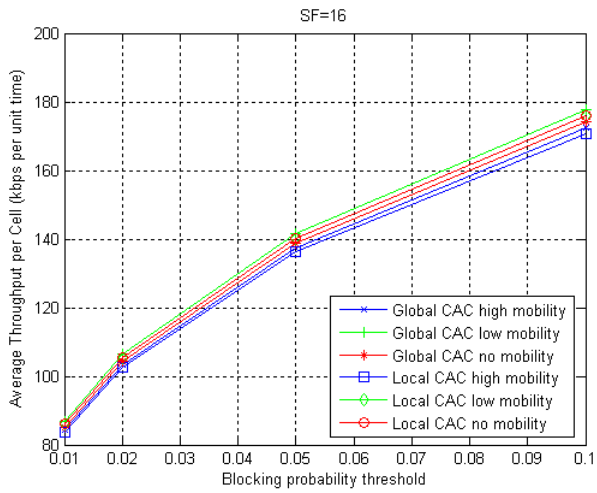

Figure 3.14. Average throughput in each cell for SF = 16.

3.5.3. *UMTS Throughput Optimization with SF of 16*

Next, setting SF equal to 16, which is used for 64 Kbps data communication as shown in Fig. 3.4. The resulting throughput, as shown in Fig. 3.14, is much lower compared to the case with SF equal to 64 or 256. Table 3.6 shows the optimized values of **N** for each cell for all three mobility cases. The throughput for local CAC is within 3% of the throughput for the global CAC algorithm for SF equal to 16.

3.5.4. *UMTS Throughput Optimization with SF of 4*

Next, setting SF equal to 4, which is used for 256 Kbps data communication between BSs and MSs. Table 3.6 shows the optimized values of **N** for each cell for all three mobility models. The throughput for all three mobility cases are almost identical as shown in Fig. 3.15. The throughput for local CAC is within 2% of the throughput for the global CAC algorithm for SF equal to 4.

3.6. Summary

The design and implementation of a local CAC algorithm for UMTS networks and simulation of network throughput for different spreading factors (256, 64, 16, and 4) and various

Table 3.6. Calculation of **N** for uniform user distribution with SF = 16 and blocking probability = 0.02.

	No Mobility	Low Mobility	High Mobility
Cell ID	N_i	N_i	N_i
$Cell_1$	3.75	3.75	3.75
$Cell_2$	3.83	3.83	3.83
$Cell_3$	3.68	3.68	3.68
$Cell_4$	3.68	3.68	3.68
$Cell_5$	3.83	3.83	3.83
$Cell_6$	3.68	3.68	3.68
$Cell_7$	3.68	3.68	3.68
$Cell_8$	3.76	3.76	3.76
$Cell_9$	3.60	3.60	3.60
$Cell_{10}$	4.46	4.46	4.46
$Cell_{11}$	4.50	4.50	4.50
$Cell_{12}$	4.46	4.46	4.46
$Cell_{13}$	3.60	3.60	3.60
$Cell_{14}$	3.77	3.77	3.77
$Cell_{15}$	3.60	3.60	3.60
$Cell_{16}$	4.45	4.45	4.45
$Cell_{17}$	4.49	4.49	4.49
$Cell_{18}$	4.45	4.45	4.45
$Cell_{19}$	3.60	3.60	3.60
$Cell_{20}$	5.21	5.21	5.21
$Cell_{21}$	5.10	5.10	5.10
$Cell_{22}$	5.10	5.10	5.10
$Cell_{23}$	5.22	5.22	5.22
$Cell_{24}$	5.22	5.22	5.22
$Cell_{25}$	5.10	5.10	5.10
$Cell_{26}$	5.10	5.10	5.10
$Cell_{27}$	5.21	5.21	5.21

Table 3.7. Calculation of **N** for uniform user distribution with SF = 4 and blocking probability = 0.02.

	No Mobility	Low Mobility	High Mobility
Cell ID	N_i	N_i	N_i
$Cell_1$	1.24	1.16	1.32
$Cell_2$	1.48	1.42	1.24
$Cell_3$	1.30	1.32	1.28
$Cell_4$	1.30	1.32	1.28
$Cell_5$	1.48	1.42	1.23
$Cell_6$	1.30	1.32	1.28
$Cell_7$	1.30	1.32	1.28
$Cell_8$	0.94	1.37	1.23
$Cell_9$	0.93	0.94	1.27
$Cell_{10}$	1.59	1.58	1.54
$Cell_{11}$	1.53	1.53	1.55
$Cell_{12}$	1.59	1.58	1.54
$Cell_{13}$	0.93	0.94	1.27
$Cell_{14}$	0.94	1.37	1.23
$Cell_{15}$	0.93	0.93	1.27
$Cell_{16}$	1.59	1.58	1.54
$Cell_{17}$	1.53	1.53	1.55
$Cell_{18}$	1.59	1.58	1.54
$Cell_{19}$	0.93	0.93	1.27
$Cell_{20}$	1.92	1.83	1.82
$Cell_{21}$	1.79	1.80	1.76
$Cell_{22}$	1.79	1.80	1.76
$Cell_{23}$	1.92	1.83	1.82
$Cell_{24}$	1.92	1.83	1.82
$Cell_{25}$	1.79	1.80	1.76
$Cell_{26}$	1.79	1.80	1.76
$Cell_{27}$	1.92	1.83	1.82

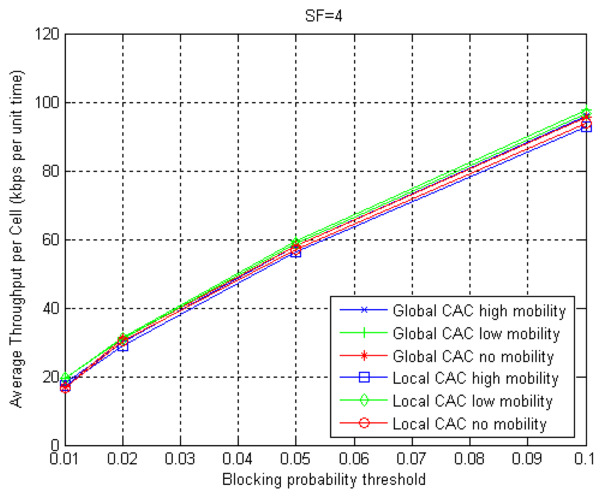

Figure 3.15. Average throughput in each cell for SF = 4.

mobility scenarios (no, low and high mobility)is discussed. The design of the local CAC algorithm uses global information; it incorporates the call arrival rates and the user mobilities across the network and guarantees the users' quality of service as well as pre-specified blocking probabilities. On the other hand, its implementation in each cell uses local information; it only requires the number of calls currently active in that cell.

