Co-operative MIMO communication in WiMAX: perspectives on implementation and standardization

Chris Adams, Alister G. Burr, Krishnamurthy Giridhar, Sabah Jassim, Vishwanatha R. Thumparthy, Anubala Varikat, and Jose Lopez Vicario

Abstract—**Multiple-Input-Multiple-Output (MIMO) technology is a part of several standards, and is expected to play a large role in the communication systems of the future. However for many applications its use is limited by the number of antennas which can be accommodated on a terminal with adequate spacing between them, as well as by the cost and complexity of implementing such antennas. Co-operative or Virtual MIMO (V-MIMO) technology is capable of addressing these spatial correlation and complexity issues by distributing the antennas among a cluster of user equipment in the neighborhood. A V-MIMO enabled device would be capable of providing higher capacity and diversity gains than practically achievable on spatially constrained MIMO enabled devices, by creating much larger virtual antenna arrays. The V-MIMO concept has been known for some time, but it has not been standardized. To enable practical application of the technique it is vital that it be incorporated into standards. In this paper, we address some of the issues and challenges involved in introducing V-MIMO technology into the WiMAX standard.**

Index Terms—MIMO; virtual; co-operative; WiMAX

I. INTRODUCTION

It is well known that one means of achieving the drastic increase in data rates that will be required by the communication systems of the future, is through the use of Multiple Input Multiple Output (MIMO) technology [33 - 37]. In sufficiently richly fading environments, MIMO systems using spatial multiplexing give a capacity improvement that is linear in the minimum of the number of antennas at the transmitter and the receiver.

However, most realistic scenarios are non-ideal. Two factors which limit the gains that are practically and realistically achievable are the following. First, due to correlation between closely spaced antennas, the MIMO gains can be reduced significantly. And on spatially constrained devices like handsets, it is problematic to accommodate more than two to four antennas with adequate spacing. Second, the hardware complexity and the number of RF chains goes up, quickly putting a ceiling on the number of antennas that are feasible.

To solve these problems, the use of cooperative or virtual MIMO (V-MIMO) techniques between User Equipments (UEs) is promising [1-3, 6, 14 – 18, 38, 39]. UEs in the vicinity of each other form a cluster and act as antennas for each other. Each UE can then make do with one or at most two RF chains. Due to the spacing between users, spatial correlation issues are largely resolved. While cooperative schemes with relay stations are being widely investigated [1 – 3], material on the specific issues involved in the use of cooperative MIMO using clusters of UEs is not readily available. Especially, the use of cooperative MIMO techniques on the DL have not been adequately addressed. In this paper, we provide an overview of the relevant issues in such scenarios, with emphasis on the applicability of cooperative MIMO technology to the WiMAX standards. We argue that there is a case for introducing enablers for V-MIMO operation into the evolving 802.16m standard.

In the V-MIMO concept we describe, a UE that wishes to communicate with a BS first finds other UEs in the vicinity that would be willing to communicate its data. For example, if the UE wishes to transmit data to the BS, it shares the data with these neighboring UEs. Once the sharing of data has been done, the UEs transmit the data in one slot, as if they were multiple antennas on a single device engaging in MIMO transmission. Similar operations occur on the downlink. Fig. 1 illustrates a V-MIMO system as considered in this paper.The V-MIMO concept as described above has been known for some time in the literature, but we are not aware of its being part of any standard. Neither do we know of any existing commercial system which implements V-MIMO technology. The variant of collaborative MIMO that is included in the WiMAX standard, and has been proposed for 3G LTE and EDGE evolution, is a significantly different one. In this variant, which is meant for the uplink, two UEs cooperate and simultaneously transmit their data to the BS. The problems with this scheme are, first, it cannot be applied to the downlink, and second, if only one UE in the neighborhood wants to communicate at a point in time, it will not be able to obtain the benefit of MIMO technology.

A reason why certain collaborative concepts are in use, while V-MIMO concepts are yet to find their way into actual implementation, could be the additional complications involved in V-MIMO. V-MIMO techniques require neighbor identification, exchange of data between neighbors and the related security issues, and synchronization of the communication of neighboring UEs. However, the benefits that V-MIMO will bring are likely to be high enough to justify this additional conceptual complexity.

