

CHAPTER ONE

INTRODUCTION

1-1 Preface

The site acquisition for macro base stations with towers becomes more difficult in dense urban areas. Its costs can get prohibitively expensive particularly in a space limited dense urban region [1]. One solution to overcome this issue is the utilization of heterogeneous network. A heterogeneous network is a network that consists of a collection of different types of low power wireless access nodes each of them having different capabilities, constraints, and operating functionalities distributed across a macro cell. There are various types of such nodes, including microcells, pico cells, relays, remote radio heads, and femtocells [2].

Heterogeneous network is one of the proposed techniques for capacity and coverage enhancements. Such scenario, however, will lead to an inevitable increase in interference levels between different nodes. It could critically affect the performances of the communication which necessitate the development of new algorithms and techniques for increasing interference reduction.

1-2 Problem Statement

Cross-tier interference between femtocells and mobile station at cell-edge of enhanced Node Base station (eNB) in heterogeneous network causes severe interference to the mobile station.

1-3 Proposed Solution

In this thesis, an alternative interference mitigation technique in TDD based system is proposed. It uses modified Macro User equipment with extra antenna for the purpose of adaptive equalization and interference to noise ratio reduction.

1-4 Objectives

The main objectives of this research are:

- 1- Design of the adaptive equalization Interference/Noise canceller in frequency above 20GHz.
- 2- Develop mathematical model for the Complex Least Mean Square (CLMS) adaptive equalization filter.
- 3- Simulate and Performance Evaluation of Complex Least Mean Square (CLMS) Adaptive Equalization Filter.

1-5 Methodology

The methodology implemented in this thesis is assumed that the modified Macro User Equipment instructs its user terminals not to transmit at a certain time interval. At this time interval, the Macro User Equipment only receives the interference came from femtocells and generated $I_{\text{femtocells}}/\text{Noise}$ by receiving antennas. At the same time during this time interval, the Complex Least Mean Square (CLMS) optimizes the coefficient of adaptive equalization filter.

At the end of the time interval, the adaptive equalization filter's coefficients are locked and the modified Macro User Equipments then allow the user terminals to start transmit again. This is done frequently perhaps on frame

basis due to the time varying nature of the channels. This is done at a very fast rate and also seen continuous by the users.

In order to implement adaptive equalization Interference/Noise cancellation scheme, a MATLAB software simulation tool environment is used.

Three channels types Complex Finite Impulse Response (CFIR) (channel fixed over a short time interval), were selected for the simulations to be tested in this thesis. An adjustment of time intervals is also taken into consideration in the adaptive time interval codes. The signal from interfering femtocell could vary from signal such as 16 QAM.

Five different values of step-size (μ) and three different values of interference to noise ratio at main antenna in dB ($(I/N)_{\text{main(dB)}}$) used in order to determine the optimum value for the step-size (μ). Varying interfering femtocells by varying the noise of extra antenna. Three loop runs were made in order to have a fairly good accurate value of the Interference suppression. Also three simulation runs in order to check our system design to mitigate strongest interfering femtocells.

1-6 Thesis Outlines

The structure of this Master Thesis will be written as follows:

Chapter Two is on some basic background of TDD system, fixed wireless technologies, technologies of femtocell and modified MUE, application of femtocells and modified MUE, and interference coordination of femtocells and modified MUE.

Chapter Three is included adaptive filters, adaptive equalization noise cancellation, adaptive equalization interference to noise ratio cancellation,

adaptive algorithms, adaptive equalization filter interference to noise ratio canceller design and simulation environment. Chapter Four is providing results from a metric that adjusted and discussion about the results. Chapter Five is summarized the work done in this thesis and recommendations for future work.

CHAPTER TWO
LITERATURE REVIEW

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LITERATURE REVIEW

2-1 Fixed Wireless Technologies

For fixed broadband wireless system, the digital service demand can be broken down into two basic classes:

1- Internet access for the public and business. The services that is most commonly used on the internet includes, E-mail, web-browsing, file, and image downloading via FTP, streaming audio files for real time audio connection, streaming of files for real time video connections, voice over internet protocol (VOIP) .

2- The second major requirement is the private high-speed rate communication for business, military, and government. This type of service can be required as the traditional domain of point-to-point (PTP) fixed wireless networks. This can includes services like the backhaul link that connects femtocells and modified Macro User Equipments to core network (CN), business wanting to connect to various campuses.

2-1-1 Local Multipoint Distribution Service (LMDS) and

Multipoint Multi-channel Distribution Service (MMDS)

This type of the technology operates in the frequency range between 2.5-50GHz.

The LMDS and MMDS are both often used for leased line, both based on the same technology as a radio relay system. LMDS and MMDS can share channel data between multiple users (i.e Point-To-Multipoint) in

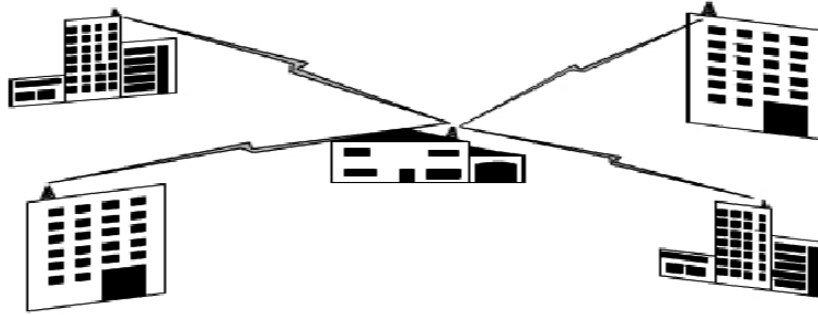
contrast to radio relays, which is usually on Point-To-Point basis. Typically, MMDS operate around 2.69GHz and 3.5GHz with a data rate of between 2-26Mbps while LMDS operates from 28-38GHz with rates between 34-38Mbps. With LMDS offering a higher data rate than MMDS, its range is though shorter than that of MMDS due to latter operating in the lower frequency range. The LMDS has coverage of 4-7Km unlike the MMDS, which has coverage in the order 15-20Km.

Consequently, the high frequency of operation of the LMDS means that Line-Of-Sight (LOS) connection to the users is a must if it is to be satisfactory. The MMDS on the other hand, can still operational in the near-line of sight scenario.

This type of technology is mostly suited to rural areas where building density is quite low and access to fixed broadband infrastructure is limited.

2-1-2 Point-To-Multipoint Network

This its simplest form comprises of a group of receivers, connected (wireless) to central transmitter [3]. It is by far the most popular topology in Fixed Broadband Wireless Access (FBWA) construction. The users located within the area covered by the central transmitter (modified Macro User Equipment) can easily be offered services through wireless connection to the modified Macro User Equipment, as soon as their equipments are installed. A point-To-Multipoint topology is shown in Figure (2-1).



Figure(2-1): Point-To-Multipoint wireless topology

2-1-3 Bandwidth of Fixed Wireless Technologies

The required transmission bandwidth for a system depends upon the over-the-air bit rate, modulation, and amplitude access scheme [4].

The type of service essentially determines the bit rate where for internet 144Kbps-2Mbps may be sufficient while up to 6Mbps is required for quality video transmission

2-2 Time Division Duplex System

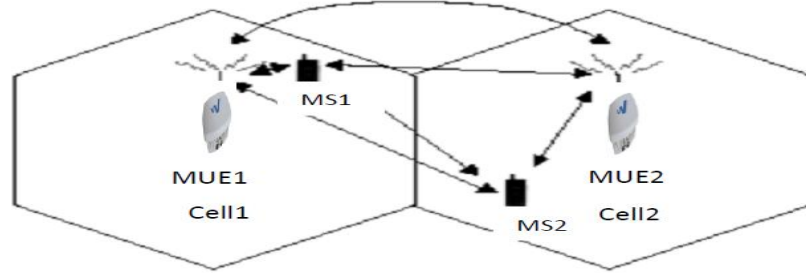
An ideal TDD should possess the following properties [4]:

- High capacity.
- Dynamic asymmetry between the uplink and downlink capacities.
- Modified Macro User Equipment and operator independent without coordination.
- No synchronization requirements between modified Macro User equipments and operators.
- Support for unlicensed operation.

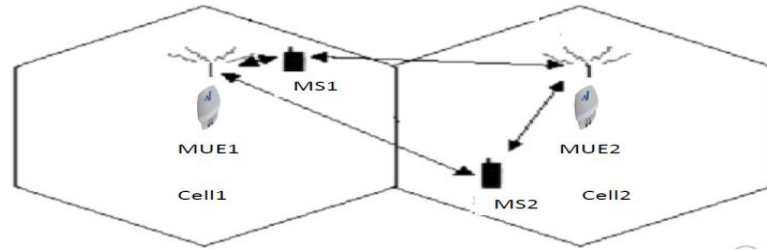
There are some characteristics that make TDD quite different from FDD. These are as follows:

- Utilization of the unpaired band: TDD can be implemented on an unpaired band, whereas in FDD systems, pair band is a must.
- Possible interference between uplink and downlink: signal from the two-way transmission can interfere since with each since they both share the same frequency as shown in Figure(2-2) below; this hardly the case in FDD where the two-way transmission is on different frequency as shown in Figure(2-3) below [5].
- Flexible capacity allocation between uplink and downlink: in a situation where traffic asymmetry exists between the uplink and downlink, capacity can be easily awarded to the desired link (UL/DL) by changing the duplex switching point; this flexibility is non-existence in FDD [6].
- Discontinuous transmission: the UE and modified Macro User Equipment transmission are discontinuous in TDD; this sets requirements on the implementation. Switching between transmission directions requires time, and the switching transients must be controlled. To avoid the overlapping of the uplink and downlink transmissions, a guard band is used in the end of each slot [7].
- Reciprocal channel: since fast fading is frequency dependent and the same frequency is used both in the downlink direction and uplink direction, fading is the same on both links based on the received signal, the TDD transceiver can use the signal, in one direction (UL/DL) to estimate the fading characteristics of the channel. The knowledge of this fast fading well help TDD system in tracking

measures such as power control and adaptive antenna techniques to overcome this effect on the return link (UL/DL) [7].



Figure(2-2): TDD interference path



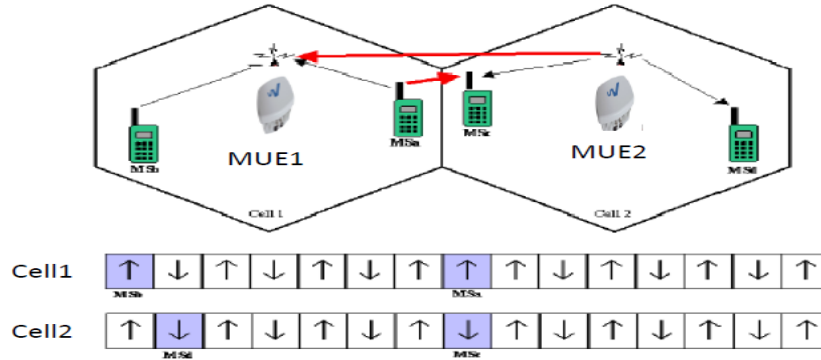
Figure(2-3): FDD interference path

2-2-1 Asymmetry of Time Division Duplex System

According to Figure(2-4), illustrates the potential interference between two adjacent TDD modified Macro User Equipments.

When the time slot in adjacent modified Macro User Equipment are opposed as shown with TS7 in modified MUE1 allocated to the uplink and TS7 in modified MUE2 allocated to the downlink, MS-MS and modified MUE-MUE interference is observed.

MS_a will be causing interference to MUE1 during this time slot. The most severe interference in this scenario will be the MS-MS due to their closeness to one another.



Figure(2-4): Interference caused by different asymmetry.

2-2-2 Synchronization of Time Division Duplex System

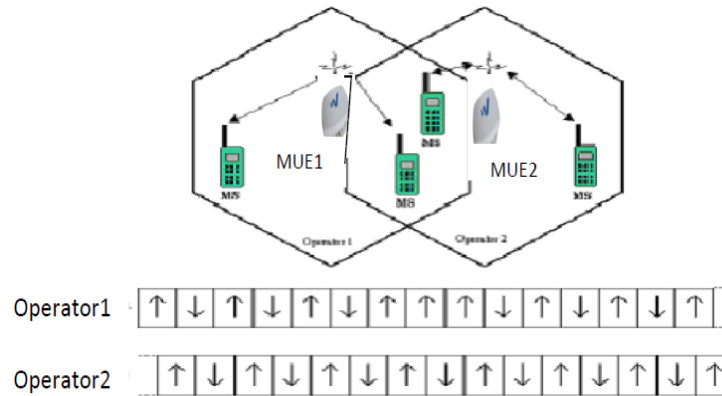
According to TDD frame synchronization is a fair assumption this cannot be assumed in situation where there is more than one operator (Inter-operator).

MS-MS, modified MUE-MUE, and MUE-MS interference can occur within the same time slot that are not aligned as shown in Figure(2-5), in this scenario, MS-MS interference can be easily dealt with unlike MUE-MUE interference which could be very challenging in an inter-operator situation.

The parameter α called synchronization parameter is defined as:

$\alpha = t_{\text{offset}}/t_{\text{slot}}$, where t_{offset} is timing difference between the time slots and t_{slot} is length of the time slot.

Studies have shown that amount of interference is dependent on t_{offset} [17]. It was further proven that small t_{offset} leads to low cell-cell and MS-MS interference and vice-versa [18]. Synchronization is easily achieved within an operators system unlike between different operators system.



Figure(2-5): Unsynchronized cells from different operators.

2-3 The Evolving Small-cell Backhaul Market

Backhaul is still one of the hottest topics in the small cell community, and rightly so. This is an area of intense innovation; driven by many new entrants and an increased presence of established backhaul vendors, where much work is still needed to ensure that backhaul does not become the cost and performance bottleneck in small cell deployments [8].

Vendors have devoted substantial effort to developing new solutions or adding new functionality to existing ones, while keeping equipment and operating costs down.

As a result, small cell backhaul is emerging as a distinct segment within the backhaul market; with products specially designed to meet a set of unique challenges. Small cells operate in continuously changing, cluttered environments over which operators have hardly any control, and which lack the physical and RF stability of cell towers or building roofs as shown in Figure(2-6) below.

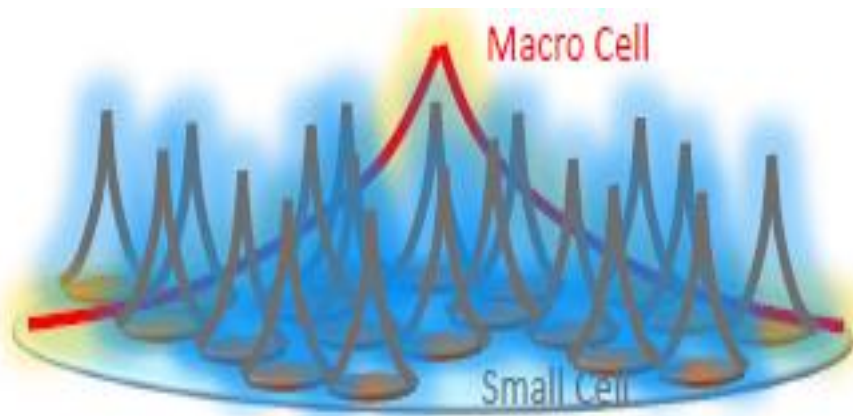


Figure(2-6): Example of 40GHz small cell backhaul

Most of the areas where small cells will be deployed, such as metro zones, are a much more challenging environment than macro cell's towers, where the equipments is securely installed in a protected location.

