PERFORMANCE ANALYSIS OF INTEGRATING DIRECTIONAL RECEPTION AND REALISTIC MULTIPATH MODELLING IN COGNITIVE COMMUNICATION SYSTEMS

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ABSTRACT

The establishment of a cost effective, reliable, and high data rate wireless communication system in rural areas remains to be a significant challenge that requires a fresh and innovative approach. In this thesis, the development of advanced nodes from a physical layer perspective is proposed with a fully directional antenna array and fast digital signal processing without any modifications in the medium access control layer. The proposed physical layer focused solution is based on the use of broadband directional antennas, integrating accurate propagation modeling resources and adaptive cognitive communication capabilities for real-time applications. It is shown that by integrating these diverse resources in the advanced base station or nodes, it is possible to address and solve the long standing problem of adequate communication and high data rate needs in rural areas.

Separate hexagonal antenna array is used for user discovery (via scanning) and for data communication with users. Each advanced base station is capable of digital beamforming, beam steering, handover, load management and coordinated multipoint transmission or reception. The directional antennas facilitate base station-to-base station and base station to mobile user connectivity. The predictable time required to estimate the Angle of Arrival (AoA), compute the beamforming weight, and apply the beamforming weights is estimated and inter-frame space where the AoA estimation and beamforming calculation can be applied for IEEE 802.11 is also offered to ensure practical implementation in available standards. Software and hardware simulations confirm that using real devices (FPGAs) it is guaranteed to behave as in the simulation and hence would satisfy the timing constraints.

As a part of effective radio network planning and design, Genetic Algorithm (GA) and geospatial assets are used to place base stations in order to optimize the cellular coverage in rural areas such as Maui Island, Hawaii and Kohala region of the Big Island, Hawaii. Main finding and major results show that instead of four isotropic regular base stations (5 dBi), only two directional antenna array based advanced base stations (19 dBi) can be used to cover approximately the same area for both the islands (~91% for Maui and ~83% for Kohala).

In perspective to this thesis, capabilities for directional antenna systems and related propagation issues to play a more important role in the system level performance of cognitive communication systems are also investigated as part of the environment awareness engine. The proposed adaptive cognitive communication approach is applied at the base station and the performances of two modern communication systems i.e. Orthogonal Frequency Division Multiple Access (OFDMA) and Multiuser Wireless System are evaluated. Investigation is carried out on trade-offs between accuracy in realistic propagation modeling (number of multipath) and computational time as well as determining the most advantageous beamwidth for directional antennas. This approach is designed to help decide not only if employing the channel parameters, and associated processing delays would help in improving the cognitive communications, but also in determining an acceptable level of modeling details that would achieve acceptable cognitive performance in adaptive and real-time processing. Simulations results show that for realistic SNR/bit values, just the path gain and AoA data for as few as 5 paths could be sufficient in forming a propagation model at the receiver while satisfying certain desired performance criteria. When compared to using all the available propagation modeling data, the use of only 5 paths or less results in 85% reduction in computation time required for generating the channel matrix.

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INTRODUCTION

Integrating mobile internet into everyone's life is not a vision but it is partly a reality of today's world. Across the United States, a certain percentage of the population especially living in remote and rural areas do not have reliable access to broadband internet communication. Advanced communication technology could bring broadband wireless service to remote areas. Recent advanced in mobile computing and enabling technologies along with rising demands for new and improved applications are the main driving forces for the evolutionary concepts of wireless systems. Directional networking integrating propagation modeling and cognitive communication is a promising concept for the realizations of smart and advanced wireless systems. Availability of such transformative technology is essential to educations, jobs, health care and economic development and enable the internet to be accessible from everywhere.

1.1 Motivation

The establishment of a cost effective, reliable, and high data rate wireless communication system in rural areas remains to be a significant challenge that requires a fresh approach and innovative solution. The vast coverage areas, rough terrain, deep forestation and mountain ranges, energy wastage in certain areas due to the use of omnidirectional antennas, sparsity of population and low node density in these areas often prohibit a cost effective implementation of standards wireless networks systems solution that is based on available technologies. While the country's major wireless carriers advertise their widespread coverage, the level of coverage for voice and data is really more of a mixed bag, at best, with shortcomings and limited performance in rural areas. To be sure, the U.S. has tremendous wireless coverage from a variety of carriers, Federal Communications Commission (FCC) in its 2015 National broadband progression report [1.1] acknowledged that 55 million people, i.e. 17 percent of the total population, still don't have good reliable broadband and high data rate wireless coverage. Over half of all rural Americans lack access to 25Mbps/3 Mbps service, and there is a significant digital divide between the urban and rural America. In an era when broadband is essential to innovation, jobs, education, and global competitiveness, the report concludes that the FCC and the nation must continue to address obstacles impeding universal broadband deployment and availability. Figure 1.1 shows significant areas and vast territories that lack adequate communications and Internet access and who could and should benefit from affordable advances in broadband wireless technologies. It may be suggested that an affordable wireless communication solution could be used to help solve the communication and lack of Internet access problems in rural areas.

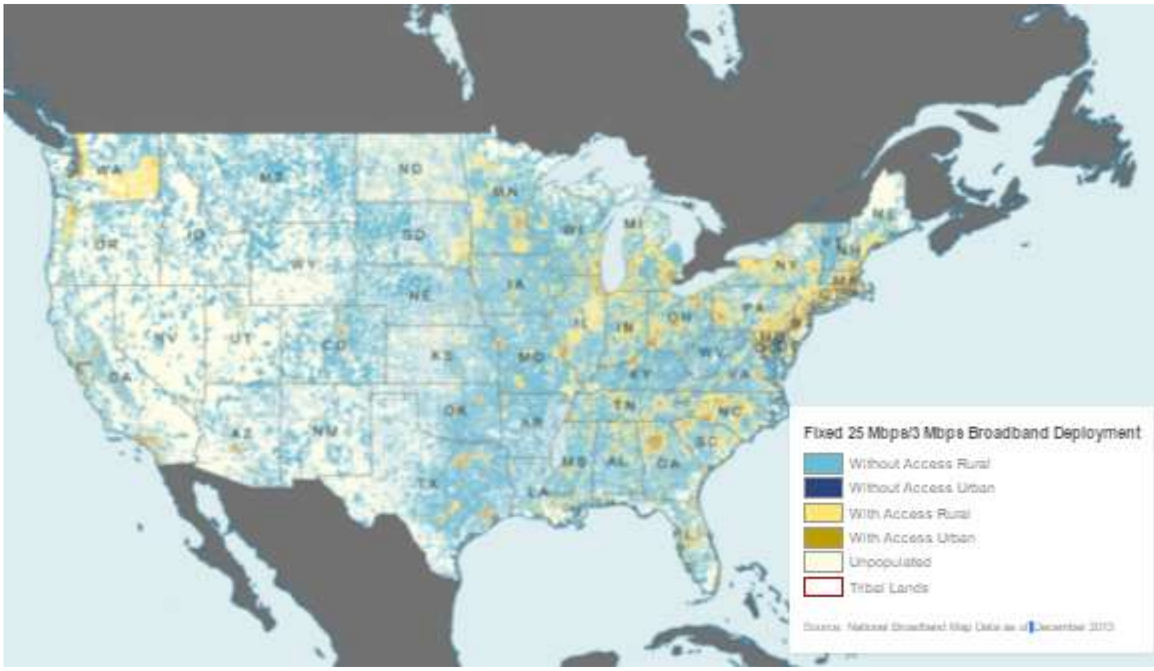


Fig. 1.1 Fixed broadband fixed broadband of 25 Mbps download and 3 Mbps upload coverage in the United States. Adapted from [1.1].

Detailed analysis of available wireless solutions, however, reveals that these technologies are developed mainly for high-density domains or fully connected networks and that they do not readily apply to rural and spare domains and especially with mountain and rough terrains. Users in rural and sparse areas are still served predominantly by either low-speed dialup access or have no data service available at all. Many research and scholarly articles have been published with suggested solution to overcome this problem. Specifically, it was suggested that new Long-Term Evolution (LTE) technology may provide the answer [1.2]. Others examined the application of Mobile ad hoc networks (MANETs) as an approach to providing connectivity under conditions where fixed communications infrastructure is non-existent [1.1]. In both cases, it is shown that while these solutions are possible their effectiveness and specifically their low-cost implementation remain a significant challenge. Furthermore, in some of these earlier publications which addressed the rural area communication problems, only partial solutions were offered in a specific technology area, e.g. networking [1.3].

Development of cognitive directional networking technology has to deal with technical and practical considerations (which are highly multidisciplinary) as well as need regulatory requirements. The key enabling technologies for a futuristic wireless communication are realistic propagation modeling, integration of directional antennas and adaptive cognitive communication systems.

1.2 Objectives

The focus of this thesis is the development of advanced nodes (base stations) from a physical layer perspective and overall system architecture supporting mobile wireless access and networking applications suitable for rural areas. The objective is to design advanced base stations with a fully broadband directional antenna array and fast digital signal processing algorithms without any modifications in the Medium Access Control (MAC) or higher upper layers, especially for challenging rural areas environment. MAC layer timing constraints should be taken in account to ensure practical implementation in available standards. Moreover, for network planning, optimized placement of developed advanced nodes in rural areas should also be analyzed. Approach should be able to evaluate the integrated effects of realistic propagation modeling and directional antennas and also provide design guidelines for performance analysis. The results should offer significant performance gains, minimal use of computational resources, novel physical layer architecture, and excellent cellular coverage, where infrastructure based cellular base stations are difficult and expensive to install. The results provided should help cellular operators, manufacturers and other researchers to adapt this new innovative technology for effective and seamless broadband wireless service for remote areas so as to connect every individual to the power of the internet.

1.3 Contributions of this thesis

One of the key novelty of this research is that, for the first time a physical layer focused solution is proposed based on the use of directional networking with broadband directional antennas, integrating accurate propagation modeling resources and adaptive communication capabilities for real time applications. It is shown that by integrating these diverse resources in advanced base stations, it is possible to address and solve the long-standing problem of inadequate communication and high data rate needs in rural areas. In this thesis, there are four key elements to the proposed cognitive directional networking solution, which is described as follows:

- Novel physical layer based architecture design of cellular base stations equipped with directional antennas arrays and fast signal processing capabilities to address the unique challenges of rural areas.
- Facilitate the proposed advanced wireless network without introducing complex modifications in the Medium Access Control (MAC) layer or upper layers for current wireless standards such as IEEE 802.11 (Wi-Fi).
- Optimize placement of advanced base stations/nodes over rural areas, using geospatial assets (such as Google Earth) and genetic algorithm as a part of network design and planning.
- Adaptive cognitive communication approach integrating realistic geospatial resources and directional antenna parameters for significant communication performance gains and optimal use of scare spectrum resources as part of environment awareness engine.

An innovative six sectoral cellular base station architecture was designed called Advanced Base Station or Node for wireless communication with mobile users. Separate hexagonal antenna array (dual polarized broadband directional antenna) equipped with additional signal processing capabilities are used for user discovery (via scanning) and for data communication with users. Each advanced base station is capable of digital beamforming, beam steering, handover, load management and coordinated multipoint transmission or reception. This enables the base station to achieve large coverage area, economical use of radiated energy and better frequency reuse due to six-sectors instead of traditional three-sector. In chapter 2, complete physical layer architecture overview starting from the computation of Angle of arrival (AoA) for each user, sector assignment, saving data in the user database, calculating the beamforming/ beamsteering weights using processing unit and directing the communication (data) beam to the respective user is clearly explained. Adaptive antenna array is proposed for wireless connections/link between advanced nodes via extremely high frequency (EHF) such as from 60- 70GHz link provides a new approach for rural area network. This wireless communication is established amongst the base stations via Internet Protocol (IP) connectivity. This interconnectivity facilitates mobile user handover, load management, and resource assignment. All the modifications due to beamforming directional antennas array are restricted to the physical layer of the Advanced Base Station.

The proposed MAC layer desirable timing considerations and analytical findings for IEEE 802.11 standards are presented to facilitate the implementation of the advanced wireless network without requiring modification to Medium Access Control (MAC) layer. The predictable time required to estimate the Angle of Arrival (AoA), compute the beamforming weight and apply the beamforming weights is estimated. Inter-frame space where the Angle of Arrival estimation and beamforming calculation can be applied for IEEE 802.11 is also presented. The advanced processing unit of the advanced nodes will perform the Angle of Arrival and beamforming computation within the inter-frame space timing, and therefore the MAC interface with directional antennas array would happen in a very short period of time (nanoseconds to milliseconds) while the antenna beam is still in receiving or transmitting position. Software and hardware simulations confirm that the calculated Angle of Arrival and Beamforming weights timing could be achieved using practical high-performance FPGAs such as Xilinx Virtex 7.

As a part of radio network planning and design, the use of Genetic Algorithm (GA) and geospatial assets (such as Google Earth) to place base stations is proposed in order to optimize the cellular coverage in rural areas. Maui Island, Hawaii and Kohala region of the Big Island, Hawaii are used as case studies in this thesis because they demonstration typical rural area characteristics and challenges. Main finding and major results show that instead of four isotropic regular base stations, only two directional antenna array based advanced base stations can be used to cover approximately the same area for both the islands (~91% for Maui and ~83% for Kohala). Due to different levels of cellular user density, the path gain at each location of the area under consideration could be assigned priority based weights which would result in variable cell sizes based on population density.

Towards the later part of the thesis, adaptive cognitive communication system is proposed with a focus on integrating realistic multipath modeling and directional reception / transmission with existing systems such as Orthogonal Frequency Division Multiplexing Access (OFDMA) and Multiuser Wireless Communication system using both isotropic and directional antennas. The obtained results show that the achievable improvements when using directional antennas depends not only on the achievable gains and reduction in beamwidth but also on the richness of multiple environment and could vary from user to user depending if its line of sight user (LOS) user or Non-Line of Sight (NLOS) user. In real-time communication applications, minimizing the computational time in generating ray-tracing data without losing the level of detail is vital for achieving improved performance. Chapter 5 examines such a tradeoff and it is shown that for realistic SNR values, just the path gain and Angle of Arrival (AoA) data for as few as 5 paths could be sufficient in forming a propagation model at the receiver while satisfying certain desired performance criteria. When compared to using all the available propagation modeling data, the use of only 5 paths or less results in 85% reduction in computation time required for generating the channel matrix. The findings of this research are used to provide guidelines regarding the trade-offs involved in using directional antennas and propagation models as a part of the environmental awareness engine to help improve the performance of the CR system.

1.4 Outline

The thesis is organized as follows:

Chapter 2 provides an overview of various rural area challenges encountered in the typical environment. It also introduces the novel advanced base station architecture and physical layer based solution approach. The overall wireless access architecture starting from scanning new users to establishing wireless links to the core network via a backhaul is also discussed. Finally, the proposed radio network planning technology using realistic propagation modeling to optimize coverage in rural areas is also discussed in brief.

Chapter 3 gives a detailed description of various operations conducted by the advanced nodes such as scanning for user discovery, angle of arrival estimation and beamforming using different methods. This chapter focusses on addressing the MAC layer requirements, estimating optimized timing schedules for advanced operations without any effect on MAC or higher upper layers. Software and hardware simulations confirming the estimated timing requirements for angle of arrival and beamforming for practical high-performance FPGAs such as Xilinx Virtex 7 is also reported in this chapter. Moreover, how these timing considerations would fit into existing wireless standards such as IEEE 802.11 is also described towards the latter half of the chapter.

Chapter 4 first discusses rural area network planning issues and challenges and finally introduces the proposed solution approach. Optimized placement of base station in rural areas using geospatial recourses and genetic algorithm (GA) is discussed taking into account the terrain related challenges offered by rural areas and the gain of the directional antenna elements used in base stations. Genetic Algorithm (GA) uses this geospatial data to optimally place the base stations in the given area. Link budget calculations are performed to obtain a path gain threshold which is used to compute the cost function (total area with bad cellular coverage, i.e. coverage below the path gain threshold) for the GA. For a given number of base stations, this cost function is minimized by the GA until the best base station locations are reached. Maui Island and Kohala Region of the Big Island, Hawaii are used in this chapter to compare the cellular coverage offered by omnidirectional Base Stations with that of Advanced Base Stations, equipped with directional antenna arrays. The major simulation results are shown in terms of path gain color map for both isotropic and directional antennas. Later the genetic algorithm convergence and comparison with other sectoral antennas are also discussed.

Chapter 5 discusses the present cognitive communication challenges for real time implementation and introduces the innovative adaptive communication system approach. First, it starts with the architectural flow of adaptive communication system. Second, the implementation of the proposed propagation modeling and directional antennas schemes on two existing systems such as Orthogonal Frequency Division Multiplexing Access (OFDMA) and Multiuser Wireless Communication system are briefly described. Later the main finding and simulation results of both communication schemes discussed. The systems are simulated in their basic form and their performance was analyzed and compared when operated using either isotropic or directional receivers. The metrics used for performance analysis are Bit-Error Rate (BER) and Capacity. Moreover, the effects of different levels of details in the site-specific realistic CSI and different number of multipath used in generating the channel matrix are also investigated. Furthermore, the trade-offs involved in determining the most advantageous beamwidth of directional antennas are also studied. The simulations in this thesis are considered initial steps towards designing an adaptive cognitive communication system that achieves the desired BER for a given SNR, employing directional antennas and using minimal computational resources for calculating the channel matrix. Later the computational requirements and challenges are discussed for real time implementation.

Chapter 6 provides a summary of the main findings and major results of this thesis and proposes work to be done in the future.

CHAPTER 2

PROPOSED TECHNOLOGY FOR RURAL AREA IMPLEMENTATION

Wireless technology experienced a fast and rapid development in the past few years. However, research and investment in wireless communications so far have been focused mainly on high-density areas or fully connected networks. The technology solutions developed for above mentioned domains do not readily apply to rural and sparse domains. The users in rural and sparse areas are still served predominately by either low-speed dialup access or have no data service available at all. Rural areas offer difficult environmental conditions for cellular coverage. These include but are not limited to uneven terrains, mountains, ridges, deep forestation, etc. Providing cellular service to these areas using omnidirectional base stations has several disadvantages, most important of which are wastage of energy in areas with no active users and less coverage area per base stations.

Advances in wireless technology and system level applications for data and communications, now embodied in the 802.11 standards and commercialized by numerous suppliers as Wi-Fi, open new possibilities for broadband fixed wireless access. The proliferation of Wi-Fi and other emerging technologies such as WiMAX, LTE has resulted in significant reductions in equipment costs. The potential of using Wi-Fi to extend internet access to less densely populated and isolated areas using full directional base stations is being explored in this chapter.

This chapter explores the largely overlooked rural and sparse region, where distance, rough terrain and low node density are the key parameters driving system design and performance. The focus of this chapter is the development of advanced nodes from a physical layer perspective and overall system architecture supporting mobile wireless access and networking applications suitable for rural areas. The use of advanced nodes with directional beamforming antennas and smart digital signal processing capabilities is proposed to address the challenges posed by rural areas. The directional antennas facilitate base station-to-base station and base station to mobile user connectivity. New adaptive array base station architecture is also offered for fully directional networking among advanced base stations. The proposed advanced base stations will aptly address the rural area challenges, increase the coverage area and improve antenna radiation energy efficiency and data rate.

Towards the later sections of the chapter, effective, accurate and cost efficient radio network planning technique proposing the use of our group's propagation modeling software and genetic algorithm for optimizing wireless coverage over challenging rural areas environments is also discussed.

Section 2.1 provides an overview of various rural area challenges encountered in a typical environment. Section 2.2 introduces the novel advanced base station architecture and physical layer based solution approach. The overall network architecture, starting from scanning new users to establishing a wireless link to the core network via a backhaul is also discussed. Finally, the radio network planning technology using realistic propagation modeling to optimize coverage in rural areas is also discussed.

2.1 RURAL AREA CHALLENGES

Providing cellular coverage to rural areas is a challenging task due to the difficult topological conditions offered by the varying stretches of rural terrains. Deep forestation, mountains and hills, land-sea transition, stretch of sparely populated land and also patches of barren land are some of the typical characteristics of rural areas. Omnidirectional or sectoral base stations are not capable of overcoming these challenges and also not covering the entire rural areas appropriately. In this thesis, various rural areas from the Islands of Hawaii are considered as test cases. Fig. 2.1 shows the map of Waimea region in the Big Island, Hawaii, highlighting some of the characteristics of a typical rural area. Two of the most important issues that omnidirectional base stations face are

- Less range and hence limited coverage area per base station
- Uniform distribution of radiated energy, resulting in wasted energy in certain unpopulated areas.

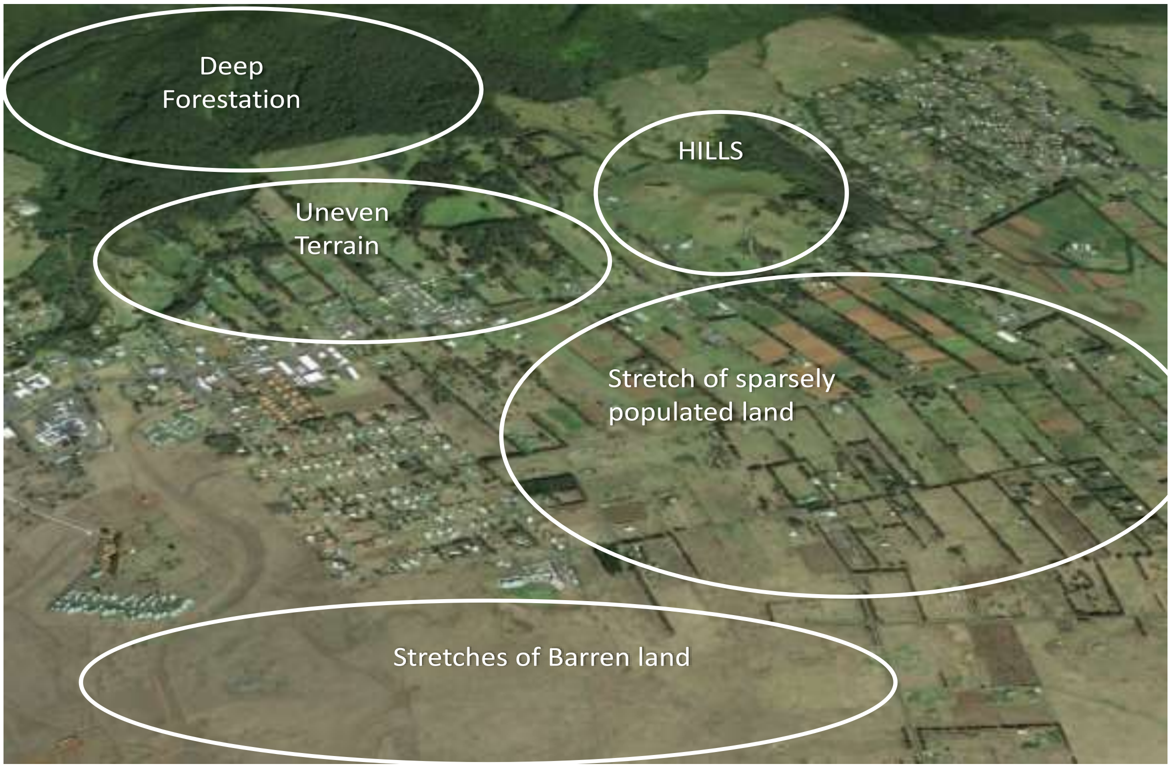


Fig. 2.1. Map of Waimea area on the Big Island, Hawaii: typical rural area characteristics are illustrated

Bringing broadband wireless service to rural areas is financially challenging as well. The cost of delivering broadband services increase substantially outside of large urban areas, which in turn greatly increase the risk of investment in broadband wireless for rural areas [2.1]. The key lies in optimal coverage of vast rural areas implementing very few base stations to lower cost. Today's new wireless technologies embodied in commercial products such as Wi-Fi, WiMAX [2.2], LTE [2.3] and use of smart beamforming antennas show considerable promises for cost-effective wireless broadband services. The effective use of sparse spectrum resources saves operators a substantial amount of money in spectrum license costs [2.4, 2.5]. All these factors contribute to the feasibility of a higher success rate in bringing broadband service to rural and spares areas. To address these challenges, our group is working towards the development of advanced base stations or nodes which will be described in detail in the following section.

2.2 PROPOSED TECHNOLOGIES: PHYSICAL LAYER BASED APPROACH

The proposed physical layer focused solution is based on the use of directional networking with broadband directional antennas, integrating accurate propagation modeling resources and adaptive cognitive communication capabilities for real time applications. It is shown that by integrating these diverse resources in advanced base station or nodes, it is possible to address and solve the long standing problem of adequate communication and high data rate needs in rural areas.

As most current radio and wireless networking protocols were designed for Omni-directional and/or fixed infrastructure environments, the use of directional antennas introduces disrupting side effects in many protocol layers of a networking system. Solving these issues is the topic of much current research [2.6, 2.7, and 2.8]. In this thesis, a novel architecture for developing a directional antennas solution that avoids most of these inter-layers links problems is described. Instead, the proposed solution is based on making changes to the architecture of the wireless nodes, and specifically, it introduces a set of set aside Advanced nodes with enhanced capabilities to facilitate the implementation of the wireless network without requiring modification to Medium Access Control (MAC) or other subsequent OSI model layers. The key aspect of the proposed design is the fact that the advanced nodes are equipped with DSP and control capabilities so as to facilitate direct interfacing with the MAC layer and without a need for modification due to the antenna directionality. This approach is similar to the Directional Ad Hoc Networking (DANTE) Project developed by the Navy [2.9] but with adaptation and significant modification to enhance capabilities and meet needs in rural areas. Besides using directional antennas and utilizing its associated advantages, the proposed approach provides an opportunity to immediately build fully directional advanced nodes using a wide range of radios and without requiring major modification to the radio or existing protocols. In the following sub-sections, an overview of the proposed system, followed by optimal distribution of these advanced nodes in rural areas will be discussed.

2.2.1 ADVANCED NODE TECHNOLOGY

Recent advances in antenna designs have shown that significant progress in developing low-cost antenna arrays systems with advanced capabilities including beamforming and beam steering can be achieved [2.10,2.11]. For wireless connection with mobile users, separate hexagonal directional antenna arrays, as shown in Fig. 2.2, one for user discovery (via scanning) and the other for data communication with users is proposed. Some of the major advantages of using separate directional antennas are lower interference, enhanced spatial reuse, longer transmission range and reduced power requirements. It will also be noted from Figure 2.2, that the advanced node design was based on six apertures or directional antennas and their beam forming controls. This topology is based on Yao's analysis which shows that six sectors each covering 60° will always result in a fully connected graph [2.12, 2.13]. Scanning antenna array would be used for locating new mobile user discovery in rural areas while the communication antenna array would be used for data communication. These two antenna arrays are used for complete mobile user access.

Adaptive antenna array is incorporated to facilitate node to node communication and networking. The adaptive array solution is simple as it involves building networks out of point to point links that are maintained on the timescale of seconds to minutes. This avoids the problems of trying to work at the micro- to millisecond time scales of MACs and is compatible with node mobility patterns and routing update timescales. In a rural communications environment, it is expected that node to node can be maintained with high reliability, hence the proposed approach is not expected to cause degradation in the overall performance of the overall wireless network. In other words, by steering beams and receiving feedback from the other adaptive array at each beam position, the advanced node is able to acquire basic information such as link state and received signal strength indicator (RSSI) for various beam positions, thus maintaining the communications link. This forms the basis for neighbor discovery, RF tracking, and topology control algorithms and equally important it is being done without the use of GPS.

