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Abstract

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Antenna Selection for Next Generation IEEE 802.16 Mobile Stations

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Abstract— **The IEEE 802.16/WiMAX standard has fully embraced multi-antenna technology and can, thus, deliver robust and high transmission rates and higher system capacity. Nevertheless, due to its inherent form-factor constraints and cost concerns, a WiMAX mobile station (MS) should preferably contain fewer radio frequency (RF) chains than antenna elements. This is because RF chains are often substantially more expensive than antenna elements. Thus, antenna selection, wherein a subset of antennas is dynamically selected to connect to the limited RF chains for transceiving, is a highly appealing performance enhancement technique for multi-antenna WiMAX terminals. In this paper, a novel antenna selection protocol tailored for next-generation IEEE 802.16 mobile stations is proposed. As demonstrated by the extensive OPNET simulations, the proposed protocol delivers a significant performance improvement over conventional 802.16 terminals that lack the antenna selection capability. Moreover, the new protocol leverages the existing signaling methods defined in 802.16, thereby incurring a negligible signaling overhead and requiring only diminutive modifications of the standard. To the best of our knowledge, this paper represents the first effort to support antenna selection capability in IEEE 802.16 mobile stations.**

I. Introduction

IEEE 802.16/WiMAX [1]–[3] has emerged as a key advanced broadband access technology for wireless metropolitan area networks [4]. It is a cost-effective alternative to existing wired solutions such as T3 lines, DSL and coaxial cables. In the past few years, several amendments to the 802.16 base standard [1] have been ratified (e.g., 802.16e [2]), all of which rely on multi-antenna technologies at the base station (BS) and mobile stations (MS), and orthogonal frequency division multiple access (OFDMA), to deliver the capacity and QoS demanded by high-speed digital services [5].

However, the superior performance of multi-antenna technologies comes at the expense of complexity since each transmit or receive antenna element requires a corresponding radio frequency (RF) processing chain. Whereas a transmit or receive RF chain is quite expensive, an antenna element is typically relatively cheap. Therefore, in an IEEE 802.16 MS, in which cost and complexity considerations assume prominence, it is desirable to use a technique that enables an MS to have fewer RF chains than antenna elements.

Antenna selection is one such technique. By means of a switch, it dynamically selects the best antenna or best subset of antennas to connect to the available RF chain(s); the objective being to maximize system performance [6]–[9]. Antenna selection has now been standardized in the high speed IEEE 802.11n wireless local area network standard [10], [11], and is being incorporated in the 3GPP LTE standard, as well [12]–[14]. Theoretical aspects of antenna selection have also been extensively studied in the literature, see [6], [15] and references therein.

While antenna selection has been standardized in 802.16e [2], it is for the BS and not the MS. Antenna selection at the BS is effectively a coarse but robust precoding technique [16], and hardware complexity reduction is not the primary concern.

This paper focuses on antenna selection at the MS, and develops an IEEE 802.16 standard compliant, low signaling overhead protocol to enable it. Such standard compliance is important because requiring only minor modifications to the current standard speeds up the acceptance and implementation of the technology. Notably, the proposed protocol supports all the major permutations defined in 802.16 such as partially used subcarrier (PUSC) and fully used subcarrier (FUSC), and accommodates both reciprocal and unreciprocal channel conditions for the downlink and uplink.

The rest of the paper is organized as follows. In Section II, we briefly describe the architecture of the IEEE 802.16 system, and highlight the relevant physical (PHY) layer features in the standard. In Section III, we propose our adaptive antenna selection protocol for the IEEE 802.16 system. Extensive simulation results are presented in Section IV, which is then followed by our conclusions in Section V.