2-3-1 Equipment Cost and Size

These days support for small cell-broadly taken to be any base stations that are smaller than a macro-cell as shown in Figure(2-7) below.



Figure(2-7): Showing bigger-better-faster small-cells

Ultimately, many of the lessons will come only once small cells are commercially deployed in fully loaded networks. In the mean time, however, it has become clear that small cells are not going to be as cheap or easy to install as initially expected. To get good performance and reliability, to manage interference and to achieve the desired capacity density, operators have to invest in best-of-breed hardware, and plan their network and choose locations carefully. It is neither quick nor cheap. As corollary, large-scale small-cell deployments will take time. This will give mobile operators the opportunity to get better understanding of how they have to evolve the network architecture and traffic management to integrate small cells and it will give vendors time to introduce the solutions that need performance, functionality and cost requirements.

2-4 Femtocell Technology of Cell-edge

New thinking on the deployment and configuration of cellular systems began to address the operational and cost aspects of small cell deployment [9], [10]. These ideas have been applied successfully to residential femtocells where cost issues are amplified.

A femtocell is fundamentally different from the traditional small cells in their need to be more autonomous and self-adaptive. Additionally, the backhaul interface back to the cellular network-which is IP-based and likely supports a lower rate and higher latency than the standard X₂ interface connecting macro and picocells-mandates the use of femtocell gate ways and other new network infrastructure to appropriately route and serve the traffic to and from what will soon be millions of new base stations.

The most viable way to meet the mobile data explosion is to reduce the cell size and there by spatial frequency reuse [11].

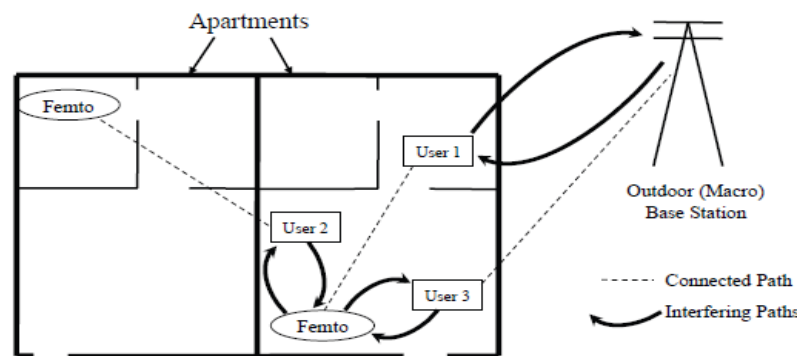
2-4-1 Femtocell Network Modeling of Cell-edge

The addition of femtocells obviously requires an evaluation of traditional cellular model. The level approaches to modeling femtocells in cellular networks, the details can vary quite a bit from research to research. Keep all the channel gains (including interfering channels) and possibly even the various per-user capacities general, without specifying the precise spatial model for the various base stations, e.g. [12], [13]. This can be used in many higher-level formulations, e.g. for game theory [14], power control, and resource allocation.

2-4-2 Interference Coordination of Femtocells

Perhaps the most significant and widely-discussed challenge for femtocell deployments is the possibility of stronger, less predictable, and more varied interference, as shown in Figure(2-8).

An additional complicating factor for the femtocell mobility is the support for features such as Selected IP Traffic Offloaded (SIPTO) [15].



Figure(2-8): Cross-tier interference for the downlink and uplink

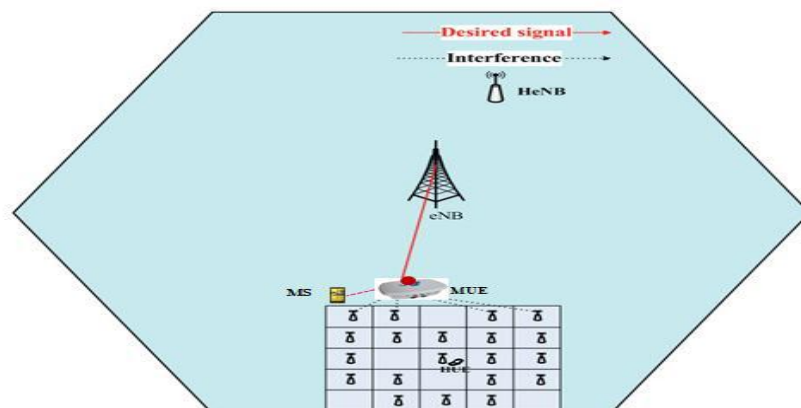
2-5 Modified Macro User Equipment of Entire Cell-edges

The cellular industry has rarely seen more exciting times as the demand for cellular data services and the network topology undergoes the most significant changes since the birth of the cellular, researchers and industry alike will not often be bored.

To get a good performance and reliability, to manage interference and to achieve the desired capacity density, operators to invest in best-of-bread hardware, and plan their network and choose locations care.

Perhaps more important than the need to provide cellular coverage infill for residential use, the mobile data explosive at the entire of the cell-edge, has mandated the need for a new cellular architecture with at least an order of magnitude more capacity [16]. The most viable way to meet this demand is to reduce the cell size unless plentiful frequencies in the tens of GHz can be harnessed for mobile broadband, which is extremely challenging.

In parallel to the escalating data demands, I suggest Low-Cost Modified Macro User Equipment as shown in Figure(2-9).



Figure(2-9): Showing a Modified Macro User Equipment at the entire of cell-edge.

One important classification for Modified Macro User Equipment that strongly affects the model is the type access control. They are Closed Subscriber Group (CSG), Open Subscriber Group (OSG). In any case, the type of access control is one of the key features in any cellular model.

An additional complicating factor for Modified Macro User Equipment mobility is the support for feature such as SIPTO. Our proposed cell are generally remotely configured and managed from operators 'core network.

Our cellular system consists of three types of nodes as shown in Table2-1 below.

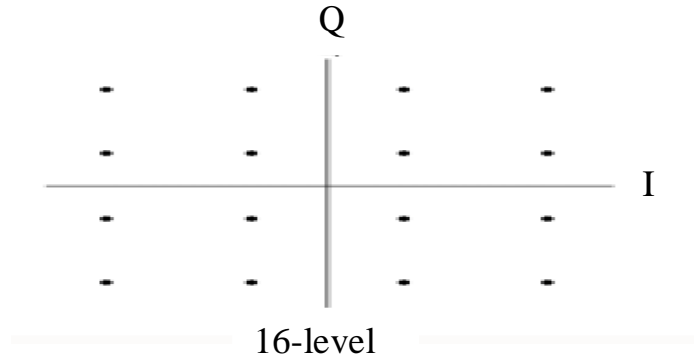
Table(2-1): Specification of different nodes in HeNet

| Types of nodes | Transmit power | Cell radius |
|-------------------------------|----------------|---------------------|
| Macrocell | 46dB | $\leq 0.5\text{Km}$ |
| Femtocells | 20dB | 10m |
| Modified Macro User Equipment | <13dB | Few m |

2-6 Quadrature Amplitude Modulations (QAM)

Since frequency spectrum is expensive, the aim of any system operator is to transmit as much as possible information bit per bandwidth. The choice in any system is based on how efficient the available bandwidth will be used. For data rate to be increased, symbols that convey more information bits with more signal constellation states are required [19]. This has lead to the popularity of the M-QAM modulation schemes where M can vary from 4 to 256 leading between 2-8bits/symbol. This means more information bits can be transmitted per Hz.

QAM is achieved through the variation of the signal constellation in both amplitude and phase as shown in Figure(2-10). Not only are the family of QAM spectral efficient, but also, comparing it to PSK family, they require lesser energy (SINR) for acceptable performance. The only drawback of QAM is the strict linearity condition placed on the amplifier used because information is based both in amplitude and phase [20].



Figure(2-10): 16-QAM signal constellation on I and Q axis.

2-7 Related Works

The body of work dealing with interference mitigation is diverse and evolving everyday along with new requirements and applications for wireless technologies. The motivation to develop specific adaptive equalization filter in this area is that the traditional approaches for general adaptive filters are not suitable in such a highly dynamic environment.

The author in [21], proposed LMS adaptive channel estimation in the rake-equalizer receiver structure is to make MMSE equalized UWB rake-equalizer receiver using in case of inter-symbol interference (ISI), multiple-access interference (MAI), and multiple-users interference (MUI) are influencing the performance of the wireless systems. This approach adjusting the receiver taps weights using Least Mean Square, Normalized

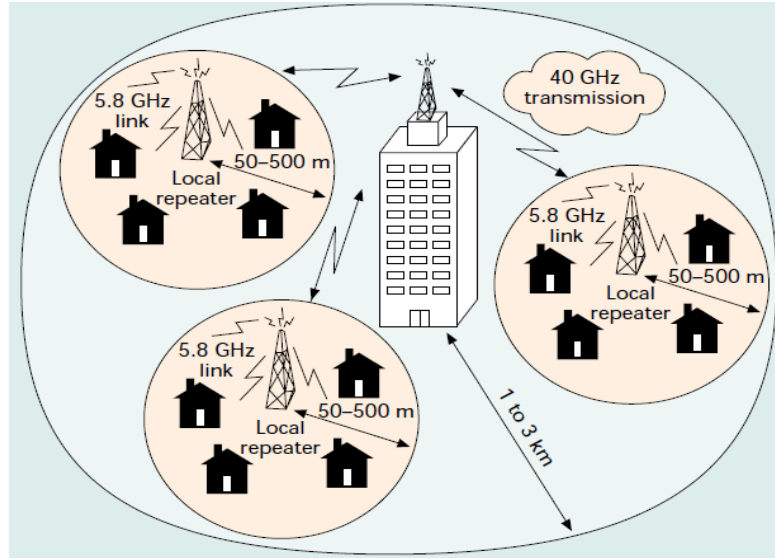
LMS, and affine projection algorithms (APA) (well known as Normalized Least Mean Square adaptive equalization filtering algorithm) to support the weak signals and mitigate the interferences. The goal of LMS adaptive channel estimation in the rake-equalizer receiver is to reduce the interferences and noise.

The author on [22], proposed adaptive filter loop-back interference suppression for OFDM signals. The goal of this to make loop-back interference suppression more effective use in case of close-loop system and hence it is important not only to suppress the interference but also to stabilize the system. They have proposed adaptive filter design for loop-back interference cancellation in amplify-forward relay stations.

The author on [23], proposed Least Mean Square adaptive filter for noise cancellation is to make LMS adaptive filter more affective in case of noise and distortions. The goal of LMS adaptive filter is to suppress the noise without changing the signal. With the variation in step-size as in noise are reduced but steady state of error increases.

Devices and protocols operating in the unlicensed frequency bands have become popular over the years, the Unlicensed National Information Infrastructure (UNII) band around 5.2GHz (US) exemplify the growth and consequent challenges.

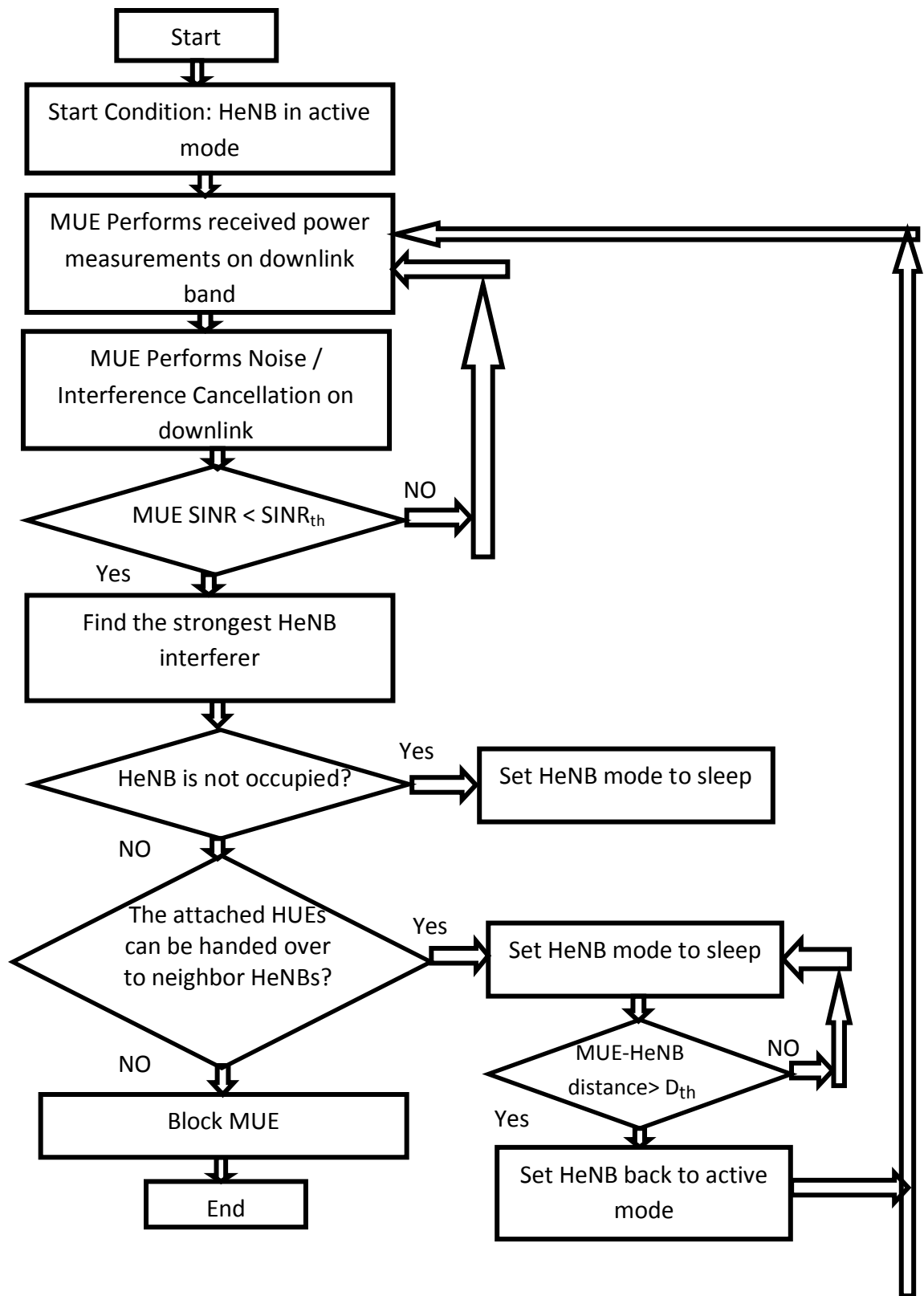
The impact of wideband interference on the performance of the two-layer LMDS includes LOS macro cells and lower frequency micro cells have been analyzed in [24]. Figure(2-11) shows two layer LMDS architectures include LOS macro cells and lower frequency micro cells.



