A Cooperative MAC for Distributed Space-Time Coding in an IEEE 802.16 Network

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***Abstract*— In the next-generation WiMAX system, cooperative communication is being considered as an advanced technique to increase the throughput and improve the signal quality. In a cooperative scenario, multiple stations can jointly emulate the antenna elements of a multi-input multi-output (MIMO) system in a distributed fashion. Unlike conventional space-time coding (STC) mechanisms used by a IEEE 802.16e antenna array, *distributed space-time coding* (DSTC) is employed across the cooperating stations to achieve a higher spatial diversity gain. In this paper, we present the framework for DSTC in the emerging relay-assisted WiMAX network, and develop a cooperative MAC layer protocol, called *CoopMAX*, for DSTC deployment in a WiMAX system. Through extensive simulations, we evaluate the performance of *CoopMAX* and show that DSTC can yield capacity gains of up to about 50% for the uplink of an IEEE 802.16 network.**

I. Introduction

As an advanced broadband wireless access technology, WiMAX has attracted a lot of research attention. While the current IEEE 802.16d/e [1], [2] have been specified for the current single-hop WiMAX network, relay-assisted WiMAX has become the focus for the future evolution of WiMAX standards, and is being actively investigated [3]. Recently, the 802.16j Relay Task group was formed to standardize a WiMAX mobile multi-hop relay (MMR) system. An MMR system enables a subscriber station (SS) to route through intermediate relay stations (RSs) in order to reach the BS. In the MMR scenario, the IEEE 802.16j baseline mainly focuses on the relay operation that allows a single intermediate station to forward the received signal to the next hop. Such a technique seems promising, but the participation of a single relay in the forwarding process may limit the benefits of multi-hop transmission, since such a data communication over a pair of links may undergo severe fading, and consequently packet corruption.

Cooperative wireless communication provides an efficient solution that provides robust forwarding by recruiting multiple intermediate stations on the fly to collaboratively transmit the source signal to the destination. These intermediate stations are called *helpers* and form a virtual multi-input multi-output (MIMO) infrastructure where the helpers act as distributed antenna array elements. Since MIMO systems allow multiple antennas to transmit together in order to achieve high diversity gains using space-time coding (STC), it is natural to apply the same functionality to a cooperative environment in a distributed fashion. STC that employs geographically distributed stations is commonly known as *distributed space-time coding* (DSTC).

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The basic idea of DSTC is to coordinate and synchronize the helpers so that each of them acts as one antenna element of a conventional STC. In a typical DSTC system, each helper participating in a DSTC is numbered in order to emulate the antenna it will mimic in the underlying STC [4], [5]. Recently, DSTC is being considered by the IEEE 802.16j/m standard task groups. Several contributions [6]–[8] are proposing to incorporate DSTC into the framework of the next-generation WiMAX standards. These contributions present the concept of *cooperation* and discuss the challenges that arise in a potential WiMAX cooperative system.

Although the research and standardization efforts aforementioned are devoted to the DSTC physical layer (PHY) studies, limited attention has been given to the Medium Access Control (MAC) layer for the deployment of DSTC in WiMAX system. An efficient MAC layer protocol should cope with the discovery of helpers, channel estimation, management message handshaking and rate adaptation, among other functions. The main contribution of this paper is to develop the MAC layer protocol in order to support the deployment of DSTC in an IEEE 802.16 WiMAX network. The proposed protocol is called *CoopMAX* in this paper. To the best of our knowledge, *CoopMAX* is the first compatible framework that facilitates the implementation of DSTC in the next-generation IEEE 802.16 network.

The remainder of this paper is outlined as follows. Section II introduces the fundamentals of the IEEE 802.16 MMR system and examines the physical layer of a DSTC system. In section III, we describe the MAC layer framework that supports DSTC in the IEEE 802.16 system. Extensive simulation results are presented in section IV that shows the significant performance gains of the new scheme. In section V, we present conclusions and future work.

II. WiMAX MMR System and DSTC PHY

A. *WiMAX MMR Ststem Overview*

The mobile multi-hop relay (MMR) architecture is being considered by the IEEE 802.16j baseline in order to extend the cell coverage and enhance the transmission rate of a conventional WiMAX system. While the multi-hop WiMAX is yet to be discussed and finalized, the basic hierarchy of a WiMAX MMR network has already been proposed [3]. In the current draft of the IEEE 802.16 standards, three network elements, a base station (BS), a relay station (RS) and a subscriber station (SS), are defined in an MMR WiMAX network (see Fig. 1).