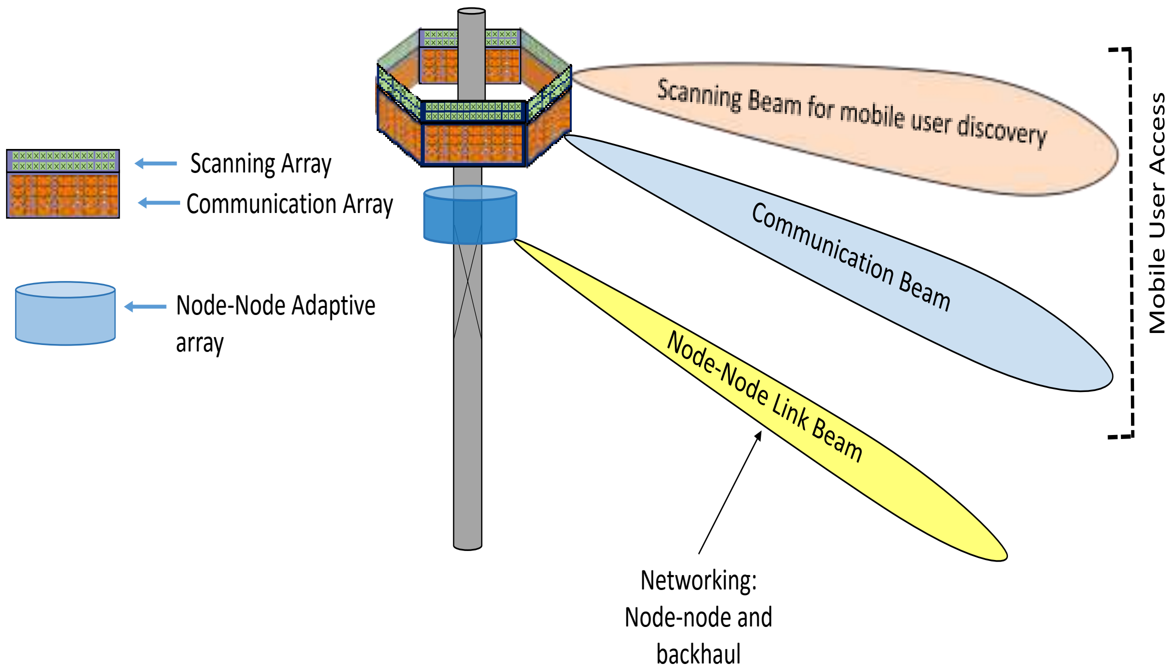


Fig. 2.2. Architecture of an Advanced Node.

For the past few years, our group has been developing a wide variety of antenna design, for example, those operating in pentaband, including DCS, PCS, UMTS, 2.5-GHz and 3.5-GHz WiMAX bands [2.14], others with low-cost beam steering capabilities using metamaterial phase shifters [2.15]. And others with an artificial mu-negative transmission line (MNG-TL) structure for wide band operation [2.16]. More recently, however, our group focused on the development of ultra-wideband antennas with dual polarization using the low cost long slot antenna technology [2.17]. In all cases, these antennas were fabricated and simulation results were compared with experimental data. Fig. 2.3 shows some of the recent work by our team showing the following (a) Long slot antenna array [2.18], (b) Circular polarized dual feed stacked patch antenna array [2.19] and high performance broadband crossover design using butler matrix [2.20], (c) Beam steering using butler matrix (d) dual polarized long slot antenna array [2.21]. Similar advanced antenna arrays can be designed as a part of advanced node for rural area communication.

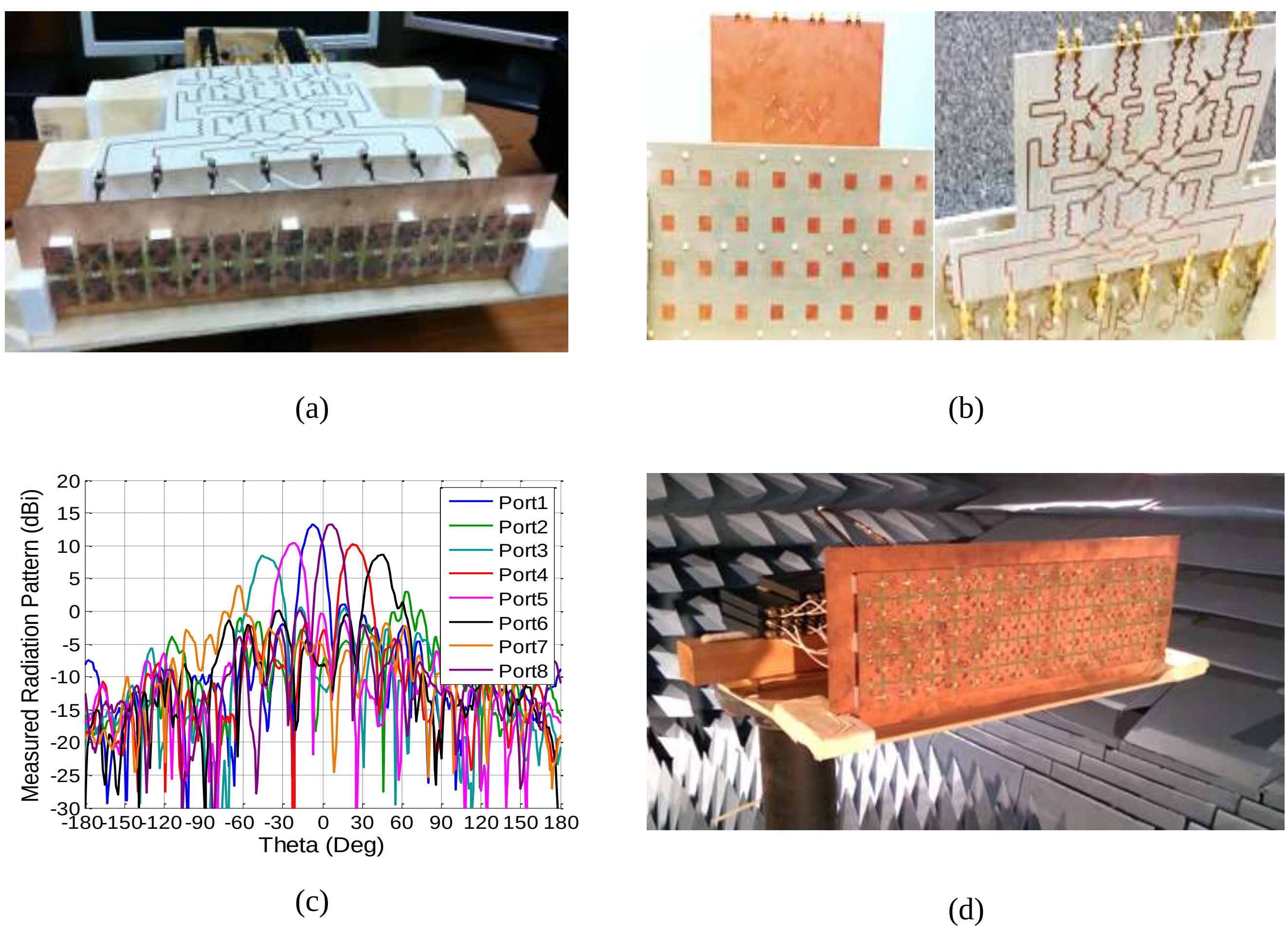


Fig. 2.3. Directional antennas research at Hawaii Center for Advanced Communications, University of Hawaii. (a) Long slot antenna array (b) Circular Pol dual-feed stacked patch antenna array and Butler matrix (c) Beam steering simulations using Butler Matrix (d) Dual-Pol Long Slot antenna array

Each sector of the advanced base station is capable of computing the Angle of Arrival (AoA) for each user via the scanning array, and based on the collected AoA user data, performing advanced sector assignment, calculating beamforming/ beamsteering weights, and finally communicating through sectoral communication array. The main advantage of using directional antennas capable of digital beamforming is that the cell size of the base station is highly dynamic, based on the density of mobile users. This allows for maximal coverage and the lack of wasted energy in uninhabited areas. It is worth mentioning that all the modifications due to the directional antennas are restricted to the physical layer of the Advanced Base Stations, thus satisfying the standards for the Medium Access Control (MAC) and upper layers.

The key aspect of the proposed design is the fact that the advanced nodes are equipped with smart digital signal processing and network control capabilities so as to facilitate direct interfacing with the MAC layer and without a need for modification due to the antenna directionality. It is known that the MAC layer required a very short period of time, milliseconds, and hence, its interface with directional antennas must happen such that the hand shake occurs while the antenna beam is still in receiving or transmitting position. Failure to do so, the sent packet say sent by a transmitter will not receive an acknowledgment, and ultimately this will cause not only disturbance at the MAC layer but throughout higher protocol layers [2.6, 2.7]. Typical wireless MAC protocols were designed to overcome the challenges of the wireless medium such as hidden terminal problem and deafness. But the unique characteristics of directional antennas provide unprecedented challenges that should be considered in the design of the MAC protocols. Some of the challenges are provided below [2.6, 2.8]:

- **Deafness:** It occurs when a transmitter tries to communicate with a receiver but fails because the receiver is beamformed towards a direction away from the transmitter. Due to these characteristics of directional beamforming, the intended receiver is unable to receive the transmitter's signal and as a result appears deaf to the transmitter.

- **Hidden Terminals:** Hidden terminal problem in wireless networks occurs when two nodes are outside the carrier sensing range of each other and each tries to communicate with a common node causing collisions. To solve this a handshaking concept (RTS/CTS) was proposed before data transmission. But in the case of beamforming directional antennas, the hidden terminal problem occurs when a potential interferer could not receive the RTS/CTS exchange due to its antenna orientation during the handshake and then initiates a transmission that causes a collision.
- **Head of Line Blocking:** The head of line blocking problem with directional antennas occurs as a result if First-In-First-Out (FIFO) queening policy. This policy works fine in the presence of omnidirectional antennas since all outstanding packets use the same medium. If the medium is busy, no packets can be transmitted. However in case of beamforming antennas, the medium is spatially divided and it may be available in some directions but not others. If the packets at the top of the queue are destined to a busy node/direction, it will block all the subsequent packets even though some of them can be transmitted.

The advanced node solution is simple as it involves scanning for new users using scanning arrays, and simultaneously maintain communication/data link with already established users via the communication array. Adaptive antenna array maintains a constant and high-performance link with other nodes for a fully connected network. The six-sectoral architecture of advanced base station eliminates the probability of deafness and hidden terminal problems. In a rural communications environment, it is estimated that node to node can be maintained with high reliability due to lack of interference, hence the proposed approach is expected to provide performance improvement of the overall wireless network.

Fig 2.4 shows the advanced node user discovery and communication process changes restricted only to the physical layer. The physical layer modifications would include scanning for new users, angle of arrival estimation, sector assignment, beamforming and applying weights to the assigned sector, and finally communicating through the sectoral communication arrays. All changes will be contained in the physical layer while no changes will be made to medium access control (MAC) or higher upper layers.

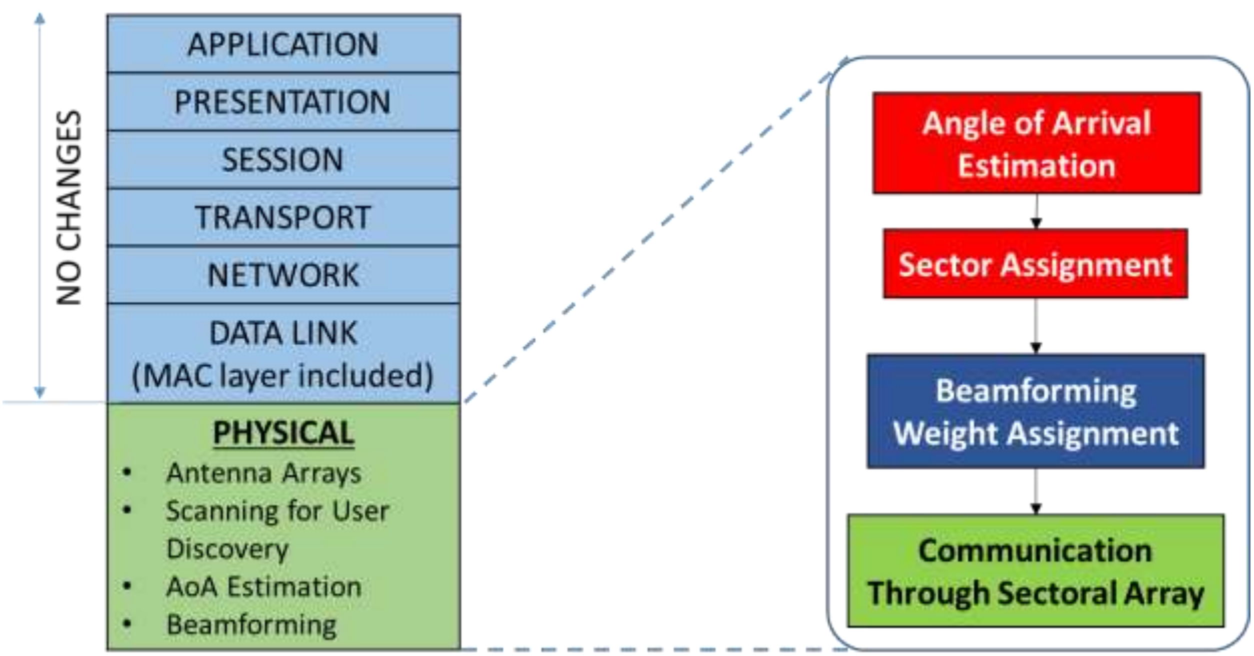


Fig. 2.4 Physical layer modifications for user discovery and communication process.

The complete advanced node architecture displaying the six sectors and offered physical layer modifications is shown in Fig 2.5. As shown in the figure, each advanced node consists of six sectors (S1, S2…S6) for broadband mobile access. Sector 4 is zoomed out to show the specific details and proposed modifications in each sector consisting of data link layer, angle of arrival estimation process and beamforming, and physical directional antenna arrays for communication and scanning procedure. Each sector acts as a single access point, which is very advantageous if any one of the sectors does not function properly due to any circumstances, then rest five sectors can still be fully operational. Since each sector acts as a single independent access point, the function of the router is to forward the data packets to the respective sectors. As the planned implementation is in IEEE 802.11 (Wi-Fi) standards, so the router shown in Fig 2.5 is a standard Wi-Fi router. After receiving information about the destination of data packets from the processing unit of the advanced node, the router forwards the data packets to the designated sector.

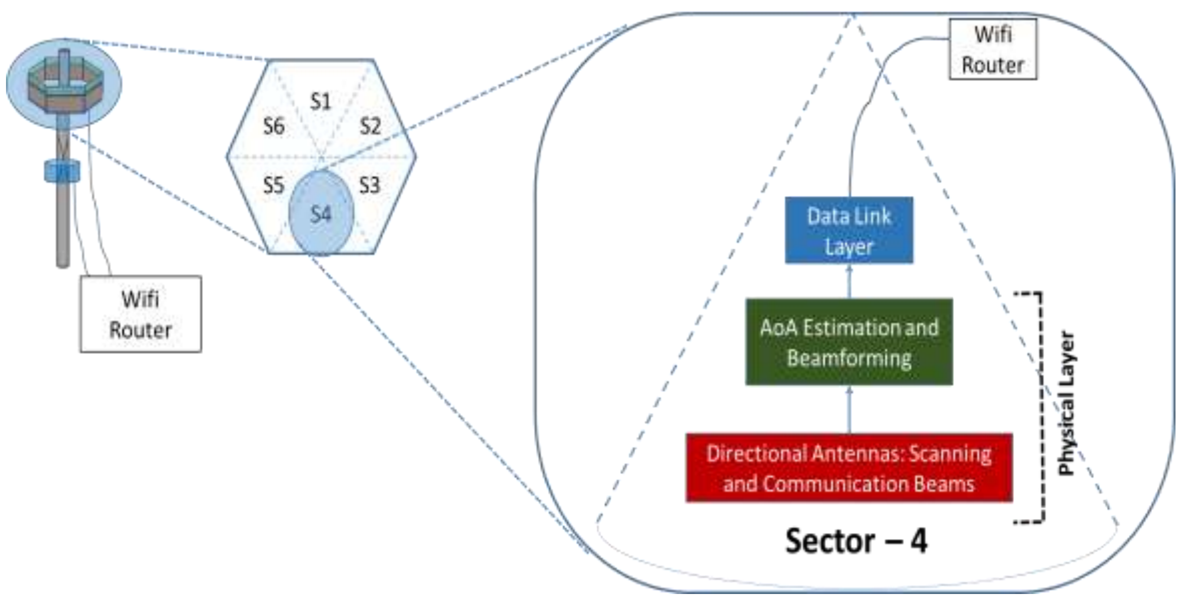
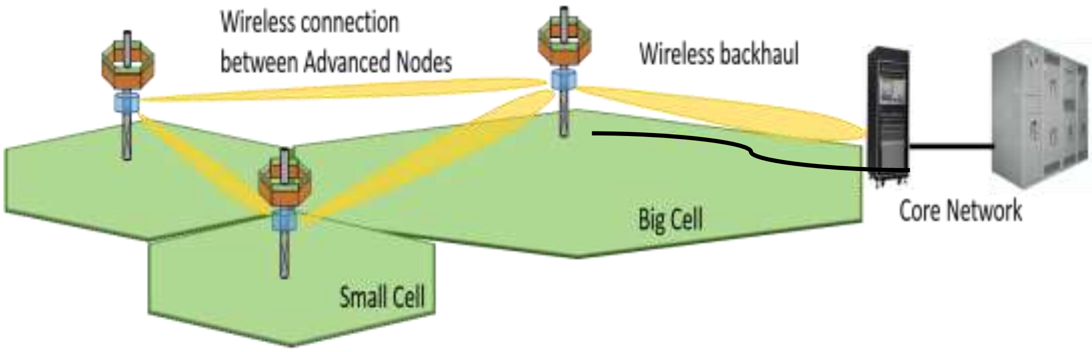


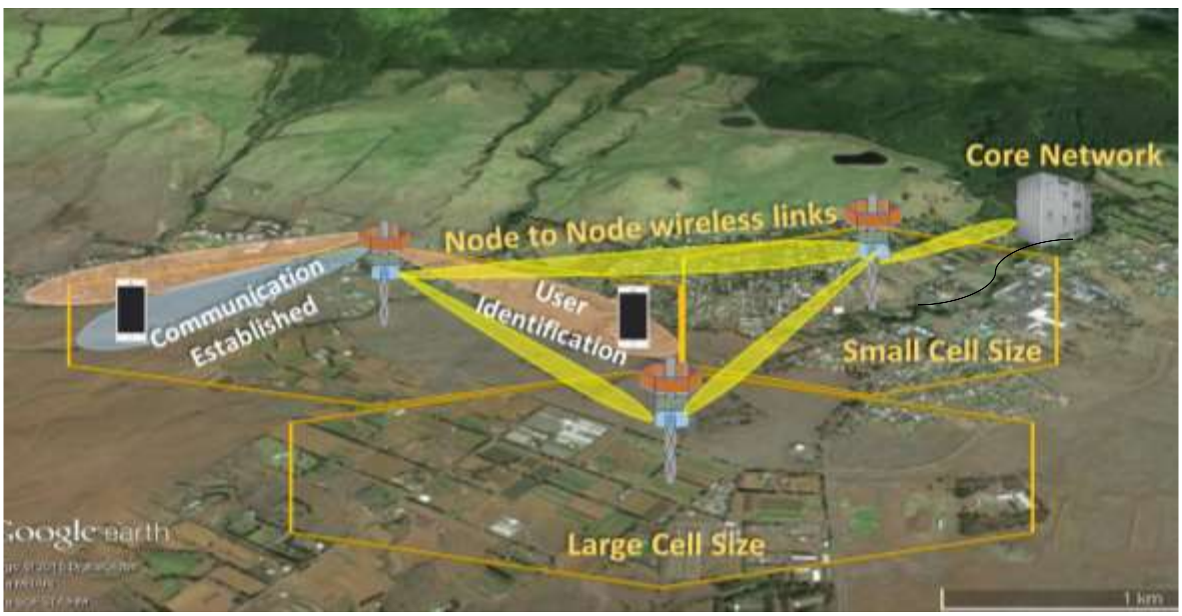
Fig. 2.5 Sector architecture of each advanced node.

Wireless links between different advanced nodes will be accomplished by a hybrid of 60-70 GHz wireless technology and fixed wired line based on their position from one another. The 60-70 GHz band is located in the millimeter-wave portion of the electromagnetic spectrum, where the wavelength varies from ten millimeters (30 GHz) down to one millimeter (300 GHz). The millimeter-wave portion of the RF spectrum has been largely unexploited for wireless application. Wireless backhaul using 60-70 GHz [2.22, 2.23, 2.24] link can be provided for line of sight (LoS) advanced nodes within a medium-cell area backhaul (few kilometers distance). A LoS wireless medium cell backhaul solution, such as microwave, 60-70 GHz, implies that there should be a direct and unobstructed visibility between the transceivers at each end of the link. A highly directional beam from the adaptive antenna array transmits data between two transceivers and transports data in a straight line with little or no fading or multipath radio interface. This is a highly efficient use of spectrum, as multiple microwave transceivers can function with a few kilometers of each other and reuse the frequency band for transmitting separate data streams. Narrow beamwidth antennas associated with 60 GHz radio enable multiple radios to operate on the same tower and provide interference immunity from other links. Wired links such as copper/ fiber links would be used for large-cell backhaul where the distance between the advanced nodes is more than few kilometers. The wireless links between advanced nodes and backhaul technology are shown in Fig 2.6 (a), where different cell sizes are shown (small, medium, big). Also, the backhaul link to the core network is also depicted via a wired and wireless connection. Depending upon the cell size and distance between the advanced nodes, either of the two choices will be selected and implemented in rural area practical scenario.

Finally, overview of the complete advanced node system, which is discussed in this section is shown for a given rural area in Fig 2.6 (b). As shown in the figure, advanced nodes are placed in the center of each cell and have two beams namely scanning beam (depicted as orange) and communication beam (depicted as blue) for mobile user access. The process of user identification and communication establishment is also shown in the figure.



(a)



(b)

Fig. 2.6 (a) Wireless links between advanced node and backhaul technology (b) Overview of the complete advanced node system in rural area.

The radio network planning technology used for placement of each advanced node for a given region or rural area is described in the next section. Wireless links between advanced nodes are shown as yellow beam emanating from the adaptive arrays. Moreover, the wired and wireless backhaul connection to the core network is also shown in the figure.

2.2.2 RADIO NETWORK PLANNING USING REALISTIC PROPAGATION MODELING

The quality of service of the GSM/UMTS system in the country, especially in rural areas is unreliable [2.25], with its accessibility and ability to retain the network is unsatisfactory. Operators are yet to meet customer's satisfaction as subscribers, so efficient placement of radio facilities with emphasis on the base station has been a concern area of research in the bid to providing better services in cellular telecommunication provision. In GSM [2.26], the network is divided into a lot of cells, and usually a base station is planted in the center of each cell. For the sake of easy analysis, the cells are represented as neighboring hexagons, while in reality they can be any kind of forms and overlap with each other. There is one important feature in GSM network planning, the coverage planning, and capacity planning are independent. The coverage planning depends on the received signal strength, that is to say the covered area is nearly only limited by the minimum signal strength at the cell edge while the later capacity planning depends mainly on the frequency allocation. The main procedure of UMTS are very similar to that of GSM, and the coverage and capacity planning play also an important role in the whole radio network planning. Since UMTS is interference limited, a big number of users will reduce the power availability at the base station to combat interference, and therefore there is a reducing in cell size. Similar to GSM our approach is based on optimizing the coverage of the base stations in rural areas only while we do not take capacity planning into account for now.

Cell planning is done to ensure proper coverage and avoid interference in a network. Deciding where to place the base station of a cellular network is a very important issue that is usually decided during the process of cell planning. Network planning is of paramount importance to the operator. Good planning will result in less project infrastructure expenses, ensure more customer satisfaction and less need for new rural sites and regions.

In general, the radio network planning process, a site survey of the area to be covered is conducted and possible sites to set up the base stations are investigated. Based on the empirical propagation models, the link budget is calculated, which will help define the cell range and coverage threshold. Empirical models such as Hata-Okumura and deterministic model such as two ray model are used for network planning. Due to the often complex outdoor propagation environments, intensive measurements are used to collect data and build empirical propagation models that could be used to determine the number and locations of transmitting base stations and establish adequate coverage in the region. The coverage of a rural area network is thus more difficult and time consuming to optimize based on empirical formulas and a limited number of measurement. Also in rural areas, especially for hilly and mountainous scenarios the limitation of empirical and deterministic models to the vertical plane leads to problems because wave could propagate along a curved valley (in the horizontal plane) not only in the vertical plane.

Based on the radio frequency of interest and the varying cell sizes needs for current and next generation wireless communication systems, ray tracing method is one of the best numerical methods which can be employed to simulate large rural regions. Ray tracing based propagation modeling provides physical insight for a propagation channel by identifying the direct line of sight, reflected, transmitted, diffracted, and scattered propagation mechanisms. The angular domain parameters such as the angle of arrival/departure are intrinsic in the ray structure while time domain parameters such as delay spread can be directly derived from the optical length of the rays. An important aspect of ray tracing simulation is the requirement of an accurate there-dimensional physical model for the propagation environment. Thanks to the rapid accumulation of geospatial data in government agencies and industries, more high resolutions 2D and 3D models can be created from the available data on the internet, such as NASA and Google Earth. Our research group specializes in fast ray tracing algorithm for realistic propagation modeling [2.27, 2.28]. The basic idea for 3D reconstruction is to use the google functions to setup calibration or key objects together with the 3D visualization so that the footprint, height of building, ridge and terrain details can be extracted accurately. For example, Fig. 2.7 shows the 3D reconstructed models created by our group from Google Earth data showing an urban area in Waikiki, Hawaii [2.29]. In general, using our group's propagation modeling software any urban, suburban or rural area data from google earth can be extracted to reconstruct realistic 3D models.

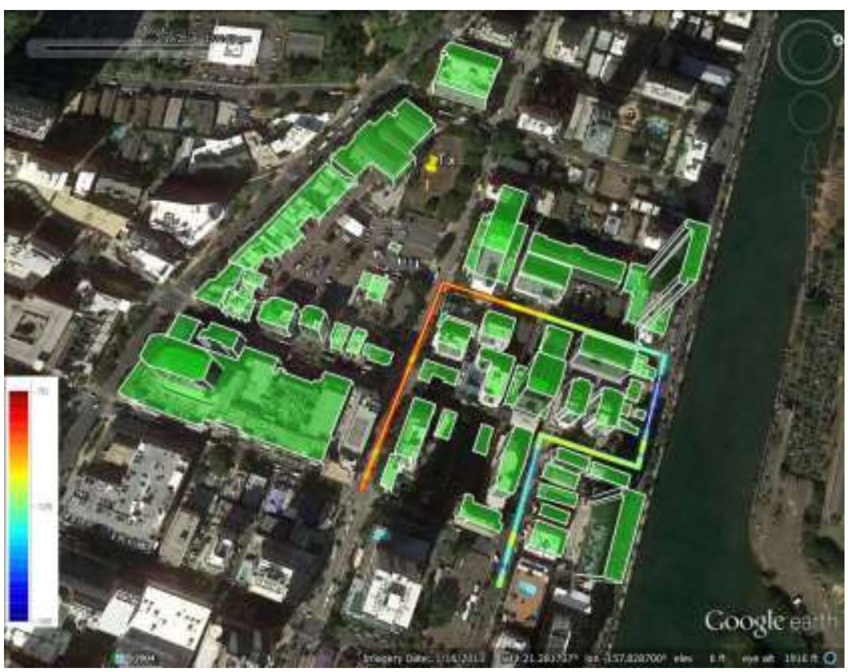


Fig. 2.7 3D reconstructed models created from Google Earth for an urban area in Wakiki, Hawaii.

Similarly for rural areas, diffraction of ridges is required for predicting radio signal in mountainous regions and mostly the realistic shape is over simplified such as knife edge or wedge [2.30]. Also, the ridge orientation is ignored and the EM waves are assumed to be normally incident on the ridge. Fig. 2.8 shows the extracted ridges for a mountains area in Oahu Island, Hawaii taking into account key features such as slope and orientation of the ridges. These keys features are highly required for accurate radio propagation prediction for advanced node technology.