The computational complexity of the implementation of the global CAC algorithm using average interference is $O(MG)$ and using actual interference is $O(M^2G)$ where M is the total number of cells and G is the total number of services, while the computational complexity of the implementation of our optimized local CAC is $O(1)$. The global CAC algorithm is inherently optimized, and therefore it is expected to perform better than the local CAC algorithm. The results show that the difference between optimized local CAC algorithm's performance and global CAC algorithm's performance is small enough (less than 5%) to justify the small tradeoff in throughput for the huge reduction in computational complexity and feasibility for implementation in networks of large size.

CHAPTER 4

DYNAMIC CHANNEL ASSIGNMENT IN IEEE 802.11 SYSTEMS

4.1. Introduction

Demand for wireless access is creating hotspots in places like university campuses, coffee-shops, and airports. Major cities are planning to set up wireless local area networks (WLANs) for public use free of cost. Although IEEE 802.11 is the preferred standard, other technologies like HiperLAN2 (Europe) and HomeRF competed with IEEE 802.11 in the formative stages of wireless LANs.

HiperLAN2 is an European standard for short range broadband radio access networks. HiperLAN2 offers high speed (up to 54 Mb/s) access to different networks like UMTS core networks, IP based networks, and wireless LAN systems for public and private use. Data, voice, and video applications are supported by HiperLAN2 while taking into consideration parameters for quality of service. HiperLAN2 operates in the frequency range of 5 GHz [42].

HomeRF using the shared wireless access protocol (SWAP) was seen as a future for wireless networking in homes. SWAP was designed for wireless digital communications between personal computers and consumer electronic devices. The specifications for SWAP define a common wireless interface for data and voice with data rates of 1-2Mbps using frequency hopping spread spectrum modulation in the 2.4 GHz frequency band. Future work on the SWAP specifications was to increase the data rates with backward compatibility. The HomeRF-SWAP working group was disbanded in January 2003 [43–45].

The IEEE 802.11 working group has set standards and defined specifications for WLANs to be interoperable with different devices manufactured by various companies. The topology, logical architecture, medium access control (MAC) layer, and physical (PHY) layer will be

Table 4.1. Comparison of IEEE 802.11 with other WLAN Standards.

Wireless technology	802.11b/g	HiperLAN2	HomeRF
Frequency spectrum	2.4 GHz	5 GHz	2.4 GHz
Physical layer	DSSS/OFDM	OFDM with QAM	FHSS with FSK
Channel access	CSMA-CA	TDMA/TDD	CSMA-CA and TDMA
Interference	Present	Minimal	Present
Security	Low	High	Low
Data rate	11/54 Mbps	54 Mbps	2 Mbps
Coverage	100 m	30-150 m	$>$ 50 m

the same for all systems. Table 4.1 shows different WLAN standards compared with IEEE 802.11 standard.

4.2. Overview of IEEE 802.11 Standard

The two topologies supported by the IEEE 802.11 standard are as follows:

- Independent basic service set (IBSS) networks, and
- Extended service set (ESS) networks.

The IBSS and ESS are also known as ad-hoc mode and infrastructure mode, respectively [46]. Fig. 4.1 illustrates the ad-hoc mode (IBSS) topology of 802.11 standard and Fig. 4.2 shows the infrastructure mode (ESS). These networks are built on basic service set (BSS) defined by the IEEE 802.11 standard, which provides a coverage area for different mobile stations and access points to be connected.

The logical architecture defines the operations of the network. The IEEE 802.11 standard logical architecture that applies to all the systems in a network consists of a single MAC and one of multiple PHY layers. Fig. 4.3 illustrates IEEE 802.11 logical architecture.

The MAC layer uses carrier sense multiple access with collision avoidance (CSMA-CA) for channel access between different systems in the WLAN network whereas PHY layer uses different types of implementations like frequency hopping spread spectrum, direct sequence spread spectrum, and high range direct sequence spread spectrum.

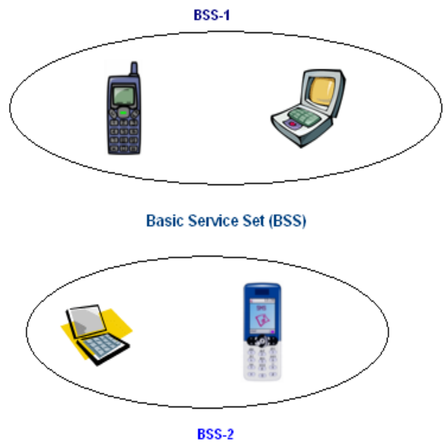

Figure 4.1. Independent Basic Service Set for 802.11 WLAN.

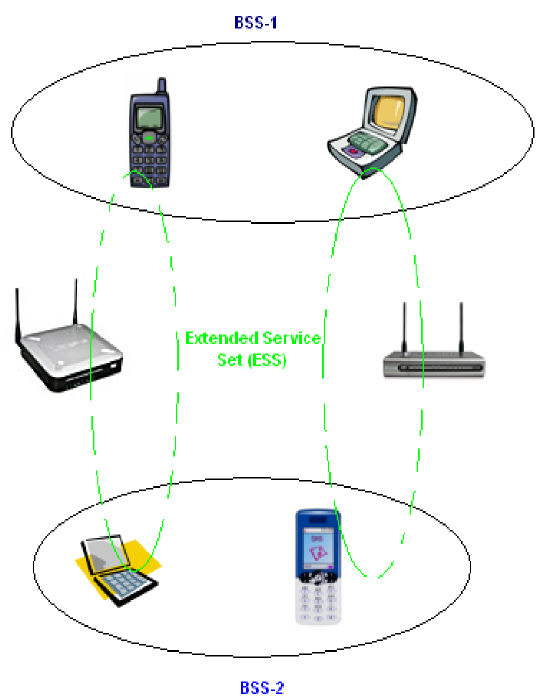

Figure 4.2. Extended Service Set 802.11 WLAN .