II. Overview of IEEE 802.16 System

The PHY layer of IEEE 802.16 system employs orthogonal frequency division multiple access (OFDMA) as the primary channel access mechanism for both the uplink and the downlink. In OFDMA, different sets of orthogonal subcarriers are assigned to different users, which can then transmit or receive simultaneously. Doing so enables the receiver to easily

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handle frequency-selective fading and narrow-band interference. Channel equalization is also simpler since the frequency response is relatively flat over a subcarrier. A low symbol rate enables guard intervals and time-spreading, and eliminates inter-symbol interference (ISI). The subcarriers are classified into different groups based on their usage such as direct current (DC), data, pilot and guard subcarriers. Some of the subcarriers in certain OFDMA symbols carry pilot signals for channel estimation and synchronization purposes.

The frequency domain subcarriers are mapped into the time domain by an inverse fast Fourier transform (IFFT). Each OFDMA symbol, of time duration T_s, includes a duration of T_b for information (data) and a configurable cylic prefix of duration T_g, which is typically a few microseconds long.

A. Frame Structure

The IEEE 802.16 standard supports both time division duplex (TDD) and frequency division duplex (FDD) modes, with the TDD mode being the most popular. Therefore, we concentrate on the TDD mode in this paper.

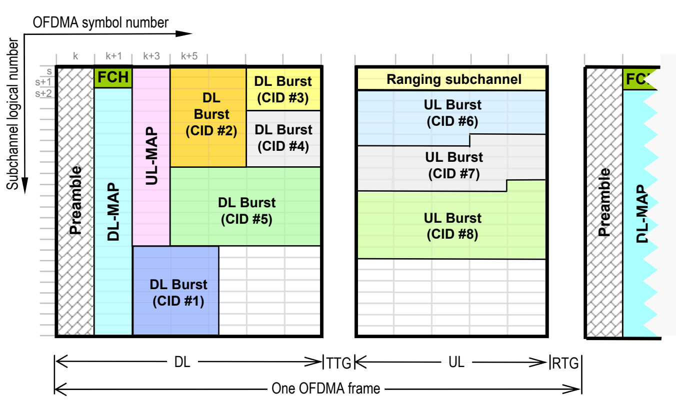

Fig. 1: OFDMA frame structure of the IEEE 802.16 TDD system.

Figure 1 shows the frame structure of an OFDMA-based IEEE 802.16 system operating in TDD mode. The horizontal axis indicates time, while the vertical axis represents logical subchannels. A subchannel is a group of subcarriers, which need not be physically contiguous. The basic unit of resource allocation in 802.16 is a *slot*, which consists of a number of OFDMA symbols in time domain and one subchannel in frequency domain. The BS divides the timeline into contiguous frames, each of which further consists of a downlink (DL) and an uplink (UL) subframe.

As illustrated in the figure, a DL subframe starts with a preamble, which helps the MSs perform synchronization and channel estimation. The first two subchannels in the first data OFDMA symbol in the downlink are used for the frame control header (FCH), which is always transmitted using a QPSK modulated rate 1/2 code that is repeated four times. The FCH specifies the length of the immediately succeeding downlink MAP (DL-MAP) message and the repetition coding used for the DL-MAP. The DL-MAP and uplink MAP (UL-MAP) messages are used by the BS to notify MSs of the resources allocated to them in the DL and UL directions in the current frame, respectively. Each MS can then determine when (i.e., which OFDMA symbols) and where (i.e., which subchannels) it should receive from and transmit to the BS.

In order to give wireless devices sufficient time to switch from the transmission mode to reception mode, and vice versa, a receive/transmit transition gap (RTG) and a transmit/receive transition gap (TTG) are inserted between consecutive subframes.

B. Permutation and Permutation Zone

Permutations and permutation zones are two concepts extensively used in both the DL and UL of IEEE 802.16 [2]. They accommodate a wide variety of antenna and physical layer configurations. A permutation defines the mapping between physical subcarriers and logical subchannels, and also determines which subcarriers (in frequency domain) of which OFDMA symbols (in time domain) are used for the pilot and data signals. These pilot tones enable the receiver to estimate the channel response. The current 802.16 [1] [2] standard specifies several permutation schemes such as PUSC, FUSC, etc.