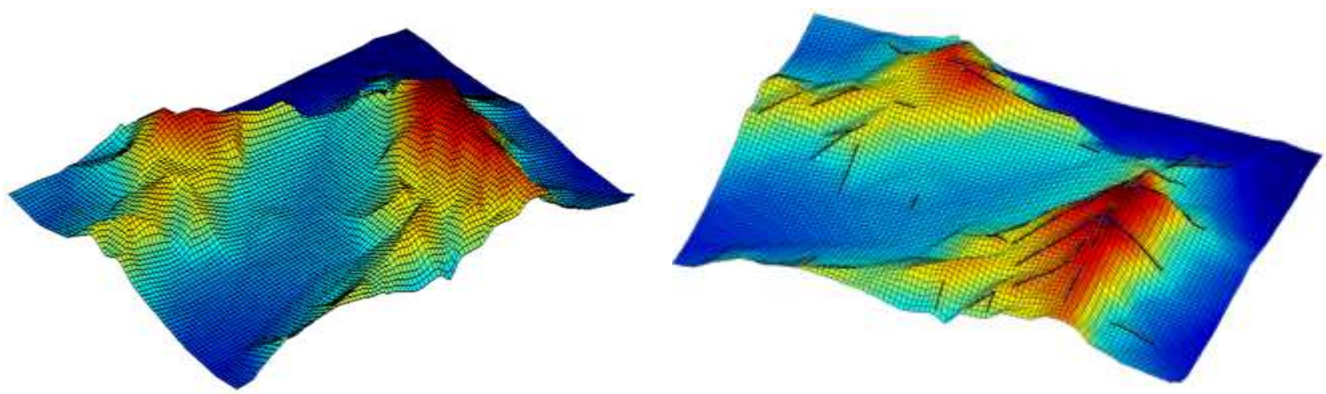


Fig. 2.8 Extracted ridges for a mountainous area in Oahu Island, Hawaii.

To help to obtain an optimized wireless coverage solution, it is necessary to integrate our group's available ray tracing engine with a suitable optimization procedure to help determine the number and locations of the advanced base stations equipped with directional antenna arrays to provide desired wireless coverage. To address this rural area wireless coverage optimization issue, the integration of ray tracing engine with genetic algorithm (GA) optimization procedure was proposed which will be described in detail in Chapter 4. This approach is similar to our group's previous research work related to optimizing coverage in indoor wireless network [2.31]. Over the years, genetic algorithms have been successfully used in optimizing many electromagnetics and antenna design problems [2.32, 2.33]. The idea of Genetic Algorithm comes from the phenomenon of human evolutions first coined by Darwin. From a set of parent points, the children can be generated. Those children are selected that show the best results when evaluating the cost function compared to the ones of their parents and their generation. The GA has iterative optimization procedure that starts with a randomly selected population of potential solutions and gradually evolves towards a global optimal solution. The genetic algorithm explores the solution space by repeatedly mutating and recombining the characteristics within any current population. The GA acts as a global optimizer rather than local optimizer. The solutions are therefore less dependent on initial values and the GA is effective at solving problems that contain many local minima. With the 3D model of the propagation environment. Simulations can be conducted in order to determine the best scheme of allocation of the base stations. The complete procedure of optimizing coverage in rural areas using geospatial assets and genetic algorithm is described in detail in Chapter 4. The following chapter, Chapter 3 illustrates the various process in the advanced node technology and ensures practical implementation in available standards.

CHAPTER 3

ADVANCED NODES TECHNOLOGY

As already described in previous chapter advanced nodes consist of various antenna arrays and digital signal processing for implementing fully directional capabilities at the base station. To make sure these new physical layer modification does not disrupt any changes in the MAC or higher layers, timing requirements has to be taken into considerations. Every wireless standard has different timing considerations which have to be met for operating the advanced base station in practical scenarios. This chapter quantitatively computes the upper bound (timing constraints) required by various processes conducted by the proposed advanced node technology such as scanning for new user discovery, angle of arrival estimation and calculating the beamforming weights to direct the communication beam towards the user. Software and hardware simulations confirming the estimated timing requirements for angle of arrival and beamforming is also reported in this chapter. Moreover, how these timing requirements would fit in available standards such as IEEE 802.11 is also described in detail towards the later part of the chapter.

3.1 SCANNING FOR USER DISCOVERY

Scanning arrays are actively used in radar technology for identifying unknown targets [3.1, 3.2]. Targets are generally found by steering the antenna repetitively through a programmed pattern, to search the volume of the sky or a surface footprint. However, scanning array has never been used as part of the base station to locate the users in a cellular industry. Usually, the initial access between a mobile phone and the cellular base station is done using the omnidirectional antennas or sectoral antennas depending on the type base stations. The major disadvantage of the using omnidirectional/ sectoral antennas for initial access is limited coverage as antennas are radiating energy is every direction. Coverage is a vital component in rural area system design and so a scanning array for user discovery process is proposed. Using a scanning array would focus the energy within the specified beamwidth, hence getting longer coverage distance than omnidirectional antenna arrays.

Usually searching for a cell tower is a passive process, where the cell phone listens to the broadcasted pilot signals and if the signals are strong enough and belonging to the right operator then the cell phone will try to attach. Since in the case of omnidirectional antennas the mobile phone user is always connected to the base station for initial access, so broadcasting channel consists of synchronization signals is always available if the user is within the cell. But for the scanning array type user discovery, the base station sends a broadcasting signal by steering/switching the antenna beam repetitively through a programmed circular pattern. This type of switch beamforming network can be implemented using Butler Matrix [3.3, 3.4] or even digitally by the use of field programmable gate arrays (FPGAs) [3.5, 3.6, 3.7]. The proposed scanning array can have either a single array for each six sectors for fast initial access and user discovery or just one antenna array for the whole 360° scanning. Depending on the actual cell size requirement and how fast the cellular operator wants the mobile user to connect in a rural scenario, one of the selections will be chosen from the above-stated options. Fig. 3.1 shows the two different scanning options proposed in this thesis, where Fig. 3.1(a) represents an advanced node with a single 360° scanning beam switching continuously and periodically at a specific rate while Fig. 3.1(b) represents six scanning beams one for each sector scanning periodically within the sector for faster user discovery process. In the figure, blue colored beams represent scanning beam for user discovery process and green colored beam represents communication/data beam for access. For both the options, the beams switch at a specified angular step and beamwidth can be programed based on the rural area requirements and size.

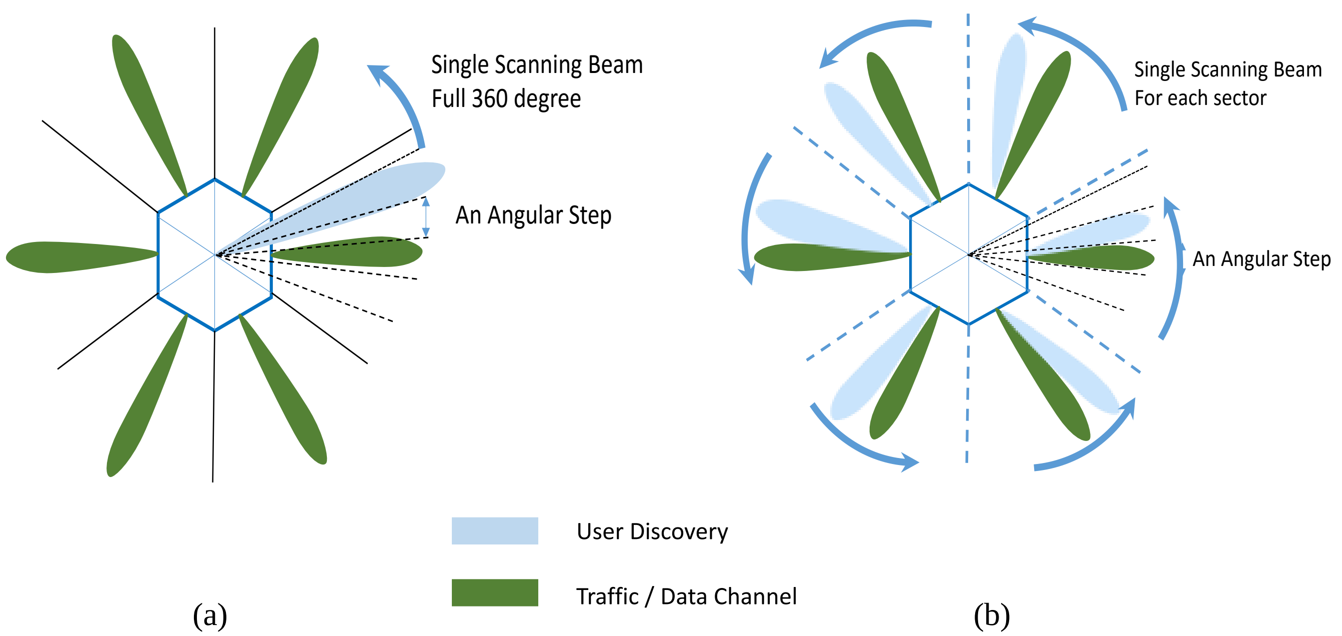


Fig. 3.1. Different options of scanning beams for user discovery (a) Single 360°scanning (b) Six 60° sectoral scanning

For a fully directional base station to appropriately broadcast signals to mobile users such that mobile users would have initial access in the shortest time, few parameters should be taken into account in the design process such as beam switching speed, beam staying time at one particular position and also mostly importantly minimum mobile user wait time.

Since the focus of implementation is in Wi-Fi, according to the IEEE 802.11 standard every compliant access point (base station) periodically sends outs management frames called beacon frames. The purpose of the beacon frames is to broadcast the presence of an access point in a particular area. All Wi-Fi networks are identified by a network name also known as Service Set Identifier or SSID. SSID is at most 32 characters string announced in beacon frames which are periodically transmitted by access points.

The time interval between two consecutive beacon frames is called the beacon interval. The beacon interval is usually measured in Time Units (TUs), where each TU equals 1024 microseconds, and the default period between beacons is approximately 100 milliseconds [3.8]. One of the other advantages is that beacon signals are configurable parameters so the value can be altered based on the type of network required. It is really important to calculate the minimum scanning time (or mobile user wait time) for the two proposed configurations namely 360°single array and 60°six sector array as discussed in this section. The minimum mobile user wait time calculations are performed as follows.

User Discovery Scanning: Mobile User Wait Time Calculations

$T_W \triangleq$ Mobile user cell search waiting time

$T_{step} \triangleq$ The transition time for a step of the scanning beam

$T_{st} \triangleq$ The duration for which the scanning beam stays in a direction

For a default beacon interval of 100 ms, T_{st}=100 ms

$BW \triangleq$ Beamwidth,

$\omega_{step} \triangleq$ Angular Step size

$ov \triangleq$ Angular overlap in scanning beam $\triangleq BW/\omega_{step}$

$N_{st} \triangleq$ Number of scanning beam steps $= ov\ 360/BW$ for single 360° scanning antenna array

It can be shown that $N_{st}\ (T_{st}+T_{step}) \leq T_W$

For single 360° scanning antenna array, T_{st}=100 ms, T_{step}=10 μs, ov=1 and BW=30°, we get $T_W \geq 1.2\ s$.

For 6 simultaneously scanning beams, one in each sector, $N_{st} = ov\ 60/BW$

For T_{st}=100ms, T_{step}=10 μs, ov=1 and BW=30°, we get $T_W \geq 0.2\ s$

Assuming wait time in a single direction is beacon interval, which is 100 ms, the scanning times are tabulated below with varying beamwidths. Since beacon interval, beamwidth of the scanning array are configurable parameters, Table 3.1 illustrates the minimum mobile user wait time required in seconds for the two options namely 360° single array and 60° six sector array for scanning array beamwidth ranging from 10° to 30°. Table 3.1 illustrates that mobile user cell search time can be as low as 0.2 s for a 60° six sector array with 30° beamwidth. And at maximum can operate at 3.6 s, when using 360° single array at 10° beamwdith.

TABLE 3.1
USER DISCOVERY SCANNING TIMINGS

Scanning Array Beamwidth	360° Single Array	60° Six Sector Arrays
10°	$3.6\ s$	$0.6\ s$
15°	$2.4\ s$	$0.4\ s$
20°	$1.8\ s$	$0.3\ s$
30°	$1.2\ s$	$0.2\ s$

3.2 ANGLE OF ARRIVAL ESTIMATION AND BEAMFORMING WEIGHTS CALCULATION

Smart antenna systems are phased array elements with smart signal processing algorithms used to determine the angle of arrival (AoA) of a radio signal, which can be used subsequently to calculate beamforming vectors needed to track and locate the intended mobile user. The AoA estimation methods are critically important in identifying the accurate position of the mobile user and also computing it in a minimum time for practical rural environment scenarios.

Angel of Arrival estimation is the process of determining the direction of an incoming signal from mobile devices to the base station transceiver station. In this process, the time “phase” difference of arrival at individual elements of the antenna array is calculated and from these delays, the angle (or direction) of the mobile devices can be calculated.

MUltiple SIgnal Classification (MUSIC) [3.9, 3.10]is a well-known high resolution multiple signal classification technique based on exploiting eigen structure of the input covariance matrix, extensively used to estimate the number of signals, and their angle of arrival. With MUSIC, several signal parameters including the number of incident signals, AoA of each signal, strengths and cross-correlation between incident signals and noise power can also be estimated. MUSIC deals with the decomposition of correlation matrix into two orthogonal matrices, signal-subspace, and noise-subspace. Estimation of direction is performed from one of these subspaces, assuming that noise in each channel is highly uncorrelated. This makes the correlation matrix diagonal.

The correlation matrix is stated as follows [3.11]:

$$R_{XX} = E[x.x^H] = E[As + n](s^H A^H + n^H) \tag{3.1}$$

$$=AE[s.s^H]A^H + E[n.n^H]$$

$$=AR_{ss}A^H + R_{nn} \tag{3.2}$$

where H= "Hermitian" means conjugate transpose, E= Expected value is the statistical average, $R_{ss} = D\ X\ D$ source correlation matrix and $R_{ss} = M\ X\ M$ noise correlation matrix. The array correlation matrix has M eigen values $(\lambda_{1,}\lambda_{2,}\lambda_{3,} \cdots \lambda_M)$ along with M associated eigenvectors $E = [e_1, e_2, .. e_{M]}$. If the eigen values are sorted from the largest to smallest, the matrix E can be divided into two subspaces $[E_N E_S.]$ The first subspace E_N is called the noise subspace and is composed of $M - D$ eigenvectors associated with the noise. And the second subspace E_S is called the signal subspace and is composed of D eigenvectors associated with the arriving signals. The noise subspace is a $M\ X\ (M - D)$ matrix. The signal subspace is a $M\ X\ D$ matrix. The noise subspace eigenvectors are orthogonal to the array steering vectors at the angles of arrival $\theta_1, \theta_2, .. \theta_D$. Because of this orthogonality condition, one can show that the Euclidean distance

$d^2 = a(\theta)^H E_N E_N^H a(\theta) = 0$ for each and every arrival angle $\theta_1, \theta_2, \ldots \theta_D$. Placing the distance expression in the denominator creates a sharp peak at the angles of arrival. The MUSIC pseudo spectrum [3.11] is given as follows:

$$PMU(\theta) = \frac{\vec{a}(\theta)^H.\vec{a}(\theta)}{\vec{a}(\theta)^H \vec{E}_N \vec{E}_N{}^H \vec{a}(\theta)} \tag{3.3}$$

MUSIC algorithm follows the above steps to determine the angle of arrival and for that, it requires various number of computations which has to be performed by the system. The system has to be capable enough to perform the tasks and computation with ease. In order to determine the time required by various systems (FPGA based) to compute the number of floating point operations, Table 3.2 is provided showing a comparison of two systems, one using Virtex 7 FPGA [3.12] and the other Raspberry pi [3.13]. The number of real-time floating point operations and time required to perform these computations are tabulated for one active user, 8 antenna elements at the scanning array, and N_b= 128, 1024 bits of received signal at the base station. The number of floating point operations were computed mathematically by calculating the complex multiplication and additions. Raspberry pi is capable of computing 41 million floating point operating per second (Mega-FLOPS or MFLOPS) [3.14] and a Virtex 7 FPGA can compute about 160 Billion FLOPS (Giga-FLOPS or GFLOPS) [3.15, 3.16, and 3.17]. In computing, FLOPS is a standard measure of computing power -Floating Point Operations per second. As can be seen from the Table 3.2, only using 1024 bits of an incident signal the Angle of Arrival can be estimated within 3.35 μs using a Virtex 7 FPGA with 160 GFLOPS. Similarly using a standard microprocessor such as Raspberry pi, the same number of real time floating point operations can be computed in 1.89 ms.

TABLE 3.2
ANGLE OF ARRIVAL ESTIMATION TIMINGS

	Number of Floating Point Operations	Virtex 7 FPGA (160 GFLOPS)	Raspberry pi (41 MFLOPS)
$N_b = 128\ bits$	77828	0.486 μs	1.89 ms
$N_b = 1024\ bits$	536580	3.35 μs	13.08 ms

Before going through the beamforming weights calculation procedure, it would be worth to discuss deterministic beamforming and also formulate the relation between the received signals at the array elements. In the context of array signal processing, beamforming is concerned with the reconstruction of source signals from the outputs of a sensor array. Classically, beamforming requires knowledge of a look direction, which is the direction of the desired source. While blind beamforming tries to copy sources without this information, relying instead on various structural properties of the problem. For simplicity of explanation, a linear array configuration is considered with continuous time signals as shown in Fig. 3.2. As shown in the figure, suppose for an incident wave arriving at an angle θ to a linear array configuration [3.18], the array response vector $\vec{S}_\theta$ is calculated as follows.

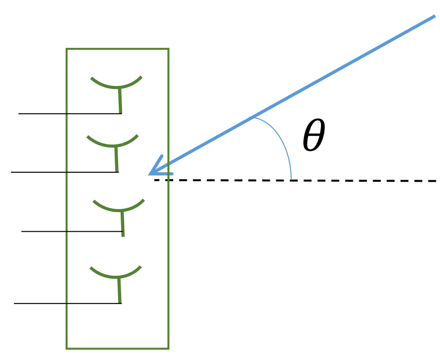


Fig. 3.2. Array Response Vector Diagram.

Let $\vec{S}_\theta$= Array Response vector of size N_{sec} X 1 for the incident angle θ, where N_{sec} denoted the sectoral array size

$$\vec{S}_{\theta} = \begin{pmatrix} 1 \\ e^{\frac{-j2\pi d sin(\theta)}{\lambda}} \\ e^{\frac{-j2\pi d.2.sin(\theta)}{\lambda}} \\ \vdots \\ e^{\frac{-j2\pi d.(N_{sec}-1) sin(\theta)}{\lambda}} \end{pmatrix}_{N_{sec}\ X\ 1} \tag{3.4}$$

where d= antenna spacing = λ/2

λ= wavelength of carrier

The AoA estimates are divided into N_b AoA bins resulting in a binary vector, $\vec{e}$ as output. Each element of the binary vector corresponds to an angular bin, for example bins from $-30°\ to\ 30°$ with increments of 10° as shown in Fig. 3.3. The choice of angular bin widths is based on 3 dB beamwidth of the sectoral antenna array.

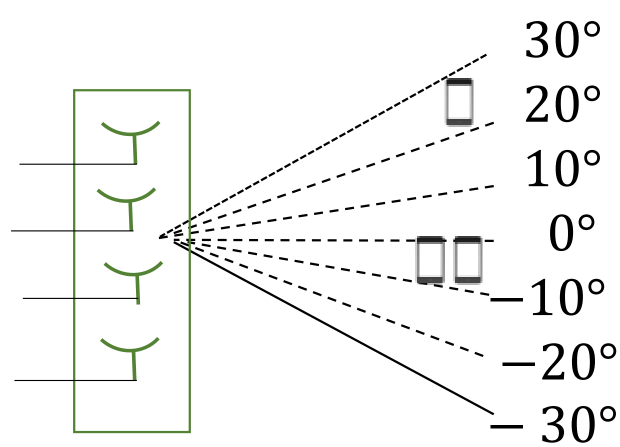


Fig. 3.3. Division of Angle of Arrival Estimates into Angular Bins.

Populating the user database and feeding data to sectoral beamformers is the next set of task to be performed by the advanced node. For the angular bins from $-30°\ to\ 30°$ and increments of $10°$, boresight of the beams is chosen to be the middle of each bin. As can be seen from the Fig. 3.4 below, beams will be formed for $-5°$ and $25°$ when sectors are to communicate with users.

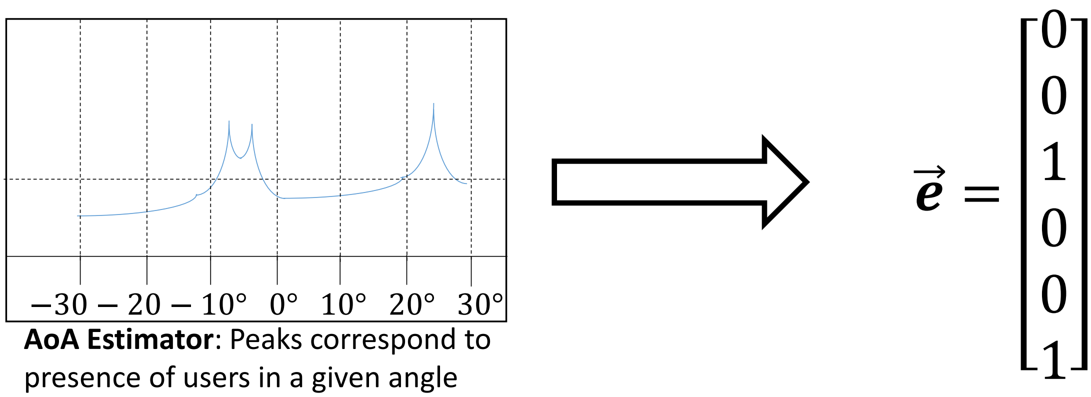


Fig. 3.4. Populating user database and feeding data to sectoral beamformers.

From the vector $\vec{e}$ the advanced node interprets which angular bins have to form beams which is shown as follows:

$$\vec{e} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 1 \end{bmatrix} \rightarrow \vec{e}_1 = \begin{bmatrix} 1 \\ 1 \end{bmatrix}\ for\ \theta_1 = -5°\ and\ \theta_2 = 25°$$

- **Moore-Penrose Pseudoinverse for Determining the Beamforming Weights**

From the above $\vec{e}$ the advanced node interprets which angular bins have to be formed, after which Moore- Penrose pseudoinverse can be applied to determine the beamforming weights [3.19]. The procedure for determining the beamforming weights is shown as follows:

Define $\vec{A} \triangleq [\vec{S}_{-5} \ \ \vec{S}_{25}]_{N_{sec}\times 2}$

It is desired that the beamforming weights have lobes at $-5°$ and $25°$

So, $\vec{W}^H\vec{A} = \vec{e}_1^{\mathrm{H}}$

where $(\cdot)^H$ is the Hermitian (conjugate-transpose) operator.

Since, $\vec{A}$ is not necessarily a square matrix, its Moore-Penrose Pseudoinverse (which is, in simple words, a Complex Least-Squares Approximation) is computed:

$$\vec{A}^{-1} \approx \left(\vec{A}^H\vec{A}\right)^{-1}\vec{A}^H \tag{3.5}$$

Solving for $\vec{W}$, we get:

$$\vec{W} = \left[\vec{e}^H{}_1 \times \left(\vec{A}^H\vec{A}\right)^{-1}\vec{A}^H\right]^H \tag{3.6}$$

- **Time for Computing the Beamforming Weights**

In perspective to this thesis, a setup of maximum 3 beams per sector is proposed. In the case when all three beams are active and a new user appears in an uncovered area, then sector-wide communication beam will be used. It is worth mentioning that the number of beams being generated at the same time (i.e. the size of the vector $\vec{e}_1$) should be less than N_{sec}.

For 3 beams/sector, number of floating point operations to get the weights is $\approx 75N_{sec} + 162$, which is mathematically computed taking complex multiplication and additions into account.

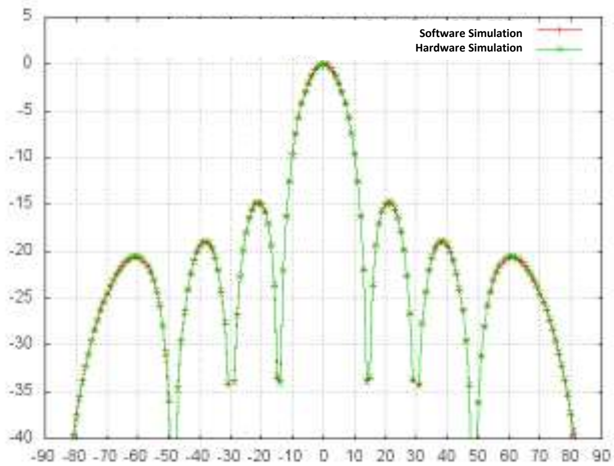
Using Virtex 7 (capable of computing more than 160 billion floating point operations per second), computation time is $\frac{762}{160\times 10^9} = 7.76\ ns$

3.3 Ensuring Practical Implementation in Available Standards

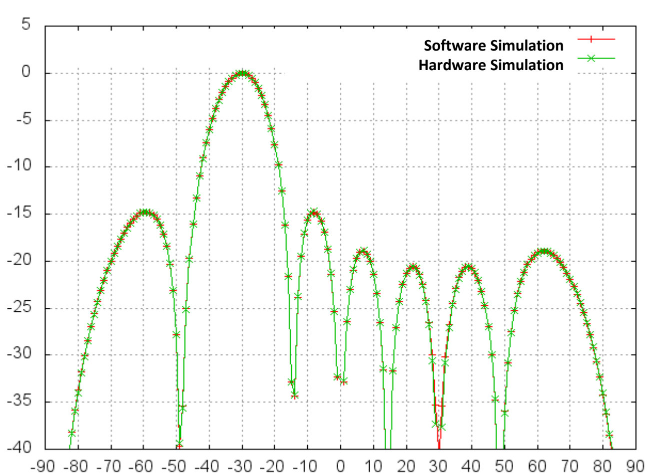
To ensure practical real-time implementation in available standards such as IEEE 802.11 (Wi-Fi), simulations were performed to ensure that the calculated computation required by the beamforming techniques would be a great fit for hardware implementation (FPGA based). The following sections describe the simulation results for deterministic beamforming.

3.3.1 Simulation Results for Deterministic Beamforming

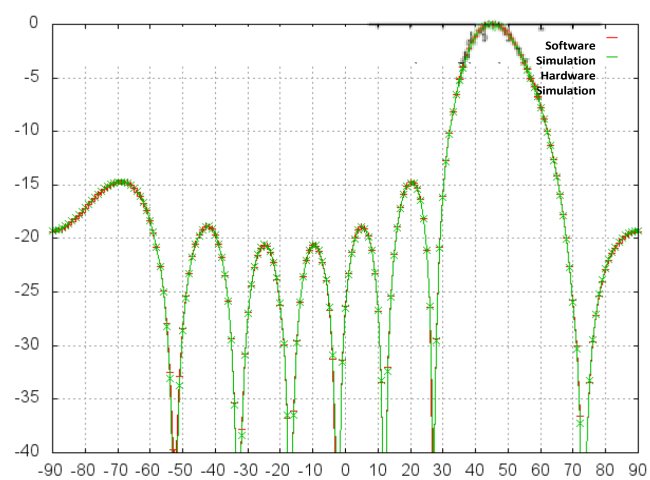
As can be seen from the previous section, the estimated computational time for AoA Estimation and beamforming using high-end Virtex 7 FPGA was around $3.5\ \mu s$. Software and hardware simulations for deterministic beamforming were performed with currently available low-end Xilinx Spartan 6 – model XC6SLX75 [3.20]. Three sets ($0^{\circ}, -30^{\circ}, 45^{\circ}$) of weights were considered for simulation comparison or a linear array with $\frac{\lambda}{2}$ separation between elements. The antenna patterns is calculated through software simulation and the same sampled input data is fed to hardware simulator and antenna pattern compared results is shown in Fig. 5. As shown in the Fig. 3.5(a), the comparison depicting software and hardware simulation for 0° angle, which is the angle perpendicular to array plane is shown. Similarly for Fig. 3.5(b) and (c) the incoming signal is at an angle -30° and 45° respectively and compared simulation results is also presented in the same figure. For these simulations, sampling frequency was set at 100 MHz, carrier frequency at 25MHz was worked on a 12-bit digitized signal. The geometry of the antenna array is not constrained but direction is described by a vector of 12 bit digitized weights. Through these simulations, it is confirmed that using real devices (FPGAs) it is guaranteed to behave as in the simulation and hence would satisfy the timing constraints.