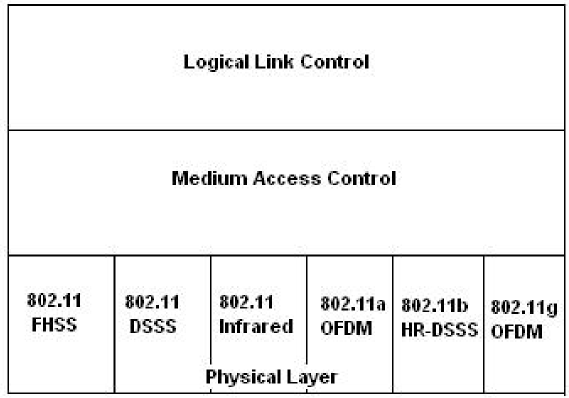

Figure 4.3. Logical Architecture of 802.11 .

Tremendous growth and wide usage of IEEE 802.11 with increasing user access has raised issues like quality of service, channel interference, and network load management. The increase in deployment of access points (APs) leads to co-channel interference from neighboring APs degrading the network throughput. Issues related to resource management and interference impede the performance of WLANs.

The current problem areas in IEEE 802.11 WLANs are:

- Radio resource management, and
- Channel interference.

Frequency assignment [47] is a major problem in designing wireless networks. All APs share the same frequency, which leads to interference that should be minimized and avoided if necessary, using efficient assignment of channels.

Channel interference is of two types: adjacent channel interference and co-channel interference. Channels which are adjacent to each other cause adjacent channel interference while APs using the same channels cause co-channel interference.

In this chapter, we design a dynamic channel allocation algorithm for IEEE 802.11 WLAN system. We analyze its implementation and performance for 4, 9, 16, and 25 APs in a network in the next chapter.

4.3. Related Work

In [47], the authors formulate an integer linear programming problem to optimize the channel assignment for hot spot service areas. The objective of their optimization is to minimize the maximum channel utilization, yielding higher throughput.

In [48], the authors discuss the implementation of IEEE 802.11 based WLANs for enterprise customers with limitations like performance under heavy load, deployment issues, and network management. The authors suggest using dynamic resource management over static radio resource management to improve performance of large scale WLANs. The need for better communication between clients and APs is discussed with the expectation that IEEE 802.11 working group will define a new technique for radio resource management. Analysis of channel assignment for 802.11b using radio interference is done in [49]. Experimental results show that performance differs with changing environmental conditions and channel separation when using different models. Also, a frequency separation of 3 or 4 channels between APs is suitable.

In [50], the authors assign frequencies to APs using an algorithm that has an exponential computational complexity. To overcome the computationally intensive algorithm, the authors also use a greedy algorithm that is close to optimal but may not yield the optimal frequency assignment for a given WLAN.

In [51], the authors propose techniques to improve the usage of wireless spectrum in WLANs. They present scalable distributed algorithms which achieve better performance than existing techniques for channel assignment. The authors emphasize that the use of a least congested channel search for assigning new channels for interfering APs is not efficient with continued growth of WLANs. Extensive simulations and experiments over an in-building wireless testbed prove that the techniques proposed by their study are efficient.

Figure 4.4. 802.11b/g channel overlap.

4.4. Channel Interference

802.11b/g networks operate between 2.4 GHz and 2.5 GHz [4, 5]. In 802.11b/g, transmissions between APs and demand clusters do not use a single frequency. Instead, the frequencies are divided into 14 channels, and use a modulation technique, direct sequence spread spectrum, to spread the transmission over multiple channels for effective uses of the frequency spectrum. Channel 1 is assigned to 2.412 GHz. There is 5 MHz separation between the channels. Thus, channel 14 is assigned to 2.482 GHz. In the United States, channels 1-11 are used. Europe uses channels 1-13. Japan uses channels 1-14. An 802.11b/g signal occupies approximately 30 MHz of the frequency spectrum. As a result, an 802.11b/g signal overlaps with several adjacent channel frequencies.

Think of the signal overlap with adjacent channels as people's conversations at a party at home with eleven different rooms [52]. This analogy shows that only three rooms can have conversations without noise from other rooms. Likewise, the three non-overlapping channels available in 802.11b/g, are 1, 6, and 11, as shown in Fig. 4.4. Channel 1 overlaps with channels 2 through 5, and channel 6 overlaps with channels 2 through 10. Channel 11 overlaps with channels 7 through 10.

Channels should be assigned to APs such that overlapping channel interference is minimized. Channels are reused because of limited availability. The same channel should be assigned to two APs, which are located far enough apart, if the overlapping channel interference signal detected by each AP is less than a given threshold.

Use of overlapping channels degrades network throughput. Interference in 802.11b causes APs and stations to send frames over and over again to increase the odds of successful transmission. Typically, if devices were to send one copy of a frame, data is transmitted at 11 Mbps (54 Mbps for 802.11g). However, if the efficiency were to drop to 50%, for instance, because of interference, the devices would still be transmitting at 11 Mbps, but it would be duplicating each frame, making the effective throughput 5.5 Mbps. Therefore, 802.11 networks will have a significant decrease in network performance because of interference.

4.5. Overlapping Channel Interference Factor

Adjacent channel interference is modeled by defining an overlapping channel interference factor, w_{ij}, to be the relative percentage increase in interference as a result of two APs i and j using overlapping channels. Thus overlapping channels assigned to APs must be chosen carefully.

The overlapping channel interference factor is defined as:

$$w_{ij} = \begin{cases} 1 - |F_i - F_j| \times c & \text{if } w_{ij} \geq 0, \\ 0 & \text{otherwise,} \end{cases} \tag{15}$$

where F_i is the channel assigned to AP i. F_i belongs to the set of available channels. c is the overlapping channel factor. In 802.11b/g, c is 1/5 where 5 is the maximum number of overlapping channels.

For instance, if channel 1 is assigned to AP i and channel 1 is also assigned to AP j, the overlapping channel interference factor between AP i and AP j, w_{ij}, is 1.0 or 100%. If channel 5 is assigned to AP j, w_{ij} is 0.2 or 20%. If channels 6 or higher is assigned to AP j, w_{ij} is 0 or 0%, which means there is no interference between AP i and AP j.

4.6. Dynamic Channel Assignment

A dynamic channel assignment algorithm for IEEE 802.11 WLAN systems is presented. Channels should be assigned to each AP in such a way that minimizes interference between APs. The closer the overlapping frequencies, the higher the interference.

