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Smart Antenna Systems for WiMAX Radio Technology

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1. Introduction

In this chapter we present our design and implementation of smart antenna systems for WiMAX radio technology in Montana State University. WiMAX offers the potential of long range (up to 50 miles) and high bandwidth (up to 50 Mb/s) radio links[Eklund 2002, Nuaymi 2007]. This new radio technology vastly exceeds the capabilities of widely used wireless such as Wi-Fi, offering features not supported by current wireless systems. The new WiMAX standard offers the potential for using adaptive antenna system (AAS), but this functionality has not been widely implemented. One notable example is Smart WiMAX[Hedayat et al. (2007)], however no technical details have been reported. This chapter serves as an introduction to the reader with a perspective on historical and recent progress in this rapidly involving field of communications research.

Smart antennas for fixed and mobile wireless communications have received enormous interest worldwide in recent decades, and a wide variety of approaches for beamforming antenna design and application have been described over the last five decades [Liberti and Rappaport 1999, Van Veen, and Buckle 1988, Widrow and Stearns 1996, Krim and Viberg 2003, Loadman et al. 2003, Godara 1997]. Unlike a conventional omni-directional antenna that wastes most of its energy in directions devoid of users, a smart antenna can form one or more beams in the direction of fixed or mobile users and create nulls toward interferences, thus greatly improving system performance. In addition, since the radiation power of a beamforming antenna is focused toward the user, a beamforming antenna equipped radio system will have a much larger range than that of a conventional omni-directional antenna equipped system. Also, this efficiency increase, in most cases, will save energy. While adaptive smart antennas have been used in the past for other applications, the technology has seen limited use due to high costs and poor integration with other radio system elements.

There are two types of smart antennas: switched beam and adaptive array. For a switched beam system, a set of specific, sometimes predetermined, beam patterns are formed with the main lobe toward the mobile node. The antenna system monitors the signal strength and switches among the lobes periodically to update beam selection. This antenna design improves performance by increasing signal strength and suppressing interferences that are not in the same direction as the signal. However, if interference is within the same lobe as

the signal, the interference will not be suppressed. This is a major disadvantage of the switched beam approach.

A phased array (or steerable array) can be viewed as a special type of switched beam. With predefined weight (array element current), a fixed beam can be formed to any desired pointing angle. In reality, due to the limitation of hardware, only limited pointing angle can be achieved.

An adaptive array utilizes sophisticated signal processing algorithms to continuously distinguish among the desired signal and interferences and can form an unlimited number of beam patterns to optimally improve signal strength and suppress interferences. The adaptive array offers higher gain, because of the precise pointing ability, than the switched beam array and greater interference rejection. Adaptive arrays may require longer computational time to converge to optimal patterns, and thus may not be suitable for real time high data rate communications where there are a large number of highly mobile nodes and interferences. Also, they will consume a greater amount of power than a switched beam system. In a system where there is low interference, a switched beam array may be adequate because it is less costly and it can produce a signal gain comparable to an adaptive array. In a system where there is considerable interference, tracking the exact location of the nodes is an integral part of increasing system performance and therefore the adaptive array may be a better choice.

This chapter is organized as follows. Section 2 presents the switched beam system. It details the function and operation of the system. Section 3 describes a phased array system architecture. The procedures used to test the smart antenna performance with a WiMAX radio and the results generated by these tests are presented. Section 3 presents an adaptive array testbed design while detailing the function and operation of the system and its modules. The type of algorithms used in the system will be discussed along with the challenges involved in their implementation. The design of the PC interface which consists of the brains operating the system. The conclusions drawn from the results are presented in the section 4.

2. Switched Beam System

A switched beam antenna is the simplest form of AAS. It creates a group of overlapping beams that together result in omnidirectional coverage. In a switched beam system, predefined beam pattern is formed with the main beam towards the user. In general an m -element array may generate an arbitrary number of beam patterns. However it is much simpler to form qm beam patterns, where $q=1,2,\dots,Q$, with $360^\circ/Qm \geq 1/10$ of the half-power beamwidth. The beam pattern is generated using specific weights, which translates into specific amplitude adjustments and phase shifts for each of the array elements.