(a) 0°- Perpendicular to array plane



(b) -30°



(c) 45°

Fig 3.5. FPGA based beamforming simulation comparision results for three cases (a) 0°- Perpendicular to array plane (b) -30° (c) 45°

The next section would introduce where these timings requirements would it in the current wireless standards. The objective is to fit the required timings with the available standards without any changes to the MAC or higher upper layers.

3.3.2 Fitting MAC Timings Schedules

In most networks, multiple nodes share a communication medium for transmitting data packets. The medium access control (MAC) protocol is primarily responsible for regulating access to the shared medium. Some of the main responsibilities of MAC layer include deciding when a node access a shared medium, resolve any potential conflicts between competing nodes, correct communication errors occurring at the physical layer, and performing other activities such as framing, addressing and flow control. The MAC protocol typically opts to maximize the channel utilization by having as much simultaneous communication as possible.

Medium access protocols for wireless communication may be classified into two major categories: contention based and contention free MAC. In contention based MAC, multiple nodes compete to access the wireless shared medium through random access. The most commonly used contention based MAC type is the Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA). CSMA/CA attempts to avoid collisions by using distributed conflict resolution algorithm. On the contrary for contention free medium, collisions can be avoided by ensuring that each node can use its allocated resources exclusively. The IEEE 802.11 Distributed Coordination Function (DCF) is one of the CSMA based protocols which has achieved great attention over the years due to its simplicity. In IEEE 802.11, before a node transmits it first performs physical carrier sensing. However, the performance of CSMA degrades significantly in multi-hop wireless networks due to the hidden terminal problem. When two nodes are outside the carrier sensing range of each other, both the nodes are said to be hidden. If both the nodes now try to communicate with a common node, a collision occurs at the node. To overcome this problem, collision avoidance is implemented by a handshaking mechanism before data is transmitted. The data transmission is preceded by transmitting a short Request to Send (RTS) packet to the intended receiver which in turn responds with a short Clear to Send (CTS) packet if the wireless channel is idle at the receiver side for Short Interframe Spacing (SIFS) period. The value of SIFS is smaller than the value of DIFS to ensure that no other device accesses the channel before the receiver can transmit its acknowledgment. Once a particular node makes a reservation using RTS and CTS control messages, other neighboring nodes overhearing the RTS message must refrain from accessing the medium until the first node's transmission has been completed and acknowledged. However, this would mean that other nodes have to continuously sense the medium to detect when it becomes idle again. This is called Virtual Carrier Sensing (VCS) and is implemented through a mechanism called the Network Allocation Vector (NAV). The node updates the value of the NAV with the duration specified in the RTS or CTS. Thus, the area covered by the transmission range of the sender and receiver is reserved. This procedure reduces the chances of a collision dramatically. Figure 3.6 shows the channel reservations operations in IEEE 802.11 MAC.

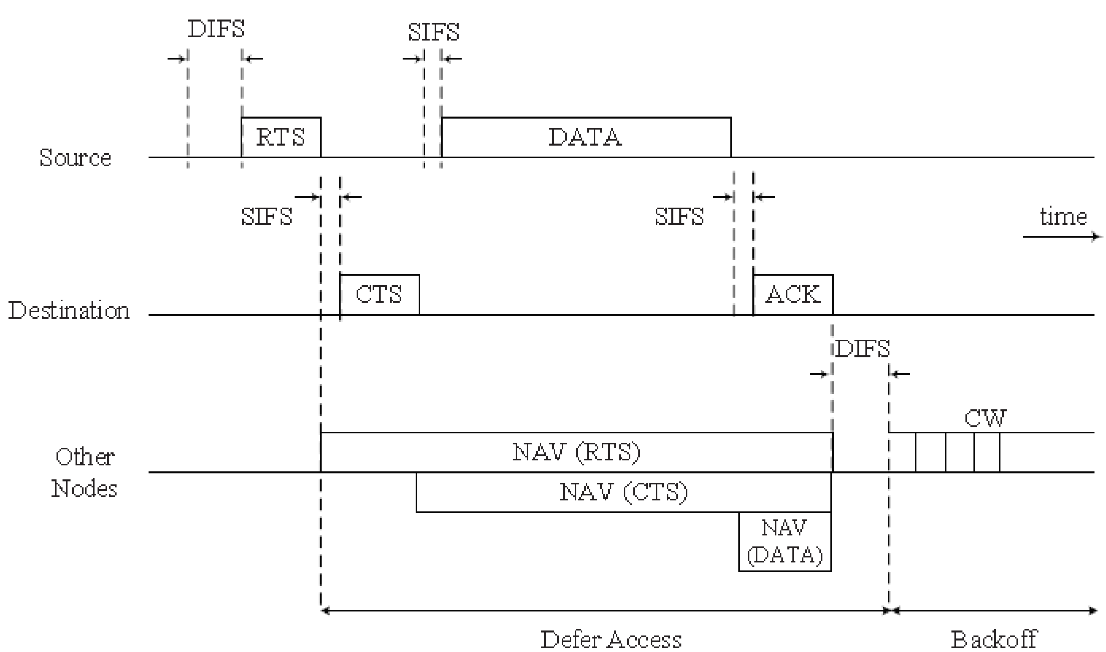


Fig 3.6. Channel reservation in IEEE 802.11 MAC [3.21, 3.22]

The IEEE 802.11 MAC protocol also uses a backoff mechanism to resolve channel contention. Before initiating a transmission, each node performs both virtual and physical carrier sensing. If NAV is not set, and the channel is sensed idle, the node defers for DCF Interframe Spacing (DIFS) before sending its packet. If the channel is found busy (by physical carrier sensing), the node chooses a random backoff interval from $[0, CW]$, where CW is called the contention window. The CW is initialized to the value of CW_{min}. After every idle slot time, the node decrements the backoff counter by one. When the counters reaches zero, the node can transmit its packet. In this case a CTS or ACK packet is not received back, the node assumes a collision has occurred with some other transmission and it invokes the binary exponential backoff algorithm. In this backoff algorithm, the node doubles it's CW, chooses a new backoff interval and tries retransmission again once the backoff timers expires. The CW is doubled until it reaches a maximum threshold, called CW_{max}. Retransmission retires are limited by a threshold after which the packet is discarded. If the medium is sensed busy during the backoff stage, the node freezes its backoff and resumes it once the medium has become idle for DIFS duration. Once a transmission is successfully transmitted, CW is initialized to its minimum value for the next transmission.

The design of IEEE 802.11 implicitly assumes an omnidirectional antenna at the physical layer. When smart beam forming antennas are used, IEEE 802.11 MAC does not work properly as the interface with directional antennas must happen such that the hand shake occurs while the antenna beam is still receiving or transmitting position. To make sure the timings considerations proposed in the previous sections to fit the MAC standards, the timings calculated must fit the smallest Interframe, SIFS time period. Since the SIFS is the smallest time period in the MAC standard, if the calculated Angle of Arrival estimation and beamforming weights timings are within the time period, then there would be no requirement for MAC layer changes. Fig 3.7

presents the proposed interval where the AoA estimation and beamforming weights calculation would fit in. For example, the standard SIFS interval for IEEE 802.11 b/g is $10\mu s$. There are two users shown in the figure, User 1 and other users, while the advanced base node acts as an access point for wireless service.

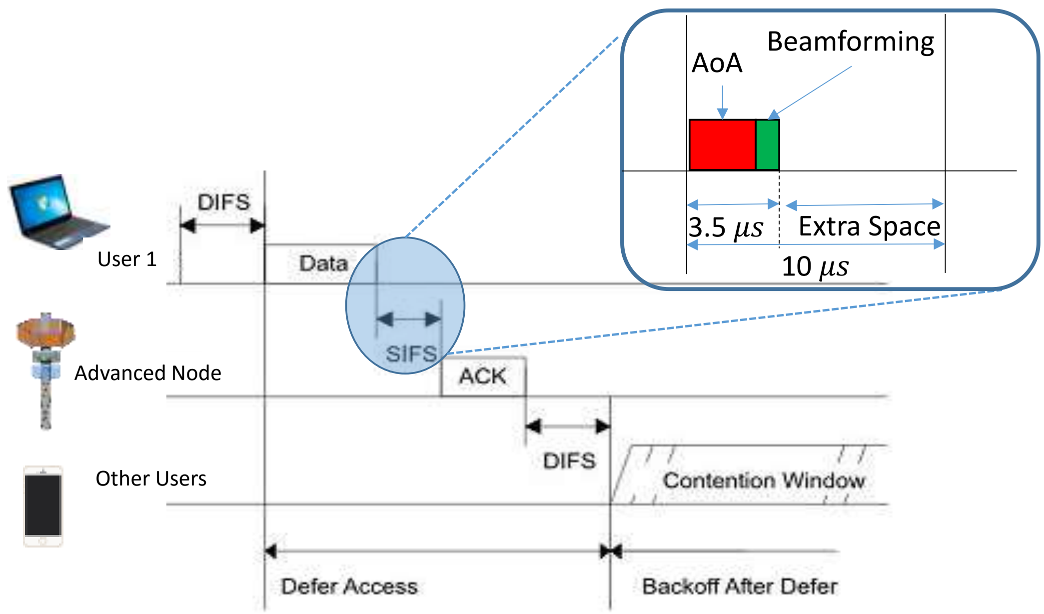


Fig. 3.7. Resolutions of Timing Issues.

As shown in the figure, the SIFS interval is zoomed in and the AoA estimation is shown in red block while the beamforming calculation is shown in green block. The estimated calculation would take at maximum $3.5\ \mu s$ of the available $10\mu s$ time period, with some extra space left. The extra space can be used for other signal processing calculations if required in the future for the advanced base station. Similarly for other IEEE standards, Table 3.3 shows that the estimated timing constraints fits other standards such as 802.11 a, b, g, and n (2.4 GHz and 5GHz).

TABLE 3.3
FITTING MAC TIMING SCHEDULES

802.11	SIFS	AOA ESTIMATION + BEAMFORMING	COMPLIANCE
a	$16\mu s$		✓
b	$10\mu s$	$\mathbf{3.5\mu s}$ (Estimated Time, using Xilinx Virtex 7 XT FPGA)	✓
g	$10\mu s$		✓
n (2.4 GHz)	$10\mu s$		✓
n (5.0 GHz)	$16\mu s$		✓

In conclusion, the scanning array scans full 360^0 or 60°sectoral scanning based on the cellular operator choice and can be divided into various steps for user discovery process. The duration for which the scanning beam stays in a direction is a beacon interval and can be configured based on the environment. For each angular step, the processing unit performs Angle of Arrival estimation and assigns sector to discovered users (users that are recognized by the advanced base station). MUSIC Algorithm for Angle of Arrival estimation process is proposed since using Virtex 7 FPGA and one active user (1024 bits received data) it is capable of computing nearly 160 Billion floating point operations per second. This computes to an estimation time of 3.35 microseconds. Moreover computing the beamforming weighs and applying them either digitally or using fast RF switches would take around 4.76 nanoseconds. So totally it would take nearly 3.5 microseconds for the whole process to complete. Since the SIFS is the smallest time period in the MAC standard, if the calculated Angle of Arrival estimation and beamforming weights timings are within the time period, then there would be no requirement for MAC layer changes. It is shown quantitatively and with software and hardware simulations that the proposed advanced base station will be able to operate in already existing wireless standards.

CHAPTER 4

NETWORKING ISSUES AND PROPOSED SOLUTION

The key network design challenges is given a rural area topology for a region is how to design an optimal network topology that minimizes the number of required base stations and achieves a certain minimum level of signal strength. Rural areas, such as the Maui Island, Hawaii or the Kohala region of the Big Island, Hawaii offer difficult conditions for cellular coverage. These include but are not limited to uneven terrains, mountains, ridges, deep forestation, etc. Providing cellular service to these areas using normal base stations (omnidirectional or sectoral) has several disadvantages, most important of which are wastage of energy in areas with no active users and less coverage area per base stations.

Advanced Base stations equipped with fully directional capabilities to address the challenges posed by rural areas is already proposed and described in Chapter 2. The proposed advanced base stations aptly address the rural area challenges, increase the coverage area and improve antenna radiation energy efficiency and data rate.

This chapter addresses the optimized placement of base stations in rural areas, taking into account the terrain related challenges offered by rural areas and the gains of the antenna elements used by the base stations. Tools developed by our research group are used to acquire path gain data from geospatial assets (such as Google Earth). Genetic Algorithm (GA) is used as an optimization technique to place the base stations in the given area. Link budget calculations are performed to obtain a path gain threshold which is used to compute the cost function (total area with bad cellular coverage, i.e. coverage below the path gain threshold) for the GA. For a given number of base stations, this cost function is minimized by the GA until the best base station locations are reached. Maui Island and Kohala Region of the Big Island, Hawaii are used as test cases to compare the cellular coverage offered by omnidirectional Base Stations with that of Advanced Base Stations, equipped with directional antenna arrays. In addition, simulations briefly examine the percentage cellular coverage of sectoral base stations with gains ranging from 9 dBi to 18 dBi, and directional antenna equipped Advanced Base Stations with array gains ranging from 19 dBi to 26 dBi.

Section 4.1 discusses the networking issues and challenges encountered in rural areas. Section 4.2 contains details on tools used for acquiring path gain data from geospatial resources and the optimized base station placement in rural areas using GA is described. This section also contains the simulation results for two test locations and briefly discusses future work on improving the cellular coverage of rural areas.

4.1 NETWORKING CHALLENGES

The increasing demand for mobile communications leads mobile services providers to look for ways to improve the quality of service to support increasing numbers of users in their systems. Since the amount of frequency spectrum available for mobile communication is very limited, efficient use of the frequency resource is highly needed. Currently, cellular system design is challenged by the need for better quality of service and the need for serving an increased number of subscribers in case of urban areas. In case of rural areas, the main bottleneck for operators is providing efficient cellular coverage in harsh terrains and rural environments.

Cellular network planning is a very complex task, as many aspects must be taken into account, including topology, morphology, traffic distributions and existing infrastructure. It becomes really challenging because a handful of constraints are involved, such as system capacity, coverage, service quality, and frequency bandwidth [4.1]. It is the network planner's task to manually place base stations and to specify parameters based on manually obtained data. In general, the radio network planning process, a site survey of the area to be covered is conducted and possible sites to set up the base stations are investigated. Based on the empirical propagation models, the link budget is calculated, which will help define the cell range and coverage threshold. Empirical models such as Hata-Okumura and deterministic model such as two ray model are used for network planning. Due to the often complex outdoor propagation environments, intensive measurements are used to collect data and build empirical propagation models that could be used to determine the number and locations of transmitting base stations and establish adequate coverage in the region [4.2]. These manual processes have to go through a number of iterations before achieving satisfactory performance and do not necessarily guarantee an optimum solution. Therefore, there is a need of intelligent techniques which may considerably alleviate planning efforts (and also associated costs), become extremely important for operators in a competitive market.

4.2 OPTIMIZED PLACEMENT OF ADVANCED BASE STATIONS

A very fundamental planning task in cellular networks is the base station location. To deal with coverage especially for rural areas, the objective of operators would be to provide satisfactory cellular services using a minimum number of base stations. Base station sites are expensive long term investments for the network operators. If the sites are selected that have a poor location or a poor set of characteristics, then system performance is likely to be poor irrespective of RF and parameter optimization. A good site location for base station should maximize coverage across the intended area while limiting interference from neighboring areas. A resulting optimization problem arises which is to determine how many and where the advanced base stations should be located in order to meet coverage and minimum signal strength requirement. In the coming sections, the proposed network planning approach integrating propagation modeling and genetic algorithm is introduced and simulations results for various test locations such as Maui Island, Hawaii and Kohala Region of Big Island, Hawaii are also presented.

4.2.1 PROPAGATION MODELING AND GENETIC ALGORITHM BASED APPROACH

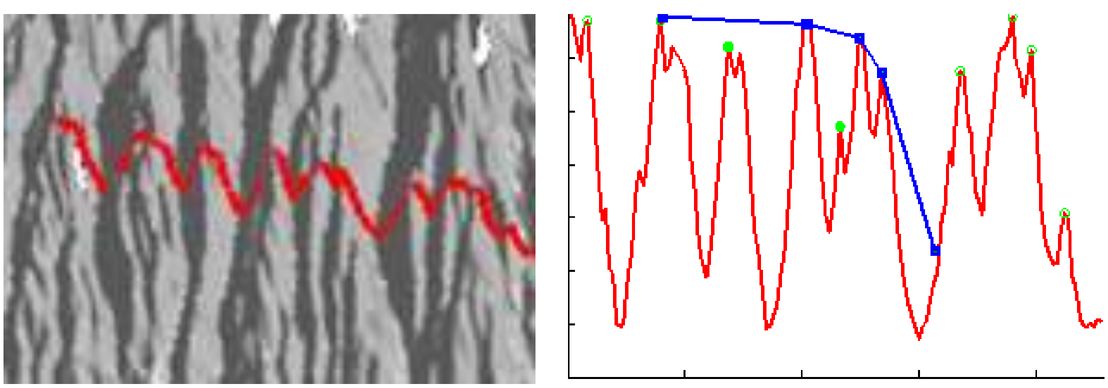
Accurate propagation modeling is fundamental to radio network planning. Ray tracing based propagation modeling provides physical insight for a propagation channel by identifying the direct line of sight, reflected, transmitted, diffracted, and scattered propagation mechanisms. The angular domain parameters such as the angle of arrival/departure are intrinsic in the ray structure while time domain parameters such as delay spread can be directly derived from the optical length of the rays. An important aspect of ray tracing simulation is the requirement of an accurate there-dimensional physical model for the propagation environment. Thanks to the rapid accumulation of geospatial data in government agencies and industries, more and more high resolutions 2D and 3D models can be created from the available data on the internet, such as NASA and Google Earth. Our research group specializes in fast ray tracing algorithm for realistic propagation modeling [4.3, 4.4]. The basic idea for 3D reconstruction is to use the google functions to setup calibration or key objects together with the 3D visualization so that the footprint, height of building, ridge and terrain details can be extracted accurately. Similarly for rural areas, diffraction of ridges is required for predicting radio signal in mountainous regions and mostly the realistic shape is over simplified such as knife edge or wedge [4.5]. To help to obtain an optimized wireless coverage solution, it is necessary to integrate our group's available ray tracing engine with a suitable optimization procedure to help determine the number and locations of the advanced base stations equipped with directional antenna arrays to provide desired wireless coverage. To address this rural area wireless coverage optimization issue, the integration of ray tracing engine with genetic algorithm (GA) optimization procedure was proposed which will be described in detail in Chapter 4. This approach is similar to our group's previous research work related to optimizing coverage in indoor wireless network [4.6].

Using this digital map and obtained data, simulations can be conducted in order to determine the best scheme of allocation of the base stations. There are various methods which are frequently used for optimization such as random walk, simulated annealing, and tabu search [4.7]. One of the most interesting optimizing technique inspired by natural evolution is Genetic Algorithm (GA) [4.8]. GA's are considered in wide range of numerical optimization methods, thanks to their versatility to solve problems in different application fields. The algorithms encode each parameter of the problem to be optimized into a proper sequence called gene and combine the different genes to form a chromosome. A proper set of chromosome, called population, undergoes the Darwinian process of natural selection, crossover and mutation until it reaches the final optimum solution under the selective pressure of the desired fitness function. Fitness function or cost function is the measure of goodness of a given chromosome. The reproduction takes places utilizing a proper selection strategy which uses the fitness function to choose a certain number of candidates. The recombination process selects at random two individuals of the reproduced population, called parents, crossing them to generate two new individuals called children. The crossover is useful to rearrange genes to produce better combinations of them and therefore more fit individuals. The mutation is used to survey parts of the solution space that are not represented by the current population.

This section is divided into three subsections. In the first subsection, the use of path gain data obtained from the geospatial is described. Second subsection described link budget calculations that are performed to obtain a path gain threshold that will be used by the GA in computing the cost function. The third subsection briefly discusses the details of the steps involved in the GA approach.

- **Acquiring Data from Geospatial Resources**

Geospatial data can be easily obtained from various online databases and applications such as Google Earth. As more digital elevation data are available with better resolutions, it is getting more convenient to extract terrain features important for radio propagation modeling such as mountains peaks and ridges. In this thesis, the digital terrain elevation data are obtained from NASA's SRTM (Shuttle Radar Topography Mission) which available online at [4.9]. NASA's SRTM database is one of the publicly available resources covering over 80% of the earth's landmass. The entire terrain is divided into grid points and the resolution of elevation data is 3 arc seconds or about 90 meters. To calculate the path loss (or gain) at a receiver (Rx) location due to a transmitter (Tx), a height profile is created for the Tx/Rx pair. In Fig. 4.1 (a), a 3D terrain is shown with a height-profile overlay (red) on it. The path gain at Rx is contributed by multiple diffractions from several ridges and can be calculated using the uniform theory of diffraction (UTD) and example diffracted ray is shown in Fig. 4.1 (b). These 3D features are commonly ignored in widely used propagation modeling methods such as knife edge diffraction.



(a) The terrain with an overlay of height profile.

(b) The height profile and a diffraction ray from Tx to Rx.

Fig. 4.1. Path loss (gain) calculation scheme.

Similarly to obtain cellular coverage in rural areas for the entire region of interest for a transmitter (Tx), such a height profile is created for each Tx/Rx pair with Tx fixed and Rx traversing all the sampling points. In order to obtain a path gain threshold that will be used in computing the cost function for the GA, downlink link budget calculations are performed. The calculations shown here are simple with an emphasis on the difference caused by antenna gains.

- ## Link Budget Calculations

In this subsection, link budget calculations [4.10] is evaluated for downlink only in order to obtain a path gain threshold that will be used in computing the cost function for the Genetic Algorithm.

The minimum detectable signal (MDS) at a receiver location is given by

$$MDS = 10\log_{10}\left(\frac{KT}{10^{-3}}\right) + E_b/N_o + 10\log_{10} W + NF \tag{4.1}$$

where K is the Boltzmann's constant (1.38×10^{-23} J/K), T is the absolute temperature (300 K), E_b/N_o is the Signal to Noise Ratio per bit (10 dB), NF is the noise figure (2 dBm) and W is the bandwidth.

Using (4.1), the MDS for $W = 20\ MHz$ is $-89\ dBm$ and that for $W = 2\ MHz$ is $-99\ dBm$. Throughout this chapter, a bandwidth of $W = 20\ MHz$ is assumed for simulation purposes. In the rural area under consideration, for a data point to be receiving good cellular coverage, the received signal power is required to be greater than the MDS. The received signal power, denoted by P_{Rx} is given in the following equation which is fundamental to link budget calculations:

$$P_{Rx}(dBm) = P_{Tx} + G_{Tx} + G_{Rx} + G_{Path} \tag{4.2}$$

where P_{Tx} is the transmitted signal power in dBm

G_{Tx} is the transmitter gain in dBi

G_{Rx} is the receiver gain in dBi

G_{Path} is the path gain in dB.

Using the requirement $P_{Rx} \geq MDS$ and (4.2), the path gain threshold is obtained as follows:

$$G_{Path} \geq MDS - (P_{Tx} + G_{Tx} + G_{Rx}) \tag{4.3}$$

In this section, a simple example is considered whereby P_{Tx} is set at 1 W ($30\ dBm$) and $G_{Rx} = 0\ dBi$. For an omnidirectional antenna with $G_{Tx} = 5\ dBi$[4.11], we have

$$G_{Path} \geq -124\ dB \tag{4.4}$$

If instead, the transmitter (Base Station) is equipped with a directional antenna given in [4.12], with $G_{Tx} = 19\ dBi$,

$$G_{Path} \geq -138\ dB \tag{4.5}$$

The above limits for path gain will be used in the chapter in order to compute the cost of the GA, discussed in the next section.

- **Genetic Algorithm Approach**

For a given rural area, the area is divided into grid points. The GA is then initialized with 500 randomly generated chromosomes, each corresponding to location of a single base station in the rural area under consideration. For each chromosome, the path gain at each grid point is computed using the geospatial data and compared with the path gain threshold, obtained via link budget calculations. Grid points with path gain values lower than the threshold are considered as points with bad cellular coverage. The cost function for each chromosome is defined as the total number of bad points in the rural area for that particular chromosome/base station location(s).

The chromosomes then go through the typical GA steps of selection, crossover, and mutations which are repeated several times until an optimal solution (for the given starting chromosome set) is reached. Once the solution is reached for one base station, the number of base stations is incremented and the process is repeated until the cost function goes below a certain cost threshold.

Fig. 4.2 shows a flowchart that shows all the steps of the optimized base station distribution via GA.

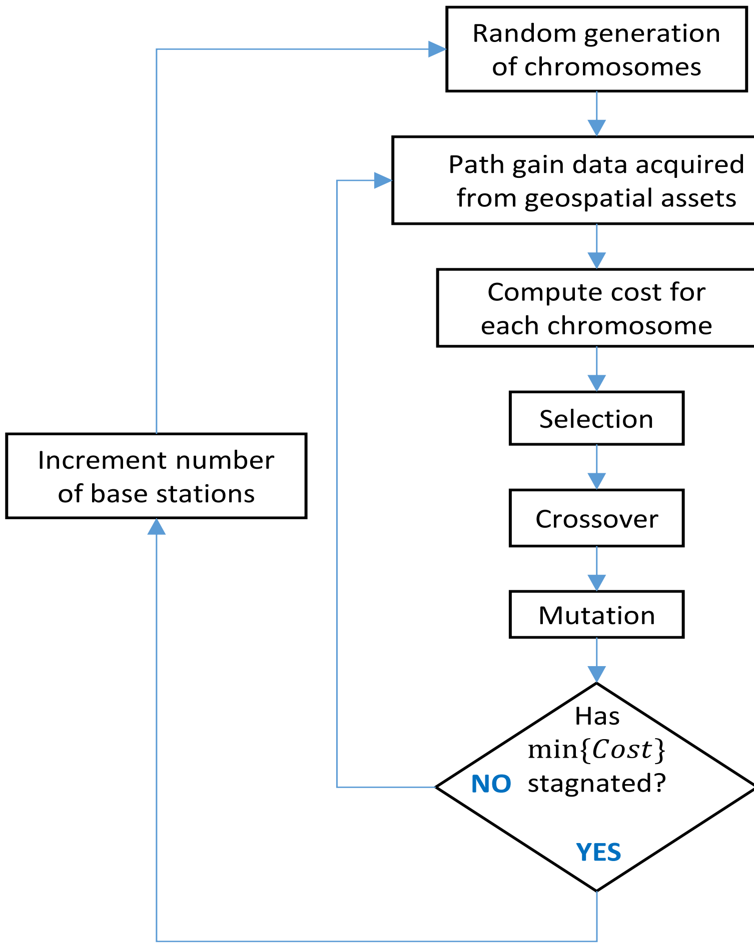


Fig. 4.2 Flowchart of optimized base station distribution via Genetic Algorithm.

The GA used in this chapter is always found to converge to an optimal solution, given the starting chromosome set. As an example, Fig. 4.3 shows the average and minimum % uncovered area vs the number of GA iterations for optimal placement of Advanced Base Stations (equipped with directional antenna arrays having gain of 19 dBi [4.12]). The vertical grid lines represent an increment in the number of Advanced Base Stations which happens when minimum cost is found to stagnate.