Formulation of dynamic channel assignment problem using the following variables is defined as follows:

- $\mathbf{A}_\text{i}$ is the set of neighboring APs to AP i.
- c is the overlapping channel factor.
- d_{ij} is the distance between AP i and AP j.
- F_i is the channel assigned to AP i.
- I_{ij} is the interference that AP j causes on AP i.
- K is the total number of available channels. 802.11b/g has 11 channels.
- $Loss$ is a function that captures the attenuation loss based on the propagation model used.
- m is a pathloss exponent.
- P_i is the transmit power of AP i.
- Q_i is the cardinality of $\mathbf{A}_\text{i}$.
- w_{ij} is the overlapping channel interference factor between AP i and AP j.

The dynamic channel assignment problem is given as:

$$\min_{F_i} \quad \sum_{j=1}^{Q_i} I_{ij}, \quad (16.1)$$

$$\text{subject to} \quad I_{ij} = \frac{w_{ij} P_j}{Loss(d_{ij}, m)}, \quad (16.2)$$

$$w_{ij} = \begin{cases} 1 - |F_i - F_j| \times c & \text{if } w_{ij} \geq 0, \\ 0 & \text{otherwise,} \end{cases} \quad (16.3)$$

$$\text{for} \quad j \in \mathbf{A}_{\mathrm{i}},$$

(16) $$\text{for} \quad F_i \in \{1, ..., K\}.$$

Objective (16.1) minimizes the maximum total interference at each AP. Constraint (16.2) defines the interference between AP i and AP j. Constraint (16.3) defines the overlapping channel interference factor between AP i and AP j, which have been assigned channels F_i and F_j, respectively.

Each AP would periodically (or when the amount of interference is above a threshold) run the above given dynamic channel assignment problem. Each AP would in turn pick its own channel that would minimize that amount of interference it receives from its neighbors. Of course as one AP changes its own channel, it would impact the interference on the APs of which it is a neighbor. Assuming that an AP would have on average six neighboring APs and since the number of total possible channels is eleven, the dynamic channel assignment can run within a few seconds, even if every possible channel is enumerated.

The questions of the existence and uniqueness of the solution and whether the iterative approach in fact converges to the solution (if a unique solution exists) are generally difficult to answer due to the complexity of the equations involved. Kelly has shown that, for fixed alternate routing, the solution to the fixed point problem is in fact not unique [53]; in all the numerical examples solved, the iterative approach converged to a unique solution.

The algorithm's implementation and simulation are discussed in the next chapter with numerical results.

4.7. Summary

Design of a dynamic channel assignment algorithm for IEEE 802.11 WLAN systems is presented. The dynamic channel assignment algorithm uses the channel information from neighboring APs in the network while selecting one of the APs as a reference AP to run the algorithm. The algorithm minimizes the interference among the APs and improves the throughput of the whole network.

CHAPTER 5

NUMERICAL ANALYSIS

5.1. Introduction

A detail discussion is presented of the numerical analysis carried out for dynamic channel assignment algorithm described in the previous chapter. A wireless local area network (WLAN) is simulated by varying the number of access points (APs), initially using 4 APs and then increasing the number of APs to 9, 16, and 25. The algorithm analyzes and minimizes the interference among APs before assigning channels dynamically.

The simulations were performed using the design procedures specified in [54]. The approach for designing 802.11 wireless LANs is composed of various steps which take into consideration issues like placement of APs while satisfying coverage of service areas and throughput requirements. The service area map and signal level map provide a picture of where APs can be placed while meeting the traffic demands and capacity of the network. Frequency assignment to APs minimizing the co-channel interference and adjacent channel interference is an important step in the design of wireless LANs.

The typical layout of our service area is a floor of a building which is 800 meters in length and 800 meters in width. APs are placed 150 meters apart from each other. We assume the following for the analysis.The transmit power of individual APs is set to 20 dBm.The receiver sensitivity threshold is -84 dBm.The pathloss exponent is 2.

The service area maps with the signal levels for 4, 9, 16, and 25 APs are shown. Fig. 5.1 shows 4 APs placed in counter clockwise direction. Figures. 5.2, 5.3, and 5.4 show service area maps consisting of 9, 16, and 25 APs, respectively.

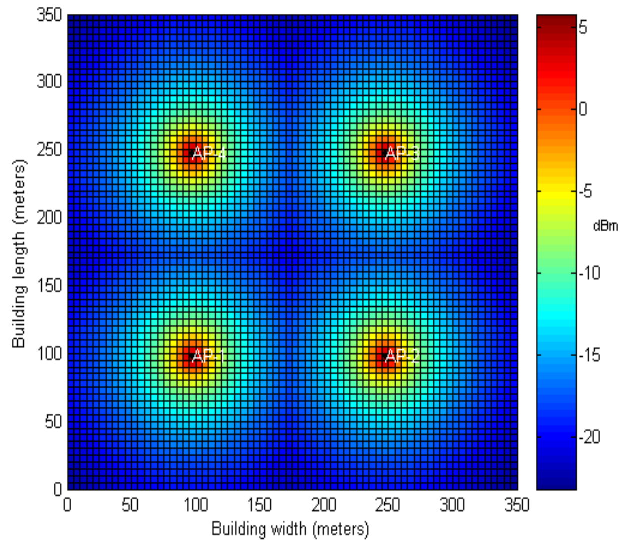

Figure 5.1. A signal level map for a floor with 4 APs.

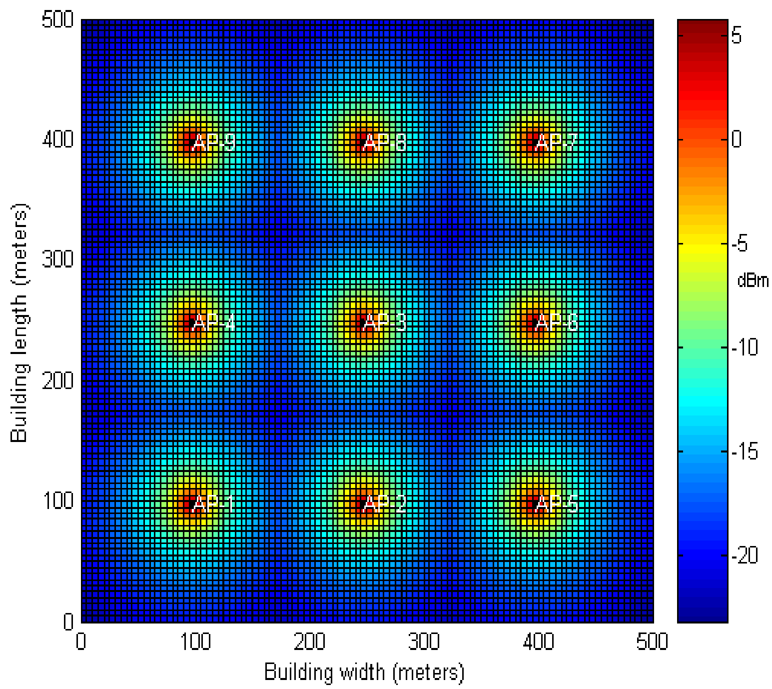

Figure 5.2. A signal level map for a floor with 9 APs.