Figure(2-11): two layer Local Multipoint Distribution Service architectures

Performance of the time domain interference cancellation for cognitive radios and future wireless systems to enhance dynamic range of the front end is presented in [25].

The impact of interference on the performance of Macro User Equipment and Home User Equipment, in terms of signal to interference plus noise ratio and the number of blocked MUEs due to the introduction of the sleep mode for femtocell base stations. In this model they adopt 3GPP LTE-A path loss models for urban deployment [26]. Figure(2-12) shows the operational flow charts of the sleep mode activation procedure for HeNBs. If the SINR of the MUE decreased under a predefined threshold (consider as 6dB here), then the MUE must detect the strongest HeNB interfere; the transition of this HeNB to sleep mode is conditional by the occupation of the cell.



Figure(2-12): Sleep mode algorithm flow chart.

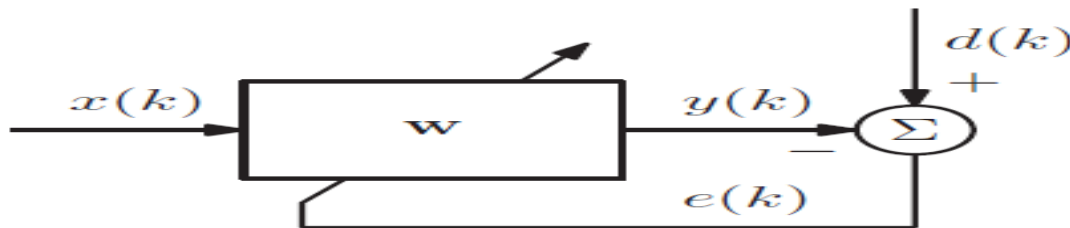
CHAPTER THREE
ADAPTIVE EQUALIZATION FILTER FOR
INTERFERENCE CANCELLATION

CHAPTER THREE

ADAPTIVE EQUALIZATION FILTER FOR INTERFERENCE CANCELLATION

3-1 Adaptive Filters

An adaptive filter may be understood as a self-modifying digital filter that adjusts its coefficients in order to minimize an error function. This error function $e(n)$, also referred to as the cost function, is distance measurement between the reference or desired signal $d(k)$ and the output of the adaptive filter. Figure(3-1) shows the basic block diagram of an adaptive filter [27], [28], and [29].



Figure(3-1): Basic block diagram of an adaptive filter.

There are two solutions to approach the problem of tracking the filter w_n [wiener filter]:

1. One has a long training signal for $d(n)$ and then adjust w_n to continuously minimize the power of $e(n)$. This is the adaptive filtering approach.

2. By splitting time into very short time interval blocks where data is approximately stationary, the wiener solution can be recomputed for every block. This approach is called block filtering.

An adaptive filter should have the following properties:

- 1- In stationary environment, the adaptive filter should produce a sequence of correction Δw_n in such way that the w_n converge to the solution to the wiener-hopf equation, as show in Equation(3-1).

$$\lim_{n \rightarrow \infty} w_n = R_x^{-1} r_{dx} \quad (3-1)$$

The autocorrelation function of the filter input R_x , and the cross-correlation between the filter input and the desired response r_{dx} .

These equations called Wiener-Hopf equations.

- 2- The knowledge of the signal statistics R_x and r_{dx} are not necessary to compute Δw_n . The statistics estimation is built in to the adaptive filter.
- 3- For non-stationary signals, the filter should be able to adapt the changing statistics and track the solutions as it is evolves in time.

From Figure(3-1), it is apparent that the error signal $e(n)$ is very important in the implement of the adaptive filter. It is the error signal $e(n)$ that is used to update the adaptive algorithm since it is $e(n)$ that allows the filter to measure its performance and determine how the filter coefficients should be modified, without $e(n)$ the filter will not be able to adapt.

Two restrictions have so far been placed on the filter:

1. The filter is linear, which makes the mathematical analysis easy to handle.

2. The filter operates in discrete time, which makes it possible for the filter to be implemented using digital hardware/software.

We will confine our attention to the use FIR filter; we do so for the following reason:

- An FIR is inherently stable, because its structure involves the use of forward paths only.
- Less demanding in computational requirements.

We may consider optimizing the filter design by minimizing a cost function, or index of performance, selected from the following short list of possibilities:

1. Mean Square value of the estimate error.
2. Expectation of the absolute value of the estimation error.
3. Expectation of third or higher powers of the absolutely value of the estimation error.

Option one has a clear advantage over the other two, because its leads to tractable mathematics.

Two entirely different approaches to overcome statistical optimization problem:

1. Principle of orthogonality, suppose now we want to find a linear estimate of $d(n)$ based on the L -most recent samples of $x(n)$, as shown in Equation(3-2).

$$y(n) = w^T X(n) = \sum_{k=0}^{L-1} w_k x(n-k), \quad w, X(n) \in R^L \text{ and } n = 0, 1, 2, \dots \quad (3-2)$$

The introduction of a particular criterion to quantify how well $d(n)$ is estimated by $y(n)$ would influence how the coefficients w_k will be computed. We propose to use the Mean Square Error (MSE), which is defined by

$$J_{MSE}(n) = E[|e(n)|^2] = E[|d(n) - y(n)|^2] \quad (3-3)$$

Where $E[.]$ is the expectation operator and $e(n)$ is the estimation error. Then, the estimation problem can be seen as finding the vector w that minimizes the cost function $J_{MSE}(w)$.

2. The error-performance surface that describes the second-order dependence of the cost function on the filter coefficients.

3-2 Adaptive Equalization Noise Cancellation

The most important method of computing desired signal corrupted by additive noise is the adaptive filter which will goal to subtract the noise only.

Least Mean Square (LMS) filter is the simplest one as decrease the instantaneous square error. Thus, the objective of operating under changing conditions and readjusts itself continuously to minimize the error is achieved by the LMS algorithm.

There are important parameters related to signal processing including step-size, and proper use of random noise signal, proper use of such parameters helps in noise cancellation.

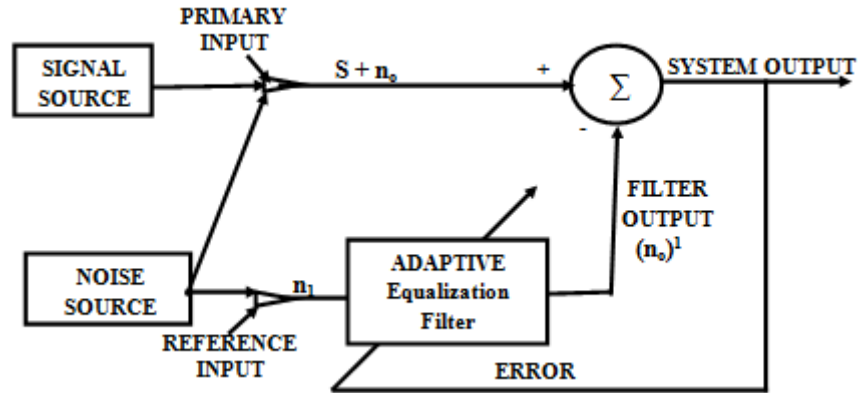
Noise cancellation is a different of traditional filter which is advantageous many other applications [23].

Noise cancellation, ranging of equalization in digital communication for extract out signals corrupted by additive noise or unwanted signals. From Figure(3-2) shows adaptive equalization noise canceller given below the system comprised of primary as well as reference input. Input to the primary one is signal source and indirectly noise source as well, input to the reference one is noise source.

Adjusting the filter to minimize the total output power, thus tremendous to causing the output z to achieve a best least square estimate of the signal s for given structure and adjustability of the adaptive filter and for the given reference input.

The weight of an adaptive equalization noise canceller is given in Equation(3-4) [23].

$$w_{n+1} = w_n + \mu (2e(n))^* x(n) \quad (3-4)$$



Figure(3-2): Adaptive equalization noise canceller [23].

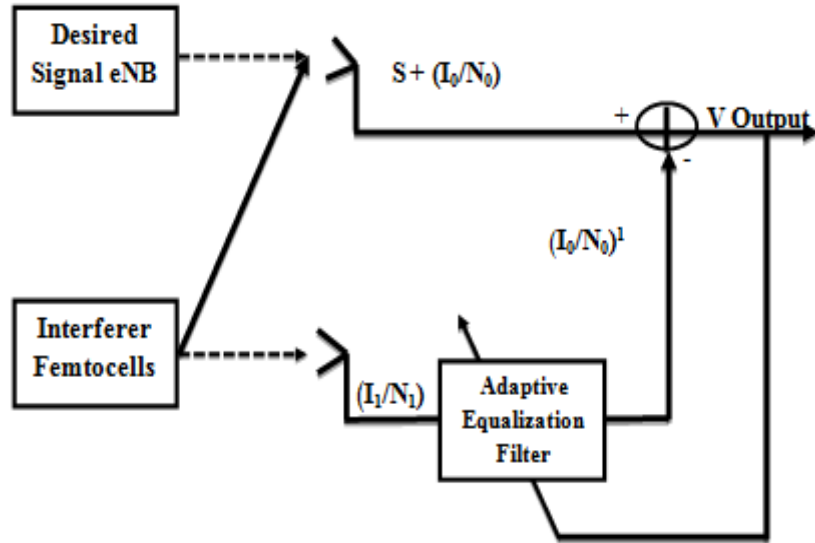
3-3 Adaptive Equalization Filter

Non-recursive adaptive filters; ranging of equalization in digital communication interference to noise suppressing, are pretty popular among

design engineers as show in Figure(3-3) adaptive equalization I/N cancellation scheme. One of the main reasons for this is that by ensuring that the filter coefficients are bonded, stability of the filter is easily controlled. Moreover, there are simple and efficient algorithms for adjusting the filter coefficients [30], [31].

A non-recursive filter for adaptive equalization for estimating a desired signal $(I_o(n)/N_o(n))^l$ from a related signal $(I_i(n)/I_i(n))$, where $i = 1, 2$, and 3 .

Assume the TDD frame is of duration 1ms, B.W is 100MHz, the roll-off factor is 0.3. The optimization period is 1%, 3%, and 5%; will be calculated to give how many samples is needed. The symbols rate R_s equal 76.92MHz, the total number of samples in a TDD frame equal 25000 sample.



Figure(3-3): Adaptive Equalization Interference/Noise Cancellation Scheme

The criteria in having a good interference suppression is the I/N equal 6, 3, 0dB.

The variance of the filter coefficient w_n around its mean is a function of step-size. Small step-size results in large accuracy of estimate but slower speed of convergence.

The interference suppression is defined as:

$$(I/N) \text{ suppression} = 10 \log [E((I-N)^2)/E(e(n)^2)] \quad (3-5)$$

The output V of figure(3.3) is given by:

$$V(t) = S(t) + I_o(t)/N_o(t) - (I_o(t)/N_o(t))^l \quad (3-6)$$

$$\text{Where } (I_o(t)/N_o(t))^l = \sum_{k=1}^K w(k) I_1(t-k)/N_1(t-k) \quad (3-7)$$

The output of adaptive equalization filter is given in Equation(3-8).

$$(I_o(n)/N_o(n))^l = \sum_{k=0}^P w_n(k) \left(\frac{I_i(n-k)}{N_i(n-k)} \right) = w_n^T (I_i(n)/N_i(n)) \quad (3-8)$$

Where $(I_i(n)/N_i(n))$ and $(I_o(n)/N_o(n))$ are assumed to be non-stationary random process and the goal is to find the coefficient vector w_n at time n which minimizes the mean-square error ($J_{MSE}(n)$), as shown in Equation(3-9).

$$J_{MSE}(n) = E\{|e(n)|^2\} \quad (3-9)$$

$$\text{Where, } e(n) = (I_o(n)/N_o(n)) - (I_o(n)/N_o(n))^l \quad (3-10)$$

Since, $(I_o(n)/N_o(n))^l = w_n^T (I_i(n)/N_i(n))$, therefore Equation(3-9) can be written as follows:

$$e(n) = (I_o(n)/N_o(n)) - w_n^T (I_i(n)/N_i(n)) \quad (3-11)$$

By the derivation of $J_{MS}(n)$ with respect to $w_n^*(k)$ and setting the result equals to zero as shown in equation(3-12), the coefficient of w_n , which minimizes the mean-square error $J_{MS}(n)$, is found. The result is thus,

$$E\{e(n)(I_i^*(n-k)/N_i^*(n-k))\} = 0; \text{ for } k = 0, 1, \dots, P \quad (3-12)$$

Substituting (3-7) in (3-11) and then applied to equation(3-12), we have

$$E\{[(I_o(n)/N_o(n)) - \sum_{l=0}^P w_n(l) \left(\frac{I_i(n-l)}{N_i(n-l)}\right)] \left(\frac{I_i^*(n-k)}{N_i^*(n-k)}\right)\} = 0 \quad (3-13)$$

Where, for $k = 0, 1, \dots, P$

Re-arranging this gives,

$$\sum_{l=0}^P w_n(l) E\left\{\left(\frac{I_i(n-l)}{N_i(n-l)}\right) \left(\frac{I_i^*(n-k)}{N_i^*(n-k)}\right)\right\} = E\left\{\left(\frac{I_o(n)}{N_o(n)}\right) \left(\frac{I_i^*(n-k)}{N_i^*(n-k)}\right)\right\}; \quad (3-14)$$

Where, for $k = 0, 1 \dots P$

Equation(3-14) is a set of $1 + P$ linear equation with $P + 1$ unknown w_n unlike the solution of the wiener-Hopf equation, w_n is dependent on time n since; $(I_i(n)/N_i(n))$ and the desired $(I_o(n)/N_o(n))$ are not jointly Wide Sense Stationary (WSS).

Equation 3-14 can be written in vector form as show in Equation(3-15),

$$R_y(n) w_n = R_{sy}(n) \quad (3-15)$$

Where s is $(I_o(n)/N_o(n))$, and y is $(I_i(n)/N_i(n))$.

Also R_y is a $(P + 1) \times (P + 1)$ Hermitian matrix of auto-correlation and R_{sy} is a vector of cross-correlation between $(I_o(n)/N_o(n))$ and $(I_i(n)/N_i(n))$.

3-4 Adaptive Algorithms

The time varying statistics in (3-15) are unknown but can be estimated. The adaptive algorithms aim at estimating and tracking the solution of w_n given the observations $\{I_i(n)/N_i(n)\}$, for $i = 1, 2$, and 3 at extra antenna, and reference signal of $\{I_o(n)/N_o(n)\}$ at main antenna.