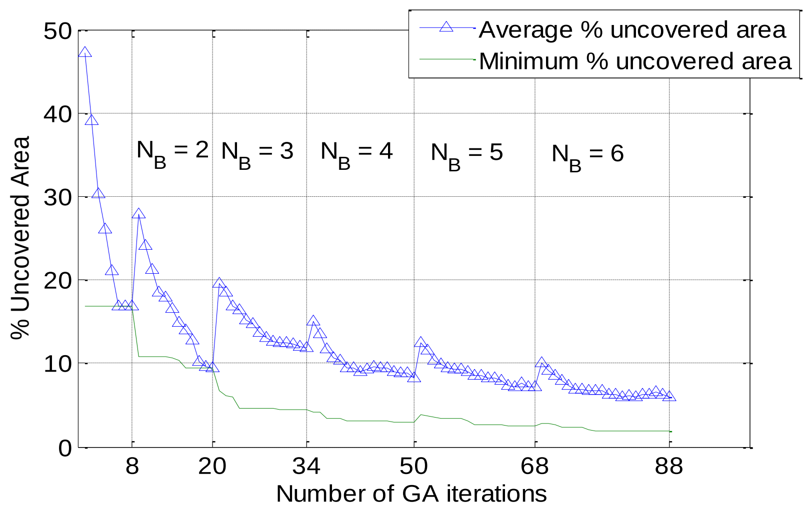


Fig. 4.3 Average and minimum % uncovered area as a function of the Number of GA iterations, in Maui Island, Hawaii.

The metrics used for analysis are % coverage and average path gain of the covered area, both of which are defined as follows:

$$\%\ Coverage = N_c/N_{Grid} \tag{4.6}$$

$$Average\ Path\ Gain\ (dB) = \left(\frac{1}{N_c}\right)\sum_{i=1}^{N_c} G_{Path,i}(dB) \tag{4.7}$$

where N_{Grid} is the total number of grid points (receiver locations) of the area under consideration, $N_c = N_{Grid} - Cost$ is the number of grid points with good coverage and $G_{Path,i}$ is the path gain at the i^{th} receiver location with good cellular coverage, for $i = 1, 2, \dots, N_c$. The Average Path Gain (dB) is used to provide a measure on the average signal strength for given base station location(s). It is worth mentioning that the averaging in (4.7) is performed in the dB scale.

The next section contains the simulation results that demonstrate the advantages of using our proposed directional antenna based Advanced Base Stations in place of omnidirectional base station setups. The first discusses the simulation results for Maui Island, Hawaii and the second, the Kohala region of the Big Island, Hawaii. Maui and Kohala regions because they exhibit typical rural characteristics. For all cases, the heights of the base stations are fixed at 40m.

4.2.2 Maui Island, Hawaii

Maui is an island in the mid-pacific, part of the Hawaiian island chain known for its dense forest, high rise mountains and uneven terrains, and is the second largest of the Hawaiian Islands at 1883 km^2(about 727 square miles). Fig. 4.4 shows the terrain of the area considered on Maui Island, Hawaii. This contains approximately 571 km^2 of land, which is inhabited with varying levels of sparsity. The area under consideration is west of the Haleakala volcano (a.k.a. East Maui Volcano), shown by the diagonal dashed line. The area behind the Haleakala Volcano is mostly unpopulated and is not considered for the GA simulations in this section.

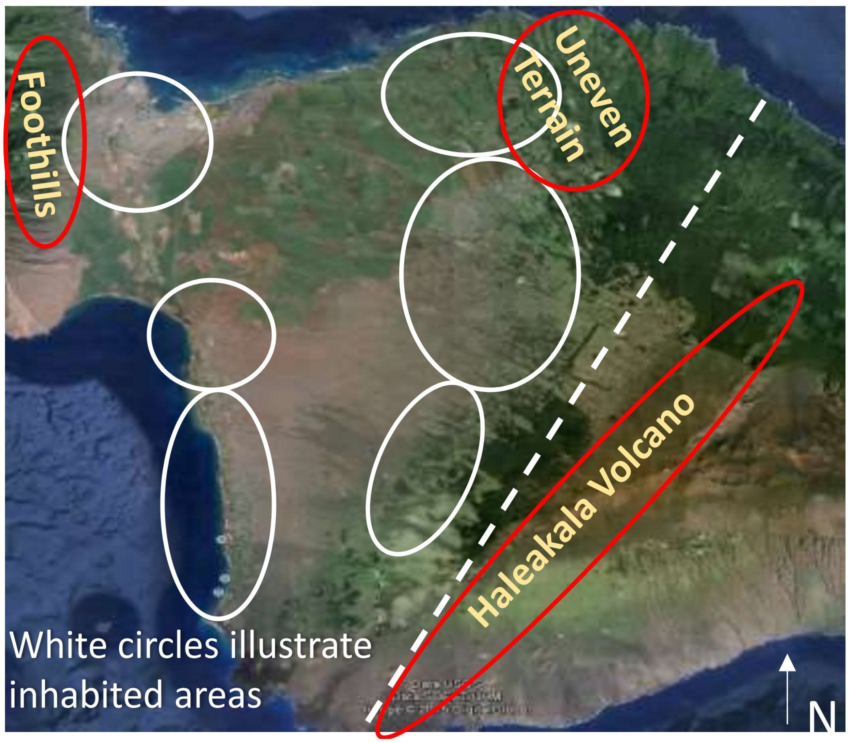


Fig. 4.4 Maui Island, Hawaii terrain.

The comparison of the cellular coverage offered by omnidirectional Base Stations (with a gain of 5 dBi [4.11]) with that of Advanced Base Stations, equipped with directional antenna arrays (with array gain of 19 dBi [4.12]). Fig. 4.5, shows the path gain color-map based on the GA results for four omnidirectional base stations which are found to cover 91% of the area at an average path gain of $-102\ dB$. In comparison, as shown in path gain color-map in Fig. 4.6, four optimally placed Advanced Base Stations cover 96% with an average path gain of $-92\ dB$. Hence, in addition to providing better coverage, Advanced Base Stations also offer stronger cellular signal levels (reflected by the higher average path gain values).

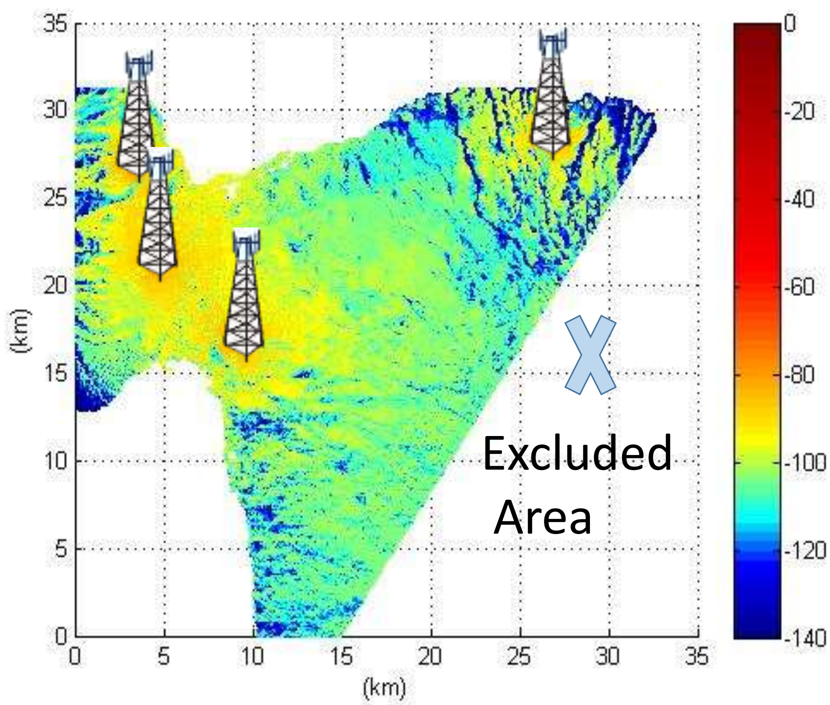


Fig. 4.5 Path gain color map for using four omnidirectional base stations ($5\ dBi$) Maui Island, Hawaii.

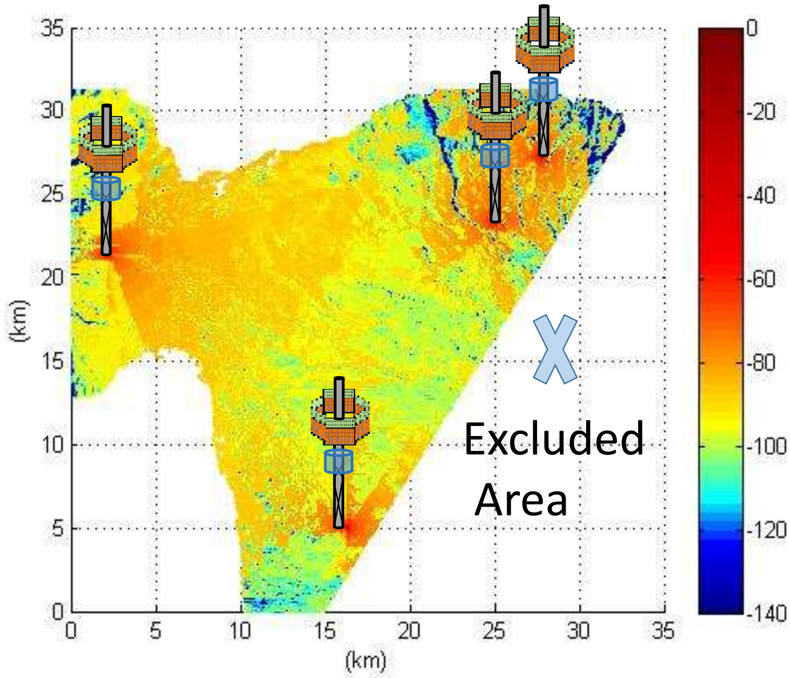


Fig. 4.6 Path gain color map for using four directional base stations ($19\ dBi$) Maui Island, Hawaii.

Since the objective of this research was to investigate if a lesser number of advanced base stations could be able to provide satisfactory cellular coverage, so more simulations were performed to validate the results. The results further show that even two Advanced Base Stations have similar cellular coverage compared to four omnidirectional base stations (91% with average path gain of $-96\ dB$), as shown in Fig. 4.7 by optimally placing them in the given area. Table 4.1 shows the percentage (%) coverage and average path gains for number of base stations, $N_B = 1, 2, 3$ and 4, using either omnidirectional base stations or Advanced Base Stations.

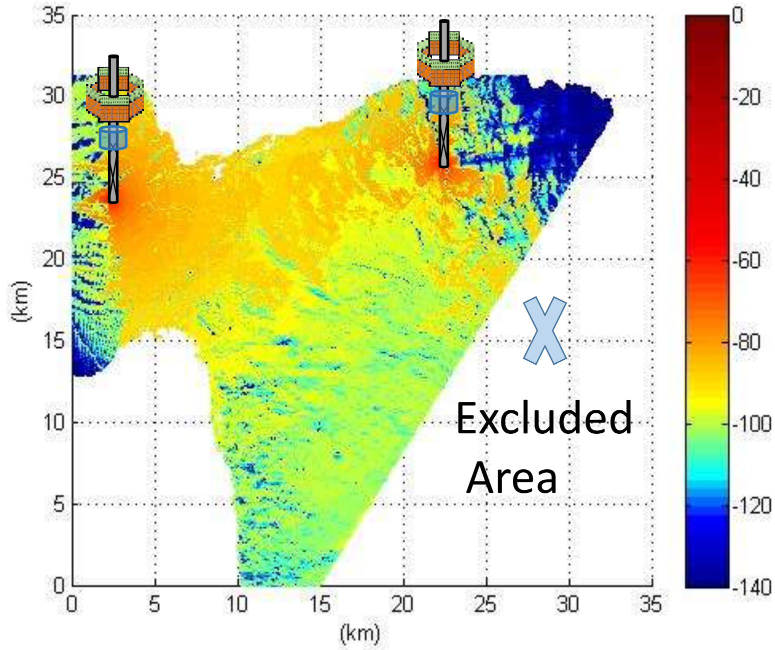


Fig. 4.7. Path gain color map for using two directional base stations (19 dBi) Maui Island, Hawaii.

TABLE 4.1
PERCENTAGE COVERAGE AND AVERAGE PATH GAIN COMPARISON DATA FOR MAUI ISLAND

N_B	Omnidirectional (5 dBi)		Directional (19 dBi)	
	Percentage Coverage	Avg. Path Gain	Percentage Coverage	Avg. Path Gain
1	66	-110	83	-99
2	81	-106	91	-96
3	86	-104	96	-94
4	91	-102	97	-92

4.4.3 Kohala Region, The Big Island, Hawaii

Big Island, Hawaii is the largest island of the Hawaiian chain of islands with an areas of approximately 10,430 km^2(about 4028 square miles). The region considered for simulation is the Kohala region, towards the northern tip of the Big Island, Hawaii. The Kohala region under consideration is shown in Fig. 4.8. The terrain, which is approximately $256\ km^2$ consists of a ridge that runs diagonally from Northwest to Southeast, deep forestation and, uneven terrain, making it a harsher rural area than Maui Island. The area in the southwest with deep forests is very harsh in terms of coverage and uninhabited and is therefore not taken into consideration for the GA simulations in this section.

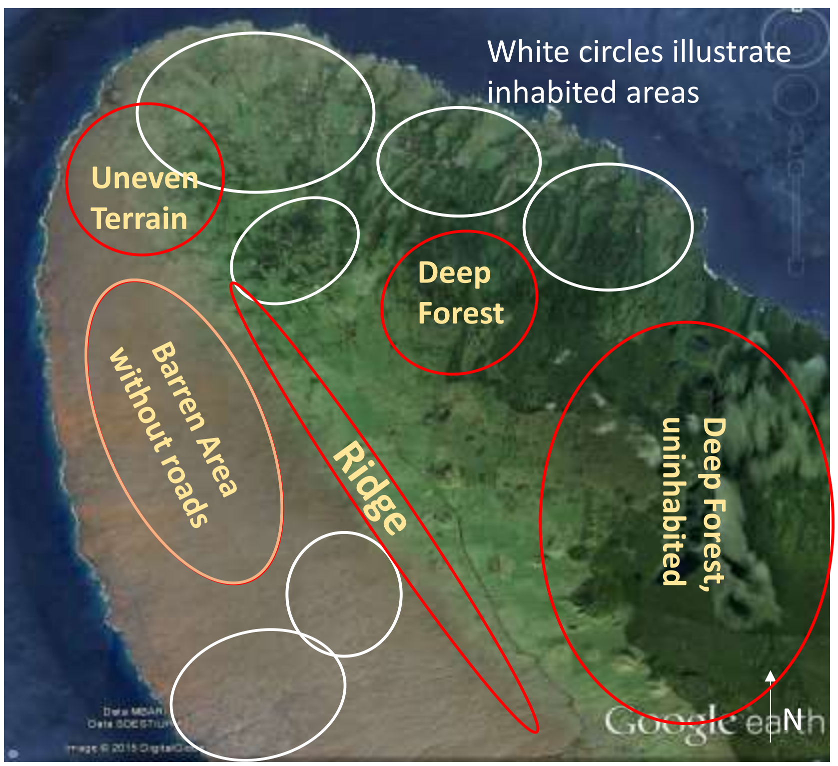


Fig. 4.8 The terrain of Kohala Region, The Big Island, Hawaii.

The comparison of the cellular coverage offered by omnidirectional Base Stations (with a gain of 5 dBi [4.11]) with that of Advanced Base Stations, equipped with directional antenna arrays (with array gain of 19 dBi). Fig. 4.9 and 4.10 show the path gain color-maps for four optimally placed omnidirectional base stations and Advanced Base Stations, respectively. In a similar manner, the simulation results for Maui Island, the deployment of four Advanced Base Stations offers better and stronger cellular coverage (95% coverage and $-90\ dB$ average path gain) when compared with four omnidirectional base stations (83% coverage and $-101\ dB$ average path gain). Again, two Advanced Base Stations are also found to closely match the coverage area of four omnidirectional base stations (81% coverage and $-93\ dB$ average path gain).

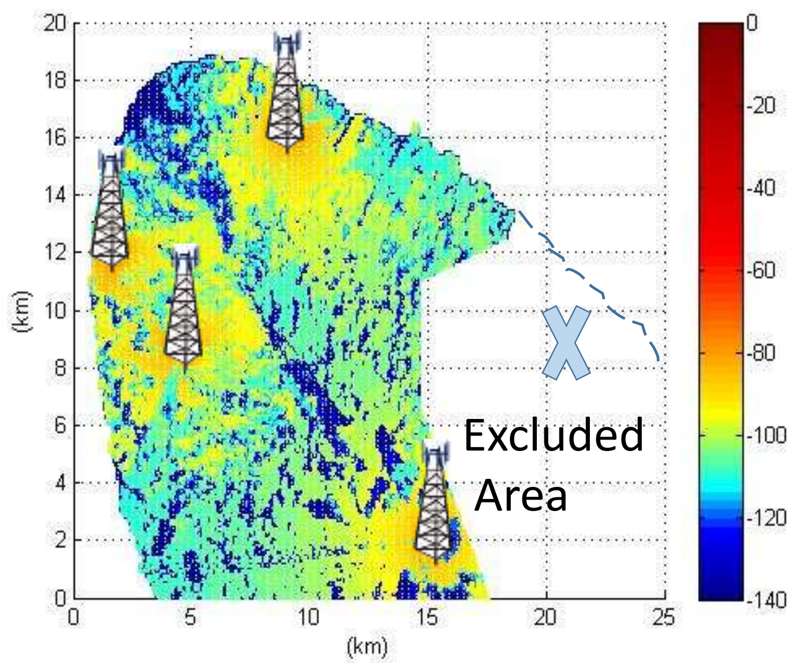


Fig. 4.9. Path gain color map for using four omnidirectional base stations ($5\ dBi$) Kohala Region, The Big Island, Hawaii.

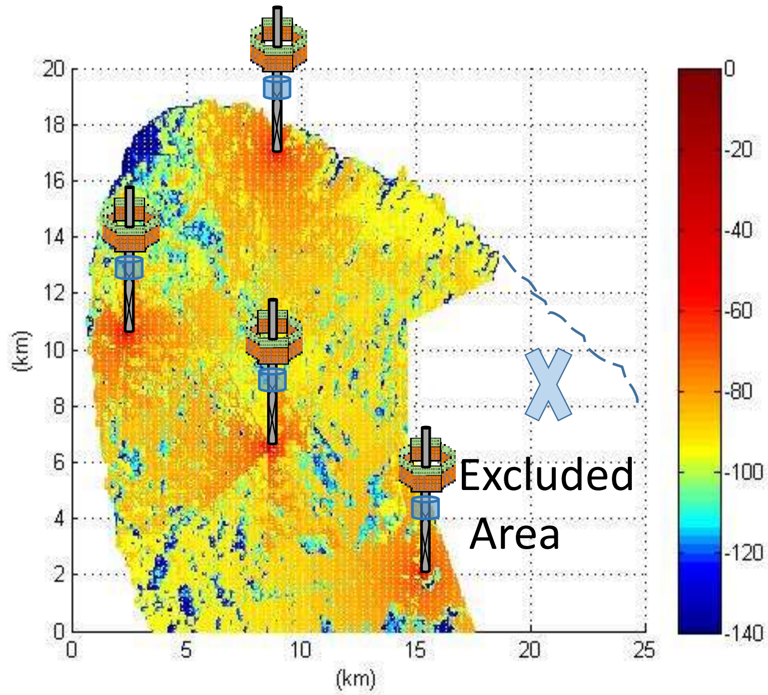


Fig. 4.10. Path gain color map for using four directional base stations (19 dBi) Kohala Region, The Big Island, Hawaii.

Fig. 4.11 shows the path gain color-map for the two Advanced Base Stations setup. Table 4.2 contains the summary of the simulation results (i.e. coverage area and average path gain for $N_B = 1, 2, 3,$ and 4) for the Kohala region of the Big Island. The results also confirm that in spite of having less total area, the Kohala region is more difficult to cover than the Maui region due to the greater level of unevenness found in the Kohala terrain.

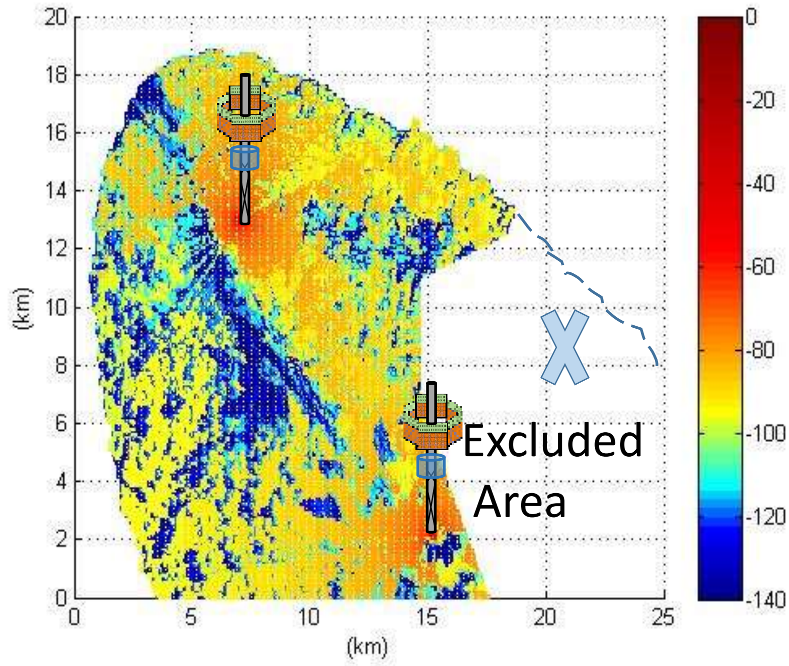


Fig. 4.11 Path gain color map for using two directional base stations (19 dBi) Kohala Region, The Big Island, Hawaii.

TABLE 4.2
PERCENTAGE COVERAGE AND AVERAGE PATH GAIN COMPARISON DATA FOR BIG ISLAND

N_B	Omnidirectional (5 dBi)		Directional (19 dBi)	
	Percentage Coverage	Avg. Path Gain	Percentage Coverage	Avg. Path Gain
1	57	-106	67	-96
2	69	-105	81	-93
3	78	-102	91	-91
4	83	-101	95	-90

- **Comparison with sectoral antennas**

Actively used sectoral antennas such as [4.13, 4.14, and 4.15] have gains ranging from 9 dBi to 18 dBi. While, in this section, the use of the antenna array with 19 dBi gain [4.12], arrays with higher gains, such as 22 dBi [4.16] and 26 dBi [4.17] could also be used for the Advanced Base Stations. Fig. 4.12 shows (a) the % coverage area and (b) average path gain for three base stations optimally placed in Kohala Region, The Big Island, Hawaii, versus the antenna gain. While Fig. 4.12 shows % coverage and average path gain as a monotone increasing functions of the antenna gain, it is worth mentioning that a focused, narrow beam, in place of a sector-wide or an omnidirectional beam would obviously allow for more economic use of the radiated energy, in addition to better coverage.

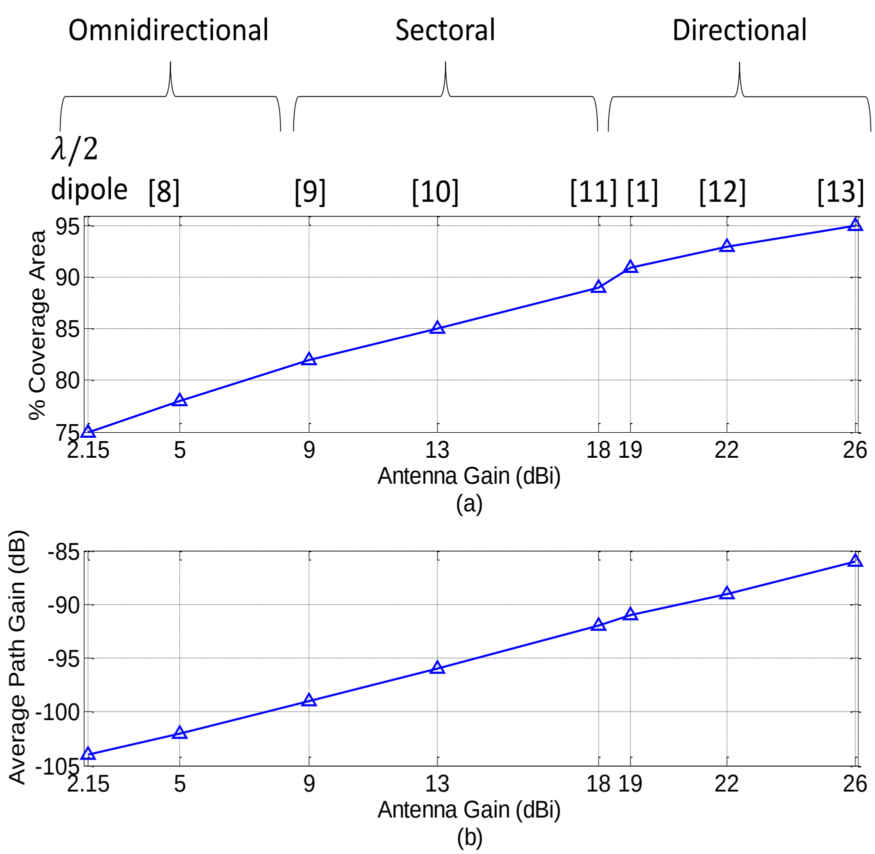


Fig. 4.12. (a) Percentage covered area and (b) Average path gain, plotted vs Antenna gains for three optimally placed base stations in the Kohala Region, The Big Island, Hawaii.

Finally, this chapter discusses the use of Genetic Algorithm and Geospatial assets (such as Google Earth) to place base stations in order to optimize cellular coverage in rural areassuch as Maui Island, Hawaii and Kohala region of the Big Island, Hawaii. Simulations indicate that instead of four omnidirectional base stations, only two directional antenna equipped base stations can be used to cover the approximately same area (~91% for Maui and ~83% for Kohala). Owing to the harsher terrain (unevenness and deep forests), the cellular coverage of the Kohala region is found to be worse than that of the Maui Island.

CHAPTER 5

COGNITIVE COMMUNICTAION ISSUES AND PROPOSED SOLUTIONS

Cognitive radio (CR) systems are quickly reforming the future of wireless communication, sensing, and data access. As of today, research in cognitive radio is aimed at developing efficient wireless communication strategies to make use of under-use spectrum. Cognitive systems are smart wireless devices that can observe their RF environment and detect unused frequency in real time. This smart system would allow more wireless devices to operate in the same frequency band, enabling more efficient use of the spectrum. Therefore, it is desirable to develop devices that can learn from observations and make decisions about when and how to transmit without disrupting and existing wireless connections.

This new requirement of operations creates a need for directional antennas for improved gain, improved communication schemes for efficient and robust performance, and propagation modeling for environment awareness systems. Various research communities, however, have different definitions of cognitive radio and each community has unique views as the defining features of CR. Communication theorists view CR as primarily about dynamic spectrum sensing while networking researches interpret CR as a device capable of cross-layer optimization. Computer academics view CR as a device capable of learning and adapting, with assumed capabilities, while RF community often view it as an evolutionary step from software defined radio [5.1]. Amidst all of these conceptions of cognitive radio, the possibilities for antenna systems and related propagation issues to play a more active role in system level performance are often ignored.

In perspective to this thesis, capabilities for antenna systems and related propagation issues to play a more important role in system level performance are investigated as part of the advanced base station. The so called advanced nodes have six antennas array with beam steering capabilities. In rural areas, these six antennas may or may not be in use simultaneously all the time. Therefore, the availability of one or more of these antennas may be put to use for available spectrum sensing and environment awareness depending on the characteristics of the propagation environment. The focus of this chapter is to showcase a unified vision for future cognitive base station communication, with an emphasis on the integrated effects of realistic propagation modeling and directional antennas on the communication system performance. Also, the objective of this chapter is to investigate through simulation the level of details in modeling the propagation environment and the associated trade off as well as the characteristics of the directional antennas as a part of the environment awareness engine to improve the overall performance of CR systems. The proposed approach is applied to the base station side and is designed to help decide not only if employing the channel parameters, and associated processing delays would help in improving the cognitive communications, but also in determining an acceptable level of modeling details that would achieve acceptable cognitive performance in adaptive and real-time processing.