The logical subchannels are, in turn, used to define permutation zones. A permutation zone is a set of contiguous OFDMA symbols in the downlink or uplink that use the same permutation. It can include multiple users, all of which have to follow the same permutation. The permutation zones primarily differ in their slot size, the number and location of data/pilot subcarriers, and whether the subcarrier grouping is adjacent or distributed. The BS informs the MSs of the location, format and length of each permutation zone by means of a certain information element (IE) in the DL-MAP and UL-MAP. Note that each UL subframe or DL subframe can contain more than one permutation zones.

As an example, we briefly explain below the PUSC permutation, which is mandatory for UL transmission. Due to the space limitations, other permutations are not elaborated upon. Interested readers are encouraged to refer to [2] for more details.

C. PUSC Permutation

Figure 2 shows how a slot in a PUSC permutation zone is generated. Recall that a slot is the smallest resource allocation unit in 802.16. Every slot in UL PUSC zone comprises six tiles, each of which further consists of three OFDMA symbols and four subcarriers. Some of the subcarriers in the OFDMA symbols are dedicated to pilots, while others are allocated to data. For PUSC, the pilot subcarriers are present in the 0th and 2nd OFDMA symbols only.

III. Antenna Selection Protocol for IEEE 802.16

The receiver can perform channel estimation based upon the pilot subcarriers defined in the various permutation modes specified in the standard. These pilots can be used to estimate

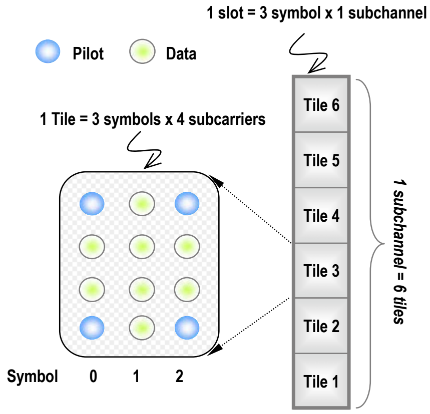

Fig. 2: PUSC permutation in IEEE 802.16.

the channel of not just one antenna but all the available antennas, by making the antennas transmit them sequentially in time. This enables the selection of the best antenna(s). This important aspect is described in detail in this section. Since the permutation determines where the pilot and data symbols are located, the specifics of how antenna selection is done depends on the permutation.

In order to determine the channel state between all the transmit antennas and the receive antennas, all the transmit antennas need to sound the channel, i.e., send pilot symbols. In general, if an MS has L RF chains and N antenna elements ($L \leq N$), all possible combinations of antenna subsets need to be sounded to select the best subset. This entails switching between different antennas, which can occur during the cyclic prefix (CP) interval of an OFDMA symbol. This is feasible since antenna switching typically takes tens or hundreds of nanoseconds, while the CP duration is several microseconds long. Therefore, no loss of data occurs, though there is a negligible loss in orthogonality between the subcarriers.

Antenna selection at the MS can be classified as transmit antenna selection (TAS), which occurs in the UL, and receive antenna selection (RAS), which occurs in the DL. Antenna switching and channel estimation can be independently performed at the MS for UL (TAS) and DL (RAS). Several criteria for selecting the best antenna(s) have been considered in the literature [17] [18]. Once the optimal antenna subset is determined and fed back (where necessary), the MS starts transmitting using it.

We now develop an adaptive protocol which conforms to the current IEEE 802.16 specifications and efficiently activates antenna selection operations whenever necessary. The protocol can support all non-AAS (Adaptive Antenna System) permutations defined in the standard, and accommodates both reciprocal and unreciprocal channel conditions.

A. Protocol Description

As illustrated in Figure 3, when an MS enters an 802.16 network, it first transmits a *subscriber station basic capability request* (SBC-REQ) message, which indicates the functionalities that the transmitting MS can support.

Based upon the received SBC-REQ message, the BS can determine the number of antenna elements (N) and RF chains (L) that the MS contains, and whether the MS supports the antenna selection functionality or not. Then, the BS sends back a *subscriber station basic capability response* (SBC-RSP) message as an acknowledgment. By exchanging SBC-REQ and SBC-RSP messages, BS and MS learn about basic physical parameters of each other.