There are two main approaches to this problem:

1. Steepest descent based (also called gradient search) algorithm
2. Recursive least squares (RLS) algorithm.

In the following sub-sections, we will look more deeply into the first option which is what is chosen as the algorithm in this thesis.

3-4-1 Steepest Descent Adaptive Filter

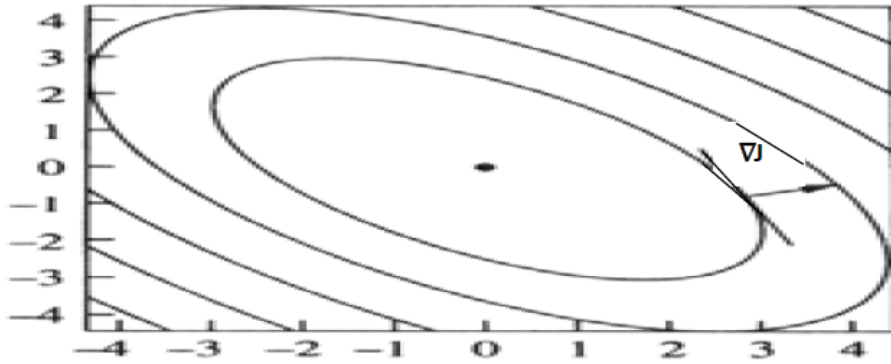
The vector w_n minimizing the quadratic error function can be found by setting its derivative with respect to filter coefficients w_n to zero. An alternative approach is to search for the solution using the iterative method of steepest descent [30], [31].

Let w_n be an estimate of the vector that minimizes the MS error $J_{MS}(n)$ at time n . At time $n+1$, a new estimate is formed by adding a correction to w_n that is designed to bring w_n closer to the desired solution. The correction involves taking a step of size μ in the direction of maximum descent down the quadratic error surface.

However, since the gradient vector points in the direction of the steepest ascent, the direction of steepest descent points in the negative gradient direction. Figure(3-4) shows that the gradient is orthogonal to the line.

Therefore, the update equation for w_n is given in Equation(3-16).

$$W_{n+1} = W_n - \mu \nabla J_{MS}(n) \quad (3-16)$$



Figure(3-4): Shows that the gradient is orthogonal to the line

For very small values of μ , the correction to \mathbf{w}_n is small and the movement down the quadratic surface is slow and, as μ increases, the rate of descent increases.

However, an upper limit exists on how large the step size could be. For values of μ exceeding this limit, the trajectory of \mathbf{w}_n becomes unstable and unbounded.

The steepest descent algorithm may be summarized as follows:

1. Initialize the steepest descent algorithm with an initial estimate \mathbf{w}_0 of the optimum weight vector \mathbf{w} .
2. Evaluate the gradient of $J_{MS}(n)$ at the current estimate of \mathbf{w} .
3. Update the estimate at time n by adding a correction in the negative gradient direction as follows:

$$\mathbf{w}_{n+1} = \mathbf{w}_n - \mu \nabla J_{MS}(n)$$

4. Go back to step 2 and repeat the process.

Assuming that w is complex, the gradient is the derivative of $E\{|e(n)|^2\}$ with respect to w^* , the result shown in equation(3-17).

$$\text{Then with } \nabla J_{MS}(n) = \nabla E\{|e(n)|^2\} = E\{\nabla |e(n)|^2\} = E\{e(n) \nabla e^*(n)\} \quad (3-17)$$

$$\text{And } \nabla e^*(n) = -\nabla \mathbf{x}_n^* \quad (3-18)$$

It follows that

$$\nabla J_{MS}(n) = -E\{e(n) \nabla \mathbf{x}_n^*\} \quad (3-19)$$

Therefore, with a step size μ , the steep descent algorithm becomes

$$\mathbf{w}_{n+1} = \mathbf{w}_n + \mu \nabla J_{MS}(n) \quad (3-20)$$

The main problem with the steepest descent algorithm is that: $E\{e(n) \nabla \mathbf{x}_n^*\}$ is unknown!.

3-4-2 The Least Mean Square (LMS) algorithm [30], [31]

To compute the gradient vector, it is necessary to know $E\{e(n) \nabla (I_i^*(n)/N_i^*(n))\}$, for $i = 1, 2$, and 3 . For the majority of the applications the exact statistics is unknown and must be estimated from the data, such as shown in equation(21).

$$E^{\wedge}\{e(n) \nabla (I_i^*(n)/N_i^*(n))\} = \frac{1}{L} \sum_{l=0}^{L-1} e(n-l) \nabla (I_i^*(n-l)/N_i^*(n-l)) \quad (3-21)$$

Incorporating the correlation estimate into the steepest descent method yields:

$$\mathbf{w}_{n+1} = \mathbf{w}_n + \frac{\mu}{L} \sum_{l=0}^{L-1} e(n-l) \nabla (I_i^*(n-l)/N_i^*(n-l)) \quad (3-22)$$

In a special case, a one-point sample mean ($L = 1$) is used

$$E^{\wedge}\{e(n) \nabla \left(\frac{I_i^*(n)}{N_i^*(n)}\right)\} = e(n) \nabla (I_i^*(n)/N_i^*(n)) \quad (3-23)$$

And the filter-update equation becomes

$$\mathbf{w}_{n+1} = \mathbf{w}_n + \mu e(n) (\nabla I_i^*(n)/N_i^*(n)) \quad (3-24)$$

Which is known as the LMS algorithm?

The simplicity of the algorithm comes from the fact that the update of the k^{th} filter coefficient only requires one multiplication and one addition, as given in Equation(2-25).

$$\mathbf{w}_{n+1, k} = \mathbf{w}_{n, k} + \mu e(n-k) (\nabla I_i^*(n-k)/N_i^*(n-k)) \quad (3-25)$$

An LMS adaptive equalization filter with $P + 1$ coefficient requires $P + 1$ multiplication and $P + 1$ addition to update the filter coefficients. One addition is needed to form an error $e(n)$ and one multiplication is required to form the product $\mu e(n)$. Finally, $P + 1$ multiplications and P additions are needed to calculate the output $(I_o(n)/N_o(n))^I$. Therefore, a total of $2P + 3$ multiplications and $2P + 2$ additions per output sample are required.

A summary of an LMS algorithm is given as follows:

1. Parameters: $P = \text{Filter Order}$

$$\mu = \text{Step Size}$$

2. Initialization: $w_o = 0$

3. Computation: For $n=0, 1, 2, \dots$

$$(a) (I_o(n)/N_o(n))^I = w^T(n)(I_i(n)/N_i(n))$$

$$(b) e(n) = (I_o(n)/N_o(n)) - (I_o(n)/N_o(n))^I$$

$$(c) w_{n+1} = w_n + \mu e(n) (\nabla I_i^*(n)/N_i^*(n))$$

The algorithm is derived under the assumption of stationary but can be used in non-stationary environment as a tracking method.

3-4-3 Complex Least Mean Square Algorithm

The complex LMS algorithm as the same suggest is a conjugate of the real LMS presented in [32]. A brief introduction to the algorithm will be discussed below.

Extended the LMS adaptive equalization approach to complex inputs obtained in equation (3-24).

The complex algorithm is defined as:

$$w_{n+1}(k) = w_n(k) + \mu e(n)^* \nabla (I_i(n-k)/N_i(n-k)) \quad (3-26),$$

and,

$$e(n)^* = (I_o(n)/N_o(n)) - (I_o^*(n)/N_o^*(n))^* = (I_o(n)/N_o(n)) - w_n^H \left(\frac{I_i(n)}{N_i(n)} \right)$$

All the quantities contented are completely same to the one in the real LMS algorithm with the only difference being that they are complex values.

I suggest the initialization:

$$w_o = |(2\pi f_{ae}) - (2\pi f)|^2 / (2\pi f_{ae})^2 + (2\pi f)^2 \quad (3-27)$$

where, f_{ae} is a given adaptive equalization frequency, and f is an excitation interference frequency.

Assume a known input magnitude of adaptive equalization filter denoted as A, we can compute the magnitude of the output signal B as follows:

$$B = A \frac{|w_{n+1} - w_n|^2}{w_{n+1}^2 + w_n^2} \quad (3-28)$$

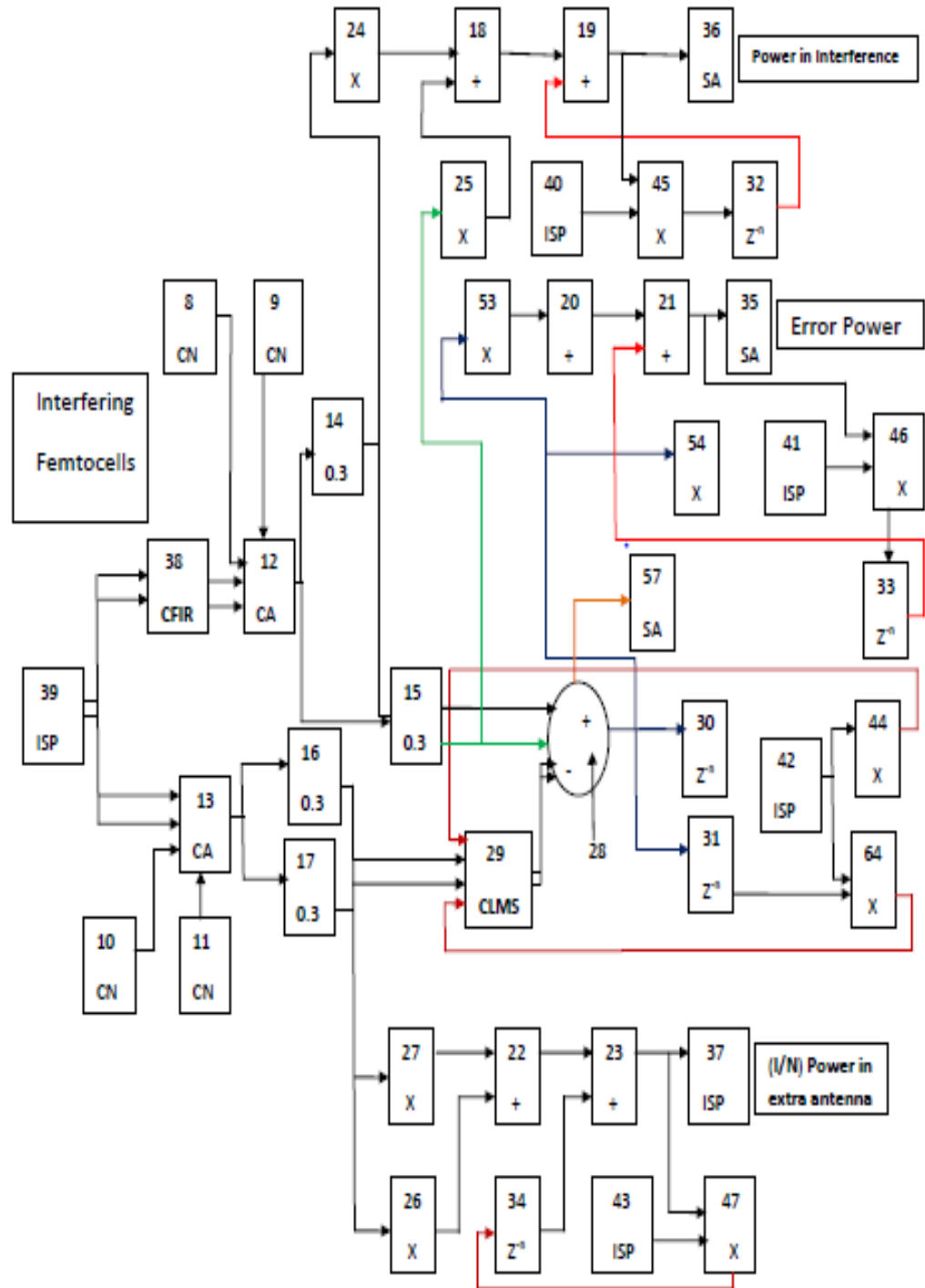
The Complex LMS algorithm converges in slightly less than as many types as the real LMS algorithm but requires twice as many arithmetic operations per step.

3-5 Adaptive Equalization Filter I/N Canceller Design and Simulations Parameters

In this thesis MATLAB is used as simulation tool of proposed design of adaptive equalization filter interference/noise canceller with other parameters show below.

3-5-1 Adaptive Equalization Filter I/N Canceller Design

The design of the adaptive equalization Interference/Noise canceller platform is shown Figure(3-5). A brief discussion of the design will be given below.



Figure(3-5): Adaptive equalization filter I/N canceller design

Modules 8 and 9: Generates the complex additive Gaussian noise at the input to the main antenna where module 8 generates the real part and module 9 the imaginary part.

Modules 10 and 11: Same as in modules 8 and 9 but this time around, at the extra antenna.

Modules 12 and 13: Complex adder, complex divider, multiplier, and sink analysis.

Modules 14 and 15: Represents the square root raised cosine filter at the main antenna with module 14 being the filter through which the real signal passes and module 15 for the imaginary signal. The roll-off factor is also 0.3.

Modules 16 and 17: same as in module 14 and 15 but in the extra antenna.

Modules 18, 19, 20, 21, 22, and 23: Represents real adder.

Modules 24 and 25: Generates the power exponent. The exponent used here is 2. This generates the square of both the real signal (module 24) and imaginary signal (module 25) for the purpose of finding the power in the Interference/Noise ratio in the main antenna.

Module 26 and 27: Same as in modules 24 and 25 but in the extra antenna.

Modules 28: The complex sub-tractor. It gives the linear equation; $e(n) = (I_o(n)/N_o(n)) - (I_o(n)/N_o(n))^*$ where $e(n)$, the output of this module, is the estimated error, $(I_o(n)/N_o(n))$ is the desired signal and $(I_o(n)/N_o(n))^*$ is the estimated $(I_o(n)/N_o(n))$.

Unit 39: generates the real and imaginary of interfering femtocells. Inside this unit contains the square-root raised cosine filters before

transmission from the interfering femtocells. A roll-off factor of 0.3 was used in both filters.

Module 40: Block containing the inverse of the square pulse to the accumulator of the power in the interfering signal in the main antenna. The square pulse is used to set the feedback error value into the CLMS to zero. The width of the square pulse is the optimization period at which the CLMS filter coefficient is set. The period depends on the size of the optimization used and in thesis, 1%, 3%, and 5% were employed.

Module 41: Block generating the inverse of the square pulse to the accumulator of the power in the error signal in the main antenna.

Module 42: Block generating the square pulse to the delay operator of real and imaginary error. The square pulse is optimization period at which the CLMS filter coefficients is set.

Module 43: Block generating the inverse of the square pulse to the accumulator of the power in the interfering signal of the extra antenna.

Module 44, 45, 46, and 47: Multipliers.

3-5-2 Simulation Environment and Channels

There are various parameters related to simulation modeling including proper selecting the channel to be used, selecting the number of samples to be used, and values of step-size to be used. This as follows:

1. Channel to be used as follows:

- Channel one is a channel where we assumed there is a dominant path between the interference femtocells and our modified Macro User Equipment as shown in table(3-1) below.