The ultimate success of V-MIMO based communication would depend on many factors, including psychological and cultural. How ready will people be to lend out to others some of the resources on a highly personal device like a mobile, and in effect, hand over to others part of the control over it? It may turn out that friends and family are willing to collaborate with each other to get higher data rates. Others may be willing to hire out their resources for extra income, or to collaborate with neighbors to obtain decent data rates in bad channel conditions.

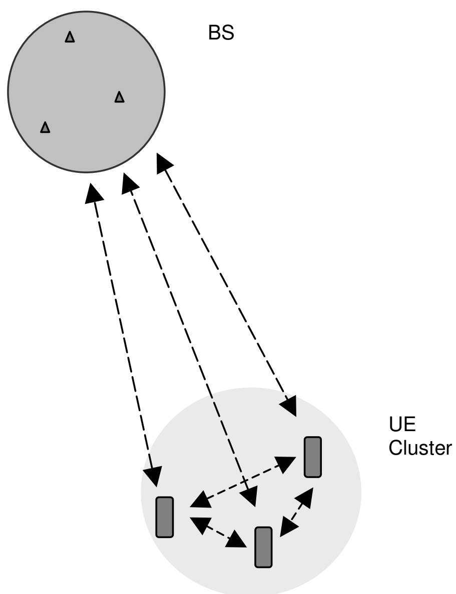

Fig. 1. A virtual MIMO system

To make cooperative MIMO communication possible, an inter-UE link (IL) needs to be implemented. The IL could use a short-range high rate RAT quite different from that used for the UL/DL, for e.g., UWB. However, the re-use of the same technology could be attractive in requiring only a single RF chain and PHY for carrying out MIMO communication.

In this paper, we look at some of the issues involved in introducing V-MIMO schemes into the WiMAX standard. In section II, some ways and scenarios in which V-MIMO operation is expected to bring benefits are described, and some design options are mentioned. In section III, challenges and open research areas in the development of V-MIMO systems are discussed, with special emphasis on WiMAX. Section IV looks at design issues in the re-use of WiMAX for the inter-UE link, and additionally, proposes some ways in which the WiMAX standard can be amended for efficient re-use on the inter-UE link. Finally, some conclusions are drawn in Section V.

II. Applicability of V-MIMO Schemes

There are several scenarios in which V-MIMO schemes can be expected to be applicable for improvement of data rates and spectral efficiency in an existing standard like WiMAX.

A first mode of applicability would be in building it around an existing wireless communication standard that supports MIMO, preferably with only software and RF additions. The developed package would ideally be independent of the underlying standard.

The intended benefit is a significant increase in the cell-edge and average rates achieved by the standard in realistic scenarios. Indeed, in practice, in non-ideal channel conditions, which is to say most of the time, most standards are known to achieve only a fraction of the maximum rates they claim to support. Hence the scope for significant improvement in data rates through V-MIMO communication.

A second mode of applicability would be in pushing the maximum data rates that a standard can support. This might require significant changes to the standard, especially as relates to the higher data rates handled.

MIMO schemes using the technique of spatial multiplexing [33 - 35] are known to perform best at high SNRs. MIMO schemes using the techniques of transmit and receive diversity are expected to perform better in poor channel conditions [37]. Hence, the use of both spatial multiplexing-based and diversity-based virtual MIMO schemes would be beneficial.

Some of the questions that arise when conceptualizing or designing a V-MIMO system are the following.

Potential gain. How much gain in throughput can be expected through the use of V-MIMO technology in realistic environments?

Changes to the standard. Will it be possible for V-MIMO to be introduced around the standard, without any changes to the standard as existing? If changes are required, how significant will they be? For e.g., issues of slots for neighbor discovery and inter-UE communication, synchronization, and latencies arise.

Independence of standards. Is it feasible to build a V-MIMO package that can easily be ported onto any standard?

Inter-UE link. Is it possible to make do without an additional RF for the inter-UE communication? Will it be necessary to completely develop the PHY and MAC for the inter-UE communication, or can an existing standard be used for the purpose? In multi-mode phones, can one of the RF chains and the multiple technologies on the UE (e.g., WiFi, Bluetooth) be used for the purpose?

Security. V-MIMO would entail the sharing of data with a neighbor. What security mechanisms should be in place to generate trust in such a paradigm? What would be the impact of this security on the resources of the sender?

III. Challenges and Open Research Areas

The design and development of a V-MIMO system would involve challenges of many kinds. Some of these are addressed in the following sub-sections, along with a discussion of some open research areas.