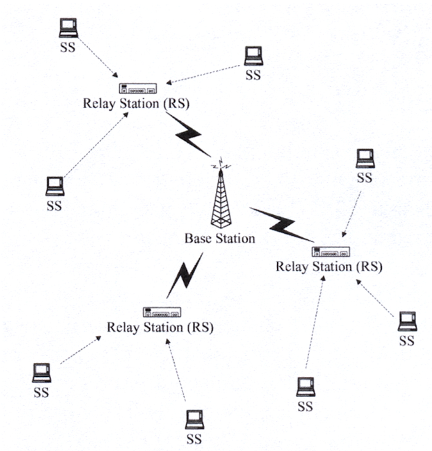


Fig. 1. IEEE 802.16 MMR System.

These three elements establish the hierarchical topology of an MMR network. In the new framework, RSs work as intermediate nodes between the BS and the SSs, and forward signals between the two ends. Based on the functionality of an RS, IEEE 802.16j has classified the RS functionality into two modes: *transparent* and *non-transparent* [3]. In the transparent mode, an RS merely forwards data traffic between the BS and the SS(s), while an RS in the non-transparent mode also constructs a management frame header for itself. Under this framework, the concept of DSTC cooperation is considered by the IEEE 802.16j/m task groups as a technique for performance enhancement. However, the protocol design remains unexplored. In this paper, we mainly focus on DSTC for the uplink scenario (from the SS to the BS). The reason is that, in the IEEE 802.16 system, the SS is mostly equipped with a single antenna due to the constraints of size and cost. Therefore, cooperative communication in the uplink makes more sense than in the downlink, where the BS can directly use STC schemes. We assume that each SS is only associated and served by a single RS for simplicity. However a number of SS(s) are employed to help with signal forwarding. In this paper, only a two-hop topology is analyzed, since a two-hop connection is sufficient in most network scenarios.

Fig. 2 depicts the uplink cooperative scenario. In this scenario, we define the following notation.

- The end target subscriber station is denoted by *tSS*.
- The end destination base station is denoted by *BS*
- The relay station participating in the cooperation is denoted by *RS*.
- The subscriber stations participating in the cooperation are denoted by *hSS*.

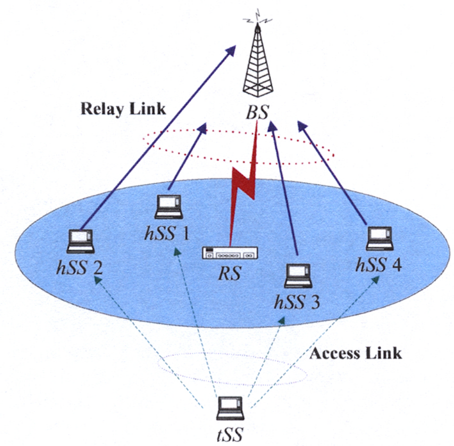


Fig. 2. Cooperative Communication Structure of IEEE 802.16 MMR System.

- The radio link from the *tSS* to the *RS* is called an *access link* (*AL*).
- The radio link from the *RS* to the *BS* is called a *relay link* (*RL*).

A centralized scheduling procedure is executed by the BS which allocates the channels and determines the transmission rates for both *tSS* and *RS* by using the channel measurements of the *AL* and *RL*, respectively.

B. DSTC Physical Layer Description

DSTC has been extensively analyzed in the literature [4], [5]. For our cooperative scheme using DSTC, each cooperative transmissions takes two time/frequency slots. In the first slot, the target subscriber station *tSS* transmits a block of information bits to its associated *RS*. At the same time, a number of surrounding SS(s), termed as *hSS*, may also overhear the signals from the *tSS* and can act as helpers together with that *RS* in the second slot. In the rest of this paper, we will denote the *RS* and *hSS* as *helpers*. Assuming that a cyclic redundancy check (CRC) code is appended to each block, each helper first decodes to verify the CRC after the reception of the packet. In the second allocated slot, only helpers that receive the packet correctly re-encode and send the packet to the *BS*. The packet transmission takes two hops, as in the IEEE 802.16j draft. However, now *multiple* helpers are allowed to send at the *same* time/frequency slot using STC. The signals of all helpers propagate to the *BS*, where they are combined and decoded by a STC receiver.