The m -element circular array receives signals from several spatially separated users. The received signals usually contain both direct path and multipath signals, which are mostly likely from different directions of arrival (DOA). Assume that the array response vector (also called steering vector) to a transmitted signal $s_1(t)$ from a DOA φ is $a(\varphi)=[1, a_1(\varphi), a_2(\varphi), \dots, a_{m-1}(\varphi)]^T$, where $a_i(\varphi)$ a complex number denoting the amplitude gain and phase shift of the signal at the $(i+1)$ antenna relative to the first antenna and superscript T is the transpose operator. For an m -element uniform circular array of radius ρ ,

$$\mathbf{a}(\varphi) = \left[1, e^{j\beta\rho\cos\left(\varphi - \frac{2\pi}{m}\right)}, \dots, e^{j\beta\rho\cos\left(\varphi - \frac{(m-1)\times 2\pi}{m}\right)} \right]^T \quad (1)$$

where $\beta = 2\pi/\lambda$ is the wave number and the superscript T is the transpose operator. In a typical open space, we can ignore the multi-path signals. Thus the total signal vector received by the array can be written as:

$$\mathbf{x}(t) = \mathbf{a}(\varphi)s_1(t) + \mathbf{n}(t) \quad (2)$$

where $\mathbf{n}(t)$ is interference and noise. If there are K sources that share the same frequency and time slot, then the signal received by the array is:

$$\mathbf{x}(t) = \sum_{k=1}^K \mathbf{a}_k(\varphi)s_k(t) + \mathbf{n}(t) \quad (3)$$

The practical switched beam operation process is based upon a simple 3-stage switched beam mechanism:

A. Target searching

After identification of the received signals as targets of interest, they are averaged over several sets of consecutive phase delays, and a beam that has the largest outcome is selected. Before the operation, we have a predetermined N set of spatial signatures corresponding to the fixed beams saved in the system. Each beam m has a specific spatial signature $\mathbf{a}_n(\varphi)$, $n = 1, 2, \dots, N$. For an m -element circular array, N may be chosen as qm , where $q=1,2,\dots,Q$, with $360^\circ/Qm \geq 1/10$ of the beamwidth. The switched beam array output vector

$$\mathbf{y}_n(t) = (\mathbf{a}_1, \mathbf{a}_2, \dots, \mathbf{a}_N)^H \mathbf{x}(t) \quad (4)$$

where the superscript H is the conjugate transpose operator. Assume there is only one target, when an $\mathbf{a}_n^*(\varphi)$ is equal or very close to the signal spatial signature $\mathbf{a}_k^*(\varphi)$, the n^{th} element in output vector will be equal or very close to the signal strength received: $\mathbf{y}_n(t) \cong (0, 0, \dots, \sqrt{P_n}, \dots, 0)^T$. Thus the target is in the region of the n^{th} beam. We will need to routinely update the DOA of the user.

Beam switching algorithms will determine when a particular beam should be selected or rejected to maintain the highest quality signal. The system continuously updates beam selection to ensure the quality of the communication. The antenna system switches through the outputs of each beam and selects the beam with maximal signal strength as well as suppressing interference arriving from the direction away from the active beam's center.

B. Beamforming

This process is based on the knowledge of the direction of the target. Once the desired direction is known, the smart antenna system (described here mainly as a receiving antenna system) will choose one sector in active mode and a properly selected phase delay is applied. Thus the signal from that specific direction will have the maximal gain. The

direction of the target is updated as required. In a TDD system where the uplink and downlink share the same carrier, we can design and keep a weight vector of the smart antenna system based on the spatial signature received at i^{th} time slot such that $w_i = a_i^*$ for the downlink. At the j^{th} slot, the signal received by the mobile user will be $(a_i^* a_j) s(t)$, where a_i and a_j are normalized vectors. If the update rate is fast enough so that the relative change ≈ 0 , the mobile user will receive maximal signal power. However if the update rate is slow so that $|a_i^* a_j| \approx 0$ or the relative change $\approx 100\%$, the mobile user will not receive any signal power. In practice, we need to set a threshold to determine which beam should be active. For communicating with more than one user, and to save energy a beam will stay at a direction as long as possible.