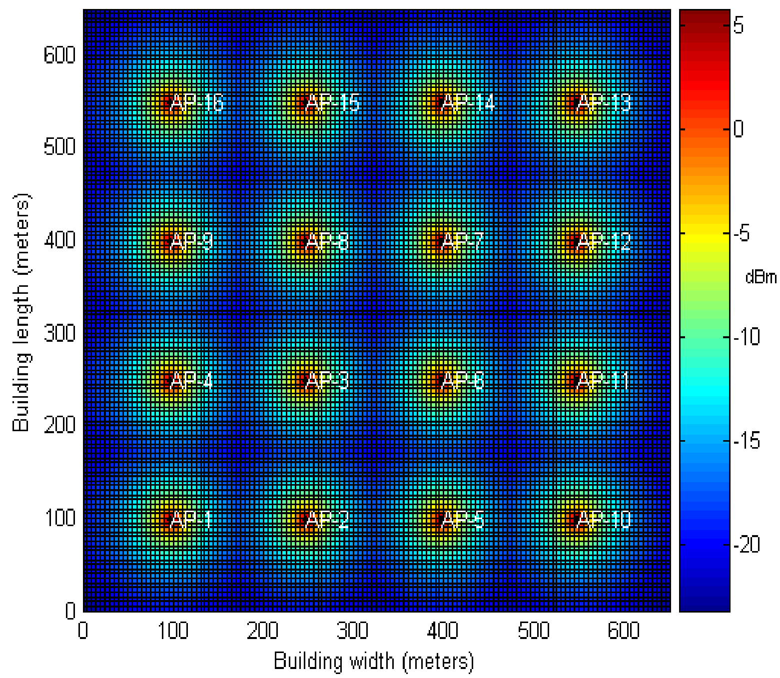

Figure 5.3. A signal level map for a floor with 16 APs.

5.2. Analysis of Simulation Results

The simulations were carried out with service areas consisting of 4, 9, 16, and 25 APs forming a wireless LAN. Initially, assigning default factory settings, i.e., all APs are assigned the same channel number, and the total interference caused on each AP from other APs in the network is calculated. These results are used as a benchmark to compare with our dynamic channel assignment algorithm.

Next, assigning the same channel for all APs starting with Channel 1 and the algorithm is simulated for 100 runs. This is repeated for Channels 2 through 11. Analysis of the algorithm is carried out using two versions developed for breaking ties for channel assignment. These are named algorithm I (pick rand) and algorithm II (pick first). Algorithm I randomly breaks ties between channels that yield the same performance and randomly selects a channel for assignment. For example if the algorithm selects 7, 8, 9, 10, and 11 as possible channels for

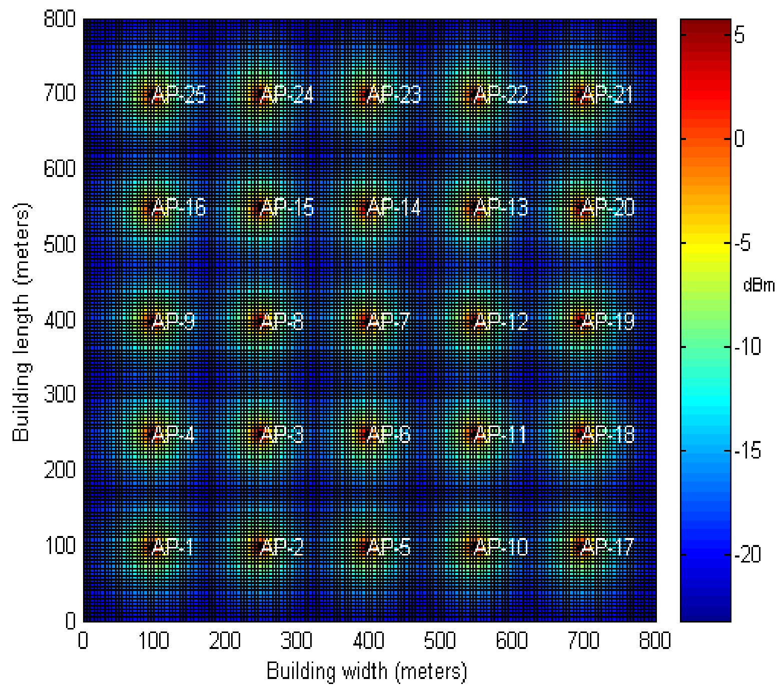

Figure 5.4. A signal level map for a floor with 25 APs.

assignment then the algorithm randomly picks say 9 in one instance. Algorithm II picks the first (smallest) channel number from channels that yield the same performance and assigns that to the AP. For example if the algorithm selects 7, 8, 9, 10, and 11 as possible channels then algorithm II assigns 7 every time.

Comparisons of the results for total interference from algorithms I and II with default factory setting for 4, 9, 16, and 25 APs forming the wireless LAN is presented. The algorithms yield better performance than default factory settings by a factor of 4.

5.2.1. *Dynamic Channel Assignment for WLAN with 4 APs*

Initially, 4 APs are placed to simulate the WLAN. Setting initially all APs to the same channels, simulation of dynamic channel assignment algorithm for 100 runs is carried out while recording the interference and channel assignment from each run. The total interference is calculated in dBm for algorithm I and II and compared with benchmark settings. The total

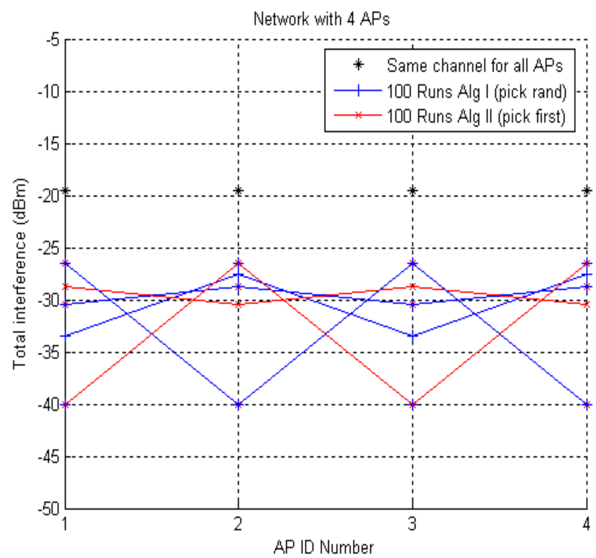

Figure 5.5. Total Interference for AP 4 using algorithm I (pick rand) and II (pick first) comparing with same channel assignment.