Table(3-1): Relative power profile in the channel one

| Tap No. | Tap delay in μs | Power in each tap in dB |
|---------|----------------------------|-------------------------|
| 0 | 0.5 | 31.4 |
| 1 | 1 | -25.7 |
| 2 | 1.5 | -55.7 |
| 3 | 2 | -44.3 |
| 4 | 2.5 | -62.5 |
| 5 | 3 | -55.7 |
| 6 | 3.5 | -62.5 |
| 7 | 4 | -74.3 |
| 8 | 4.5 | -85.7 |
| 9 | 5 | -44.3 |

- Channel two represents a channel where the weight decreases linearly. This could be seen as a channel with each reflected signal being linearly weaker the longer the propagation distance they cover before reaching our modified Macro User Equipment of interest show table(3-2) below.

Table(3-2): Relative power profile in the channel two

| Tap No. | Tap delay in μs | Power in each tap in dB |
|---------|----------------------------|-------------------------|
| 0 | 0.5 | 5.8 |
| 1 | 1 | 3.3 |
| 2 | 1.5 | 0.4 |
| 3 | 2 | -0.8 |
| 4 | 2.5 | -5.8 |
| 5 | 3 | -8.75 |
| 6 | 3.5 | -15 |
| 7 | 4 | -25 |
| 8 | 4.5 | -35 |
| 9 | 5 | -77.5 |

- Channel three represents a channel with four main dominant reflect interference, show table(3-3) below.

Table(3-3): Relative power profile in the channel three

| Tap No. | Tap delay in μs | Power in each tap in dB |
|---------|----------------------------|-------------------------|
| 0 | 0.5 | 28.6 |
| 1 | 1 | 28.6 |
| 2 | 1.5 | -37.5 |
| 3 | 2 | -45.7 |
| 4 | 2.5 | -67.5 |
| 5 | 3 | -57.5 |
| 6 | 3.5 | 28.6 |
| 7 | 4 | 28.6 |
| 8 | 4.5 | -85.7 |
| 9 | 5 | -45.7 |

2. Selecting the number of samples to be used: one of the critical values that must be taken into consideration is number of samples. This so because if it uses too long in optimizing the coefficients, not only is precious resource wasted during this time but also the services provided to the user will not be optimal (continuous). TDD frame is of duration of 1ms with bandwidth (BW) of 100MHz, and the roll-off factor of the filter is 0.3. For the purpose of working, the optimization period for the three scenarios will be calculated to give how many samples is needed. Given that $BW = R_s (1 + \alpha)$, where R_s is the symbol-rate, $R_s = 76.92\text{MHz}$. Converting a TDD frame into $f_{\text{TDD}} = 1 \text{ KHz}$. Number of symbols in a TDD frame =

$R_s/f_{\text{TDD}} = 76.92\text{K}$ symbol. We use sampling rate 4Hz in our simulation:

Number of sample in a TDD frame = $76.92\text{K symbol} \times 4 = 307680$ sample. Number of samples for optimization period: 1% optimization period = $307680 \times 0.01 = 3076.8$ samples, 3% = 9230.4 samples, 5% = 15384 samples. It represents when optimization process is active, this process is repeated over every frame being received at the Proposed Macro User Equipment or Broad-band Mobile. A total of 25000 samples will be used in the coming simulation. The interference/Noise suppression after that is defined as:

$(I/N)_{\text{suppression}} = 10 \log [E ((I_i(n) - N_i(n))^2)/E (e(n)^2)]$, Where $E[\]$ is the expectation operator, $i = 1, 2$, and 3 .

3. Values of the step-size to be used: five different values of μ is used, these are 0.0002, 0.0006, 0.0008, 0.002, and 0.02

CHAPTER FOUR

RESULTS AND DISCUSSION

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RESULTS AND DISCUSSION

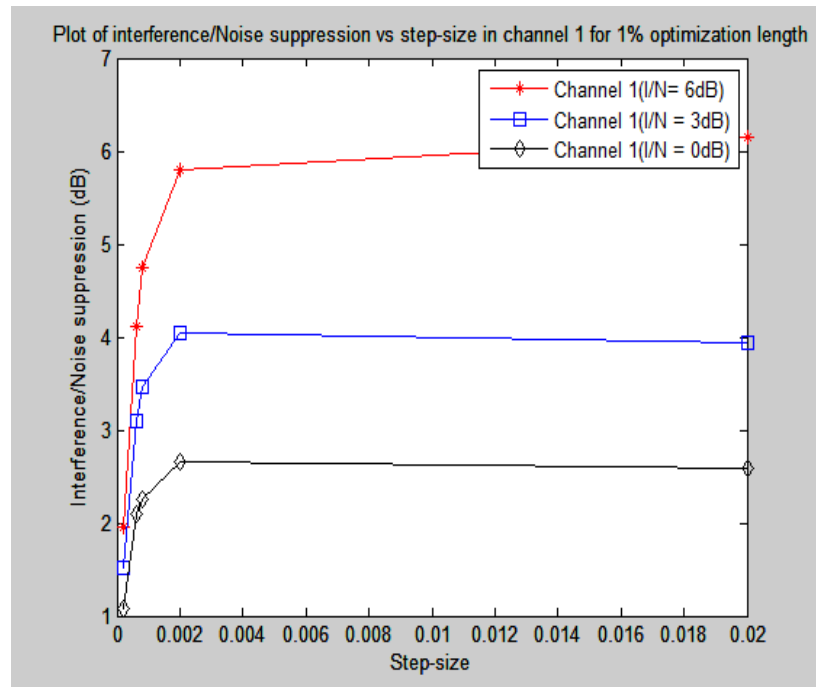
4-1 Selecting the Step-Size

Five different values of step-size (μ) and three different values of $(I/N)_{\text{main(dB)}}$ used in order to determine the optimum value for the step-size μ . The simulation implemented using MATLAB code (see appendix A) and related simulation results assist in building the theoretical foundation for setting performance limits on the implemented adaptive equalization filter interference-to-noise ratio canceller.

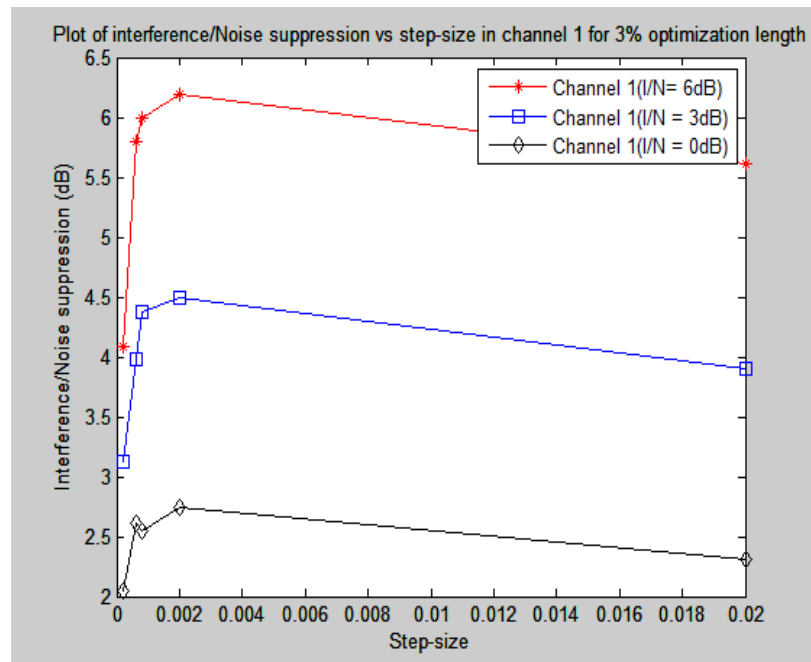
The $(I/N)_{\text{main(dB)}}$ values is 0, 3, and 6dB, and $(I/N)_{\text{extra(dB)}}$ = value is fixed to 15 dB throughout the whole simulation. This represents a noise in the extra antenna path of 0.0822V standard deviation. The values of the $(I/N)_{\text{main(dB)}}$ were generating by setting the standard deviation of the noise in the main antenna path to 1.180V, 1.685V, and 2.349V in channel one, 1.065V, 1.525V, and 2.149V in channel two, and 2.485V, 3.565V, 4.975V in channel three respectively.

Three loop runs were made in order to have a fairly good accurate value of the Interference/Noise suppression.

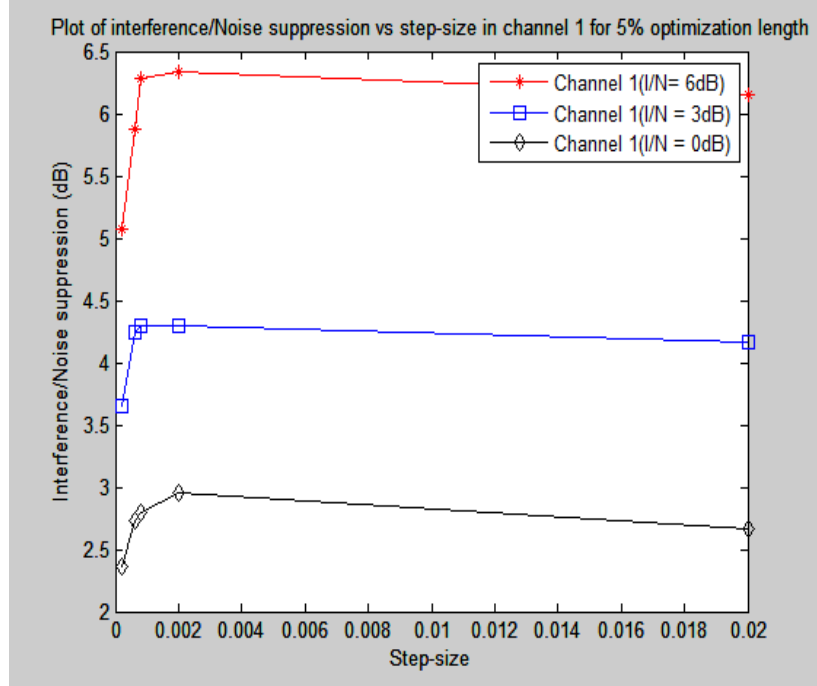
From Figure(4-1) to Figure(4-3) show step-size of about 0.002 could be chosen as the optimum value in channel one(1% of the TDD frame length, 3%, and 5%). Another interesting show is that the optimization period is not affect on the performance of the filter.



Figure(4-1): Interference/Noise (I/N) suppression vs step-size in channel one (1% of the TDD frame length)



Figure(4-2): Interference/Noise (I/N) suppression vs step-size in channel one (3% of the TDD frame length)



Figure(4-3): Interference/Noise (I/N) suppression vs step-size in channel one (5% of the TDD frame length)

For the channel one case (optimization period equal 1% of the TDD frame, 3%, and 5%), interference-to-noise ratio suppression ($(I/N)_{\text{suppression}}$) vs Step-size is shown for interference-to-noise ratio at main antenna in dB ($(I/N)_{\text{main(dB)}} = 6\text{dB}$), and interference-to-noise ratio at extra antenna in dB ($(I/N)_{\text{extra(dB)}} = 15\text{dB}$) in Figure(4-1) to Figure(4-3). The red path represents $(I/N)_{\text{suppression}}$ measurement due to channel one for $(I/N)_{\text{main(dB)}} = 6\text{dB}$, the blue sky path represents $(I/N)_{\text{suppression}}$ measurement due to channel one for $(I/N)_{\text{main(dB)}} = 3\text{dB}$, and khaki dark path represents $(I/N)_{\text{suppression}}$ due to channel one for $(I/N)_{\text{main(dB)}} = 0\text{dB}$. The transient interval (step-size < 0.002) provide accurate value of $(I/N)_{\text{suppression}}$ and low speed of convergence, and steady state (step-size ≥ 0.002) provide less accurate and fast speed of convergence.

Table(4-1) shows comparison between different values of optimization period (1% of the TDD frame, 3%, and 5% for channel one) in (I/N) suppression for different values of step-size, interference-to-noise ratio in dB $((I/N)_{\text{main(dB)}} = 6\text{dB}$, and $(I/N)_{\text{extra(dB)}} = 15\text{dB}$.

Table(4-1): $(I/N)_{\text{suppression}}$ in channel one (6dB interference-to-noise ratio at main antenna)

| Step-size | Channel one (1%) $(I/N)_{\text{suppression(dB)}}$ | Channel one (3%) $(I/N)_{\text{suppression(dB)}}$ | Channel one (5%) $(I/N)_{\text{suppression(dB)}}$ |
|-----------|--|--|--|
| 0 | 2 | 4.1 | 5.1 |
| 0.002 | 5.8 | 6.3 | 6.4 |
| 0.006 | 5.78 | 5.9 | 6.35 |
| 0.01 | 5.85 | 5.8 | 6.3 |
| 0.014 | 5.98 | 5.6 | 6.25 |
| 0.02 | 6.2 | 5.5 | 6.20 |

From Table(4-1) note that the maximum value of interference-to-noise ratio suppression at step-size equal 0.002. Another interesting note is that a maximum of about 0.5dB enhancement in the interference-to-noise ratio suppression is achieved from using 1% to 5%.

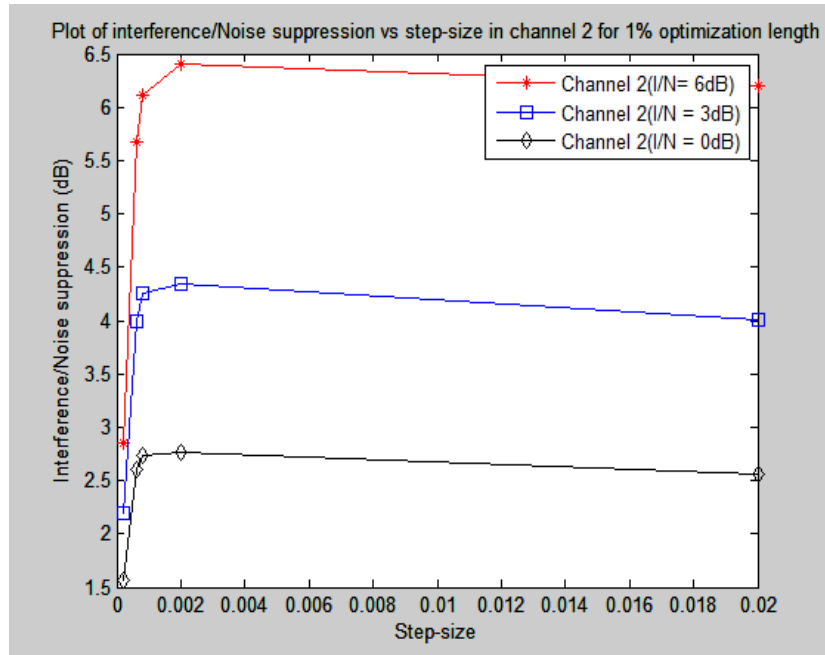
Table(4-2) shows comparison between different values of interference-to-noise ratio at main antenna $((I/N)_{\text{main(dB)}} = 0, 3, 6\text{dB}$ for different values of step-size, and interference-to-noise ratio at extra antenna $((I/N)_{\text{extra(dB)}} = 15\text{dB}$.