To reduce the side lobes of a particular beam pattern, the channel signals are shaped by a window function, e.g. Chebyshev, Hamming, Hanning, Cosine, triangular, etc. This is the simplest way to beam form in order to maximize the signal to interference ratio of a switched beam array. By carefully controlling the side lobes in a non-adaptive windowed array, most interference can be reduced to an acceptable level by as little as 6 dB or as much as 12 dB.

C. Update tracking

When there is only one target, this task is very simple since the target will not change its location dramatically (i.e. the direction of arrival from the desired target will not change much at moderate distances during the communication). Assume that at the time, beam m is chosen. To update, we may compare the signal strength from beam m and its neighbor beams: beam $m-1$ and beam $m+1$, and choose the strongest one as the updated beam. The tracking cycle is properly chosen so that the target will not travel out of the small range (between beam $m-1$ to beam $m+1$). When there are more mobile users, the communication system needs to have a table to record the location of each user. The table will update periodically.

3. Phased array system

Phased array system can be viewed as a special case of switched beam system. The algorithm is as follows. Assume that a fixed-frequency incident plane wave projects onto the array from a particular DOA. The wave crests of the signal will arrive at one end of the array first and will arrive at each successive array element at a progressively later times. The output of the array can be analyzed in such a manner that the signals arriving at the array from that specific DOA can be enhanced, and all those from other DOAs can be attenuated. This is achieved by adding carefully-chosen phase delays to the signals arriving at the analyzer from the different array elements: if the phase delays are chosen to compensate exactly for the time delays of the wave crests from one specific DOA, then summation of all outputs at the analyzer will maximize the component from that DOA. Waves with different DOAs will arrive at each array element with different set of time delays, and summation of the outputs with a set of delays inappropriate for that DOA will result in a much smaller summed signal. A single antenna array can be used to differentiate signals from a variety of DOAs simultaneously. This is achieved by configuring the analyzer to carry out simultaneous but independent sets of processing operations, each one corresponding to

“tuning” the analyzer to signals from a different DOA. Each of these independent processes is characterized by the addition of a different (and unique) set of phase delays to the signals arriving from the array elements, corresponding to the phase delays of signals arriving from a specific DOA.

We have recently designed and developed an 8-element uniform circular array (UCA) antenna prototype operating at 5.8GHz that can cover a 360° field of view and beam form toward multi-users as shown in Figure 1 [Huang 2008, Huang et al. 2009]. The core algorithms have been derived and preliminary simulations of the approach have been carried out. Simulation studies, as well as lab and initial field test results show that the smart antenna is capable of tracking mobile targets, communicating directionally with desired users, suppressing interference and jamming, and covering a long range with high throughput and reliable connection.

Fig. 1. A photo of the phased array antenna system

There are basically two types of approaches in phased array antenna systems. The analog architecture is usually based on RF phase shifters, while the digital systems commonly consist of a digital signal processor (DSP) that calculates and applies weight vectors to each sampled data at base band frequencies. The digital beamforming (DBF) architecture offers several fascinating functionalities, including simpler architecture, programmable control of antenna radiation pattern, direction-of-arrival (DOA) estimation, and adaptive steering of its beams and nulls to enhance the signal-to-interference-noise ratio (SINR). It is generally recognized that these advantages can only be carried out by digital technology. The analog approach, on the other hand, is re-emerging to create an alternative architecture of adaptive array antennas. Analog approaches are expected to offer dramatically low power consumption in smart antennas, especially for battery-operated wireless terminal devices. Analog approaches are capable of adapting to existing single channel radios. Figure 2 shows the diagram of the analog beamforming architecture we have used for our design. The concept of analog beamforming itself was proposed more than forty years ago, but it is considered practically impossible for analog systems to provide the smart functionalities that DBF does. If analog beamforming is available in the RF stage of adaptive antenna arrays, it should be able to provide drastic improvement in both DC power dissipation and fabrication costs since it could eliminate the need for frequency converters and analog to digital converters by the number of array branches. The initial RF prototype control uses one USB DAQ card to control a Xilinx Spartan FPGA which delivers 96 control lines to 16 phase and attenuation ICs on a RF board.