The transceiver at the helper is depicted in Fig. 3. Note that that this diagram only depicts the signal processing for the relaying function. The DSTC functionality can be implemented by using embedded software at the helper. On the other hand, the BS normally has more sophisticated functionality, being equipped with multiple antenna elements.

Each helper employs a regular single-input and single-output (SISO) decoder to decode the information sent by the source in the first hop. It then re-encodes the information

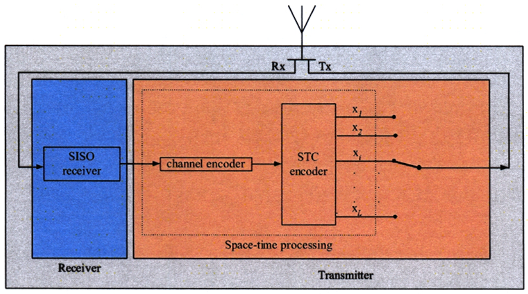


Fig. 3. Signal processing for relay stations

bits and passes them to a space-time coding (STC) encoder. Assume that there are N helpers. Then the output from the encoder is in the form of N parallel streams, each corresponding to the signal of an antenna in a transmitter with N antenna elements. We assume an underlying full rank space-time code $\mathcal{G}$ of size $N \times K$, where K denotes the number of symbols. Each helper picks up a predefined stream to emulate a physical antenna of a regular STC encoder. For the ith relay, $(i = 1, 2, \cdots, N)$, at time m (within a block of K symbols times), the transmitted signal is $\sqrt{E_s}\mathbf{X}_i$. E_s is the symbol energy, and $\mathbf{X}_i$ are the coded symbols from the STC encoder and corresponds to the mth column of the space time code $\mathcal{G}$.

The destination receiver, *BS*, is equipped with a regular STC decoder. The received signal at the antenna at the mth symbol time can be expressed by

$$y(m) = \mathbf{H}\mathbf{X}(m) + w(m). \tag{1}$$

Here $\mathbf{H}$ is the $1 \times N$ channel vector representing channel gain from each helper to the destination. The Additive White Gaussian Noise (AWGN) is $w(m)$ and has a power spectrum density of $N_0/2$.

We assume a block fading channel, in which the fading level for each symbol is the same for a code block. For a given $\mathbf{H}$, the pairwise error probability (PEP) between two space time coded symbol $\mathcal{G}_i$ and $\mathcal{G}_k$ is

$$\mathbb{P}\{\mathcal{G}_k \to \mathcal{G}_i|\mathbf{H}\} = Q\left(\sqrt{\frac{E_s\|\mathbf{H}(\mathcal{G}_i - \mathcal{G}_k)\|^2}{2N_0}}\right), \tag{2}$$

where $\|\cdot\|$ represents the Frobenius norm. Using $Q(x) < e^{-x^2/2}$, we have

$$\mathbb{P}\{\mathcal{G}_k \to \mathcal{G}_i|\mathbf{H}\} < e^{(-\frac{E_s\|\mathbf{H}(\mathcal{G}_i-\mathcal{G}_k)\|^2}{4N_0})}. \tag{3}$$

We assume that the channel undergoes independent Rayleigh fading. The pairwise error probability averaged over fading is upper bounded by [9]

$$\begin{aligned} PEP_{ik} &\triangleq \mathbb{E}_H\{\mathbb{P}\{\mathcal{G}_k \to \mathcal{G}_i|\mathbf{H}\}\} \\ &= \frac{1}{det(\mathbf{I} + \frac{1}{4}\frac{E_s}{N_0}\mathbf{A}_{ik}\mathbf{\Sigma}_h)} \\ &\leq \frac{1}{det(\mathbf{I} + \frac{1}{4}\frac{E_s}{N_0}(\lambda_{min}^{ik})^2\mathbf{\Sigma}_h)}, \end{aligned} \tag{4}$$

where $\mathbf{A}_{ik} = (\mathcal{G}_i - \mathcal{G}_k)(\mathcal{G}_i - \mathcal{G}_k)^*$, and λ_{min}^{ik} is the minimum eigenvalue for $\mathbf{A}_{ik}$. The ith diagonal element of the matrix $\mathbf{\Sigma}_h$ is the path loss from helper i to the receiver and all other elements are zero.