In the 802.16 TDD system, the UL and DL transmissions share the same frequency spectrum. Accordingly, the channel state in an 802.16 network is measured in the DL and UL within a downlink subframe and an uplink subframe by the MS and BS, respectively. As described in Section II-B, the pilot symbols and subcarriers enable channel estimation.

When the MS receives pilot signals from the BS, it feedbacks the measurement results to the BS through the channel quality information channel (CQICH) or by means of a channel measurement report response (REP-RSP) message, as defined in [2]. The BS, upon receiving channel measurements from an MS, compares the DL and UL channel estimates and then determines whether the DL and UL channels are reciprocal or not.

When the DL and UL channels are reciprocal, their channel states and qualities are substantially similar. In this case, the MS keeps monitoring received pilot signals and itself triggers antenna switching when its perceived signal quality drops below a predefined threshold. By selecting different L out of N antenna subsets and connecting them to the L RF chains one by one, the MS eventually can receive pilot signals from the BS over all its possible antenna subsets. Thereafter, the MS performs receive antenna selection (RAS) for the DL by comparing and selecting the subset of antennas with the best channel gain. Since the DL and UL channels are reciprocal, the MS can use the same antenna subset for UL TAS transmissions as well.

Nevertheless, channel reciprocity does not always occur due to MS mobility, intra-cell or inter-cell interference, etc. In addition, since different UL and DL time-frequency resources may be allocated to an MS, the antenna set selected for one direction may not be optimal for the reverse direction. As a result, the DL and UL antenna selection at an MS may need to be handled separately. Even in an unreciprocal channel, it is easy to see that the RAS procedure in the DL is identical to that for the reciprocal channel. However, UL TAS is different and is performed as follows.

The BS monitors the UL pilot signals from the MS and receives the DL channel state information by requesting channel measurements from the MS via the CQICH or REP-RSP messages. When BS realizes the channel is unreciprocal, it notifies the MS to trigger UL transmit antenna selection procedure (at the MS) by means of an antenna selection control (ASC) UL information element (IE) in the UL MAP. After being notified by the BS, the MS uses the current antenna subset to transmit pilot signals in the first available pilot symbol, and then sequentially uses other different antenna subsets