Section 5.1 discusses the cognitive communication challenges and also talks about how no advancement was conducted in the environment awareness domain of cognitive radio. Next, section 5.2 introduces the proposed adaptive cognitive communication system approach and also the directional antenna and propagation modeling parameters taken into account to formulate the channel matrix. Section 5.3 and 5.4 describes and presents simulations results for two existing wireless systems namely orthogonal frequency division multiplexing (OFDMA) and Multiuser wireless systems. The sections present quantified data that illustrates the minimum information needed for accurate channel estimation given a BER constraint. It also discusses the interplay between the beamwidth of directional antennas and the ability to capture and use the advantageous multipath signals to enhance the performance of CR systems.

5.1 Cognitive Communication Challenges

It is well known that the cognitive engine in the overall CR system includes three basic components: the location awareness engine, the spectrum awareness engine, and the environment awareness engine, as discussed in [5.2]. In literature, most of the research emphasis is on the spectrum awareness engine and location awareness engine of the CR system will little or no effort has been made to develop the environment awareness engine of CR system. The possibilities for antenna systems and related propagation issues to play a more active role in system level performance are often ignored in the design process of CR systems. The advantages of directional antennas are not restricted to higher gain and enhanced data capacity, but the study on the interplay between the beamwidth of directional antenna and the ability to capture and use these multipath signals can be of great importance for the performance improvement of CR systems. So there is a greater need for quantified study of the different aspects of antenna and propagation parameters affecting the CR performance as part of the base station.

Another major obstacle in implementing cognitive communication systems by integrating propagation modeling capabilities is the computation time requirement of ray tracing tools. While adding details vegetation, trees, dense forest, small lamp posts and even people to environmental models can make the extracted data more realistic, but the amount of time required in acquiring this data becomes extremely large. For real time communications, the tradeoff between the computational complexity in acquiring the realistic ray tracing data and the level of modeling details should be taken into account. While the computers nowadays are very capable and the time taken in performing the computations required to generate a channel matrix are minimal, real-time applications are more demanding. With an increasing number of active users in real-time communications applications, it is desirable to minimize the use of computational resources in generating the channel matrix for each user. Moreover, the base station capable of cognition should be able to determine which level of detail (i.e path gain, angle of arrival, angle of departure and delay spread) should be used based on the rural environment, propagation range, frequency and antenna types.

Effective integration of these resources could lead to significant performance gains in CR's. The application of advanced environment awareness assets in CR, however, needs to be done in real-time, hence, it is imperative that the integration of propagation modeling capabilities with the cognitive engine happens quickly and with minimal use of computational resources.

5.2 Adaptive Cognitive Communication System Approach

Cognitive radios are reconfigurable radio communication devices that have the ability to sense the radio environment and optimally decide suitable communication parameters to adapt to it. This cognitive ability cannot simply be realized by observing the power in a frequency band of interest: more sophisticated techniques are required in order to capture the temporal and spatial variations in the radio environment and avoid interference to other users. Prior to establishing a base station-mobile user link with the base station and after synchronizing, the cognitive radio has to detect the network and communicate only when time-frequency resources are available. Many approaches have been developed and algorithms designs to help with sensing the environment, identifying available spectrum, and establishing effective communication channels with minimal interferences with existing users.

In our group's prior work [5.3, 5.4, 5.5], it is shown that it is possible to utilize geospatial resources (such as google Earth) to develop an accurate and realistic characterization of the propagation environment as part of the environment awareness engine in a cognitive communication system. In this section, an adaptive approach based on utilizing minimal levels of detail in propagation modeling, satisfying certain desired performance criteria (e.g. BER $\leq$ 1%) is introduced. The tradeoffs involved in employing directional antennas in cognitive communication systems is also examined. While others have discussed effects of channels characteristics on cognitive radio performance [5.6], focus of this thesis is placed on utilizing realistic channel parameters such as path gain, angle of arrival/departure and delay spread information that is provided by site-specific propagation modeling assets. The proposed approach is designed to help decide not only if employing the channel parameters, and associated processing delays would help in improving the cognitive communications, but also in determining an acceptable level of modeling details that would achieve acceptable cognitive performance in adaptive and real-time processing.

For optimal utilization of realistic temporal, spectral and spatial data, obtained from the available ray-tracing tools, an adaptive cognitive communication system is proposed. Fig. 5.1 shows the flowchart that delineates the architecture of the cognitive communication system.

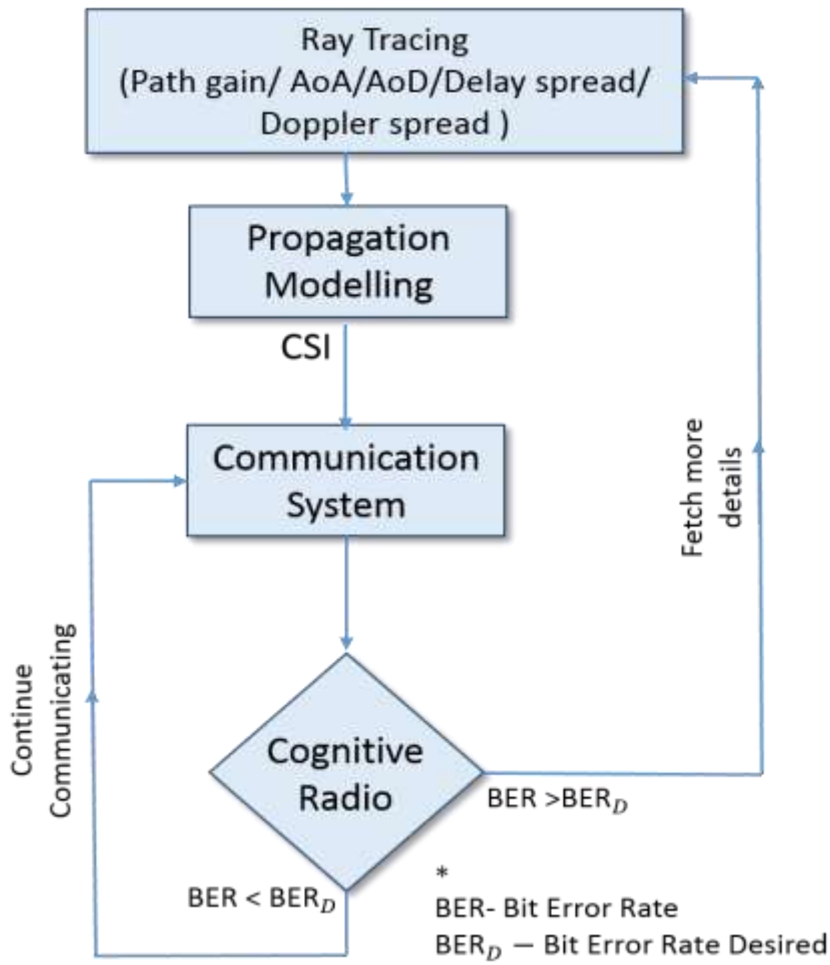


Fig. 5.1 Flowchart of adaptive cognitive communication system.

The Ray-tracing tool in [5.7] is used to form a propagation model of a given area. This information is integrated with an available communication system for optimizing cognitive radio based communication system performance. For a given noise variance, a packet/bit error rate is obtained based on the ACK/NACK (Acknowledgement/Negative-Acknowledgement) information accumulated at the receiver. If the obtained error rate is higher than the desired error rate, the receiver requests the propagation modeling module for a CSI with more propagation modeling details. This process repeats itself, as shown in Fig. 5.1, until all available ray tracing information is being used. At that point, the best potential BER is reached for the given SNR/bit and that BER can be improved only if, either the transmitted signal power is increased, or the receiver hardware is improved and antennas with high gain are employed. The proposed approach is applied to the base station side and is designed to help decide not only if employing the channel parameters, and associated processing delays would help in improving the cognitive communications, but also in determining an acceptable level of modeling details that would achieve acceptable cognitive performance in adaptive and real-time processing. In the following sections, detailed implementation of the propagation modeling and directional antenna parameters will be described.

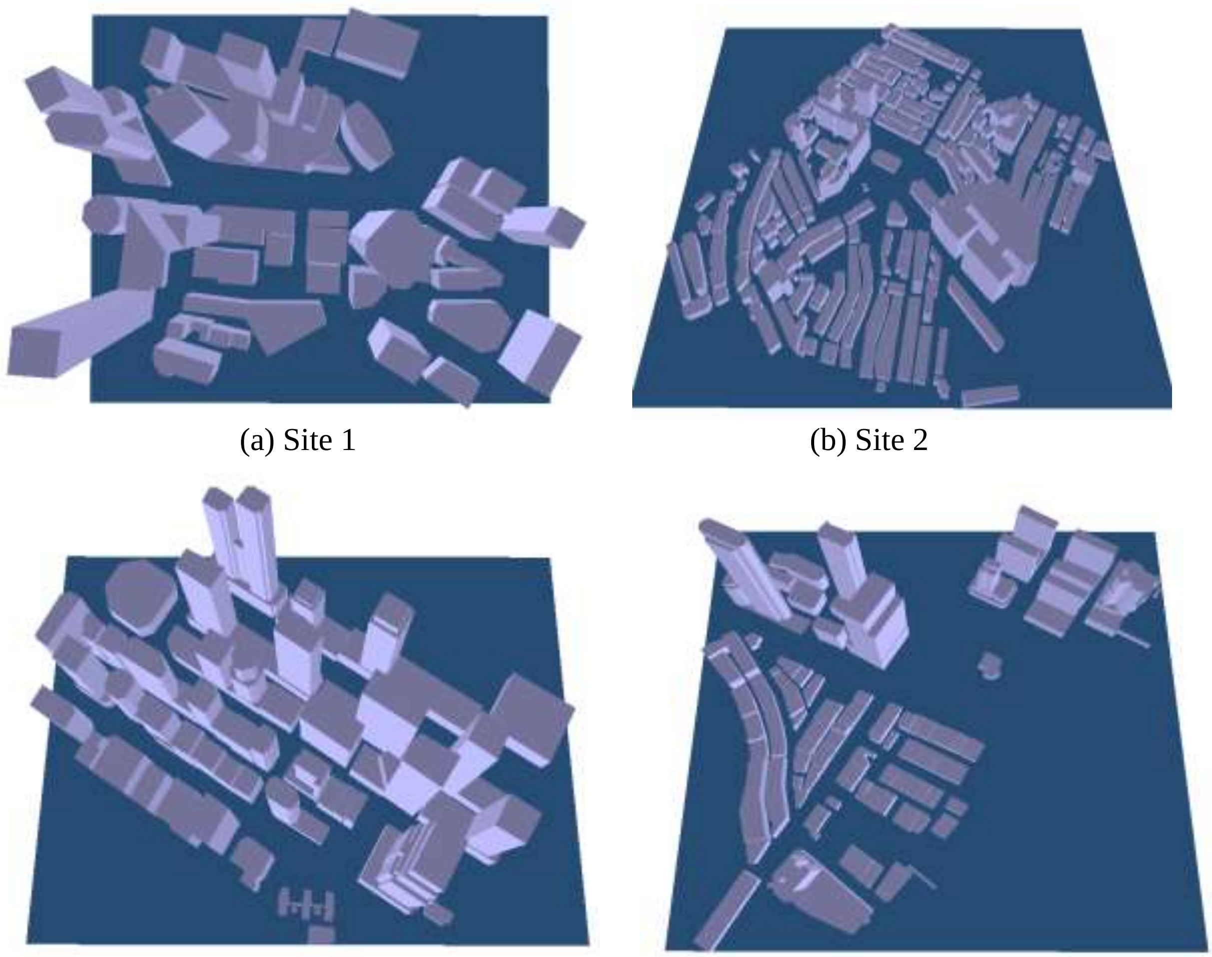
5.2.1 Integrating Propagation Modeling and Directional Antenna Parameters

The ray tracing method can provide data that includes path gain, delay spread, Doppler spread and Angles of Arrival/Departure for computing the channel matrix. The channel models obtained via ray tracing have been shown in prior research in the literature, such as [5.4, 5.8], to be accurate and reliable. Our group has expertise in developing advanced propagation models in realistic and challenging environment [5.7]. In order to get realistic propagation modeling data for generating the channel matrix our group's ray-tracing tool is used. The accuracy of the employed ray tracing method has amply been verified and experimentally validated using full-wave electromagnetics calculations, e.g., the finite-difference time domain (FDTD) method [5.9] and in realistic propagation environments [5.7, 5.3]. The ray tracing tool takes the 3D model of the area of observation and the coordinates of the transmitter and receiver to calculate multipath data. This data includes vectors corresponding to the incidence and departure of each path taken by the rays emanating from the transmitter, the complex path gains and the delay in arrival of each of the paths. Using the incident and departing path vectors, the (azimuthal and elevation) Angles of Arrival (AoA) and Angles of Departure (AoD) are computed.

In perspective of this thesis, four different urban sites, all in Downtown, Singapore, are considered and the details on the propagation parameters and site properties, such as the number of buildings, total area covered and base station heights are tabulated in Table 5.1. For all the sites, the carrier frequency (f_c) is 1 GHz and no vegetation is taken into account. Fig. 5.2 contains the models for each of the four sites. Four urban sites where considered rather than rural sites as the effectiveness of rich multipath can be observed in case of urban scenario where the number of multipath is very high rather than rural scenarios where the number of multipath received is very less.

TABLE 5.1
PROPAGATION MODELLING PARAMETERS

Site #	No of Building	Area Covered (km^2)	Building Density (Buildings per km^2)	Base Stations Height
1	~35	0.256	137	40
2	~150	0.855	175	40
3	~50	0.289	173	40
4	~45	0.398	113	40



(a) Site 1 (b) Site 2

(c) Site 3 (d) Site 4

Fig. 5.2 Sites in Downtown, Singapore.

Fig 5.2 shows four different site location which differs from one another with respect to building density, area covered, building height profiles and multipath effects. It can be observed that Site 2 is highly dense (number of building per km^2) while Site 4 is less dense. These sites were reconstructed from Google Earth 2D images using our group software tool. While our group's ray tracing tool is site specific, it is still very general in the sense that given any site, a model can be constructed and ray tracing data obtained such as path gain, delay spread, angle of arrival/departure and Doppler spread. Typical values for electrical permittivity and conductivity for buildings are taken into account while building realistic models. Fig. 5.3 shows an example 3D setup for the first site, consisting of a Base Station, a Line of Sight (LOS) mobile user, and buildings (thus creating a typical urban site with multipath environment). The setup data, in its raw form, assumes isotropic transmitting antennas elements. In the upcoming OFDMA section, a 4-user OFDMA communication setup is simulated which uses realistic ray-tracing data in order to model the channel. As an example, Table 5.2 provides ray-tracing data of five strongest paths for User 2 (LOS). Angle of Arrival (azimuthal and elevation), path gain and delay are the types of data that will be integrated in the adaptive CR system. In Fig. 5.4 (a), the path gain values for all the paths of the example setup are plotted vs their respective azimuthal and elevation angles of arrival. Similarly, Fig. 5.4 (b) contains the 3D plot for the delay values of each path. This data helps in identifying the strongest and/or quickest (minimal delay) paths as well as shows clusters of multipath arriving at the receiver from different directions. This information is utilized by the adaptive CR algorithm to optimize performance.

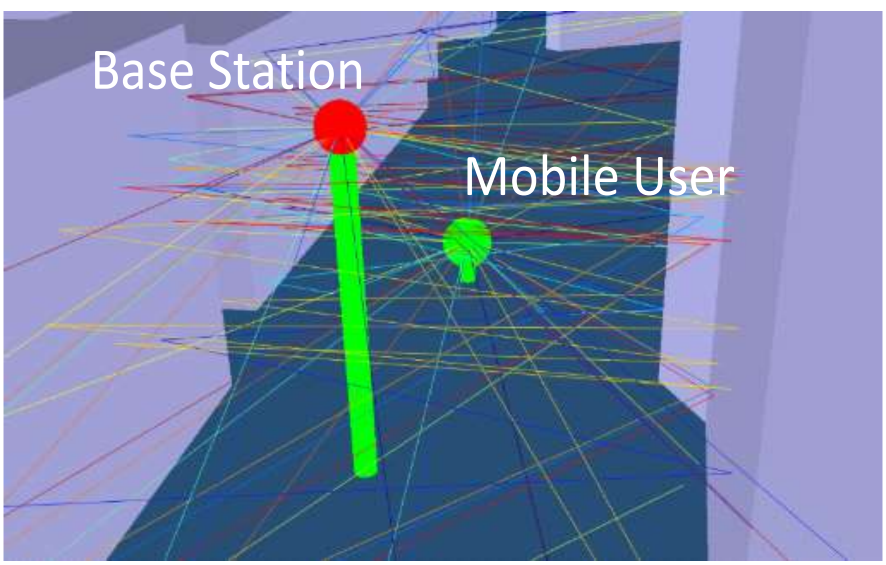
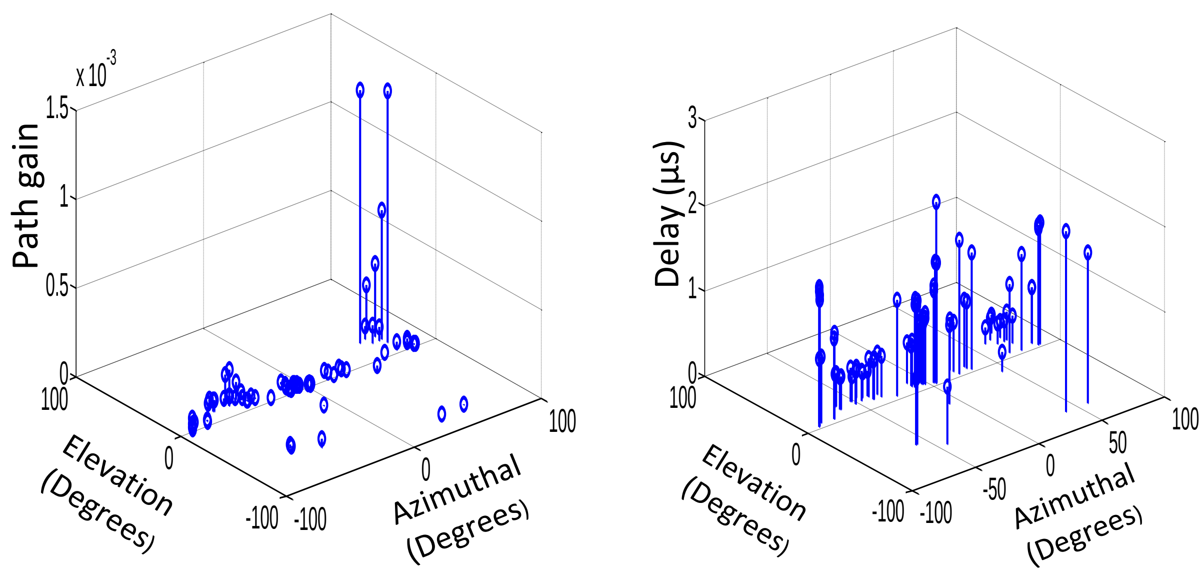


Fig. 5.3 Side View of Base Station and Mobile User.

TABLE 5.2
PROPAGATION MODELLING DATA FOR USER 2

Path #	AoA Azimuthal	AoA Elevation	Path Gain (dB)	Delay (μs)
1	-39.72°	24.41°	-27.96	0.2018
2	74.08°	7.59°	-32.18	0.6315
3	82.87°	31.80°	-33.01	0.1582
4	82.87°	40.97°	-35.23	0.1781
5	60.40°	12.30°	-35.23	0.3916



(a) (b)

Fig. 5.4 (a) Path gain and (b) Delay plotted against azimuthal and elevation angles of arrival, from propagation modelling data for user 2 in OFDMA Section 5.3.1

To help with further improvement of the CR performance in low SNR/bit conditions, the tradeoffs involved in using directional antennas of varying beamwidths are also examined. In addition to increased gain, directional antennas also provide higher data carrying capacity, reduced power, higher link reliability and increased coverage area. Further tradeoffs involved in determining the most advantageous beamwidth (30° and 10°) of directional antennas were also analyzed. The beams of the directional antennas are of uniform gain in the designated beamwidth and suppress beams from other directions. Table 5.3 contains the key parameters that are used in modeling the radiation patterns for the simulated directional antennas. Further details regarding the properties of the antennas we have used can be found in [5.10, 5.11].

TABLE 5.3
DIRECTIONAL ANTENNA PROPERTIES

	Azimuthal Beamwidth	Elevation Beamwidth	Gain (dBi)	Front to back (dB)
1 [13]	30°	30°	14	25
2 [6]	10°	30°	20	25

The strongest paths and the multipath clusters surrounding it play a very important role in determining the most effective beamwidth as well as direction. It is important to point out that the path gain and the delay spread are propagation parameters that are often reported independent of the specific antenna used in transmission. Specifically, path gain/loss is normalized with respect to the incident power and delay spread is solely dependent on the propagation environment. The impact of the characteristics of directional antennas is the number of multipath and received power for SNR consideration.

In the following sections, detailed implementation of the two simulated wireless systems and channel modeling will be described. It is worth mentioning that for all presented simulation results, only the uplink communication direction is considered in this thesis. This is because (a) for

Frequency Division Duplexing, the frequency difference between uplink and downlink channels is very small and results in minimal changes in the propagation environment; and (b), for Time Division Duplexing, the same frequency band is occupied thus resulting in identical ray tracing data.

5.2.1 Channel Modeling

Consider a transmitter array with P elements and a receiver array with Q elements. To represent the space-time channel over a signaling duration T and two-sided bandwidth W. In the absence of noise, the transmitted and received signal are related as

$$x(t) = \int_{-W/2}^{W/2} H(t,f)S(f)e^{j2\pi ft}df\,, \quad 0 \leq t \leq T \tag{5.1}$$

where $s(t)$ is the P- dimensional transmitted signal, $S(f)$ is the Fourier transform of the transmitted signal, $x(t)$ is the Q- dimensional received signal, and $H(t,f)$ denotes the time-varying frequency response matrix coupling the transmitter and receiver elements. For simplicity the focus is on one-dimensional ULAs of antennas at the transmitter and receiver and consider far-field scattering characteristics. Let d_T and d_R denote the antennas spacing's at the transmitter and receiver. The channel matrix can be described via the array steering and response vectors given by

$$a_T(\theta_T) = \frac{1}{\sqrt{P}}[1, e^{-j2\pi\theta_T}, \ldots e^{-j2\pi(P-1)\theta_T}]^T \tag{5.2}$$

$$a_R(\theta_R) = \frac{1}{\sqrt{Q}}[1, e^{-j2\pi\theta_R}, \ldots e^{-j2\pi(Q-1)\theta_R}]^T \tag{5.3}$$

where θ is related to the Angle of Arrival (AoA)/Angle of Departure (AoD) variable $\emptyset$ as

$\theta = \frac{d\sin(\emptyset)}{\lambda} = \alpha\sin(\emptyset)$, λ is the wavelength of propagation, and $\alpha = d/\lambda$ is the normalized antenna spacing. The channel matrix $H(t,f)$ can be generally modeled as shown below [5.8],

$$H(t,f) = \sum_{n=1}^{N_p} \beta_n \alpha_R(\theta_{R,n}) \alpha_T^H(\theta_{T,n}) e^{i2\pi v_n t} e^{-j2\pi\tau_n f} \quad (5.4)$$

which corresponds to signal propagation along N_p paths with $\{\theta_{T,n} \in [S_{T-}, S_{T+}] \subset [-0.5, 0.5]\}$ and $\{\theta_{R,n} \in [S_{R-}, S_{R+}] \subset [-0.5, 0.5]\}$ as the spatial angles (AoAs/AoDs) seen by the transmitter and receiver, respectively, $\{v_n = v(\theta_{R,n}, \theta_{T,n}) \in [-f_{max}, f_{max}]\}$ and $\{\tau_n = \tau(\theta_{R,n}, \theta_{T,n}) \in [0, \tau_{DS}]\}$ as the Doppler shifts and delays respectively, and $\{\beta_n\}$ as the corresponding independent complex Gaussian path gains. Note that v_n and τ_n depend on the spatial location of scatters, τ_{DS} denotes the delay spread and f_{max} denotes the one-sided Doppler spread.

Since the focus of our study is to formulate the frequency selective wireless channel for now, so using the above equation (5.4), the channel can be modeled for the frequency selective wireless channel. So using the obtained ray tracing data (such as that in table II), a physical frequency-selective wireless channel can be modeled which represent signal propagation over N_P paths as follows:

$$H(f) = \sum_{n=1}^{N_p} \beta_n \mathrm{a}_R(\theta_{\mathrm{R,n}}) \mathrm{a}_T^H(\theta_{\mathrm{T,n}})\, e^{-j2\pi\tau_n f} \quad (5.5)$$

β_n is the complex path gain for the n^{th} path,

$\mathrm{a}_R(\theta_{R,n})$ is the array response vector, where $\theta_{R,n} = \left(\frac{d_R}{\lambda_c}\right)\sin(AoA_n)$

$\mathrm{a}_T(\theta_{T,n})$ is the array response vector, where $\theta_{T,n} = \left(\frac{d_T}{\lambda_c}\right)\sin(AoD_n)$

d_R and d_T denote the antenna spacing at the receiver and transmitter , respectively and λ_c denotes the wavelength corresponding to the center frequency, f_c

τ_n denotes the delay associated with the n^{th} path.

5.3 OFDMA

Orthogonal Frequency Division Multiplexing (OFDM) is a modulation scheme known for its ability to withstand frequency selective fading. As per OFDM, the available band is divided into subcarriers and each subcarrier carries a bit of the data to be communicated.

For a system of N_o subcarriers, the transmitted OFDM signal, comprised of N_o data bits is defined as follows:

$$x(t) = \sqrt{\varepsilon}\sum_{n=0}^{N_o-1} x_n e^{j2\pi(fc+n\Delta f)t} \qquad 0 \leq t < T \qquad (5.6)$$

where ε is the energy of the OFDM signal

x_n is the n^{th} data bit,

f_c is the carrier frequency,

Δf is the smallest frequency increment,

T is the duration of each subcarrier.

What makes the subcarriers of an OFDM signal orthogonal is the frequency separation, Δf. For an available bandwidth, W, the frequency separation is $\Delta f = W/N_o$ and, accordingly, the duration of each subcarrier is $T = 1/\Delta f = N_o/W$. If the magnitude of the Fourier transform for each subcarrier is observed, the nulls of each subcarrier can be found to occur precisely at the same frequency as the peaks of the other subcarriers. Hence, each subcarrier is orthogonal to the other.

On reception with an isotropic receiver, after demodulating the carrier f_c and performing matched-filter with each of the subcarriers, the output corresponding to matched-filtering with the n^{th} subcarrier is given by

$$r_n = \sqrt{\varepsilon}\, x_n \sum_{l=1}^{N_p} \beta_l e^{-j2\pi n\Delta f \tau_l} + w_n \qquad (5.7)$$

where w_n is filtered, additive noise

The β_l and τ_l values belong to the set of realistic data, obtained using ray-tracing tools. For a directional receiver, (5.7) can be represented as, either a gain, corresponding to the direction arrival of the l^{th} path, or with an array response vector for each of the N_p paths.

Orthogonal Frequency Division Multiple Access (OFDMA) is OFDM with multiple users accessing the same frequency band. For this, the N_o subcarriers of the OFDM signal in (5.6) are evenly distributed between users, such that each user is assigned an orthogonal "comb" of subcarriers. Coherent detection is used on the outputs in (5.7) to estimate the transmitted data bits, which are assumed in this thesis to be biphase, (i.e. either $+1$ or -1).

In the next section, results of simulating the OFDMA communication schemes for one site and then summarized results for all for sites are presented. These systems are simulated in their basic form and their performances were analyzed, and compared when operated using either isotropic or directional receivers. The metrics used for performance analysis are Bit-Error Rate (BER) and Capacity. Furthermore, the trade-offs involved in determining the most advantageous beamwidth of directional antennas are also examined. The simulations in this chapter are considered initial steps towards designing an adaptive cognitive communication system that achieves a desired BER for a given SNR, employing directional antennas and using minimal computational resources for calculating the channel matrix.