Table 5.1. Interference calculated at the APs after running dynamic channel assignment algorithm for WLAN with 4 APs.

AP ID	CHANNEL F_i	INTERFERENCE (dBm)
AP_1	11	-30.5115
AP_2	3	-28.7506
AP_3	8	-30.5115
AP_4	1	-28.7506

interference ranges between -34 dBm to -26 dBm for both algorithm I and II while if all APs were still assigned the same channels, it is at -19.5 dBm. Fig. 5.5 shows the results of total interference in dBm for Algorithm I and II compared to same channel assignment.

Fig. 5.6 shows the channel assignment map for WLAN with 4 APs after running the dynamic channel assignment algorithm for 100 runs. We can observe from the figure that one channel assignment is 11, 3, 8, and 1 for APs 1, 2, 3, and 4, respectively. Table 5.1 shows the interference values in dBm for the individual APs after dynamic channel assignment.

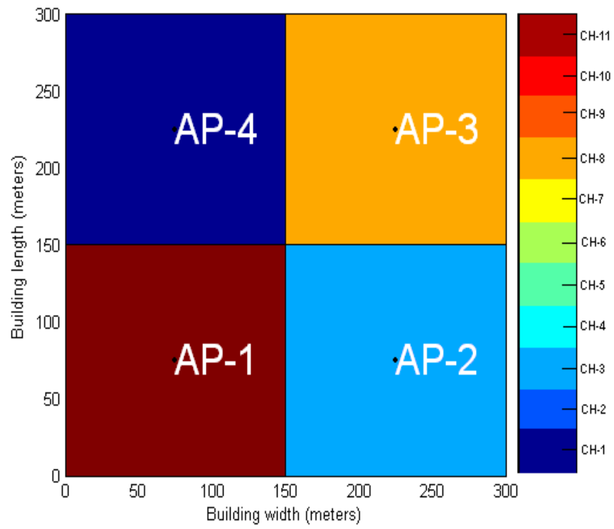

Figure 5.6. Dynamic channel assignment map for WLAN with 4 APs.

5.2.2. *Dynamic Channel Assignment for WLAN with 9 APs*

Next, 9 APs are simulated. Following the same procedure described in 5.2.1, the results are generated and the total interference is calculated. Fig. 5.7 shows the total interference from algorithm I and II compared with same channel assignment. The total interference for algorithm I and II varies from -28 dBm to -20.5 dBm while for the same channel assignment, it varies from -18 dBm to -15.5 dBm. We can observe that AP 3 has the highest interference compared to other APs as it is at the center as seen in Fig 5.2. Also, with the increase in the number of APs in WLAN there is an increase in the total interference. The results show an improvement of 6 dBm or 4 times that of the total interference from default factory settings.

Fig. 5.8 shows a channel assignment map for WLAN with 9 APs after running the dynamic channel assignment algorithm. Table 5.2 shows the interference values for the corresponding channel numbers from the channel assignment map.

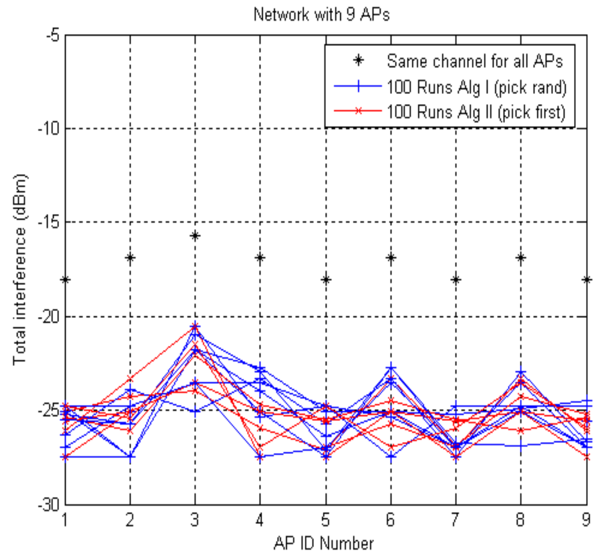

Figure 5.7. Total Interference for AP 9 using algorithm I (pick rand) and II (pick first) comparing with same channel assignment.

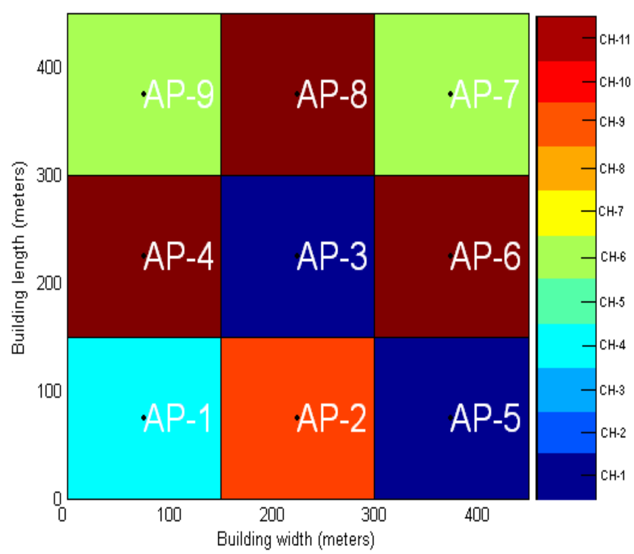

Figure 5.8. Dynamic channel assignment map for WLAN with 9 APs.

5.2.3. *Dynamic Channel Assignment for WLAN with 16 APs*

Next, simulation of 16 APs is performed. Fig. 5.9 shows the total interference from algorithm I (pick rand) and II (pick first) compared with same channel assignment. The total

Table 5.2. Interference calculated at the APs after running dynamic channel assignment algorithm for WLAN with 9 APs.