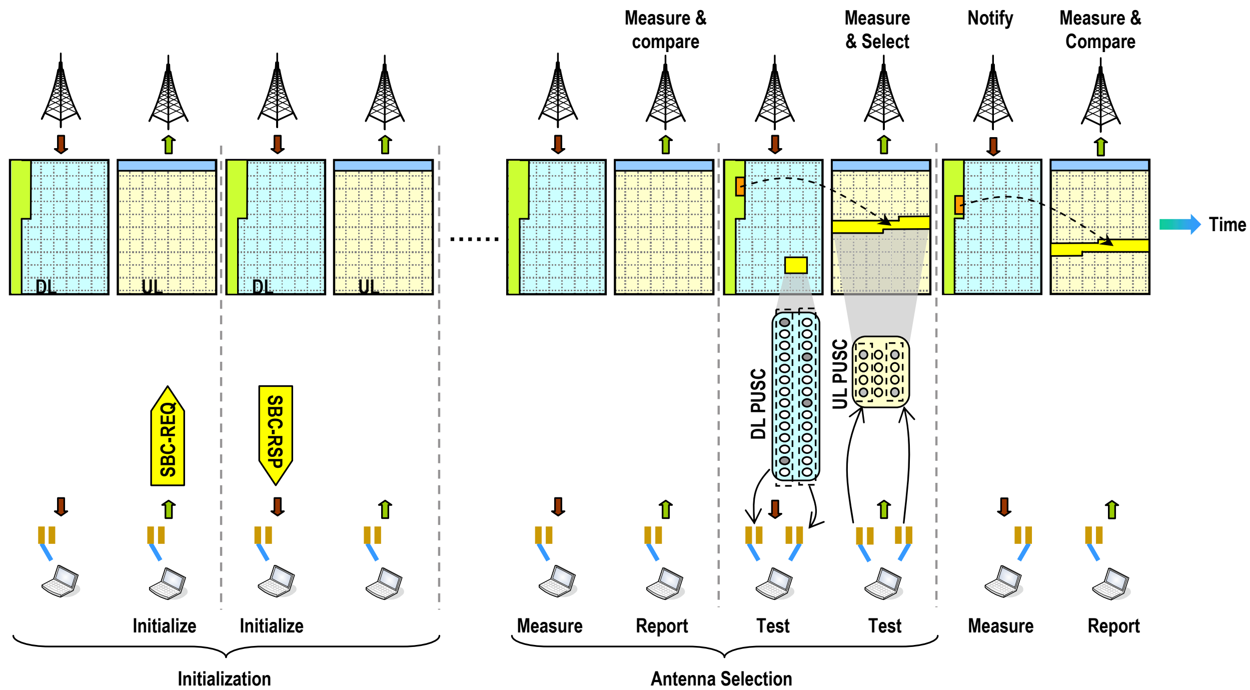

Fig. 3: Adaptive antenna selection protocol in the IEEE 802.16 system.

to transmit subsequent pilot signals. Since the permutation defines pilot number, location and distribution, the time period to complete antenna switching and selecting is different for permutation types. Thus, the BS can estimate the channel response associated with each different antenna subset used by the MS in the UL. These estimates enable the BS to determine the optimal transmit antenna subset at the MS; the BS then notifies the MS about this subset by means of a 2-byte long ASC UL IE. The MS then uses the selected best antenna subset to transmit subsequent packets in the UL subframe.

TABLE I: Antenna Selection Control IE

Syntax	Size (bit)
Antenna_Selection_Control_IE()	
{	
Extended UIUC	4
Length	4
UL_AS_Indication	1
UL_AS_Selection	7
}	

As defined in Table I, this new ASC UL IE requires only a marginal modification of the current IEEE 802.16e standard, and is fully compatible with existing systems. The "extended UIUC" field in the ASC UL IE, which has a value "0x0B", indicates that this IE is an extended UIUC IE. The "length" field indicates the length of the subsequent "UL_AS_Indication" and "UL_AS_Selection" field. The "UL_AS_Indication" field, when set to 1 (unreciprocal case), indicates that the MS should perform uplink TAS in the current frame. If this field is set to 0, then the MS uses the "UL_AS_Selection" field to determine the antenna subset selected by the BS. Specifically, the value of the "UL_AS_Selection" field indicates which antenna set has been selected for future transmission. For example, if the "UL_AS_Selection" field is "0x01", then the antenna set switched to immediately after using the original antenna set should be chosen for subsequent uplink transmission. "0x00" makes the MS use the same antenna set.

In summary, the same set of antennas can be used for TAS and RAS at the MS when the DL and UL channels are reciprocal. This simplifies the antenna selection for the MS, as the antenna subset selected for the downlink can be directly reused for the uplink, and vice versa. On the other hand, TAS and RAS follow different procedures when the channels are unreciprocal. Thus, the proposed protocol can handle both reciprocal and unreciprocal channel states. Using signal quality measures, such as SNR, to trigger antenna selection makes it efficient and adaptive. The rate at which antenna selection is done depends on how frequently the channel condition varies. When the channel fades dramatically, antenna selection does not perform well since all channel estimation is always outdated and can not predict the channel quality accurately.

IV. Performance Evaluation

In order to evaluate the proposed adaptive antenna selection protocol, we have implemented it in the OPNET 802.16 platform. The uplink transmissions in a single cell 802.16 system were simulated. The simulations in this section assume that each MS employs only one RF chain. Path loss attenuation and a flat Rayleigh channel fading are simulated. The transmit and receive antennas are assumed to be uncorrelated. A saturated traffic load was fed to each MS in order to evaluate the maximum throughput of the system. The simulation scenarios and corresponding configurations are further detailed in Table II.