The above pair-wise error probability assumes that all antennas are transmitting their respective branch signal waveform out of the STC encoder, which requires all the designated helpers decode the signal from *tSS* successfully. Since the diversity order for the *AL* transmission is only 1, it is possible that some helpers cannot decode due to fading or interference. In such cases, one or more helpers cannot participate in the *RL* delivery, and therefore the performance of the DSTC can degrade significantly.

III. MAC Layer Design for DSTC

This section describes the design of *CoopMAX* for DSTC support in the framework of the IEEE 802.16 system. The *CoopMAX* protocol supports several functions as follows.

A. Helper Discovery

When a subscriber station enters the MMR network, it is assigned to a relay station *RS* according to a certain criterion [3]. In our system, a subscriber station can be used as a helper for cooperative communication. Hence, mechanisms to discover potential helpers with cooperation capability should be addressed. In the IEEE 802.16 standards, the basic capabilities of each SS are negotiated between the BS and the SS via network entry management messages, during the initialization stage. A *cooperative capability* field can be included into these messages to inform as to whether the specific SS is able to serve as a helper.

B. Channel Estimation

In most wireless networks, channel estimation is essential for efficient rate adaptation. In a DSTC deployment, channel estimation is a key requirement to optimize the data rates of the two hops and define the best helpers. In the WiMAX MMR network, the channel conditions over the access and relay links are probed and reported to the *BS*. The *BS*, based upon the channel measurements, is then able to set the DSTC size, select the optimal helpers, and determine the date rates over the first and second hops. When the BS needs to collect the latest channel conditions in the *AL* and *RL*, the following steps are triggered by the BS.

1) Access Link: Once every few frames, the *tSS* can decode the frame header, which contains the channel allocation information, to find out the number of SS(s) available in the system and locate the time-frequency blocks for the SS(s) in the current frame. By overhearing the transmissions of all SS(s), the *tSS* can determine the potential SS helpers (*hSS*) based on the channel quality. In order to retrieve the *AL* channel measurements, the BS would request reports of the potential *hSS* Connection IDs(CIDs) with their associated CINR (carrier-to-interference-noise-ratio) from the *tSS* periodically or in an on-demand manner. The feedback from the *tSS* to the

BS can be sent via feedback channels or piggybacked data [2].

2) Relay Link: The BS sends a downlink preamble every frame. All SSs monitor the downlink preamble signal or downlink pilot/data signal [2] in order to estimate the *RL* channel condition. As stated in [2], the BS retrieves the channel measurements of *RL* from each *hSS* via feedback messages or piggyback.

After collecting the channel measurements from the *AL* and *RL*, the *BS* can centrally determine the size of the DSTC associated with the best helpers. These selected *hSS(s)*, together with the *RS* are numbered so as to mimic a MIMO system, followed by a broadcast message sent with this information in the frame header notifying each helper associated with the specific *tSS*.

C. Channel Estimation Updates

The accuracy of channel estimation can be further improved by updating the channel conditions. Since the *BS* knows the specific set of *RS* and *hSS(s)* which act as the helpers, the relevant channel gain in the second hop (*RL*) can be instantly updated whenever UL data is transmitted from those helpers. At the same time, the *tSS* keeps monitoring the UL data traffic from all helpers over the first hop (*AL*), such that the relevant channel gains can also be updated continuously and reported to the BS via the feedback channel. The above described process for updating channel estimation does not need extra signaling messages and therefore is bandwidth efficient.

D. Rate Adaptation

In order to optimize performance metrics, such as throughput and delay, the PHY operations should be coupled with those at the MAC layer. Most wireless networks use rate adaptation to handle different received signal-to-noise ratio (SNR) levels at the receiver, so that a satisfactory error probability can be maintained. It is essential for any station with multi-rate capabilities to efficiently use the channel resource. One of the criteria for rate adaptation is to keep the error rate below a pre-set threshold, while maximizing the throughput for each source-destination pair.

In the above IEEE 802.16 network, the BS needs to carefully select the rates for both hops (*AL* and *RL*), since the effective throughput significantly depends on the coding and modulation schemes. Generally speaking, the higher the data rate for the *AL* transmission, the less time is consumed for the first hop. But then fewer relays can decode the first transmission and participate in the second hop. Fewer relays means the supported data rate for the second hop is expected to be lower and more time is needed for the second-hop transmission. Therefore, there is a tradeoff between the data rates of the first and the second hop to maximize the end-to-end throughput.