AP ID	CHANNEL F_i	INTERFERENCE (dBm)
AP_1	4	-26.3202
AP_2	9	-23.9314
AP_3	1	-25.0708
AP_4	11	-23.3099
AP_5	1	-25.7403
AP_6	11	-23.3099
AP_7	6	-27.4473
AP_8	11	-22.9148
AP_9	6	-26.7094

interference for algorithm I and II varies from -27 dBm to -20 dBm while for the same channel assignment, it varies from -18 dBm to -15 dBm. We can observe that APs 3, 6, 7, and 8 have high interference compared to other APs due to their placement as seen in Fig 5.3. The results show an improvement of a factor of 4 over default factory settings leading to higher throughput of the entire network.

Fig. 5.10 shows a channel assignment map for WLAN with 16 APs after running the dynamic channel assignment algorithm. The corresponding interference values (dBm) are shown in Table 5.3.

5.2.4. *Dynamic Channel Assignment for WLAN with 25 APs*

Finally, simulation of 25 APs forming WLAN is performed. Fig. 5.11 shows total interference from algorithm I (pick rand) and II (pick first) compared to same channel assignment. The total interference from algorithm I and II varies from -25 dBm to -19 dBm while for the same channel assignment, it varies from -17 dBm to -14 dBm. With the increase in the number of APs in the network, we observe an increase in the total interference generated at the

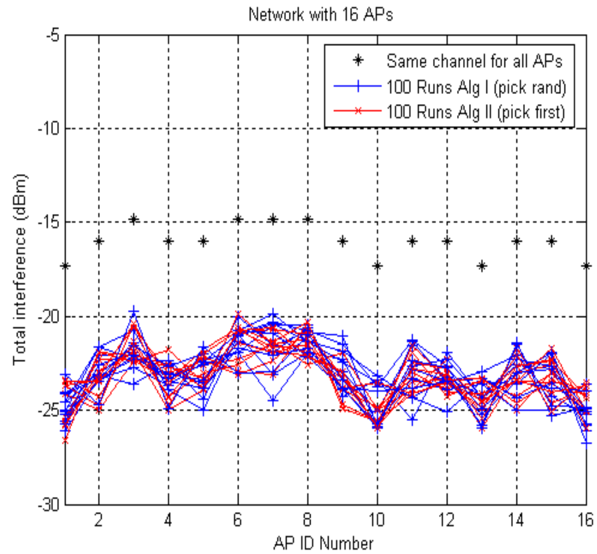

Figure 5.9. Total Interference for AP 16 using algorithm I (pick rand) and II (pick first) comparing with same channel assignment.

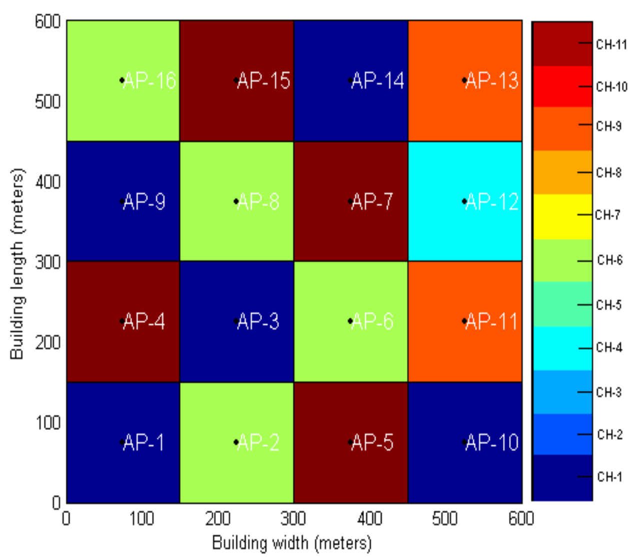

Figure 5.10. Dynamic channel assignment map for WLAN with 16 APs.

APs in the WLAN. When compared to default factory settings, the results are consistently better by a factor of 4.

Table 5.3. Interference calculated at the APs after running dynamic channel assignment algorithm for WLAN with 16 APs.

AP ID	CHANNEL F_i	INTERFERENCE (dBm)
AP_1	1	-23.6595
AP_2	6	-23.3692
AP_3	1	-21.8192
AP_4	11	-24.9920
AP_5	11	-23.9314
AP_6	6	-20.7229
AP_7	11	-21.6185
AP_8	6	-21.5906
AP_9	1	-23.2224
AP_{10}	1	-25.8278
AP_{11}	9	-21.5286
AP_{12}	4	-23.3506
AP_{13}	9	-23.3458
AP_{14}	1	-24.6180
AP_{15}	11	-23.4146
AP_{16}	6	-24.1758

Fig. 5.12 shows a channel assignment map for WLAN with 25 APs after running the dynamic channel assignment algorithm. Table 5.4 shows the corresponding interference values for the APs.

5.3. Summary

The implementation and simulation of dynamic channel assignment algorithm for IEEE 802.11 WLAN systems is presented. Analysis of the algorithm using different number of APs (4, 9, 16, and 25) and two versions (I: pick rand and II: pick first), calculating the interference caused on an individual AP while minimizing the interference by dynamically assigning channels. The results from algorithm I (pick rand) and II (pick first) are compared with the results of default settings of having all APs use the same channels. The results

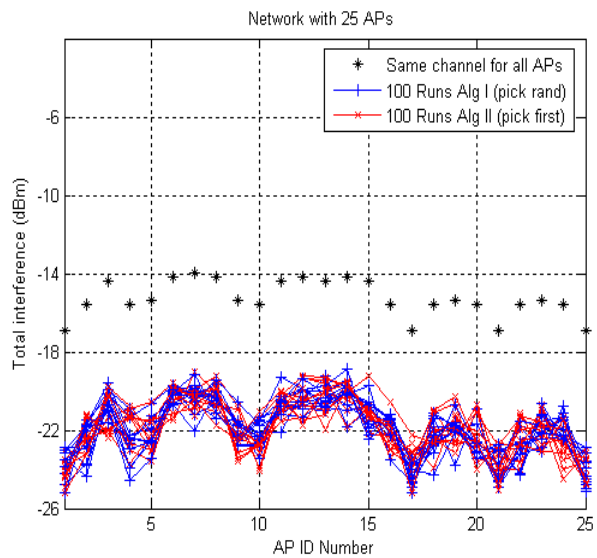

Figure 5.11. Total Interference for AP 25 using algorithm I (pick rand) and II (pick first) comparing with same channel assignment.