TABLE II: Antenna Selection Parameters

Parameters	**Value**
Coherence Time	50 milliseconds
Distance between MS and BS	500 $\sim$ 1800m
MS Transmit Power	50 mW
BS Antenna Gain	15 dB
MS Antenna Gain	-1 dB
Number of Antennas	4
Number of RF chains	1
Modulation & Coding Rate	64QAM, CC1/2
Scheduling Type	rtPS
OFDMA FFT Size	2048
Path Loss Model	Free Space
UL to DL Bandwidth Ratio	1/3
UL Permutation Type	PUSC
ARQ Mechanism	Go-Back-N ($N = 512$ blocks)

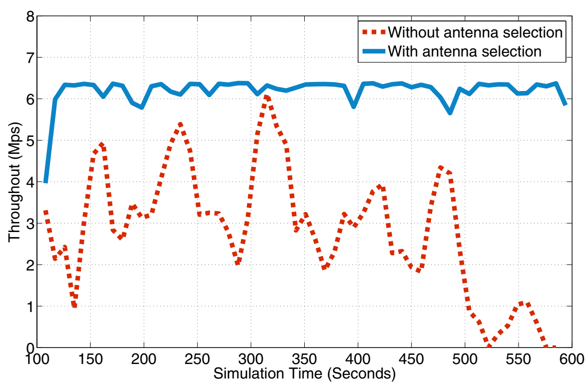

Fig. 4: Instantaneous throughput with ARQ.

Figure 4 plots the instantaneous throughput over time when the MS and the BS are 700 meters apart. As the channel gain for a particular propagation path varies with time, its associated SNR fluctuates accordingly. This results in the variation of throughput. When antenna selection is not applied, a fixed antenna element continuously transmits data. As shown in the figure, the instantaneous throughput varies over a wide range from 0 to 6 Mbps, with an average of 3 Mbps. When antenna selection is enabled at the MS, the antenna element with the best channel gain (and highest SNR) is selected for UL data transmission. The resultant instantaneous throughput is much more stable and hovers around 6 Mbps. The AS mechanism with 4 antennas has double the throughput of a terminal with only a single antenna.

Figures 5(a) and 5(b) illustrate the cumulative distribution function (CDF) of the packet delays experienced by an ARQ-enabled MS without and with antenna selection, respectively. Plotting the CDF is useful because it provides information about the entire probability distribution. The two figures clearly demonstrate that antenna selection can significantly lower system latency. This is because of the better channel gain achieved by antenna selection, which considerably reduces the number of retransmissions.

In Figures 6(a) and 6(b), the average SNR and the average throughput are plotted as a function of the BS to MS distance. When compared with no-antenna selection, using antenna selection clearly increases the average SNR and the average throughput. In the figure, antenna selection, in fact, enhances the system throughput by as much as 100% in specific situations. At the same time, we also observe for small BS-MS distances, e.g., 500 meters or less, the throughputs with and without antenna selection are quite similar despite the difference between the corresponding SNR values. This saturation in throughput for high SNRs occurs because of the limiatation on throughput imposed by the maximum modulation constellation size.

We have also investigated the impact of the number of antenna elements on antenna selection performance. We find that when the number of antenna elements exceeds four in an IEEE 802.16e system, the throughput improvements are marginal. The corresponding simulation results are not presented herein due to the space limitations.

V. Conclusion

This paper proposes the use of antenna selection as an efficient and cost-effective solution for enhancing the system performance of next generation IEEE 802.16 mobile terminals. An adaptive antenna selection protocol tailored for use by the IEEE 802.16 mobile terminals is proposed. The protocol supports all the permutation schemes defined for the non-AAS zone, and can accommodate both reciprocal and unreciprocal channel conditions. As verified by extensive simulations, the protocol substantially improves the SNR, throughput and delay performance, and incurs a negligible signaling or implementation complexity overhead.