A. System simulation and radio channel models

The evaluation of new proposals, like V-MIMO, for wireless networks, is known to be a very difficult problem. While field trials are clearly essential before such a new concept is put into practice, they are impractical as a means of evaluating the performance of the network as a whole (in terms, for example, of the user capacity: the total number of users that can be accommodated), for three reasons:

1) Since user capacity is usually dominated by interference from other cells, and often by aggregated interference from many other users, a large network would be required to obtain accurate results, and this would be prohibitively expensive for a prototype system;

2) Performance, especially for MIMO systems, will also be strongly influenced by radio propagation, and this is determined by the site of a trial. Hence it is difficult to ensure that performance comparisons are representative based on trials carried out in only a few locations;

3) Such trials are unlikely to involve a truly 'live' network, and therefore will not be carrying truly representative traffic, in terms of the services required and its spatial and temporal distribution.

Hence the evaluation of complete systems has in practice to be carried out by computer simulation. This is a difficult and complex problem, but leads to greater insight into the factors and the parameters that affect user capacity. It also allows generic radio propagation models to be used that provide a standardised means of comparison, that incorporate random variation and therefore both take into account most eventualities and allow statistics to be collected, and that can therefore result in more generally applicable comparisons. Similarly representative traffic distributions can be used, using realistic models based on experience in live networks.

The most common system simulation approach is simply to simulate the transmission of relatively large amounts of data over simulated links between relatively large numbers of randomly distributed terminals, subject to randomly generated propagation channels (including interfering channels). This we will refer to as *direct simulation*, and can be used to gather any required statistics on the performance of the system. However it is, of course, very computationally intensive.

In evaluating earlier wireless systems, especially cellular systems, a simplified approach was developed [40] which separated the simulation of the *link level* (i.e. the radio propagation and the physical layer for the link between each pair of nodes, and not to be confused with the data link layer of the OSI model) and the *network level* (i.e. the network as a whole – not to be confused with the network layer of the OSI model). In the simplest case the network level simulation would account only for the power received at one victim receiver from all other interfering users in the whole system, taking into account the propagation, and hence could determine the distribution of the signal to interference ratio. This would then be used in the link level simulation to determine its performance. Hence only one link need be simulated in full detail.

However this method becomes significantly more complex in a MIMO system, since the influence of interference now depends not only on the level of the interference, but also on its directional properties. Thus link BER becomes a random rather than a deterministic function of the signal to interference ratio, depending on random parameters of the link signal and interference, as well as their power ratio. Nevertheless there has been similar work in this case also [7, 8], and it has been successfully applied in MIMO cellular systems [9, 10]. MAC layer protocols can also affect the interference characteristics by making access dependent on link performance, and hence resulting in interactions between link and network level within the system. Such situations must be dealt with on a case-by-case basis.

For a V-MIMO system still further complexities occur. Now the interference is not characterised only by its direction, but more generally by its joint distribution at each of the UEs in the cluster. Moreover the interference is measured at each UE, and may not accurately be known to all the UEs in the cluster: hence the inter-UE protocol is essentially involved in the system performance.

A great deal of work has been carried out on mobile and wireless channel characterisation, leading to a wide range of channel models. Recently it has been recognised that *double-directional models* are required in MIMO systems to account for the directions of multipath signals at both the transmitter and receiver [11: chapter 6]. They have also led to double-directional channel models used in standardisation, the best known of which is the 3GPP spatial channel model (SCM) [12]. Like all subsequent models this assumes multipath components occur in clusters. However still more recent work, especially in IEEE 802.16 and 3GPP LTE standardization, has been concerned more to simplify the models for use in direct wide area simulations of the sort described above [13, 41], and these are usually *non-physical* models, based on direct synthesis of the channel matrices, although these may be derived from consideration of a physical model.

It is not clear, however, whether existing models, especially as recently simplified, will accurately account for the behavior of V-MIMO channels. In particular the correlation of fading at UEs in a cluster needs to be accurately modelled, and the distances involved are significantly larger than those between antenna elements in an MEA, which will mean that the clusters must be more accurately modelled.

B. Relaying strategies and spatial re-use

Consider an M × M V-MIMO communication system, in which M UEs communicate with an M-antenna base station.