Another task of the MAC design is to choose a suitable STC to be used by the helpers. *CoopMAX* attempts to choose a STC dimension as close as possible to the number of available helpers to maximize the diversity gains. However, in practice, a well-designed STC only exists for a selected set of values of N's. The PHY layer is designed to handle BPSK, QPSK and other QAM constellations. We denote the rates that the PHY layer can support as R_p, $p = 0, ..., P$, where R_0 is the basic rate at which the SSs exchange control information. We assume that there are M SSs in the network. We further assume that the packet header is transmitted at the basic rate R_0, and that the received signal strength is available at the MAC.

For each rate R_p, let $\mathbf{A}_p = \{a_{p,ij}\}$ be the correspondent adjacency matrix, where $a_{p,ij} = 1$ means that station i can communicate with station j using rate p, and $a_{p,ij} = 0$ means that it cannot. In the previous sections, we have described how the channel conditions are updated. Thus the matrices $\mathbf{A}_p$ could be accordingly updated as well. We further assume that if two stations communicate directly, they always do so at the maximum possible rate.

Rate adaptation is essential to maximize the performance of the network. The goal is to pick the coding, modulation and space-time coding schemes for each transmission. For example, to maximize the MAC layer throughput, we could minimize the transmission time, T_c, of a packet of B bits, where $T_c = B/R_{AL} + B/R_{RL}$, and R_{AL} and R_{RL} are the data rates for the first hop and the second hop, respectively. Here we neglect the MAC layer overhead. A cooperative transmission is employed whenever it takes less time than direct transmissions.

The effective rate for a cooperative transmission, denoted by R_c, is given by

$$R_c = 1/(1/R_{AL} + 1/R_{RL}). \quad (5)$$

Note that $1/R_c$ is the time required to send a information bit, without considering the MAC overhead.

For DSTC cooperation, the number of helpers for the subscriber station s transmitting at rate p, is denoted by $N_{p,s}$ and given by

$$N_{p,s} = \sum_{k=1, k \neq s}^{M} a_{p,sk}, \quad (6)$$

where k is the index of other subscriber stations.

Cooperative helpers, capable of connecting with the *tSS* at a rate greater or equal to R_p, might be able to support a higher rate towards the *BS* than any of them does alone. Note that the performance does not only depend on the number of helpers, but also relies on the average channel quality of helpers. Let $q_{p,i}$ denote the channel quality of the ith helper for *tSS* using rate p to the destination *BS*, and let Q_p=[$q_{p,1}$, $q_{p,2}$, ... ,$q_{p,N}$] denote the vector of channel qualities from all helpers to the *BS*. Then, the optimum rate supported towards the *BS* by the $N_{p,s}$ helpers is expressed by a function $f(R_p, N_{p,s}, Q_p)$.

Overall, assuming that the helpers adopt a decode-and-forward strategy, the maximum rate for the MAC layer is given by

$$arg \max_{p} \; Rc = \frac{R_p f(R_p, N_{p,s}, Q_p)}{R_p + f(R_p, N_{p,s}, Q_p)}. \quad (7)$$

IV. Performance Evaluation

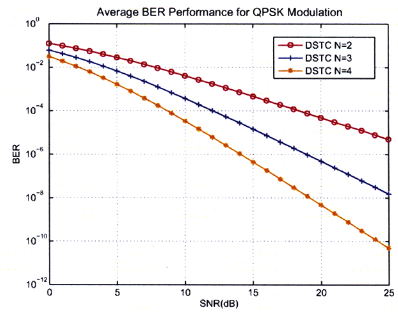
We conducted a numerical simulation to evaluate the performance of our proposed *CoopMAX* protocol in the WiMAX system. In our simulations, the *BS* is located at the center of the network and the SS(s) are independently and uniformly distributed within a circle of 5000 meters radius. Following the IEEE 802.16 standard, the modulation schemes used in the simulation are QPSK, 16-QAM and a 64-QAM, and the channel coding schemes include rate 1/2, 2/3 and 3/4 convolutional codes, as listed in Table I. The theoretical maximum data rate of the system is 73.19 Mbps per channel configured with a 20 MHz spectrum and using a 64-QAM 3/4 code rate.

Considering practical limitations, each helper supports STC with an antenna size up to $N = 4$. The deployed STC [10] is a 2×2 Alamouti code (code rate = $1/2$) for $N = 2$. For $N = 3$, the code is of size 3×4 (code rate = $3/4$). For $N = 4$, the code is 4×4 with a code rate of $3/4$. The targeted block error (BLER) probability is 10%. The transmission power is such that the most robust physical layer mode (QPSK 1/2 coding rate) can reach the boundary of the network.