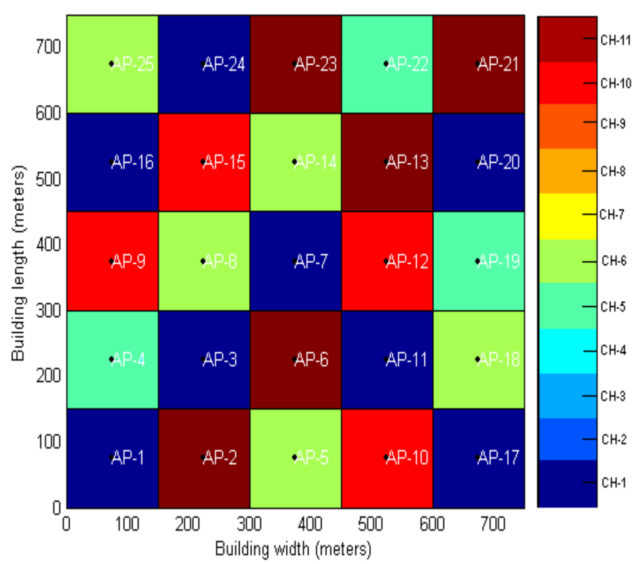

Figure 5.12. Dynamic channel assignment map for WLAN with 25 APs.

showed an improvement by a factor of 4 over the default settings. This results in significantly better network throughput.

Table 5.4. Interference calculated at the APs after running dynamic channel assignment algorithm for WLAN with 25 APs.

AP ID	CHANNEL F_i	INTERFERENCE (dBm)
AP_1	1	-22.6745
AP_2	11	-22.6418
AP_3	1	-20.5696
AP_4	5	-21.8568
AP_5	6	-22.9029
AP_6	11	-20.4941
AP_7	1	-20.5552
AP_8	6	-20.3750
AP_9	10	-21.6051
AP_{10}	10	-21.6470
AP_{11}	1	-20.8541
AP_{12}	10	-19.5659
AP_{13}	11	-19.6376
AP_{14}	6	-20.6079
AP_{15}	10	-20.0170
AP_{16}	1	-22.4759
AP_{17}	1	-23.3011
AP_{18}	6	-21.4209
AP_{19}	5	-20.7232
AP_{20}	1	-23.1058
AP_{21}	11	-22.7518
AP_{22}	5	-22.5916
AP_{23}	11	-21.4080
AP_{24}	1	-22.8317
AP_{25}	6	-24.0713

CHAPTER 6

CONCLUSIONS

6.1. Summary

Resource management in wireless networks is an active area of research. With the need for high speed data access and connectivity at any place and at any time, we are observing an evolution of wireless systems for the future, leading to new problems in resource allocation. There have been technical enhancements added to present networks to improve the download speeds and enabling new services like mobile TV. There is also a growing need for mobile internet access with the wide usage of wireless access points (AP) in homes and businesses. Interference among APs impedes the performance of the network. Therefore, minimal interference leading to the improvement of network throughput is highly desired. Solutions have been proposed to the problem of resource management in cellular networks and wireless LANs by addressing the issues of call admission control (CAC) in third generation universal mobile telecommunications system (UMTS) wideband code division multiple access (WCDMA) systems and channel assignment of access points for IEEE 802.11 wireless local area networks (WLAN) systems, respectively.

In Chapter 2, a global CAC algorithm was designed and implemented for UMTS networks, which was used as a benchmark since it is inherently optimized and uses global information in making every call admission decision. Global CAC yields the best possible performance but has an intensive computational complexity. the interference was calculated taking into consideration the average and actual interferences for calls entering the network and individual cells. The computational complexity of the implementation of the global CAC algorithm using average interference is $O(MG)$ and using actual interference is $O(M^2G)$ where M is the total number of cells and G is the total number of services.

In Chapter 3, a local CAC algorithm was designed and implemented for UMTS networks and simulation of network throughput for different spreading factors (256, 64, 16, and 4) and various mobility scenarios (no, low and high mobility) was carried out. The design of the local CAC algorithm uses global information; it incorporates the call arrival rates and the user mobilities across the network and guarantees the users' quality of service as well as pre-specified blocking probabilities. On the other hand, its implementation in each cell uses local information; it only requires the number of calls currently active in that cell.

The computational complexity of the implementation of the global CAC algorithm using average interference is $O(MG)$ and using actual interference is $O(M^2G)$ where M is the total number of cells and G is the total number of services, while the computational complexity of the implementation of our optimized local CAC is $O(1)$. Global CAC algorithm is inherently optimized, and therefore it is expected to perform better than local CAC algorithm. Results show that the difference between optimized local CAC algorithm's performance and global CAC algorithm's performance is small enough (less than 5%) to justify the small tradeoff in throughput for the huge reduction in computational complexity and feasibility for implementation in networks of large size.

In Chapter 4, a dynamic channel assignment algorithm for IEEE 802.11 WLAN systems was designed. The dynamic channel assignment algorithm uses the channel information of neighboring APs in the network while selecting one of the APs as a reference AP to run the algorithm. This algorithm minimizes the interference among the APs and improves the throughput of the whole network.

In Chapter 5, implementation and simulation of dynamic channel assignment algorithm for IEEE 802.11 WLAN systems was presented. Analysis of the algorithm was carried out using different number of APs (4, 9, 16, and 25) and two versions (I: pick rand and II: pick first), calculating the interference caused on an individual AP while minimizing the interference by dynamically assigning channels. The results from algorithm I (pick rand) and II (pick first) were compared with the results of default settings of having all APs use the same channel. Results showed an improvement by a factor of 4 over the default settings. This results in significantly better network throughput.

6.2. Future Research

The following is the outline for possible directions for future research:

- Fourth generation (4G) is the next revolutionary technology for cellular and mobile networks promising high speeds of 100 Mbps in full-mobility and 1 Gbps in low-mobility for multiple classes of services (voice, video, data, and multimedia broadcast or mobile TV). WLAN systems will complement WCDMA based cellular systems. Further investigation is required to study the impact of call admission control and channel assignment in an integrated wireless network.
- A dynamic channel assignment for IEEE 802.11 systems which improves the network throughput by minimizing the interference among APs was presented. A further extension of this work would be to include dynamic load balancing at the APs taking into consideration traffic conditions present in the network and connectivity issues between mobile stations and APs.

APPENDIX

2G	Second Generation
3G	Third Generation
4G	Fourth Generation
AP	Access Point
CAC	Call Admission Control
CDMA	Code Division Multiple Access
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
DSSS	Direct Sequence Spread Spectrum
FHSS	Frequency Hopping Spread Spectrum
GoS	Grade of Service
IMT-2000	International Mobile Telecommunications-2000
ITU	International Telecommunications Union
QoS	Quality of Service
SF	Spreading Factor
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunications System
WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network

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