In the array illustrated in Figure 1, the operation frequency is at 5.8GHz. The array electric size βr is 3.0, where r is the array radius. The smart antenna unit is composed of three functional blocks: the monopole array, the ground plane with ground skirt, and the beamformer. The former two blocks provide an essential mechanical function as well as a

passive electrical function to properly transmit and receive the signal into/from the air with minimal attenuation and distortion, particularly at the proper frequency. The ground skirt provides a virtual infinite ground plane for the array as well as a mechanical rigidity. The infinite virtual ground plane is crucial in forming a uniform and almost level vertical beam. The array gain is 13-15 dBi depending on the beamforming algorithm used. Our operating frequency range (200MHz bandwidth centered at 5.8GHz) will be in a relatively flat gain range. The antenna easily accommodates WiMAX channels, which range up to 20MHz in bandwidth.

Fig. 2. Analog beamforming system diagram

The beamforming board (in Figure 2) is a digitally controlled analog beamforming system. The beamforming system consists of five functional blocks: the controlling unit, the analog beamforming circuitry, the radio interface, power detection, and power regulation. The controlling unit provides precise, digital, beamforming control via FPGA. The FPGA constantly delivers 96 control lines to eight separate phase shifters and eight attenuators in no more than 100 nanoseconds of combined propagation and delay time. The analog beamforming circuitry consists of an 8-way power divider/combiner, a 6-bit attenuator, a 6-bit phase shifter, two T/R switches, an amplifier stage for both transmit and receive, and filtering. The active circuitry after the power divider/combiner is duplicated eight times to provide the exact analog path for each of the eight channels. The radio interface is composed of circuitry for conditioning and current driving capabilities of a radio's T/R signal for proper synchronization. Low voltage control logic gates with high current driving capabilities are used to condition the signal and direct the signal to drive the switches and amplifiers with a delay no greater than 100 ns. When operating as a switched beam system it is able to form predefined beams in both Tx and Rx mode using co-phasal excitation or several windowing functions, such as chebyshev. The RF processing gain in receive mode is about 8 dB and in transmission mode 0 dB.

Local power regulation is kept to a minimum since a majority of the regulation is done by the Power Distribution System (PDS) system, however; there are crucial Low Drop-out (LDO) regulators and energy storage components which make up the power regulation block. A dual-output, power sequencing LDO supplies regulation for the FPGA and the radio interface circuitry. A very low-noise LDO supplies power for the power detection

circuitry because of its need for a clean reference. Also, a bank of low ESR, high energy, tantalum caps provide energy storage at the power input connector to mitigate the high current transients caused by the amplifiers.

Co-phasal excitation is the simplest of all spatial filtering schemes for beamforming. If a desired signal from a known DOA is chosen then the main beam of the antenna array can be steered towards this direction. Simply multiply each element by a complex weight, corresponding to a phase delay, so that when the signals are combined the signal from the desired direction at each element add completely in phase. Figure 3 shows the simulated beam pattern and lab measured beam pattern using the co-phasal excitation beamforming algorithm.

Fig. 3. Co-phasal beam pattern. Left: Matlab simulation; Right: lab measured pattern

Many lab tests and field tests have been carried out. Two cases have been tested: 1) new beamforming antenna at one side and a directional antenna ($G=17\text{dBi}$) at the other side and 2) new beamforming antennas at both sides. Both scenarios incorporated two Airspan Radio Units, WiMAX compliant to the IEEE 802.16d-2004 standard. The results are summarized in Tables 1 and 2. The field test results show that we can achieve high throughput at very long distance with our new beamforming antenna.

Stationary Tests:	Gain Ant1/ Ant2 (dBi)	Distance (Miles)	Throughput (Mbps)
1	17/15	11	10.9
2	17/15	11	9.7
3	17/15	11	9.6

Table 1. Beamformer To Fixed Directional Antenna

Stationary Tests:	Gain Ant1/ Ant2 (dBi)	Distance (Miles)	Throughput (Mbps)
1	15/15	11	17
2	15/15	11	16.2
3	15/15	24	2.5-4
Mobile Tests:	Gain Ant1/ Ant2 (dBi)	Distance (Miles)	Throughput (Mbps)
1	15/15	4.5-6	10-12

Table 2. Beamformer to Beamformer

4. Adaptive Array Testbed

An adaptive array utilizes sophisticated signal processing algorithms to continuously distinguish among the desired signal and interferences and can form an unlimited number of beam patterns to optimally improve signal strength and suppress interferences.