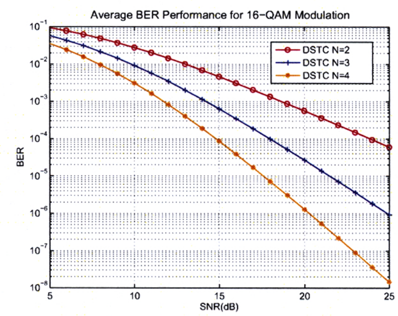
In Fig. 4, we depict the BER performance for various size DSTC using different modulation schemes. The assumption here is that all the designated relay stations receive the information bits from the source without any error, so that each row of the space time code is transmitted by one relay. The slope of the curves in the high SNR region reflects the diversity order achieved. From those figures, we confirm that the larger the number of relays is, the higher the diversity order achieved, and the lower the BER. For example, in Fig. 4(a), the BER for $N = 4$ DSTC decreases from 10^{-8} to 10^{-10}, when the SNR increases from 19dB to 24dB. Thus for each 2.5dB improvement on the SNR, the BER decreases by a 1/10 factor. The achieved diversity order is 4 in this case. For our cooperation scheme, it is possible that one of the relays cannot successfully decode from the source. They will either not be able to forward (if a CRC code is appended to the data) or forward incorrect information to the destination (if there is no CRC). In both cases, the BER performance is expected to be worse than what is shown here. In the subsequent simulation results, we assume the transmitted block is corrupted whenever any helper fails to forward the correct information to the BS.

For the purpose of showing saturated throughput, the system is assumed to be heavily loaded. The transmission buffers for all stations are non-empty during the simulation. The simulation assumes that the MAC layer scheduling policy guarantees an equal share of the network throughput (Max-Min fairness).

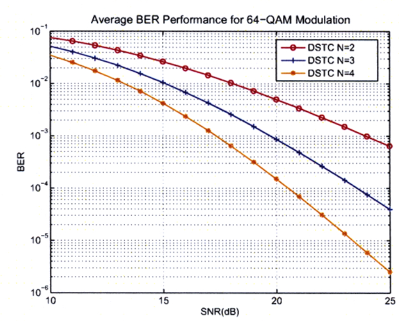
Fig. 5 shows the average network throughput as a function of the number of SS(s) in the network. We compare the proposed DSTC based cooperation scheme with the conventional IEEE 802.16e single-hop transmission scheme, and the regular two-hop single-relay scheme as proposed in the IEEE 802.16j. From those results, our DSTC based cooperation yields up to a 50% throughput gain over the standard IEEE 802.16e. Also, this proposed cooperation scheme can support



(a) QPSK



(b) DSTC performance for 16-QAM modulation



(c) DSTC performance for 64-QAM modulation

Fig. 4. BER performance for DSTC.

up to approximately 20% more traffic than the two-hop single-relay approach in 802.16j. The network throughput is also a monotonic increasing function of the number of SS(s) in the network. This is because, for a larger network, each *SS* is able to find more helpers on the average and can use a larger size DSTC. Even if the number of available helpers exceeds the largest size of the DSTC, it is possible to find a better set of helpers to assist its transmissions when the number of candidate helpers is larger. Consequently, a higher modulation and/or channel coding scheme can be employed at the second-hop (*RL*) to reach the destination, while satisfying the targeted BLER.

A theoretical upper limit on the throughput can be derived. For example, for such *tSS(s)* that need two hops to reach the *BS*, this limit is around half of the maximum data rate. The reason is, when the SS(s) are densely located in the network, any *tSS*, even far from the *BS*, can transmit at its peak data rate over the first hop (*AL*). A sufficiently large number of helpers could be recruited to support peak data rate transmissions over the second hop (*RL*), giving rise to this upper bound. For a generic WiMAX system with a cell radius of 5km where all SS(s) are uniformly distributed, Table I summarizes the adopted modulation and coding schemes with their respective maximum transmission ranges [2].