The inter-UE link works as follows. For the uplink, the UE divides its data into M streams. It sends (M – 1) of these streams to the (M – 1) neighboring UEs. In a second stage, the M UEs simultaneously transmit the M streams of data to the base station. For the downlink, the base station transmits M multiplexed streams of data. The multiplexed signal is received by each of M UEs. The (M – 1) neighbors re-transmit this signal to the UE for whom it is intended.

With a particular technology selected for the BS-UE link, the main requirement for the inter-UE link is the ability to support the corresponding data rates. To achieve the expected MIMO gains in data rates, it is of course necessary that the inter-UE link does not become a bottle-neck in the communication.

The relaying strategies for the inter-UE link need to be designed taking into consideration the special features of the uplink and the downlink communication. Amplify-and-forward (AF) and decode-and-forward (DF) strategies [14 -

18] can be considered for the uplink communication.

For the DL, the requirement is considerably more complex. To achieve the MIMO capacity, the data received at the *M* UEs need to be decoded in one stage. This means that the signals received at each UE cannot be decoded independently of the others, and the signal received by the UEs must be relayed without decoding. AF, sample-and-forward (SF) [17, 18], and compress-and-forward (CF) [14, 19] strategies could be considered here.

AF relays, in acting as analog repeaters, tend to produce some loss in performance compared to DF and SF schemes. SF schemes are bandwidth-consuming, while CF schemes are highly complex.

It may be noted that efficient AF techniques for OFDMA would not be as simple as direct amplification and re-transmission at the RF or analog levels. This is because in OFDMA, only a part of the bandwidth of a received signal is occupied by the signal of a user. Retransmitting the whole signal would be highly wasteful of bandwidth. Hence, at the relay, a complete chain of OFDM processing as shown in Fig. 2 will need to be carried out before the signal of interest can be separated out and retransmitted, potentially on different sub-carriers or on a different band.

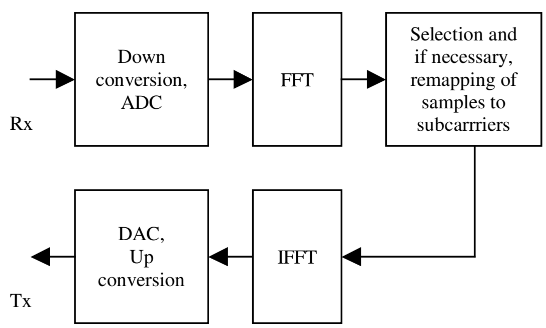

Fig. 2. The processing chain for Amplify-and-Forward relaying in OFDMA.

A drawback of using AF techniques in V-MIMO systems is that, even with processing as described above, their use would not be able to provide any part of the expected MIMO gain in spectral efficiency unless the relaying slot is spatially re-used. DF techniques, on the other hand, would be able to provide data rate improvement by cashing in on the higher capacity of the inter-UE link through adaptive modulation and coding. CF techniques may also be able to provide such improvement through compressing the data taking into account spatial correlations between the signals at the multiple UEs.

The above considerations would become important in a situation where the penetration of V-MIMO devices is not high, and hence, simultaneous operation of multiple users in the V-MIMO mode is unlikely. With higher penetration, while it remains imperative that the inter-UE link supports certain data rates, the spectral efficiency of the link may not be as crucial, since, through frequent spatial re-use of the inter-UE channel, it will be possible to improve the overall spectral efficiency of the system.

Further, if unlicensed bands are used for the inter-UE link, the inefficiency of the link may not be a primary concern from a user's or operator's point of view.

Suitable relaying strategies will need to be designed taking these factors into account.

C. *Neighbor discovery and synchronization*

Before a UE can enter into V-MIMO communication with a base station, it needs to discover neighbors who can act as antennas for itself, and to synchronize with them.

Both localized schemes, where UEs use local information to form UE clusters, and centralized schemes, where the BS is involved in the formation of the clusters, could be considered. Further, means of obtaining globally optimal clusters, as well as simpler means of obtaining non-optimal clusters could be considered. A criterion to choose the best neighbors would be channel information obtained through pilots transmitted by the UEs.

Both time and frequency synchronization between the UEs will need to be accomplished. In WiMAX, while the UEs will be ranged with respect to the base-station, and are also expected to have a fairly accurate frequency synchronization, attention has to be paid to whether this will automatically ensure UE to UE communication. New ranging mechanisms could be investigated that enable not only synchronization of the UE to the base-station, but also enable UE to UE synchronization in time and frequency. The impact of power-control and near-far effects on this process will need to be studied and addressed.