5.3.1 Simulation Results for One Site

In this subsection, a four-user OFDMA communication system is simulated in Site 1 of the four simulated sites in Downtown, Singapore. Fig. 5.5 shows the modeled OFDMA setup, where the base station is at a height of 30 m while each user is at 5 m high. The data for all users is tabulated in Table 5.4. Table 5.5 contains AoA and raw path gain results for the strongest path of each user.

To generate the channel matrix for the simulations in this subsection, the raw path gains for each of the users are normalized to the strongest raw path gain amongst all the users.

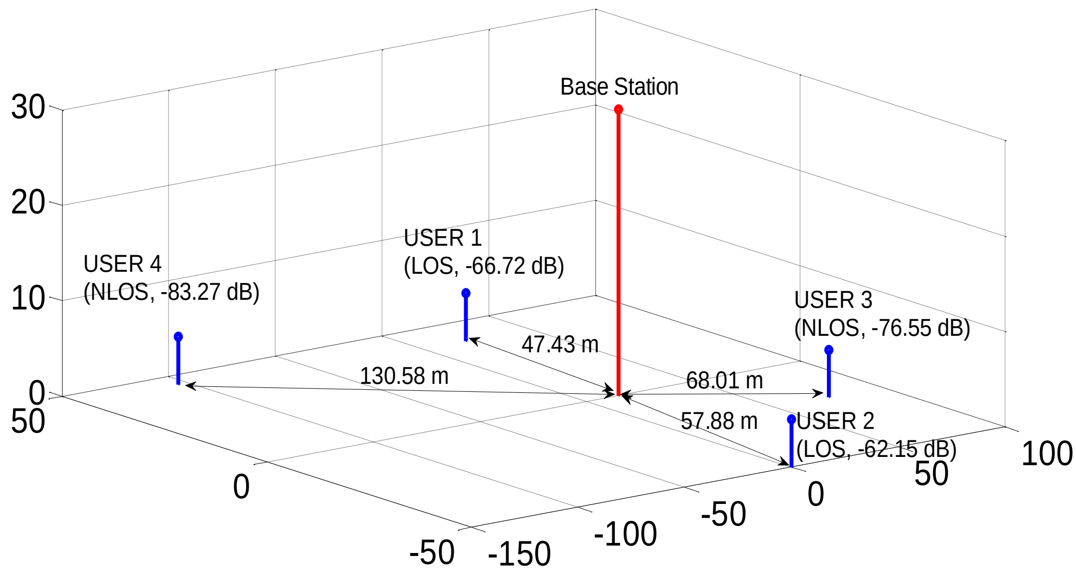


Fig. 5.5 OFDMA communication setup including Base Station and four mobile users.

Fig. 5.6 contains the BER vs SNR/bit curves for each user while using an isotropic receiver. As can be observed, for realistic SNR/bit values, good BER is maintained, for LOS users but, as expected, this is not the case for NLOS users. To demonstrate the advantages of directional reception, Fig. 5.7 contains BER vs SNR/bit curves for each user while using (a) a directional receiver with (a) 30° azimuthal beamwidth [5.11] and (b) 10° azimuthal beamwidth [5.10]. The antenna specifications for these directional receivers are tabulated in Table 5.3.

TABLE 5.4
DATA FOR ALL USERS

User#	Distance from Base Station (m)	Number of subcarriers	Path gain (dB)
1 (LOS)	47.43	2^5	-66.72
2 (LOS)	57.88	2^5	62.15
3 (NLOS)	68.01	2^5	-76.56
4 (NLOS)	130.58	2^5	-83.27

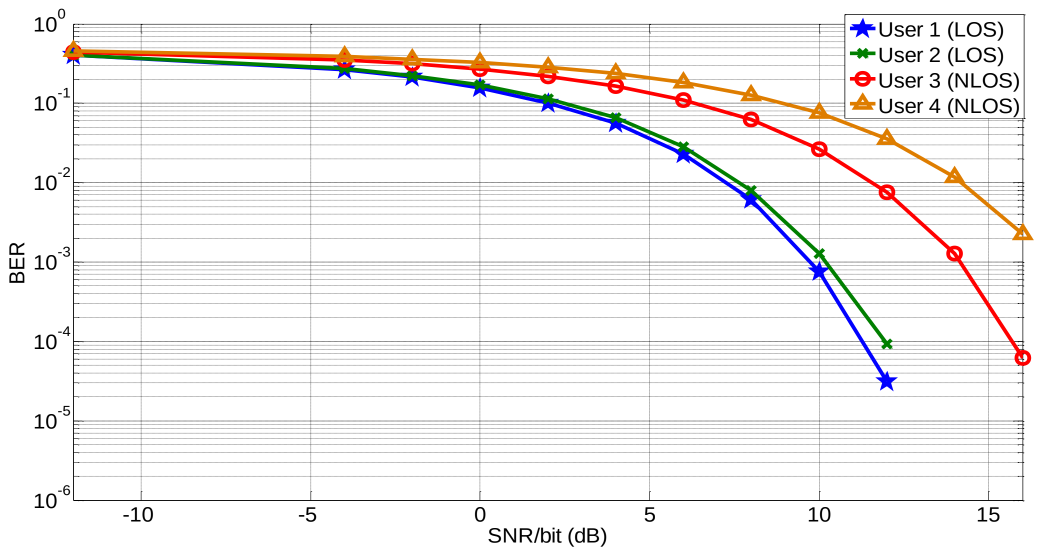
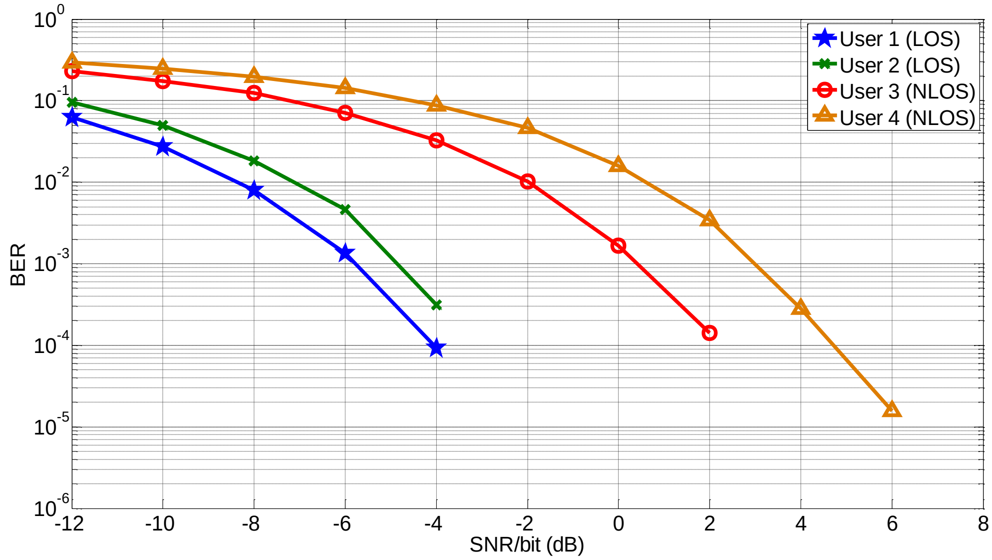
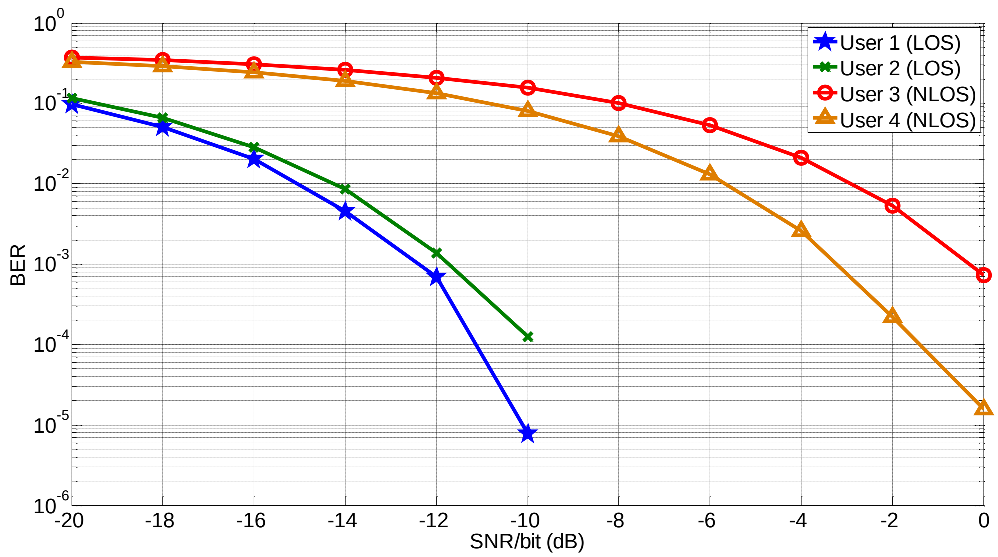


Fig. 5.6 BER vs SNR curves for all users, while using isotropic receivers.



(a)



(b)

Fig. 5.7 BER vs SNR/bit curves for all users, while using directional receivers, directed towards the strongest path in each case; (a) 30° beamwidth and (b) 10° beamwidth.

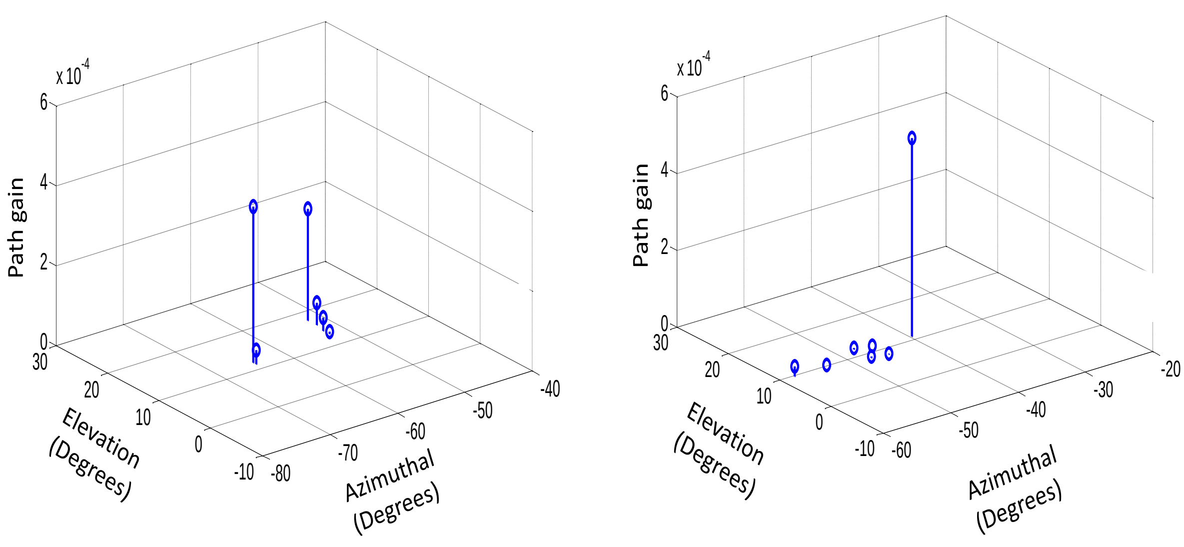
TABLE 5.5
DATA FOR STRONGEST PATHS OF ALL USERS

User#	Angle of Arrival Azimuthal	Angle of Arrival Elevation	Raw Path gain (dB)
1	-39.72°	24.41°	-27.96
2	60.40°	24.30°	-28.53
3	-64.58°	11.95°	-34.09
4	-39.72°	10.92°	-32.92

When comparing the BER's of 30° beamwidth directional receiver (Fig. 5.7 (a)) with those of isotropic receiver (Fig. 5.6), it is observed that at SNR/bit of -12 dB, BER decreases by a factor of ~5.11 for LOS users and ~1.70 for NLOS users. In comparison to the BER results for isotropic receiver, the BER using 10° beamwidth receiver (Fig. 5.7 (b)) for LOS users is decreased by a factor of ~388.07, but for NLOS users, the BER decreases only by a factor of ~2.61. Furthermore, it may be observed that changes in BER values for non-line of sight receivers depends on location. For example, while the BER for user 4 has decreased further for 10° beamwidth directional receiver, the BER for user 3 has increased. This effect can be better explained by observing Fig. 5.8 which contains the path gains vs Azimuthal and Elevation angles of arrival for (a) user 3 and (b) user 4.

As can be seen from Fig. 5.8 (a), the strongest raw path gain of user 4 is greater than that of user 3, but for user 3, there is another path with AoA close to the strongest path and with similar path gain. Hence, for isotropic receiver (Fig. 5.6) and for directional receiver with 30° azimuthal beamwidth (Fig. 5.7 (a)), the two strong paths of user 3 combine to give a better BER than that of user 4. For directional receiver with 10° azimuthal and 30° elevation beamwidth (Fig. 5.7 (b)), the second strongest path of user 3 is suppressed due to lying outside the narrow beam. As a result, the strongest raw path gain of user 4 enables the user to achieve a better BER than user 3. This simple observation clearly illustrates some of the trade-offs that need to be considered when implementing directional antennas in a multipath propagation environment, especially in the case of NLOS users. Due to the special angle spread of multipath signals, it may be observed that while narrower beamwidths are often associated with higher gains and improved Signal to Interference and Noise Ratio (SINR), these narrower beams may limit gaining advantages of combining multipath signals and improving BER in a multiuser communication channel.

It can be concluded from the simulations in Fig. 5.6 and 5.7 that, in general, while narrow beamwidth may help in link performance, it may limit the extent to which the richness of multipath is captured. The case of User 3 serves as a good example: when the beam of the antenna is pointed to the strongest path and the beam is too narrow, the second strongest path gets suppressed because of its angular separation from the strongest path, as shown in Fig. 5.8 (a).



(a)

(b)

Fig. 5.8. Path gains vs azimuthal and elevation angles from propagation modelling data for (a) user 3 and (b) user 4.

Simulations are also performed to help analyze the BER for each user when paths having gain less than a prescribed level are discarded in order to generate the channel matrix at the receiver. The objective of this part of the simulations is to develop an implicit understanding of the minimum number of paths that are needed for generating an effective channel matrix for maintaining desired performance characteristics at the receiver. These simulations clearly have a direct impact on the time required to generate a channel matrix and hence, provide an illustration of how the performance of a typical communication system depends on the level of detail provided by realistic propagation modeling data. Fig. 5.9 contains curves showing BER vs normalized path gain (i.e. path gain normalized to the strongest path gain among the four users) levels for all users for fixed SNR/bit = 10 dB, while using an isotropic receiver. Likewise, Fig. 5.10 contains the curves BER vs normalized path gain levels for all users while using a directional receiver, for beamwidth (a) 30° (fixed SNR/bit = -6 dB) and (b) 10° (fixed SNR/bit = -12 dB).

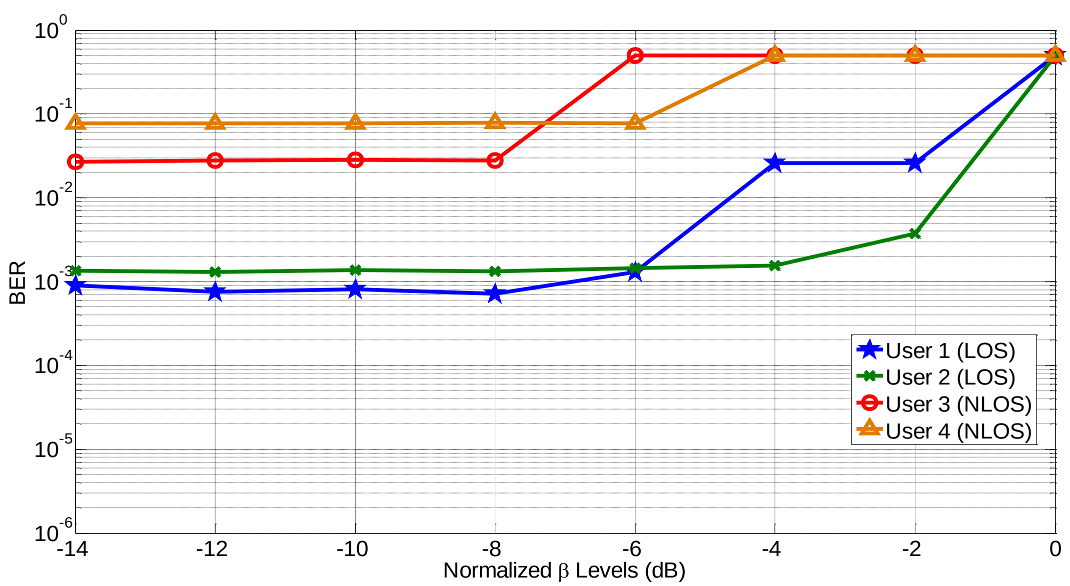


Fig. 5.9. BER vs normalized path gain (β) level curves for all users, while using isotropic receivers (SNR/bit = 10 dB).

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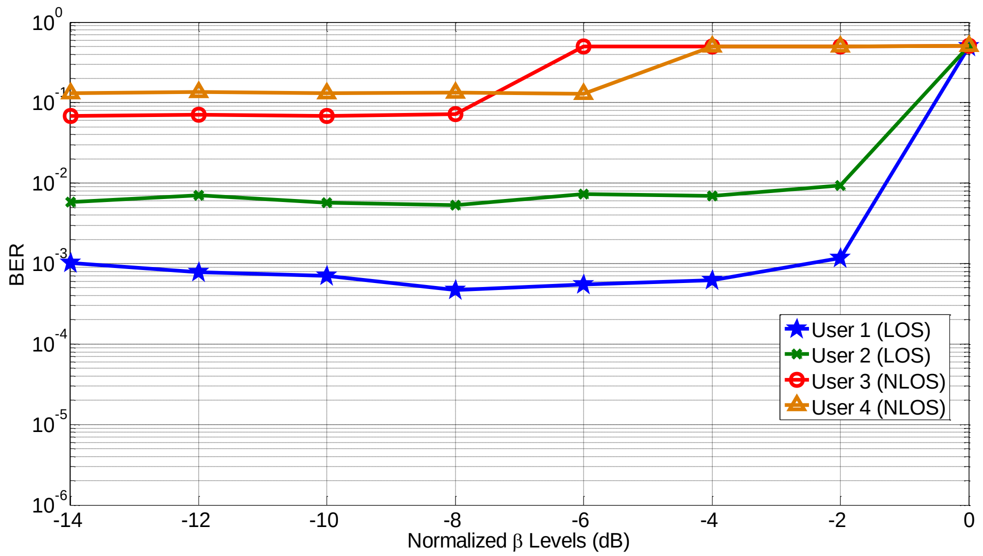
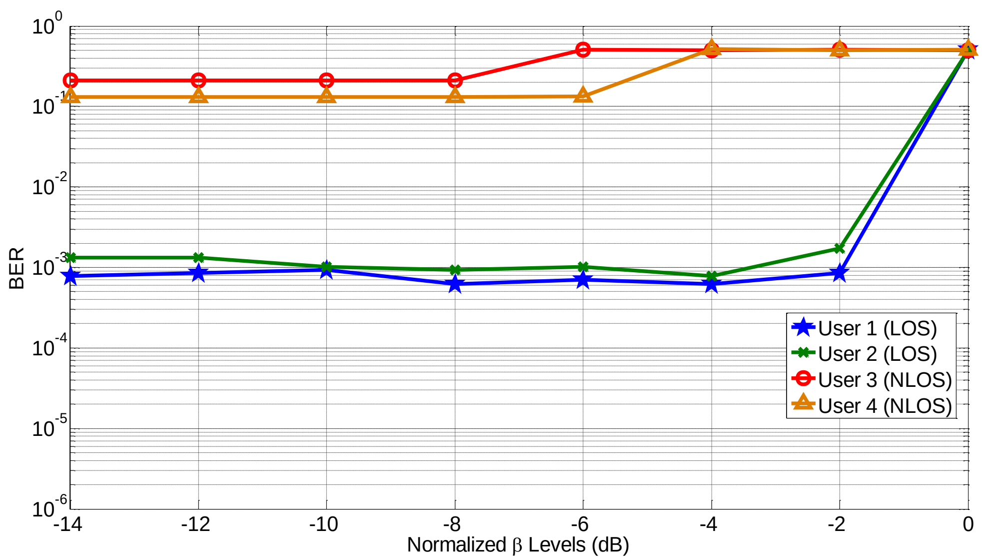


(a)



(b)

Fig. 5.10. BER vs normalized path gain (β) level curves for all users, while using directional receivers, directed towards the strongest path in each case; (a) 30° beamwidth (SNR/bit = -6 dB) and (b) 10° beamwidth (SNR/bit = -12 dB).

The results in Fig. 5.9 shows that beyond a sufficient level of path gains, the weaker paths have insignificant effect on the overall system performance and hence, can be neglected. In the simulated setup, for 8 dB SNR/bit, paths with normalized path gains that are less than -8 dB for LOS users and less than -10 dB for NLOS users can be neglected. Neglecting unneeded paths enable the receiver to maintain good performance levels while using much less computational resources.

For the results in Fig. 5.10 (directional receivers), paths with normalized gains that are less than -4 dB for LOS users and -10 dB for NLOS users can be neglected. In comparison with the curves in Fig. 9 (where isotropic receivers are used), the results in Fig. 5.10 show that the use of directional antennas allows the receiver to neglect more paths and operate at lower SNR/bit (0 dB for 30° beamwidth and -4 dB for 10° beamwidth), thus further reducing the computational cost of generating the channel matrix.

5.3.2 Summarized Simulation Results for All Sites

To validate the observations in Section 5.3.1, this section contains detailed analysis of the four sites, all in Downtown, Singapore. Specifically, for each site, four base station locations were randomly chosen and for each base station location, two LOS and two NLOS users are randomly located, for uplink OFDMA communication, similar to Section 5.3.1. For SNR/bit = -12 dB, the BER is computed using isotropic and directional receivers with 30° and 10° beamwidths. For each site, the factors of improvement, denoted by λ_{LOS} and λ_{NLOS} (for LOS and NLOS users, respectively), are presented in Table 5.6, which contains the average and maximum improvement factors. Table 5.6 also contains the maximum delay spread (τ_{rms}) for all users (LOS and NLOS) for each site. In general, similar to the results in Section 5.3.1, BER improvement for LOS users is observed to be consistently much greater than that for NLOS users, for all sites.

TABLE 5.6
BER IMPROVEMENT FACTOR FOR OFDMA COMMUNICATION AND MAXIMUM τ_{rms} FOR EACH SITE

Site #	Beamwidth	Avg. λ_{LOS}	Max. λ_{LOS}	Avg. λ_{NLOS}	Max. λ_{NLOS}	τ_{rms}
1	30°	15	33	2	3	1.21 μs
	10°	3230	12264	6	14	
2	30°	6	12	3	9	1.96 μs
	10°	282	1042	53	204	
3	30°	62	223	1	2	1.60 μs
	10°	1059	3449	2	4	
4	30°	29	105	2	3	1.98 μs
	10°	2701	10758	3	7	

While the ray tracing tool used is site specific, it is still very general in the sense that given any site, a model can be constructed and ray tracing data obtained such as path gain, delay spread, angle of arrival/departure and Doppler spread. Therefore, any site or area (urban, suburban, and rural) can be from Google Earth, reconstructed using the ray tracing tool and the channel state information can be obtained. Typical values for electrical permittivity and conductivity for buildings are taken into account while building realistic models. In order to determine if the model is a typical urban environment to validate our results obtained in Section 5.3.2, the root mean-squared delay, defined as

$$\tau_{rms} = \sqrt{\frac{1}{N_p}\sum_{i=1}^{N_p}\tau_i} \quad (5.8)$$

was calculated and compared results from ray tracing. According to [5.13], for an environment to be considered typical urban, τ_{rms} has to lie between 0.3 and 2 μs. This was found to be the case for all the mobile users in this section, LOS or NLOS. For each site, the maximum τ_{rms} is tabulated in Table 5.6.

5.4 Multiuser Wireless Communication System

This subsection briefly describes the multiuser wireless system in [5.8] and the implementation of the proposed approach in this system. Fig. 5.11 illustrates the overall structure of the system.

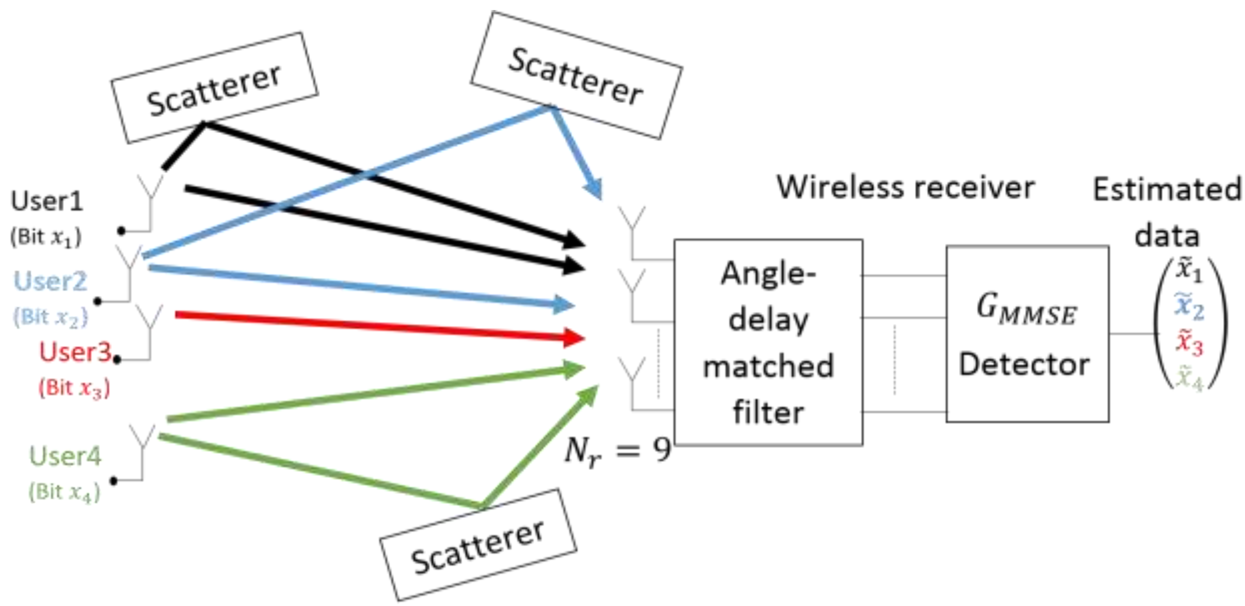


Fig. 5.11. Multiuser wireless communication setup

In this system, each user is assigned the same spreading code. In order to distinguish between the received data from each user, the receiver relies on the channel matrix (more specifically, the spatial characteristics) corresponding to each user. For this system, the physical channel matrix in (5.5) is sampled in delay and angle [5.8].

At a given time instance, the transmitted data bit by each of the K users, i.e. $x_1, x_2, \ldots, x_K$, can be expressed as a vector:

$$\boldsymbol{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_K \end{bmatrix} \tag{5.9}$$

At the receiver, angle-delay matched filtering is performed, in order to be able to distinguish between the active users:

$$r_{i,l} = \left(\frac{1}{\sqrt{N}}\right) \int_0^T \mathrm{a}^H \left(\frac{i}{N}\right) r(t) q^* \left(t - \frac{l}{W}\right) dt \tag{5.10}$$

where, N is the number of antenna elements at the receiver, $r(t)$ is the received signal (with incorporated channel matrix), $q(t)$ is the spreading code that is assigned to each user, T is the length of the spreading code and W is its two sided bandwidth, The angle index i ranges from $i = 1, 2, \dots, N$ and the delay index, l ranges from $l = 1, 2, \dots, L$ (where L is the number of allowed delay bins).