Table(4-2): $(I/N)_{\text{suppression}}$ in channel one (0, 3, and 6dB interference-to-noise ratio at main antenna in dB $(I/N)_{\text{main(dB)}}$)

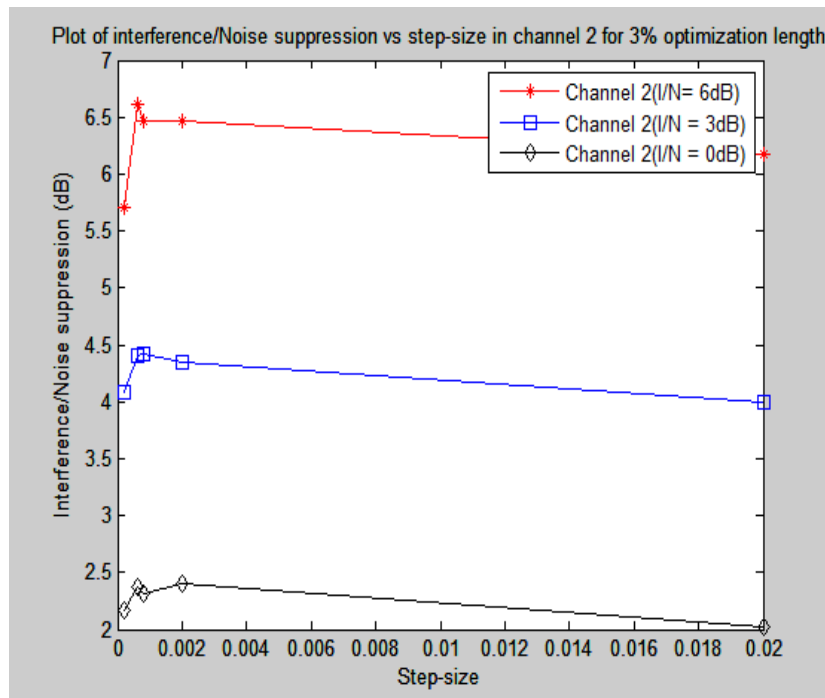
| Step-size | Channel one (3%) $(I/N)_{\text{main(dB)}} = 0\text{dB}$ $(I/N)_{\text{suppression(dB)}}$ | Channel one (3%) $(I/N)_{\text{main(dB)}} = 3\text{dB}$ $(I/N)_{\text{suppression(dB)}}$ | Channel one (3%) $(I/N)_{\text{main(dB)}} = 6\text{dB}$ $(I/N)_{\text{suppression(dB)}}$ |
|-----------|--|--|--|
| 0 | 2 | 3.2 | 4.1 |
| 0.002 | 2.8 | 4.5 | 6.3 |
| 0.006 | 2.6 | 4.4 | 6.1 |
| 0.01 | 2.5 | 4.3 | 5.9 |
| 0.014 | 2.45 | 4.1 | 5.7 |
| 0.02 | 2.3 | 3.95 | 5.6 |

From Table(4-2) note that the most important criteria in having a good interference-to-noise ratio suppression is interference-to-noise ratio (I/N) . As long as the (I/N) is large enough, a good interference-to-noise ratio suppression is guaranteed.

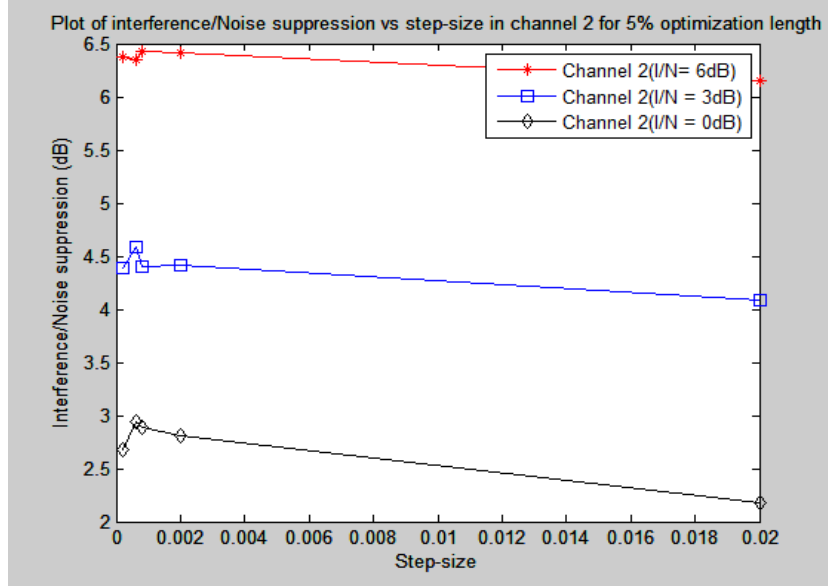
From Figure(4-4) to Figure(4-6) show step-size of about 0.002 could be chosen as the optimum value in channel two(1% of the TDD frame length, 3%, and 5%). Another interesting show is that the optimization period is not affect on the performance of the filter.



Figure(4-4): Interference/Noise (I/N) suppression vs step-size in channel two (1% of the TDD frame length)



Figure(4-5): Interference/Noise (I/N) suppression vs step-size in channel two (3% of the TDD frame length)

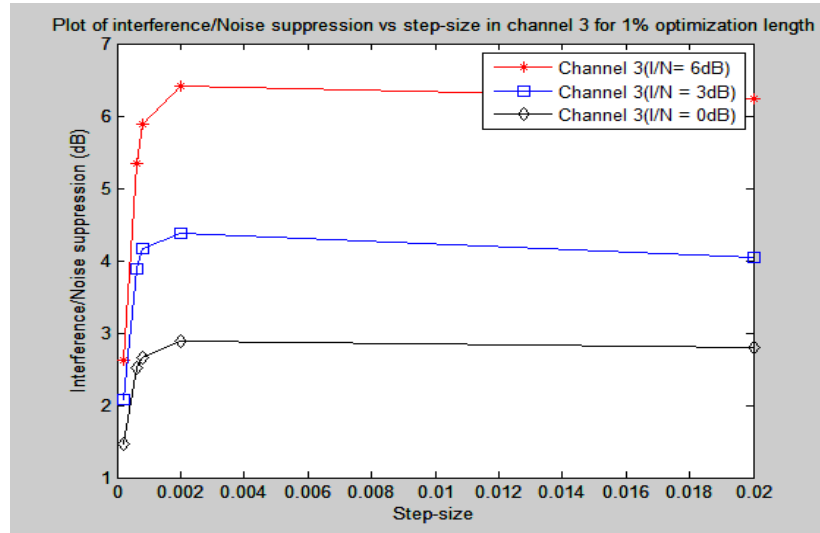


Figure(4-6): Interference/Noise (I/N) suppression vs step-size in channel two
(5% of the TDD frame length)

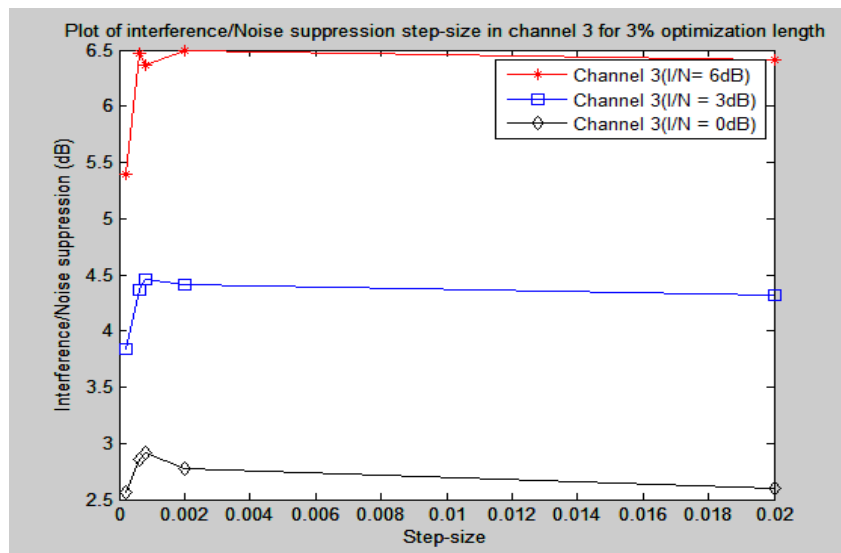
For the channel two case (optimization period equal 1% of the TDD frame, 3%, and 5%), interference-to-noise ratio suppression ($(I/N)_{\text{suppression}}$) vs Step-size is shown for interference-to-noise ratio at main antenna in dB ($(I/N)_{\text{main(dB)}}$) = 6dB, and interference-to-noise ratio at extra antenna in dB ($(I/N)_{\text{extra(dB)}}$) = 15dB in Figure(4-4) to Figure(4-6).

From Figure(4-4) to Figure(4-6) note that the maximum value of interference-to-noise ratio suppression at step-size equal 0.002. Another interesting note is that a maximum of about 0.5dB enhancement in the interference-to-noise ratio suppression is achieved from using 1% to 5%. Another important note that the most important criteria in having a good interference-to-noise ratio suppression is interference-to-noise ratio (I/N). As long as the (I/N) is large enough, a good interference-to-noise ratio suppression is guaranteed.

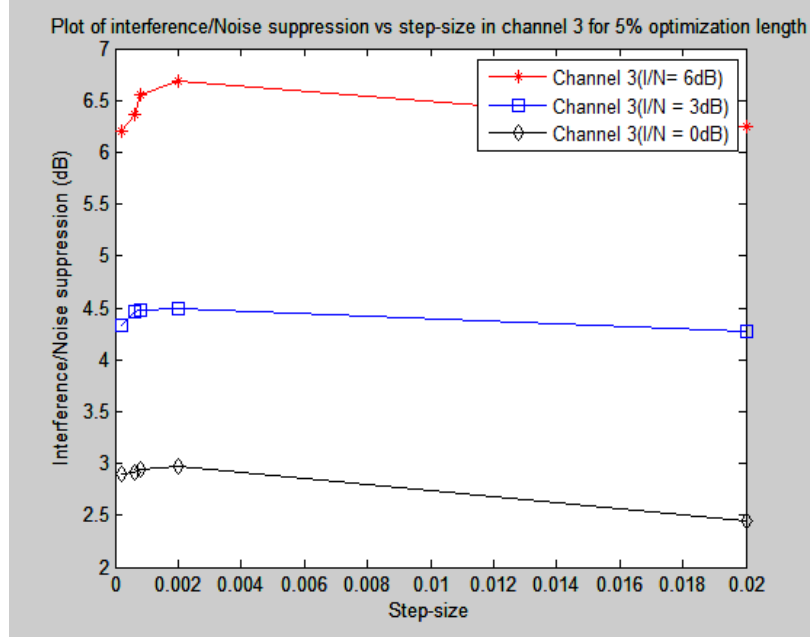
From Figure(4-7) to Figure(4-9) show step-size of about 0.002 could be chosen as the optimum value in channel three(1% of the TDD frame length, 3%, and 5%). Another interesting show is that the optimization period is not affect on the performance of the filter.



Figure(4-7): Interference/Noise (I/N) suppression vs step-size in channel three (1% of the TDD frame length)



Figure(4-8): Interference/Noise (I/N) suppression vs step-size in channel three (3% of the TDD frame length)



Figure(4-9): Interference/Noise (I/N) suppression vs step-size in channel three (5% of the TDD frame length)

For the channel three case (optimization period equal 1% of the TDD frame, 3%, and 5%), interference-to-noise ratio suppression ($(I/N)_{\text{suppression}}$) vs Step-size is shown for interference-to-noise ratio at main antenna in dB ($(I/N)_{\text{main(dB)}} = 6\text{dB}$), and interference-to-noise ratio at extra antenna in dB ($(I/N)_{\text{extra(dB)}} = 15\text{dB}$) in Figure(4-7) to Figure(4-9). The red path represents $(I/N)_{\text{suppression}}$ measurement due to channel one for $(I/N)_{\text{main(dB)}} = 6\text{dB}$, the blue sky path represents $(I/N)_{\text{suppression}}$ measurement due to channel one for $(I/N)_{\text{main(dB)}} = 3\text{dB}$, and khaki dark path represents $(I/N)_{\text{suppression}}$ due to channel one for $(I/N)_{\text{main(dB)}} = 0\text{dB}$. The transient interval (step-size < 0.002) provide accurate value of $(I/N)_{\text{suppression}}$ and low speed of convergence, and steady state (step-size ≥ 0.002) provide less accurate and fast speed of convergence.

Table(4-3) shows comparison between different values of optimization period (1% of the TDD frame length, 3%, and 5% for channel three) in (I/N) suppression for different values of step-size, interference-to-noise ratio in dB $((I/N)_{\text{main(dB)}} = 0\text{dB}$, and $(I/N)_{\text{extra(dB)}} = 15\text{dB}$.

Table(4-3): $(I/N)_{\text{suppression}}$ in channel three (0dB interference-to-noise ratio at main antenna)

| Step-size μ | Channel Three (1%) $(I/N)_{\text{suppression(dB)}}$ | Channel Three (3%) $(I/N)_{\text{suppression(dB)}}$ | Channel Three (5%) $(I/N)_{\text{suppression(dB)}}$ |
|--------------------|--|--|--|
| 0 | 2.57 | 5.4 | 6.24 |
| 0.002 | 6.44 | 6.5 | 6.68 |
| 0.006 | 6.39 | 6.48 | 6.63 |
| 0.01 | 6.34 | 6.47 | 6.45 |
| 0.014 | 6.29 | 6.44 | 6.4 |
| 0.02 | 6.24 | 6.42 | 6.35 |

From Table(4-3) note that the maximum value of interference-to-noise ratio suppression at step-size equal 0.002. Another interesting note is that a maximum of about 0.5dB enhancement in the interference-to-noise ratio suppression is achieved from using 1% to 5%.

Table(4-4) shows comparison between different values of interference-to-noise ratio at main antenna $((I/N)_{\text{main(dB)}} = 0, 3, 6\text{dB}$ for different values of step-size, and interference-to-noise ratio at extra antenna $((I/N)_{\text{extra(dB)}} = 15\text{dB}$.