An interesting topic to investigate in future work is the impact of link adaptation [19] [20] on the antenna selection protocol. Another worthwhile exercise is to evaluate the performance of the protocol in an 802.16 system with high mobility.

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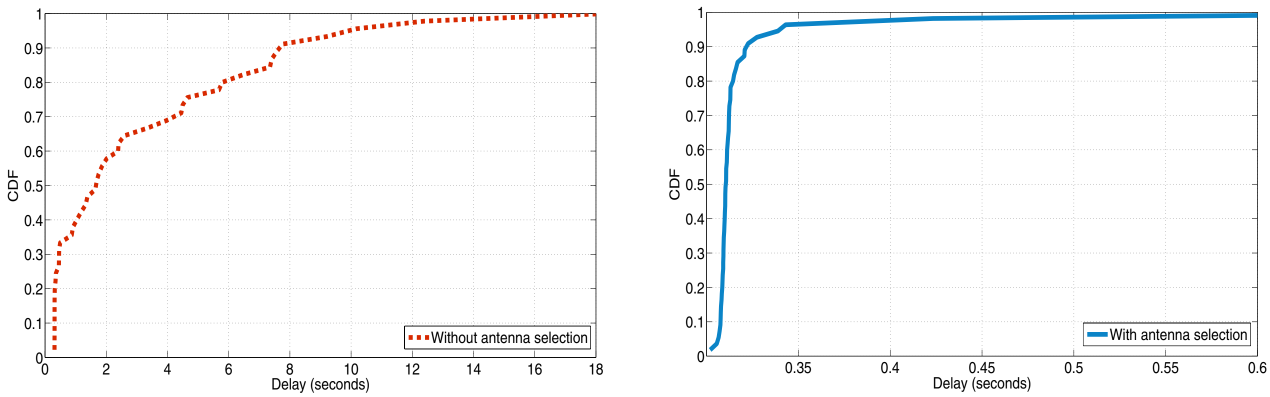
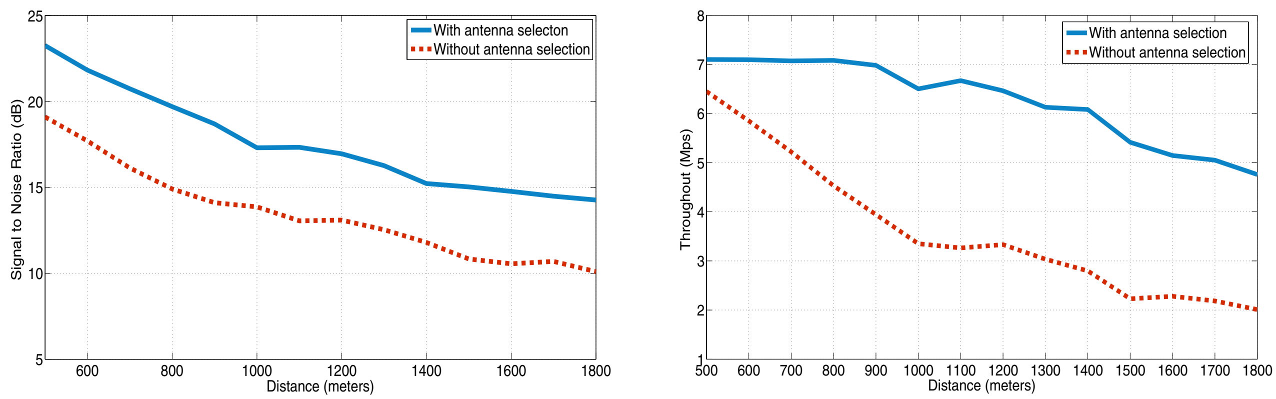


(a) Delay CDF without antenna selection

(b) Delay CDF with antenna selection

Fig. 5: Delay performance of antenna selection.



(a) Signal to noise ratio

(b) Throughput

Fig. 6: Performance of antenna selection as a function of BS-MS distance.

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