TABLE I
WIMAX DATE RATE OVERVIEW (20MHZ)

Modulation & Coding	Raw Rate (Mbps)	Transmission Range
QPSK 1/2	R_0=16.26	r_0=5000m
QPSK 3/4	R_1=24.40	r_1=3922m
QAM16 1/2	R_2=32.53	r_2=3155m
QAM16 3/4	R_3=48.79	r_3=2282m
QAM64 2/3	R_4=65.05	r_4=1730m
QAM64 3/4	R_5=73.19	r_5=1499m

According to Table I, the SS(s) transmit at multiple rates, depending on their location. Let us denote $F_i, i = \{0, 1, 2..., 5\}$ as the fractions of SS(s), respectively at rates $R_i, i = \{0, 1, 2..., 5\}$ listed in Table I. Thus, F_i can be formulated by

$$F_i = \begin{cases} (r_i^2 - r_{i+1}^2)/r_0^2 & i = 0, 1, 2, 3, 4 \\ r_5^2/r_0^2 & i = 5. \end{cases} \quad (8)$$

In Table I, suppose the maximum transmission rate is denoted by R_{max}, where R_{max}=R_5. As stated, the two-hop transmission could enhance the throughput of a *tSS* up to half of maximum rate R_{max}/2 and $R_3 > R_{max}/2 > R_2$. Therefore, a *tSS* which is able to send directly at R_3 or higher rates, should transmit directly to the *BS*. In other cases, it is preferable to transmit through two hops. Accordingly, the overall throughout upper bound for the whole WiMAX system is given by S_{max},

$$S_{max} = \frac{1}{\sum_{i=0}^{2} F_i \times 2/R_{max} + \sum_{i=3}^{5} F_i \times 1/R_i}. \quad (9)$$

Herein we assume the SS(s) are densely distributed so that a sufficient number of helpers are always available and an arbitrary large size of DSTC can be implemented. In an ideal case, each *tSS* can always recruit enough helpers to communicate with the *BS* via two hops at the peak rate. Packet loss is omitted for simplicity. In such a scenario, the upper bound of the overall WiMAX system throughput can be derived from equation (9) as 39.8Mbps, a value higher than the limit for two-hop subscriber stations. This is because the SS(s) who can send at rates R_3 and above will transmit directly to the *BS*. As illustrated in Fig. 5, when the number of stations is increasing, the achieved throughput approaches this bound. This bound is more than 50% higher than the throughput upper bound for the non-DSTC single-hop scenario, which can be similarly derived to be 23.9Mbps.

Fig. 6 reveals the average delay performance for different transmission schemes. Delay for each packet transmitted consists of two parts, the queuing delay and the service delay.

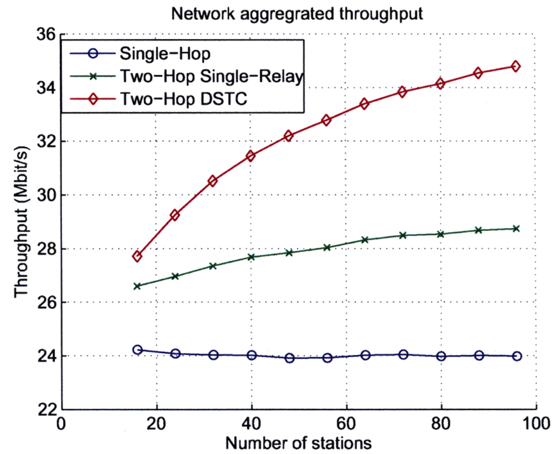


Fig. 5. WiMAX network aggregated throughput

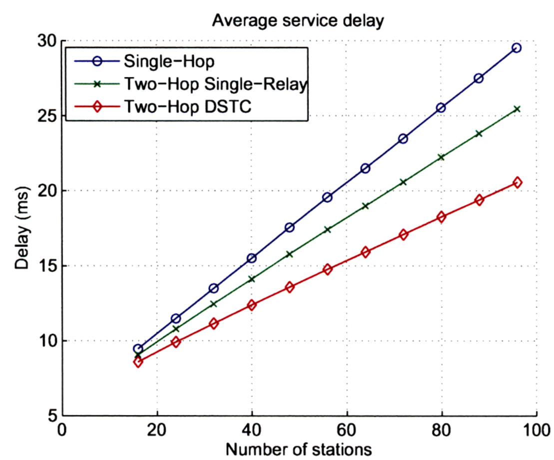


Fig. 6. Service delay

Service delay is defined as the time period from the instant that a packet becomes the head-of-line packet in the buffer to the instant that the packet is received by the *BS*. As illustrated in the figure, the average service delay for a packet is also considerably reduced using DSTC based cooperation.