Table(4-4): $(I/N)_{\text{suppression}}$ in channel three (0, 3, and 6dB interference-to-noise ratio at main antenna in dB $(I/N)_{\text{main(dB)}}$)

| Step-size μ | Channel Three (3%) $(I/N)_{\text{main(dB)}} = 0\text{dB}$ $(I/N)_{\text{suppression(dB)}}$ | Channel Three (3%) $(I/N)_{\text{main(dB)}} = 3\text{dB}$ $(I/N)_{\text{suppression(dB)}}$ | Channel Three (3%) $(I/N)_{\text{main(dB)}} = 6\text{dB}$ $(I/N)_{\text{suppression(dB)}}$ |
|--------------------|--|--|--|
| 0 | 2.56 | 3.85 | 5.4 |
| 0.002 | 2.77 | 4.4 | 6.5 |
| 0.006 | 2.72 | 4.35 | 6.48 |
| 0.01 | 2.67 | 4.3 | 6.47 |
| 0.014 | 2.62 | 4.25 | 6.44 |
| 0.02 | 2.57 | 4.2 | 6.42 |

From Table(4-4) note that the most important criteria in having a good interference-to-noise ratio suppression is interference-to-noise ratio (I/N) . As long as the (I/N) is large enough, a good interference-to-noise ratio suppression is guaranteed.

From Table(4-1) and Table(4-3) show step-size of about 0.002 could be chosen as the optimum value in all the three channel types. It gives generally the best interference interference-to-noise ratio suppression in all the simulation that was performed. Another interesting discovery is that the optimization period of the filter is of much lesser importance in the interference-to-noise ratio suppression property of the adaptive equalization filter interference-to-noise ratio canceller design. A maximum of about 0.5dB enhancement in the interference-to-noise ratio suppression property is achieved from 1% to 5%.

From Table(4-2) and Table(4-4), as interference-to-noise ratio at main antenna in dB is large enough, a good interference-to-noise ratio suppression is guaranteed.

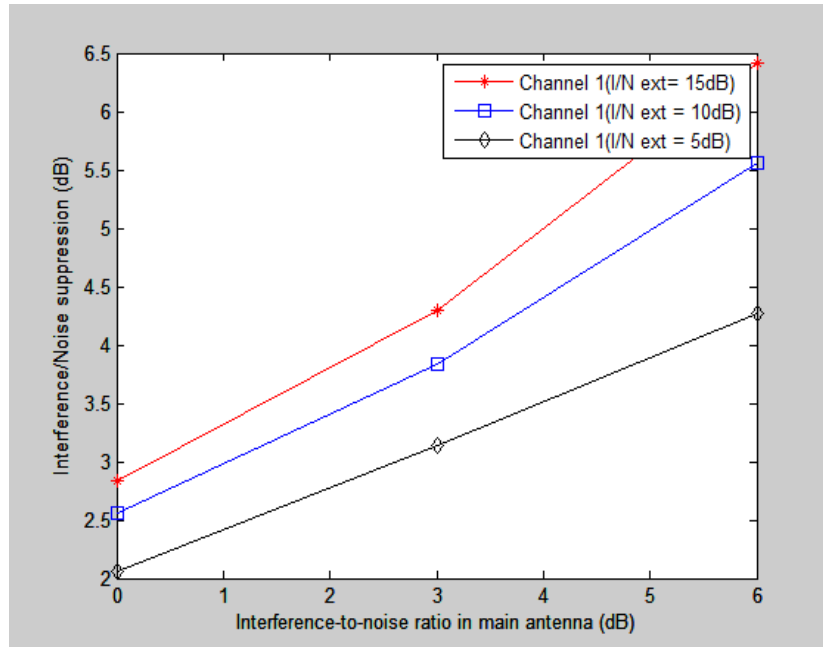
The TDD adaptive equalization filter (I/N) canceller design has achieved a noticeable interference-to-noise ratio suppression up to 6.5dB on same cases, thus our adaptive equalization filter interference-to-noise ratio canceller design performance is independent of the channel types.

4-2 Performance with Varying Interfering Femtocells by

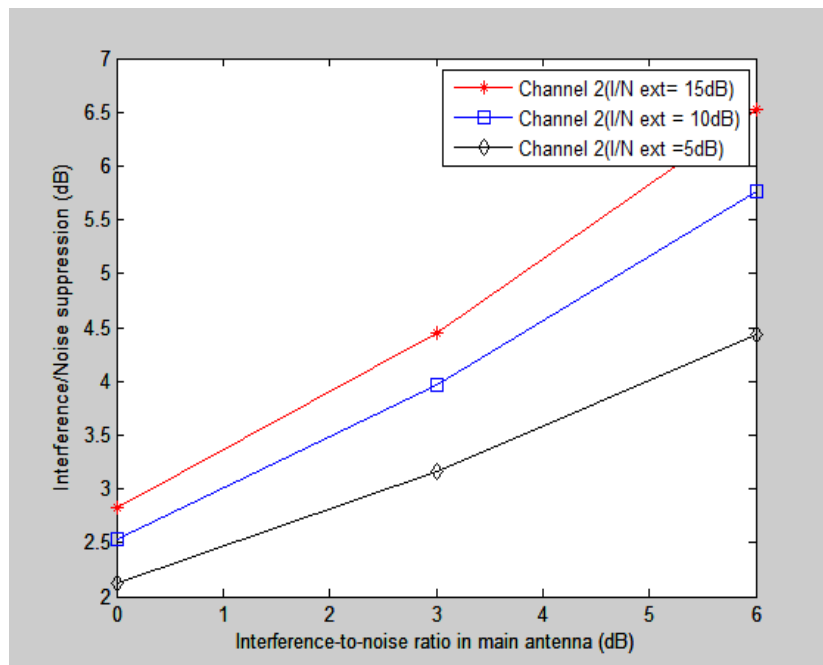
Varying the Noise of Extra Antenna

In this section we will be trying to see if (I/N) suppression also depend on the value of the $(I/N)_{\text{extra}}$ for our adaptive equalization filter (I/N) canceller and adaptive equalization filter noise canceller [23]. The value of the step-size selected is 0.002 and optimization period is 3% of the TDD frame length for the two schemes. The simulation implemented using MATLAB code (see appendix B, C, D and E). The (I/N) suppression will be plotted against three fixed values of $(I/N)_{\text{main(dB)}}$. These are 6dB, 3dB, 0dB. The (I/N) on the extra antenna path will be varied; the values used are: 15dB, 10dB, and 5dB. We will be investigating if varying the interfering femtocells ($(I/N)_{\text{extra(dB)}}$) affects the (I/N) suppression property of our system design.

From Figure(4-10b) and Figure(4-10c) its clear that the Interference/Noise property of our adaptive equalization filter (I/N) canceller design for channel one and channel two depend on $(I/N)_{\text{extra(dB)}}$.



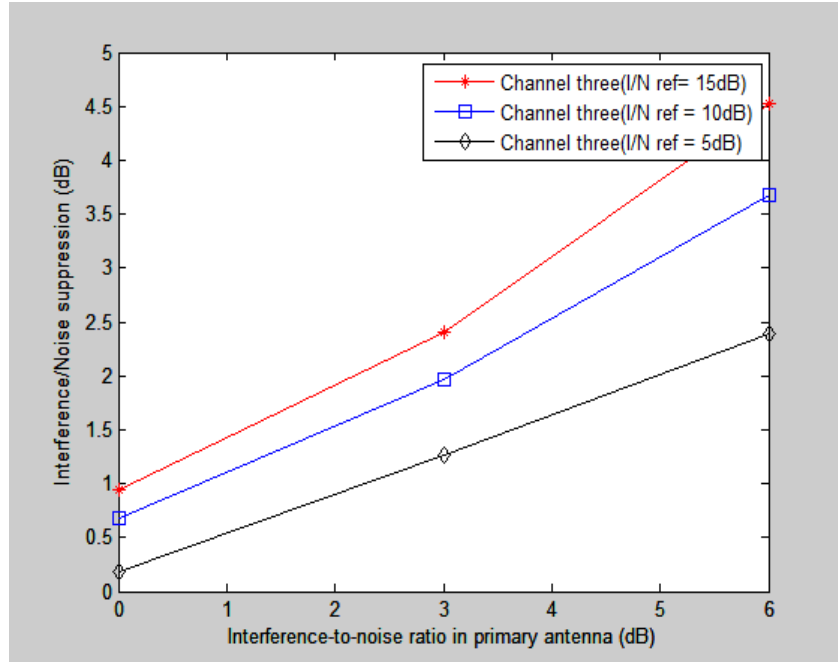
Figure(4-10b): interference-to-noise ratio suppression vs $(I/N)_{\text{main(dB)}}$ in channel one of proposed system design



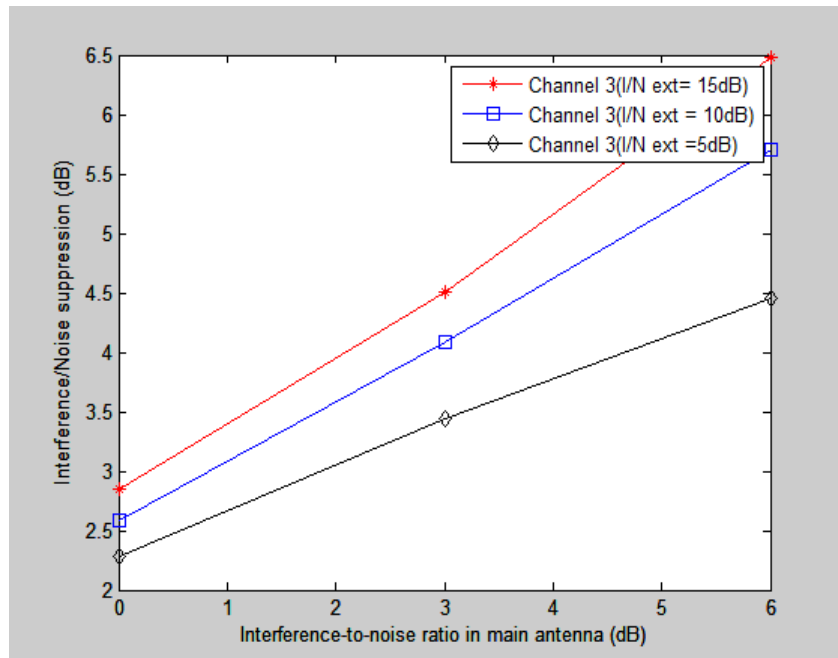
Figure(4-10c): interference-to-noise ratio suppression vs $(I/N)_{\text{main(dB)}}$ in channel two of proposed system design

From Figure(4-10b) and Figure(4-10c), as the interfering femtocells increases so does the (I/N) suppression magnitude of adaptive equalization filter (I/N) canceller design for channel one and channel two. From Figure(4-10b) and Figure(4-10c) its clear that when the $(I/N)_{\text{main(dB)}}$ is 0dB, over 2dB interference-to-noise suppression in channel one and channel two could still be achieved.

From Figure(4-10d) and Figure(4-10e) its clear that the Interference/Noise property of our adaptive equalization filter (I/N) canceller design and adaptive equalization filter noise canceller[23] depend on $(I/N)_{\text{extra(dB)}}$.



Figure(4-10d): interference-to-noise ratio suppression vs $(I/N)_{\text{main}}(\text{dB})$ in channel three of adaptive equalization filter noise canceller [23]



Figure(4-10e): interference-to-noise suppression vs $(I/N)_{\text{main}}(\text{dB})$ in channel three of proposed system design

For the channel three case (optimization period equal 3% of the TDD frame), interference-to-noise ratio suppression $((I/N)_{\text{suppression}})$ vs interference-to-noise ratio at main antenna in dB $((I/N)_{\text{main(dB)}})$ is shown in Figure(4-10d) to Figure(4-10e) for interference-to-noise ratio at main antenna in dB $((I/N)_{\text{main(dB)}}) = 0, 3, \text{ and } 6\text{dB}$, and interference-to-noise ratio at extra antenna in dB $((I/N)_{\text{extra(dB)}}) = 5, 10, \text{ and } 15\text{dB}$. The red path represents $(I/N)_{\text{suppression}}$ measurement due to channel three for $(I/N)_{\text{extra(dB)}} = 15\text{dB}$, the blue sky path represents $(I/N)_{\text{suppression}}$ measurement due to channel three for $(I/N)_{\text{extra(dB)}} = 10\text{dB}$, and khaki dark path represents $(I/N)_{\text{suppression}}$ due to channel three for $(I/N)_{\text{extra(dB)}} = 5\text{dB}$.

Table(4-5) shows the comparison between our proposed system design and adaptive equalization filter noise canceller(given scheme)[23] in (I/N) suppression for different values of (I/N) at main antenna and 15dB (I/N) at extra antenna.

Table(4-5): (I/N) suppression in varied values of $(I/N)_{\text{main(dB)}}$ and 15dB at extra antenna

| $(I/N)_{\text{main(dB)}}$ | Proposed System $(I/N)_{\text{suppression(dB)}}$ | Given Scheme [23] $(I/N)_{\text{suppression(dB)}}$ |
|---------------------------|---|---|
| 0 | 2.89 | 0.95 |
| 3 | 4.55 | 2.44 |
| 6 | 6.50 | 4.50 |

From table(4-1) note that the (I/N) suppression in our proposed system and given scheme depend on (I/N) at main antenna. It could be seen from Table(4-5) when (I/N) at main antenna is 0dB, 2.89dB (I/N) suppression in our proposed system and 0.99dB (I/N) suppression in equalization filter noise canceller(given scheme)[23] are achieved.

Table(4-6) shows the comparison between our proposed system and equalization filter noise canceller[23] in interference-to-noise ratio (I/N) suppression for different values of interference-to-noise at extra antenna $(I/N)_{\text{extra(dB)}}$, interference-to-noise ratio at main antenna in dB $((I/N)_{\text{main(dB)}}) = 6\text{dB}$.

Table(4-6): (I/N) suppression in varied value of $(I/N)_{\text{extra}}$ in dB

| (I/N) at Extra Antenna in dB | (I/N) Suppression Percentage |
|---------------------------------|---------------------------------|
| 15 | 44% |
| 10 | 54% |
| 5 | 87.5% |

From table(4-6) note the interference-to-noise ratio suppression percentage in our proposed system design depend on $(I/N)_{\text{extra(dB)}}$ and $(I/N)_{\text{main(dB)}}$ (max equal 6dB), thus the best $(I/N)_{\text{extra(dB)}}$ that must be use is 10dB to get interference-to-noise ratio suppression.

Our adaptive equalization filter interference-to-noise ratio canceller design work on interference-to-noise ratio suppression with less error, the adaptive equalization filter design with proper digital signal processing. Thus even if the weights are varied by small amount, optimal weight are affected. However mean of the adaptive equalization filter coefficients would be in accurate, if the variance is large.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

The main ideas presented in the thesis are collected and summarized in this chapter as well as recommendation for future work.

5-1 Conclusion

Interfering femtocells at the proposed system leads it to be rigid. Therefore propose a new method with use of an extra antenna is employed and an adaptive equalization filter. Thus Interference/Noise can be adaptively mitigated.

Based on the simulations performed in this thesis, the results is quite encouraging with Interference/Noise suppression of up to 6.5dB being measured in some cases. The magnitude of the (I/N) suppression as was shown in this thesis, is highly dependent on the (I/N) in both the main antenna and the extra antenna. The higher these values are, better the Interference/Noise (I/N) suppression property of proposed system design.