An open-loop adaptive smart antenna testbed was developed to explore the feasibility of using AAS with high bandwidth radio systems [Panique 2008, Huang 2008, Khallaayoun 2009]. Despite the fact that closed loop systems are the most popular methods, an open loop approach was chosen though more complex to implement. Closed loop systems performance functions do not have unique optima and might converge to a local one, or even worst the algorithm might diverge, in addition, and as any in closed loop system instability becomes a concern [Widrow and Stearns, 1985]. Contrary to the closed loop approach that broadcasts to be able to detect sources, the open loop approach is solely based on the receive signal which makes the system very secure which is a wanted attribute in army related communication intelligence. In addition, the DOA estimation computational burden in the open loop scheme is done away from traffic which improves on throughput.

The adaptive array testbed consists of an eight element UCA operating at 5.8GHz, a translation board that down converts 5.8GHz to the baseband and a/d conversion, a beamforming board, a Data Acquisition (DAQ) card and a PC interface that uses LabVIEW PC interface for the testbed control.

In order to appropriately test a particular system, the different parts constituting the system should be tested individually and collectively. The testbed was designed to provide a flexible testing environment. For example, the testbed allows one to test the DOA estimation along with the beamforming modules individually to make sure that they function properly, one can then use the same testbed to examine the performance of the system utilizing both modules simultaneously.

The UCA array was designed to operate at a center frequency of 5.8 GHz. Because UCA offer a 360 degree beamsteering without a significant effect on the beamshape, along with the fact that no angular estimation ambiguity is inherent in the system, the circular geometry was chosen instead of the linear one.

An automatic calibration system was developed [Weber and Huang 2009] for multi-channel beamforming board calibration, which includes correction of RF circuit errors and mutual coupling effects for operating in both transmission and receiving modes.

The translation board represents the hardware responsible for taking the 5.8 GHz signal to baseband and delivering the information with minimal phase and magnitude jitter to the DAQ card. The translation board uses a single stage image reject mixing to achieve frequency translation to baseband. The RF signal is amplified, filtered and mixed using a distributed local oscillator; the oscillator can be tuned to any desired frequency. The baseband frequency is solely dependent on the speed at which one can acquire the signals. The Manual Gain control settings are used to provide an acceptable level to the DAQ card. The RF from the antenna array is fed onto the 8 top inputs shown in the snap shot. The lower SMAs are the baseband output with the LO fed at the center SMA. The Manual gain control settings are located on the back of the board. The WiMAX radios used are a product the "Airspan" company, the BS and SS units used fall under the MicroMAXd family which are based on the IEEE802.16-2004 standard.

The AAS starts by locating the bearings of the users and interference sources using the DOA estimation module. Once the impinging signals are acquired the processing is done via the

PC interface which exploits a variety of algorithms to estimate the bearings of users and interference sources. The algorithms are implemented in MATLAB and vary from spectral-based (Bartlett [Bartlett 1950] and Capon [Capon 1969]) to subspace-based (Multiple Signal Classification (MUSIC) [Schmidt 1986]). The next step consists of calculating the appropriate weights necessary to form a beam toward the wanted users and null the directions from which interference signals are originating from. The beamforming and nullsteering are achieved by translating the calculated weights into phase and magnitude settings which are sent to another DAQ card to the CPLD. The beamforming algorithms used are based on cophasal excitation and nullsteering. The WiMAX incoming or outgoing signals are fed to the beamforming board and become subject to spatial multiplexing. In DOA estimation, the MUSIC algorithm was implemented to determine the bearing of the impinging signals. A detailed simulation study of different DOA estimation algorithms have been carried out, showing that MUSIC offers the best resolution but is computationally expensive. An alternative algorithm, namely the spatial-selective MUSIC [Khallaayoun 2007], has been developed that use greatly reduces the computational cost while not affecting the resolution. By splitting the space into sections using a switched beam method (computationally inexpensive) and by using the symmetric property of the array, one can reduce the number of element needed in performing DOA estimation. The PC interface is used to process the incoming signals after acquisition in order to determine DOA, second it is used to beamform towards the users and null the interferences in addition to tracking mobile users [Panique 2008]. LabVIEW is used to control all the instrumentation and hardware. A snapshot of the PC interface front panel is shown in Figure 4.