The output of (5.10), in vector form, is denoted by $\boldsymbol{r}$ with dimensions $LN \times 1$. Using this output, the correlation matrix, $\boldsymbol{R}$ is obtained:

$$\boldsymbol{R} = E[\boldsymbol{r}\boldsymbol{r}^H] = N\varepsilon \boldsymbol{H}\boldsymbol{H}^H + \boldsymbol{I} \tag{5.11}$$

where $\boldsymbol{I}$ is an identity matrix,

$E[\cdot]$ is the expected value operator,

ε is the user signal energy,

$\boldsymbol{H}$ is the sampled channel matrix, each column of $\boldsymbol{H}$ contains the individual angle-delay sampled channel vector (of dimension $LN \times 1$) corresponding to each active user.

The output of the angle-delay matched filter is passed through a Minimum Mean Squared Error (MMSE) detector [5.12] from which, data bits transmitted by each user are extracted. The MMSE detector is given by

$$\boldsymbol{G}_{MMSE} = \boldsymbol{H}^H \boldsymbol{R}^{-1} \qquad (5.12)$$

Assuming that the transmitted data bits are biphase (i.e. $x_k \in \{-1, 1\}$), the estimated data bits vector can be extracted from the output of the MMSE detector in (5.12) as shown below:

$$\hat{\boldsymbol{x}} = sign\{real(\boldsymbol{G}_{mmse}\boldsymbol{r})\} \qquad (5.13)$$

Details on the described system can be found in [5.8]. A four-user case of this system is simulated in Section 5.4.1. Due to the reliance on the spatial characteristics of each active user in order to distinguish between them, the performance of the receiver depends on the number of receiver antennas. This dependency will also be discussed in the Section 5.4.1. Moreover, the effects of different levels of detail in the site-specific realistic CSI and different number of multipath used in generating the channel matrix are also investigated.

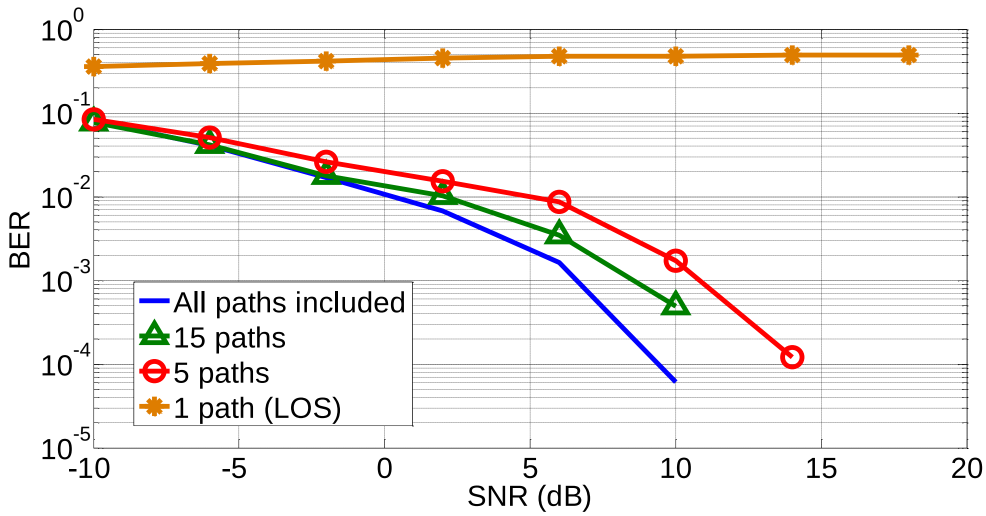
5.4.1 Simulation Results for One Site

In this subsection, the performance of the multiuser wireless system [5.8] that is briefly described in above section is examined in terms of BER and Capacity. This system is also set up in Site 1 of the four Singapore Downtown sites. The Capacity, i.e. the maximum possible rate of reliable data reception, depends on the channel matrix, H, and the transmitted signal energy from each user, ε. Channel Capacity *C(H)* is given by [5.8]:

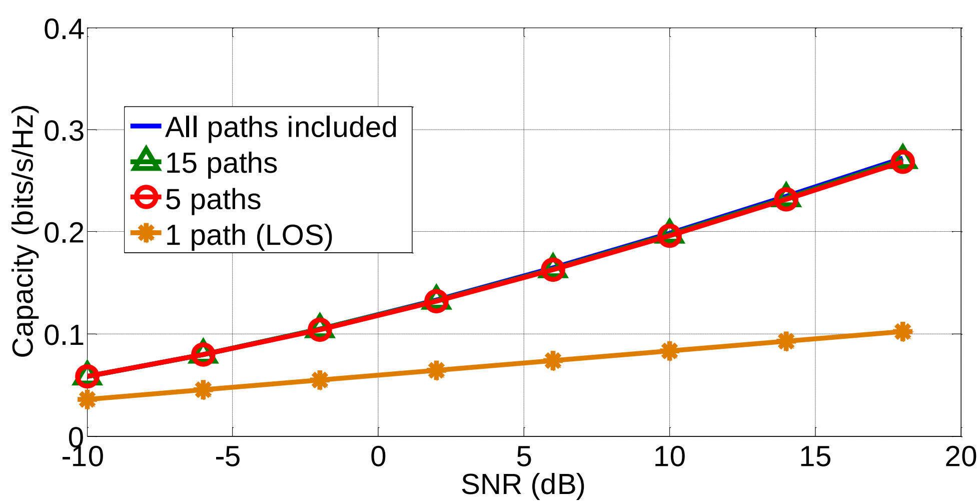
$$C(H) = \frac{1}{TW+L} \sum_{k=1}^{K_{eff}} \log_2(1 + \varepsilon N \lambda_k) \qquad (5.14)$$

where K_{eff} is the rank of the matrix HH^H and $\{\lambda_k\}$ are the eigenvalues of the matrix HH^H.

Fig. 5.12 (a) shows the combined BER vs SNR/bit curve for the multiuser wireless system with $K = 4$ active users, $N_r = 9$ antenna elements and for a variety of N_p used in generating the channel matrix. The combined BER is simply the mean BER for all 4 users. For each user, all path gains that are used in generating the channel matrix are normalized to the strongest path gain for that particular user. Using the ray tracing tool, the total number of paths, N_p, for each user varied around 32-37. The users are at a distance of approximately 177 m from the receiver.



(a)

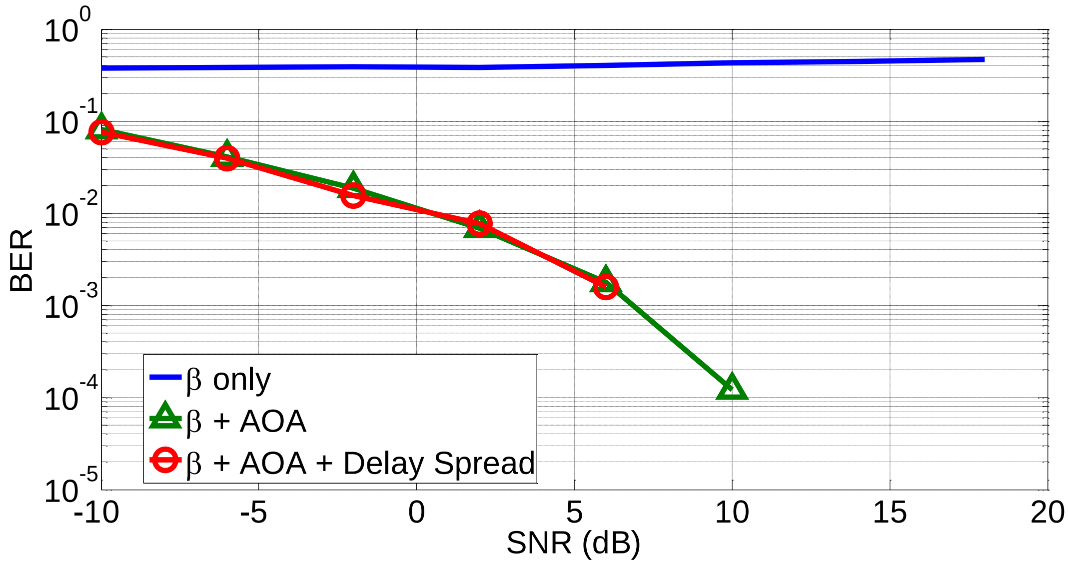


(b)

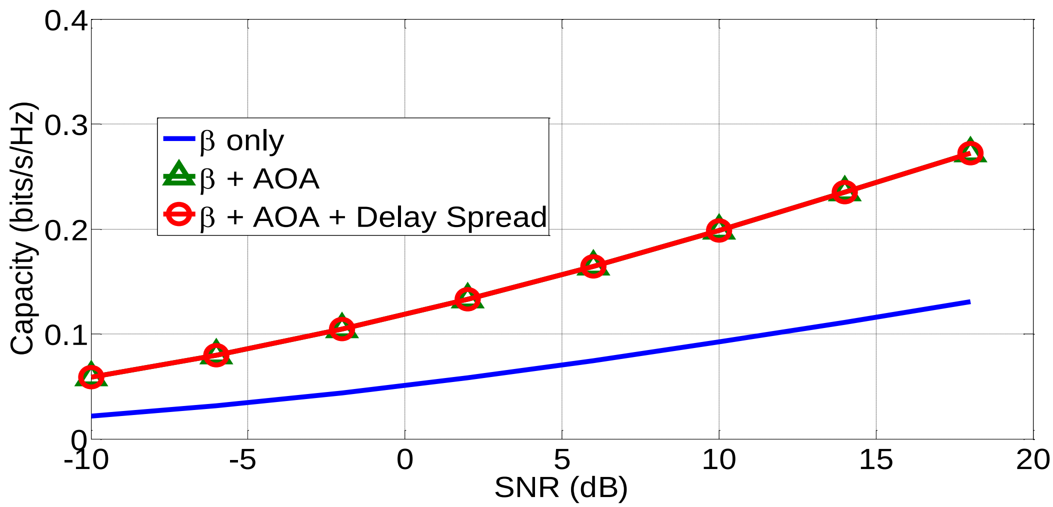
Fig. 5.12. (a) BER vs SNR/bit curves and (b) Capacity vs SNR/bit for a four-user wireless system with different number of paths used in generating the channel matrix

It is observed from Fig. 5.12 (a) that BER decreases as more paths are used in generating the channel matrix. However, for a given SNR/bit, it may be sufficient to use fewer paths in generating the channel matrix in order to meet a desired BER. For example, for a desired BER of 1%, and SNR/bit of 6 dB and higher, only 5 paths are found to be sufficient and the rest could be neglected. This, in turn, would greatly reduce the amount of computations required in generating the channel matrix. Further, the capacity (Fig. 5.12 (b)) for channel matrix generated using 5 paths is only negligibly less than that for the channel matrix generated using all paths. It is worth mentioning that relying on the strongest path only is insufficient in generating the channel matrix, hence, the bad BER results when only 1 path is taken into account.

In addition to disregarding weak paths, it is also possible to use fewer levels of details in the CSI that is used to generate the channel matrix. Fig. 5.13 (a) and (b) show the BER vs SNR/bit and Capacity vs SNR/bit curves, respectively. For both Fig. 5.13 (a) and (b), curves are plotted while using channel matrix at the receiver that uses either β_n only, or β_n and AoA, or β_n, AoA and τ_n. For all the plots in Fig. 5.13, $N_r = 12$. From Fig 5.13 (a) it can be clearly seen that similar performance (e.g. a BER of 10^{-4} for 10 dB SNR/bit) can be achieved by only using β_n and AoA for generating the channel matrix rather than using β_n, AoA and τ_n. Similarly from Fig 5.13 (b) it is noticed that similar capacity can be obtained using only β_n and AoA rather than β_n, AoA and τ_n. Once again, this reduces the computational cost associated with implementing propagation modeling in cognitive communication systems.



(a)

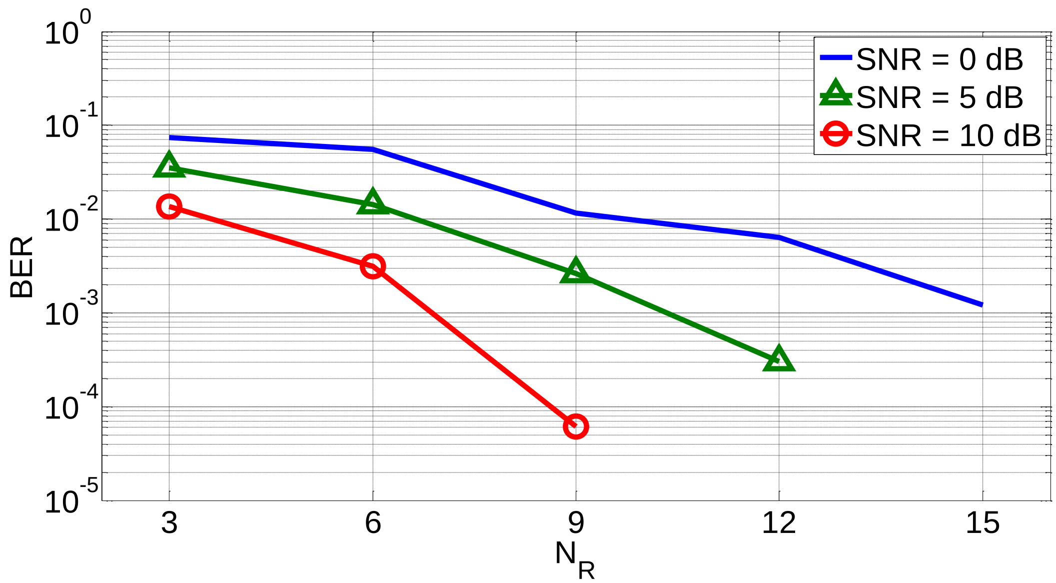


(b)

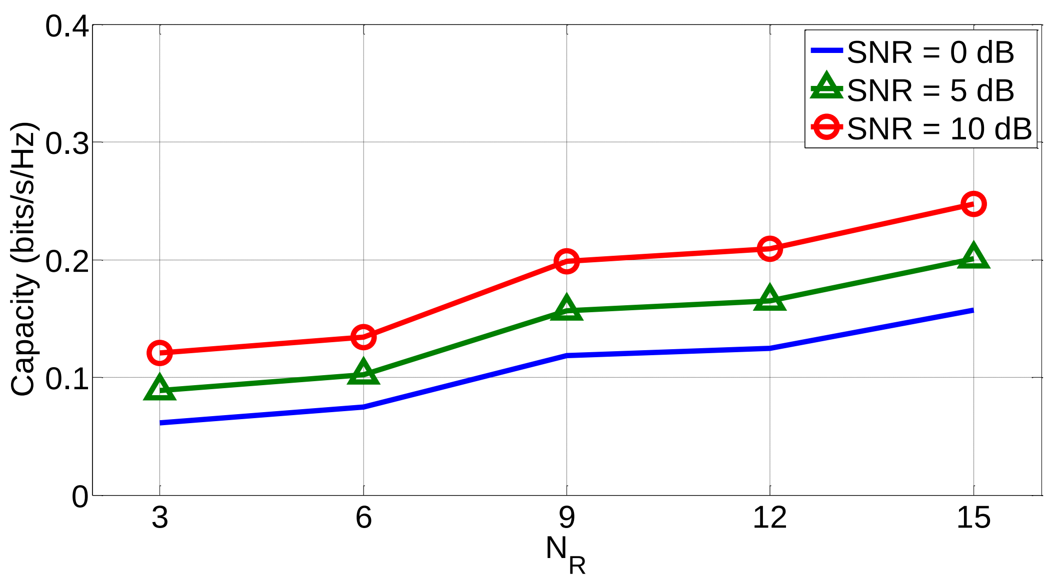
Fig. 5.13. (a) BER vs SNR/bit curves and (b) Capacity vs SNR/bit curves for four-user wireless system with different levels of details in generating the channel matrix.

Since the multiuser wireless system relies entirely on the spatial characteristics of each user to generate the channel matrix, we examined the performance of the system while varying the number of antennas at the receiver array, N_r. Fig. 5.14 contains (a) the BER vs N_r and (b) Capacity vs N_r

curves for the four-user wireless system modeled in the simulations, for SNR/bit = 0 dB, 5 dB and 10 dB.



(a)



(b)

Fig. 5.14. (a) BER vs number of antennas at the receiver array (N_r) curves and (b) Capacity vs N_R curves for four-user wireless system, for SNR/bit = 0 dB, 5 dB and 10 dB.

For the simulations in Fig. 5.14, the channel matrix is generated using all paths and all levels of details. From Fig. 5.14, it can be seen that BER is a monotone decreasing function of N_r whereas the capacity is a monotone increasing function of N_r. While more receiver array antennas improve the performance of the system, the improvements come at the cost of extra computations, as will be explained in the next subsection. The tradeoff between performance improvement and extra computations due to higher N_R needs to be considered when designing the system. As an example, for desired BER of 2 % and for 10 dB SNR/bit, only 3 antennas would be enough to achieve the desired BER, whereas, for 5 dB SNR/bit, 6 antennas and for 0 dB SNR/bit, 9 antennas would be needed, at the cost of more computations (i.e. additions and multiplications) as described in the next subsection.

5.4.2 Summarized Simulation Results for All Sites

Analysis was also carried out to find the minimum number of multipath required in modeling the channel while meeting some certain desired performance criteria. For each of the base station locations chosen in Table 5.7, four LOS users are randomly selected and four separate multiuser wireless systems (similar to a single site) are simulated for each site, with fixed SNR/bit of 5 dB. Table 5.7 contains, for the LOS users at each site, the average minimum number of paths required to satisfy BER constraints of 1% and 0.1%. The results show that for all sites, the average number of paths in meeting a 0.1% BER criterion is 6, i.e. ~85% paths can be discarded. The next subsection on computational requirements quantifies the benefits for discarding paths and using minimum information in sufficiently modeling the channel.

TABLE 5.7
NUMBER OF PATHS FOR 1% AND 0.1% BER WITH SNR/bit FIXED AT 5 dB

Site #	Avg. N_p	Avg. N_p for 1% BER	Avg. N_p for 0.1% BER
1	31	6	13
2	40	2	3
3	43	4	4
4	44	3	3

In previous subsections, it is shown that good performance can be achieved using limited number of the available ray-tracing data (e.g. less number of multipath and also by neglecting τ_n data). In this subsection, the computations required in generating the channel matrix, using the realistic data, are further discussed. Table 5.8 contains the number of adders and multipliers (as a function of the number of paths, N_p and the number of receiver antennas, N_R) required for generating the channel matrix using {β_n only}, {β_n and AoA} and {β_n, AoA and τ_n}. For $N_p = 5$ and using β_n and AoA only, the computational savings in both additions and multiplications are ~ 85 % as can be computed using the expressions in Table 5.8. On the other hand, for a fixed number of paths, the use of smaller number of antennas at the receiver also reduces the computations. As an example, for $N_r = 9$ instead of 3, $N_p = 5$ and while using β_n and AoA only, the number of additions and multiplications is reduced by 61% and 66%, respectively.

TABLE 5.8

THE NUMBER OF ADDERS AND MULTIPLIERS REQUIRED IN GENERATING H[1,2]

	ADD	MUL
β_n only	$2N_p - 2$	0
β_n + AoA	$2(1 + N_r)N_p - 2$	$4N_pN_r$
β_n + AoA + τ_n	$2(2 + N_r)N_p - 2$	$4(1 + N_r)N_p$

Realistic propagation modeling and directional antennas are two key features that make a cognitive communication system intelligent and adaptive in various challenging environmental conditions. This chapter analyzes the performance of two modern wireless communication systems viz. OFDMA and a multiuser wireless system, while modeling the channel using environmentally realistic ray-tracing data for four sites in Downtown, Singapore, and using both isotropic and directional receivers [5.10, 5.11]. Simulation results show that, for -12 dB SNR/bit the use of directional receivers with 30° beamwidth on average improves the Bit-Error Rate (BER) by a factor of 28 for LOS users and 2 for NLOS users, in comparison with isotropic receivers. When the beamwidth is reduced to 10°, LOS users give an average BER performance improvement of 1818 whereas the NLOS users give a much smaller average BER performance improvement of 16. These results clearly illustrate that the achievable improvements when using directional antennas depend not only on the achievable gain and reduction in beamwidth but also on the richness of multipath and it could vary from user to user (e.g line of sight vs non-line of sight users). While focusing the energy of directional antennas in a narrow beam has its benefits, making the beam too narrow does not allow full use of the richness of multipath.

In summary, the main objective of this chapter is. While interference mitigation is an essential part of any communication system, this chapter does not analyze causes of interference and dealing with them. Examining this and other aspects of a full cognitive radio will be a part of future research in this area.

One of the challenges in implementing the proposed adaptive cognitive communication systems is the real-time execution of propagation modeling tools including those based on ray-tracing methods. As stated earlier there exists a tradeoff between the computational time in acquiring ray-tracing data and the level of details required to develop an effective channel matrix. In real-time communication applications, minimizing the computational time in generating ray-tracing data without losing the level of detail is vital for achieving improved performance. This chapter examined such a trade off in this thesis and it is shown that for realistic SNR/bit values, just the path gain and AoA data for as few as 5 paths could be sufficient in forming a propagation model at the receiver while satisfying certain desired performance criteria. When compared to using all the available propagation modeling data, the use of only 5 paths results in 85% reduction in computation time required for generating the channel matrix.

Results of this research can be used to guide design efforts in minimizing the resources needed to meet certain desired performance characteristics of an adaptive cognitive communications system. It also reemphasizes the importance of using directional reception while highlighting some of the trade-offs involved.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Summary and Conclusion

A novel six sectoral cellular base station architecture was designed called Advanced Base Station or Node for wireless communication with mobile users. Separate hexagonal antenna array equipped with additional signal processing capabilities are used for user discovery (via scanning) and for data communication with users. Each advanced base station is capable of digital beamforming, beam steering, handover, load management and coordinated multipoint transmission or reception. This enables the base station to achieve large coverage area, economical use of radiated energy and better frequency reuse due to six-sectors instead of traditional three-sector. Complete physical layer architecture modifications include computation of Angle of arrival

(AoA) for each user, sector assignment, saving data in user database, calculating the beamforming weights using dedicated processing unit and directing the communication (data) beam to the respective user. Adaptive antenna array was also proposed for wireless connections/link between advanced nodes via extremely high frequency such as from 60-70GHz link, which provides a new approach for rural area network. This wireless communication is established amongst the base stations via Internet Protocol (IP) connectivity. This interconnectivity facilitates mobile user handover, load management, and resource assignment. All the modifications due to beamforming directional antennas array were restricted to the physical layer of the Advanced Base Station

To make sure these new physical layer modification does not disrupt any changes in the MAC or higher layers, timing requirements of MAC layers was taken into considerations. Quantitative analysis was conducted to compute the upper bound (timing constraints) required by various processes conducted by the proposed advanced node technology such as scanning for new user discovery, angle of arrival estimation and calculating the beamforming weights to direct the communication beam towards the user. The scanning array scans full 360^0 or 60° sectoral scanning based on the operator's choice and can be divided into various steps for user discovery process. The duration for which the scanning beam stays in a direction is a beacon interval and can be configured based on the environment. For each angular step, the processing unit performs Angle of Arrival estimation and assigns sector to discovered users (users that are recognized by the advanced base station). MUSIC Algorithm for Angle of Arrival estimation process was simulated for one active user (1024 bits received data) and estimated timing requirements was calculated for Virtex 7 FPGA which is capable of computing nearly 160 Billion floating point operations per second. This computes to an estimation time of 3.35 microseconds. Moreover, computing the beamforming weights and applying them either digitally or using fast RF switches would take around 4.76 nanoseconds. So totally it would take nearly 3.5 microseconds for the whole process to complete. Software and hardware simulations for deterministic beamforming were performed with currently available low-end Xilinx Spartan 6 – model XC6SLX75 and simulations confirmed that using real devices (FPGAs) it is guaranteed to behave as in the simulation and hence would satisfy the timing constraints. It was proposed that the modifications would fit within the SIFS time period as it is the smallest time period in the MAC standard and since the calculated Angle of Arrival estimation and beamforming weights timings are within the time period, then there would be no requirement for MAC layer changes for any IEEE 802.11 wireless standard.

Next, the thesis discusses the use of Genetic Algorithm and Geospatial assets (such as Google Earth) to place base stations in order to optimize cellular coverage in rural areas such as Maui Island, Hawaii and Kohala region of the Big Island, Hawaii. Simulations results indicate that instead of four omnidirectional base stations (5 dBi gain), only two directional antenna (19 dBi) equipped base stations can be used to cover the approximately same area (~91% for Maui and ~83% for Kohala). Due to the harsher terrain (unevenness mountains and deep forests), the cellular coverage of the Kohala region is found to be worse than that of the Maui Island.

In perspective to this thesis, capabilities for directional antenna systems and related propagation issues to play a more important role in system level performance of cognitive communication systems are also investigated as part of the environment awareness engine. The performances of two modern communication systems i.e. OFDMA and Multiuser Wireless System were analyzed. Accurate site-specific propagation modeling data (such as path gain, angle of arrival/departure and delay spread) for four typical urban sites in Downtown, Singapore is used for channel modeling. Specifications of existing directional antennas are used to model the directional antennas with 30° and 10° azimuthal beamwidths, for the simulations in this thesis. For

-12 dB SNR per Bit, simulation results show that, in comparison with isotropic receivers, the use of directional receivers with 30° beamwidth improves the Bit-Error Rate (BER) on average by a factor of 28 for LOS users and 2 for Non-Line of Sight users. When the beamwidth is reduced to 10°, line of sight users get an average performance improvement of 1818 whereas non-line of sight user BER values were decreased by a factor of only 16. This tradeoff between decreasing the beamwidth of directional antennas and the incomplete utilization of rich multipath, especially for non-line of Sight users is thoroughly discussed in this thesis. The performance gains due to the use of directional receivers are shown to be achievable using as small as 5 paths and utilizing only AoA and path gains, in generating the channel matrix. This results in significant savings (85%) in computational cost, thus emphasizing the potential practical implementation of the proposed approach in cognitive communication applications as part of the environment awareness engine.

6.2 Future Work

Based on the proposed advanced base station in the thesis and simulations carried out, the following suggestions are proposed for future work:

- It is worth mentioning that simulation results for the angle of arrival estimation and beamforming weights calculation for the advanced base node were considered individually. So a complete system level simulation, integrating the modifications (scanning, angle of arrival and beamforming weights process) with an existing IEEE 802.11 simulator would be the focus of our future research. Open source software such as OpenAirInterface [6.1] and licensed MATLAB Toolboxes (LTE, 802.11) can be integrated with our existing code for complete system level simulation.

- Since the current focus of research was on IEEE 802.11 standard, future work would include investigations and simulations for latest wireless access technologies like 3GPP LTE. Open source LTE simulator [6.2, 6.3] can be integrated with our modified code to make a complete simulation package for directional base stations. Incorporation would involve AoA assisted beamforming and scanning array for user discovery to analyze the delays involved.
- In case of networking design and planning, due to different levels of cellular user density, the path gain at each location of the area under consideration could be assigned priority based weights which would result in variable cell sizes based on population density. Investigating the effect of the path gain weights on the resultant variable cell sizes could be a topic of future research. Various interesting sites such as land-sea transitions, deserts, and dense forest could also be incorporated into the propagation modeling for more realistic data and visualization
- For the adaptive cognitive communication system, only assets for the environment awareness engine was developed which is included in the thesis. A complete implementation of the cognitive radio system including spectrum sensing engine, location awareness, and environment awareness would be a part of future research.
- Finally, a complete hardware demo system, presenting the complete advanced base station properties starting from user discovery using scanning arrays, angle of arrival estimation and finally beamforming the communication array to the desired user would be a great addition to future implementation. Some initial investigation has been done to identify the parts required to completely realize the hardware setup. Individual parts and already existing base station setup such as Amarisoft LTE [6.4] has been identified, and could be used for complete hardware realization of the proposed advanced base station.

The ultimate goal of the project is implementing the proposed advanced base station which is capable of transmitting and receiving data on the fly, and observing the effects of directional networking on signal quality such as BER, audio quality, signal strength and network capacity. The final setup should be able to demonstrate multiple beams within a sector, provide wireless access to moving users, exhibit sectorial handover and also establish base station to core network link via the backhaul. The work done in this thesis provides a promising start and important step towards achieving this goal.

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