It was also proven that the optimization period at which the system instructs its user terminal to stop transmitting so that the adaptive equalization filter can measure the channel for the purpose of locking its coefficient to the channel before the user terminal starts transmitting again, is of lesser important. Three values of optimization period were used. It was shown that the difference in Interference/Noise suppression magnitude between using an optimization period of 1% to using 5% is about 0.5dB. This gives optimize the spectrum usage of the system and also provide the user a sense of continuous transmission.

5-2 Recommendations

It could be possible to change in the adaptive equalization filter itself, by choosing the type of filter and the order of the filter. Adaptive equalization filter is done on femtocells-to-modified Macro User Equipment interference; it can also be achieved in various applications, where pure signal is needed.

It is recommended in future research:

- To use a dynamic system analysis environment such as lab view for the design and simulation.
- To use the radio spectrum above 20GHz for the bandwidth demand of future mobile broadband systems and increase interference reduction at cell-edge.
- To propose and examine different parameters such as channels to be used and high-order for adaptive equalization filter to reduce the severe interference.

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Appendices

Appendix A

Interference/Noise suppression vs step-size for various channels types

```
% Used for plotting interference/noise suppression vs step-size.
% CHANNEL 1
% my = stepsize
% supp_6dB_5per = Interference/Noise suppression when interference-to-
noise ratio at the main antenna is 6dB and 5% optimization length.
my=[0.0002 0.0006 0.0008 0.002 0.02];
% Used for plotting interference/noise suppression vs my for 5%
optimization
% period with I/N = 6dB,3dB and 0dB.
supp_6dB_5per=[5.07 5.87 6.28 6.33 6.15];
supp_3dB_5per=[3.65 4.24 4.29 4.30 4.17];
supp_0dB_5per=[2.36 2.73 2.8 2.95 2.66 ];
% Used for plotting interference/noise suppression vs my for 3%
optimization
% period with I/N = 6dB,3dB and 0dB.
supp_6dB_3per=[4.08 5.79 5.99 6.19 5.61];
supp_3dB_3per=[3.13 3.98 4.37 4.49 3.9];

supp_0dB_3per=[2.04 2.61 2.54 2.75 2.31];
% Used for plotting interference/noise suppression vs my for 1%
optimization
% period with I/N = 6dB,3dB and 0dB.
supp_6dB_1per=[1.95 4.11 4.75 5.8 6.15];
supp_3dB_1per=[1.52 3.1 3.46 4.04 3.94];
supp_0dB_1per=[1.08 2.09 2.25 2.65 2.59];
% Plots the graph at 1percent optimization length in channel 1
figure(1)
plot(my,supp_6dB_1per, '-r*');
hold on
plot (my,supp_3dB_1per,'-bs');
hold on
plot(my,supp_0dB_1per,'-kd');
legend('Channel 1(I/N= 6dB)','Channel 1(I/N = 3dB)','Channel 1(I/N =
0dB)')
xlabel('Step-size (my)');
```

```

ylabel('Interference/Noise suppression (dB)');
title('Plot of interference/Noise suppression vs step-size in channel 1 for 1%
optimization
length');
% Plots the graph at 3percent optimization length in channel 1
figure(2)
plot(my,supp_6dB_3per,'-r*');
hold on
plot (my,supp_3dB_3per,'-bs');
hold on
plot (my,supp_0dB_3per,'-kd');
legend('Channel 1(I/N= 6dB)','Channel 1(I/N = 3dB)','Channel 1(I/N =
0dB)');
xlabel('Step-size (my)');
ylabel('Interference/Noise suppression (dB)');
title('Plot of interference/noise suppression vs step-size in channel 1 for 3%
optimization

length');
% Plots the graph at 5percent optimization length in channel 1
figure(3)
plot (my,supp_6dB_5per,'-r*');
hold on
plot (my,supp_3dB_5per,'-bs');
hold on

plot (my,supp_0dB_5per,'-kd');
legend('Channel 1(I/N= 6dB)','Channel 1(I/N = 3dB)','Channel 1(I/N =
0dB)');
xlabel('Step-size (my)');
ylabel('Interference/Noise suppression (dB)');
title('Plot of interference suppression vs step-size in channel 1 for 5%
optimization
length');
% CHANNEL 2
my=[0.0002 0.0006 0.0008 0.002 0.02]
% Used for plotting interference/noise suppression vs my for 5%
optimization
% period with I/N = 6dB,3dB and 0dB.
supp_6dB_5per=[6.38 6.35 6.43 6.42 6.15];

```

```

supp_3dB_5per=[4.39 4.58 4.4 4.41 4.09];
supp_0dB_5per=[2.68 2.94 2.89 2.81 2.18];

% Used for plotting interference/noise suppression vs my for 3%
optimization
% period with I/N = 6dB,3dB and 0dB.
supp_6dB_3per=[5.71 6.61 6.46 6.47 6.18];
supp_3dB_3per=[4.08 4.41 4.42 4.35 3.99];
supp_0dB_3per=[2.17 2.37 2.32 2.40 2.02 ];
% Used for plotting interference/noise suppression vs my for 1%
optimization
% period with I/N = 6dB,3dB and 0dB.
supp_6dB_1per=[2.85 5.67 6.11 6.40 6.20];
supp_3dB_1per=[2.19 3.99 4.25 4.35 4.01];
supp_0dB_1per=[1.57 2.61 2.74 2.77 2.56];
% Plots the graph at 1percent optimization length in channel 2
figure(1)
plot (my,supp_6dB_1per, '-r*');
hold on;
plot (my,supp_3dB_1per, '-bs');

hold on;
plot (my,supp_0dB_1per,'-kd');
legend('Channel 2(I/N= 6dB)','Channel 2(I/N = 3dB)','Channel 2(I/N =
0dB)')
xlabel('Step-size (my)');

ylabel('Interference/Noise suppression (dB)');
title('Plot of interference/noise suppression vs step-size in channel 2 for 1%
optimization
length');
% Plots the graph at 3percent optimization length in channel 2
figure(2)
plot (my,supp_6dB_3per, '-r*');
hold on;
plot (my,supp_3dB_3per, '-bs');
hold on;
plot (my,supp_0dB_3per,'-kd');
legend('Channel 2(I/N= 6dB)','Channel 2(I/N = 3dB)','Channel 2(I/N =
0dB)');
xlabel('Step-size (my)');

```

```

ylabel('Interference/Noise suppression (dB)');
title('Plot of interference/noise suppression vs step-size in channel 2 for 3%
optimization
length');
% Plots the graph at 5percent optimization length in channel 2

figure(3)
plot (my,supp_6dB_5per,'-r*');
hold on;
plot (my,supp_3dB_5per, '-bs');
hold on;
plot (my,supp_0dB_5per,'-kd');
legend('Channel 2(I/N= 6dB)','Channel 2(I/N = 3dB)','Channel 2(I/N =
0dB)');
xlabel('Step-size (my)');
ylabel('Interference/Noise suppression (dB)');
title('Plot of interference suppression vs step-size in channel 2 for 5%
optimization
length');
% CHANNEL 3
my=[0.0002 0.0006 0.0008 0.002 0.02]
% Used for plotting interference/noise suppression vs my for 5%
optimization
% period with I/N = 6dB,3dB and 0dB.

supp_6dB_5per=[6.21 6.37 6.56 6.68 6.25];

supp_3dB_5per=[4.33 4.47 4.48 4.49 4.28];
supp_0dB_5per=[2.9 2.92 2.94 2.97 2.45];

% Used for plotting interference/noise suppression vs my for 3%
optimization
% period with I/N = 6dB,3dB and 0dB.
supp_6dB_3per=[5.39 6.47 6.36 6.49 6.41];
supp_3dB_3per=[3.84 4.36 4.46 4.41 4.32];
supp_0dB_3per=[2.57 2.86 2.91 2.78 2.6 ];
% Used for plotting interference/noise suppression vs my for 1%
optimization
% period with I/N = 6dB,3dB and 0dB.
supp_6dB_1per=[2.62 5.35 5.89 6.41 6.23];
supp_3dB_1per=[2.08 3.89 4.16 4.38 4.04];

```

```

supp_0dB_1per=[1.47 2.51 2.65 2.89 2.80];
% Plots the graph at 1percent optimization length in channel 3
figure(1)
plot(my,supp_6dB_1per,'-r*');
hold on
plot (my,supp_3dB_1per,'-bs');
hold on

plot (my,supp_0dB_1per,'-kd');
legend('Channel 3(I/N= 6dB)','Channel 3(I/N = 3dB)','Channel 3(I/N =
0dB)')
xlabel('Step-size (my)');
ylabel('Interference/Noise suppression (dB)');
title('Plot of interference/noise suppression vs step-size in channel 3 for 1%
optimization
length');
% Plots the graph at 3percent optimization length in channel 3
figure(2)
plot (my,supp_6dB_3per,'-r*');
hold on;
plot (my,supp_3dB_3per,'-bs');

hold on;
plot (my,supp_0dB_3per,'-kd');
legend('Channel 3(I/N= 6dB)','Channel 3(I/N = 3dB)','Channel 3(I/N =
0dB)');
xlabel('Step-size (my)');
ylabel('Interference/Noise suppression (dB)');
title('Plot of interference/noise suppression step-size in channel 3 for 3%
optimization length');
% Plots the graph at 5percent optimization length in channel 3
figure(3)
plot (my,supp_6dB_5per,'-r*');
hold on;
plot (my,supp_3dB_5per,'-bs');
hold on;
plot (my,supp_0dB_5per,'-kd');
legend('Channel 3(I/N= 6dB)','Channel 3(I/N = 3dB)','Channel 3(I/N =
0dB)');
xlabel('Step-size (my)');

```



```
ylabel('Interference/Noise suppression (dB)');  
title('Plot of interference/noise suppression vs step-size in channel 3 for 5%  
optimization length');
```

Appendix B

**(I/N) suppression vs $(I/N)_{\text{main(dB)}}$ for varying value of $(I/N)_{\text{extra(dB)}}$
in channel one of our adaptive equalization (I/N) canceller**

```
% CHANNEL One
% Plotting the varying value of I/N of the extra antenna in channel one
% ext_15 = interference to noise ratio in extra antenna is 15dB and the
% values of interference/noise suppression at interference-to-noise ratio in
the main antenna
%0,3 and 6dB are given in the vector.
% Channel one I/N extra = 15dB
ext_15dB = [2.83 4.29 6.41];
% Channel one I/N extra = 10dB
ext_10dB = [2.56 3.84 5.56];
% Channel one I/N extra = 5dB
ext_5dB = [2.06 3.14 4.27];
% values of the interference-to-noise ratio in the main antenna
in_m = [0 3 6];
figure(1)
plot(in_m,m_15dB,'-r*');

hold on
plot (in_m,m_10dB,'-bs');
hold on
plot (in_m,m_5dB,'-kd');

legend('Channel one(I/N ext= 15dB)','Channel one(I/N ext =
10dB)','Channel one(I/N ext = 5dB)')
xlabel('Interference-to-noise ratio in main antenna (dB)');
ylabel('Interference/Noise suppression (dB)');
%title('Plot of interference/Noise suppression vs interference-to-noise ratio
in the main antenna with varying value of interference-to-noise ratio in
extra antenna');
```

Appendix C

**(I/N) suppression vs $(I/N)_{\text{main(dB)}}$ for varying value of $(I/N)_{\text{extra(dB)}}$
in channel two of our adaptive equalization (I/N) canceller**

```
% CHANNEL Two
% Plotting the varying value if I/N of the extra antenna in channel two
% Channel two I/N extra = 15dB
m_15dB = [2.83 4.45 6.53];
% Channel two I/N extra = 10dB
m_10dB = [2.54 3.97 5.77];
% Channel two I/N extra = 5dB
m_5dB = [2.12 3.16 4.44];
in_m = [0 3 6];
figure(1)
plot(in_m,m_15dB,'-r*');
hold on
plot (in_m,m_10dB,'-bs');
hold on
plot (in_m,m_5dB,'-kd');

legend('Channel two(I/N ext= 15dB)','Channel two(I/N ext = 10dB)','Channel two(I/N ext = 5dB)')
xlabel('Interference-to-noise ratio in main antenna (dB)');
ylabel('Interference/Noise suppression (dB)');
%title('Plot of interference/noise suppression vs interference-to-noise ratio in the main antenna with varying value of interference-to-noise ratio in extra antenna');
```

Appendix D

(I/N) suppression vs (I/N)_{primary(dB)} for varying value of (I/N)_{reference(dB)} in channel three of adaptive equalization (I/N)

canceller [25]

```
% CHANNEL Three
% Plotting the varying value of I/N of the reference antenna in channel
Three
% ref_15 = interference to noise ratio in reference antenna is 15dB and the
% values of interference suppression at interference-to-noise ratio in the
primary antenna
% 1,2 and 5dB are given in the vector.
% Channel three I/N extra = 15dB
ref_15dB = [0.95 2.41 4.53];
% Channel three I/N reference = 10dB
ref_10dB = [0.68 1.96 3.68];
% Channel three I/N reference = 5dB
ref_5dB = [0.18 1.26 2.39];
% values of the interference-to-noise ratio in the primary antenna
in_m = [0 3 6];
figure
plot(in_m,ref_15dB,'-r*');
hold on
plot (in_m,ref_10dB,'-bs');
hold on
plot (in_m,ref_5dB,'-kd');
legend('Channel three(I/N ref= 15dB)','Channel three(I/N ref =
10dB)','Channel three(I/N ref = 5dB)')
xlabel('Interference-to-noise ratio in primary antenna (dB)');
ylabel('Interference/Noise suppression (dB)');
%title('Plot of interference suppression vs interference-to-noise ratio in the
primary antenna with varying value if interference-to-noise ratio in
reference antenna');
```

Appendix E

**(I/N) suppression vs $(I/N)_{\text{main(dB)}}$ for varying value of $(I/N)_{\text{extra(dB)}}$
in channel three of our adaptive equalization (I/N) canceller**

```
% CHANNEL Three
% Plotting the varying value if I/N of the extra antenna in channel 3
% Channel three I/N extra = 15dB
m_15dB = [2.85 4.51 6.48];

% Channel three I/N extra = 10dB
m_10dB = [2.58 4.08 5.7];
% Channel three I/N extra = 5dB
m_5dB = [2.28 3.44 4.45];
in_m = [0 3 6];
figure(1)
plot(in_m,m_15dB,'-r*');
hold on
plot (in_m,m_10dB,'-bs');
hold on
plot (in_m,m_5dB,'-kd');
legend('Channel three(I/N ext= 15dB)','Channel three(I/N ext = 10dB)','Channel three(I/N ext = 5dB)')
xlabel('Interference-to-noise ratio in main antenna (dB)');
ylabel('Interference/Noise suppression (dB)');
%title('Plot of interference/noise suppression vs interference-to-noise ratio in the main antenna with varying value if interference-to-noise ratio in extra antenna');
```