The interface GUI contains the needed inputs needed to run the system in a flexible manner. The system characteristics, RF board control, beamforming parameters along with calibration data are shown in the GUI and can be changed as the user desires.

Fig. 4. PC interface front panel

Figure 5 illustrates the software conceptual flow diagram used in the PC interface. Once the signal is acquired, it goes through the DOA block determining the bearing of impinging sources which utilizes MUSIC algorithm. The sources are analyzed to determine if they are wanted users or interference sources. If interferences are detected nullsteering is used to null those bearings, if multi-users are detected the multibeam block activates and calculates

the appropriate weights. The tracking is also activated to lock to mobile users or moving interference sources.

Fig. 5. Conceptual software diagram

The performance of the beamforming portion of the testbed was based on comparing the measured accuracy of the pointing angle, the height of the sidelobes and the depth the nulls with simulation results.

Co-phasal excitation and several window beamforming algorithms, including Chebyshev window filter have been tested. Figure 6 shows a comparison of a measured beam pattern with the simulated pattern with co-phasal beamforming.

Fig. 6. Comparison of simulation with measured results for beamforming

The simulated beam and measured beam show very similar behavior, the measured beam point to within a few degrees of the expected bearing. The sidelobes measured were at the same location and just a few dB higher than the simulated results. The beamforming hardware and algorithms performed very well and almost matched the simulation results. When there is interference signal, the system will operate in nullsteering mode. We have analyzed a nullsteering algorithm that can form deep null even in the main beam [Huang 2007]. Figure 7 depicts the simulation vs. the measured results with a desired target at 90 degrees and an interference source at 180°. The results indicated that the null in the measured pattern is 3° away from the interference location. The depth of the null was measured at -22 dB. Since the tuning table in our poor man anechoic chamber has 2 degrees error, the actual angle error may be smaller than 3°.

Fig. 7. Nullsteering pattern comparison.

5. Conclusion

This chapter reviews our design of smart antennas for WiMAX radio system. Our studies of smart antenna technologies indicate that compact, low cost, lightweight, highly directional antennas are feasible for mobile applications and can be inter-worked with emerging WiMAX chip sets following the IEEE 802.16d-2004 standard. Our design will be resulting in commercially available compact smart antennas for a WiMAX radio system. This will enable effective solutions to major problems in wireless networks in remote areas where a complete path from a source to a destination does not exist or where such a path is highly unstable. The smart antenna will also be effective in dense areas where interference mitigation is a critical consideration. This will also be the first commercial technology to consolidate several advanced techniques in one small size, light weight, multi-function, low cost communication unit providing users easy access to a communication network. The future work will include digital beamforming system design, FPGA based DOA estimator and phase shifterless phased array development.

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WIMAX New Developments

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WiMAX (Worldwide Interoperability for Microwave Access) is a wireless broadband access network named by industry group called the WiMAX forum formed in June 2001. It is Wireless MAN with IEEE 802.16 family standards. Loosely, WiMAX is a standardized wireless version of Ethernet that enables the last mile, intended primarily as an alternative to wire technologies (such as Cable Modems, DSL and T1/E1 links) to provide broadband access to customer premises. Mission of the WiMAX forum is to promote and certify compatibility and interoperability of broadband wireless products. This book touches most of the above issues in form of 22 individuals' papers containing research work in WiMAX domain in particular. WiMAX has two important standards/usage models: a fixed usage model IEEE 802.16-2004 for Fixed Wireless Broadband Access (FWBA) and a portable usage model IEEE 802.16e-2005, which is mainly concentrated on Mobile Wireless Broadband Access (MWBA). Both are released as standards and amendments are available in form of drafts. Higher data rate transmissions (@ 100 Mbps) are achieved in IEEE 802.16-2004 WiMAX through LOS communications which incorporate a stationary transmitter and receiver but IEEE 802.16e supporting NLOS communication is much complicated and little less bit rate is achieved. 2-11 GHz licensed band is the range of frequencies with TDD and FDD supports. The book will provide a wide horizon to visualize the WiMAX technology and its developments leading towards 4G systems. It will provide a good platform to the researchers with clues to the innovative ideas in WiMAX domain. I wish all the best to the authors and readers of this book in their successful research of WiMAX technology.

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