From the above results, it is clear that our distributed, DSTC based cooperation improves the bit error performance and throughput for stations that are not near the center of the network, i.e., the slow stations in the WiMAX network, with rates corresponding to R_0, R_1 and R_2 in Table I. This provides a more fair access to the network. Without cooperation, the BS has to allocate much more channel time for these slow stations. With cooperation, channel time is saved and the whole network benefits.

The signaling overhead cost associated with *CoopMAX* can be estimated as follows. In general, each SS only consumes limited bandwidth to convey signaling messages, such as handshaking and channel estimation. This signaling overhead can be carried using existing management messages in the WiMAX system, and needs marginal additional network resources. The amount of overhead can be measured in terms of bit rates and depends on the system environment, such as mobility and channel coherence time. For example, let us assume that the system environment undergoes a 10ms coherence time (2 WiMAX frames), and that each *tSS* is served by 4 helpers. Suppose the set of helpers for a *tSS* is reselected every 100ms. In a WiMAX system, the *BS* needs to transmit a 1-byte request message to each helper and the *tSS* every 10ms for channel measurements on the RL and AL, respectively. Then, each helper feeds back a report message with 1 byte for its measured CINR value, while the *tSS* responds with a message of 12 bytes (a 2-byte CID plus a 1-byte CINR value for each helper). In addition, every time the set of helpers is reselected, the *BS* has to associate the new helpers with the *tSS* by sending a message of 3 bytes (a 2-byte CID of the *tSS* plus 1 byte for the DSTC size and antenna index information) to each helper. Therefore, the estimated bandwidth for signaling overhead for each *tSS* can be approximately obtained as 18kbps, which is given by $1000/10 \times (2 \times 4 + 1 + 12) \times 8 + 1000/100 \times 3 \times 4 \times 8$. This overhead cost is small compared to the throughput enhancement achieved by the *tSS*.

V. Conclusion

In this paper, we discussed the MAC layer design for a cooperative scheme that uses DSTC in the WiMAX system. The proposed *CoopMAX* enables robust cooperative communications in a multi-hop environment. The signaling protocol and rate adaptation algorithm are described. Our proposed MAC layer architecture is compatible with current WiMAX systems, and only requires marginal modifications to IEEE 802.16d/e standards. Further study is needed to evaluate the performance of DSTC in an 802.16 system with high mobility. The deployment of DSTC in the downlink of a WiMAX system also needs to be explored.

References

[1] "IEEE standard for local and metropolitan area networks- Part 16: Air interface for fixed broadband wireless access systems," *IEEE 802.16-2004*, Oct. 2004.

[2] "IEEE standard for local and metropolitan area networks- Part 16: Air interface for fixed broadband wireless access systems, Amendment 2 and Corrigendum 1," *IEEE 802.16e*, Feb. 2006.

[3] "Part 16: Air interface for fixed and mobile broadband wireless access systems: Multihop relay specification," *IEEE Baseline Document for Draft Standard for Local and Metropolitan Area Networks*, Apr. 2007.

[4] J. N. Laneman, D. Tse, and G. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. on Info. Theory*, vol. 50, no. 12, December 2004.

[5] X. Guo and X. Xia, "A distributed space-time coding in asynchronous wireless relay networks," *IEEE Trans. on Wireless Communications*, vol. 7, no. 5, May 2008.

[6] W. Ni, G. Shen, and S. Jin, "Cooperative relay in IEEE 802.16j MMR," in *IEEE C802.16j-06/006r1, IEEE 802.16 Broadband Wireless Access Working Group*, May 2006.

[7] ——, "Cooperative relay approaches in IEEE 802.16j," in *IEEE C802.16j-07/258r1, IEEE 802.16 Broadband Wireless Access Working Group*, Apr. 2007.

[8] J. Chui, A. Chindapol, and Y. Sun, "Cooperative relaying scheme for IEEE 802.16j," in *IEEE C802.16j-06/264, IEEE 802.16 Broadband Wireless Access Working Group*, Nov. 2006.

[9] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication.* Cambridge University Press, 2005.

[10] S. N. Diggavi, A. R. Calderbank, S. Dusad, and N. Al-Dhahir, "Diversity embedded space-time codes," *IEEE Trans. Information Theory*, vol. 54, no. 1, pp. 33–50, Jan. 2008.