D. *Security*

A V-MIMO system involves a number of nodes that rely on each other for relayed information. Because of the nature of wireless networks, signals/packets can be collected by anyone with proper equipment in a certain range. Hence the need for mechanisms to ensure that no knowledge can be gained from the packets without authorization. However, security of V-MIMO systems is essential not only to prevent unauthorized access to sensitive information, but also to protect the system from malicious attacks which could lead to deterioration of V-MIMO system performance.

Just as in the case of wireless ad hoc networks, this would be a source of vulnerability and attacks by malicious nodes [21, 22], leading to significant deterioration in network performance. Typical attacks to spatial multiplexing environments like Denial-of-Service attacks, Replay attacks and Man-in-the-Middle-attacks would need to be investigated in the context of V-MIMO systems. Beside the black-hole effect, malicious nodes can mount synchronisation attacks.

These potential attacks need to be investigated and suitable security mechanisms developed. For e.g., a trust-credit scheme [23] could be incorporated and complemented with scenario-dependent cryptography mechanisms.

E. *Impact of the distributed physical layers*

The application of MIMO in the PHY layers of WiMAX is based mainly on linear pre-coding at the transmitter, which can be implemented by multiplication by a pre-coding matrix, although space-time block codes (STBC) are also available as an option, especially for control channels. Similarly at the receiver optimum detection in general also involves multiplication of the received signals by an appropriate matrix, also some detectors may also contain non-linear elements.

The separation of the antennas in V-MIMO gives rise to challenges for both the UL and the DL. For the UL:

- How to implement a matrix multiplication across multiple UEs?
- If the antennas are separated, is it feasible to provide the channel knowledge for closed loop schemes?
- Must the channel knowledge be shared between the UEs in the cluster?

For the downlink:

Similarly, implementation of a matrix multiplication across multiple UEs

- How should the received information be shared between the UEs in the cluster (e.g. amplify- and-forward, quantize-and-forward, compress-and-forward)?
- Is it feasible to obtain adequate channel knowledge at the receiver?
- Again, must channel knowledge be shared between UEs?

The use of OFDMA, which gives rise to what is known as the scheduling issue: i.e. which sub-bands to use for which users. For MIMO systems, this also involves the choice of precoding matrices. Here there may be implications in a V-MIMO system arising from the separation of the antennas, which may affect optimum joint scheduling and precoding assignment algorithms.

F. Cross-layer techniques

In a scenario adopting cooperative communications, it is of special interest to consider the interaction between the physical (PHY) and medium access control (MAC) layers. This is because in a V-MIMO configuration several users must simultaneously access the medium to perform the cooperative transmission strategy. Therefore, resource allocation strategies should take into consideration the V-MIMO strategies adopted at the physical layer. This plays an important role in a WiMAX environment. Although the description of several resource allocation algorithms is provided in the standard, specific details of the algorithms have been left undefined so that vendor implementations can provide different solutions. Hence, there exists an open area of research to design and implement efficient scheduling algorithms. Such algorithms should be designed in order to exploit the V-MIMO strategies used in the physical layer. In other words, a cross-layer design which handles the functionalities at both the PHY and MAC layers can improve the overall performance of the cooperative system.

The adoption of Cross-Layer designs in wireless communication systems has considerably increased in recent years [23 - 25]. This is mainly because current layered protocols were originally designed for wireline environments, resulting in several difficulties when adopted to a wireless scenario. Basically, wireless scenarios introduce special problems such as high error rate, time varying link capacity, power constraint of the mobile hosts, etc. Therefore, information exchange between layers seems to be essential in order to improve the performance of a wireless system. Studies adopting cross-layer designs in MIMO environments have been extensively carried out in the literature [26 - 31]. For standard deployment, some cross-layer techniques, such as the use of channel status-aware scheduling algorithms have been considered in HSDPA recommendation of UMTS and CDMA 2000. However, the use of cross-layer techniques taking explicit consideration of MIMO techniques at the physical layer is not present in current standardization. In such a context, there is scope for the enhancement of the system by means of cooperative strategies (i.e., by using V-MIMO techniques) based on cross-layer optimization.

IV. SOME CONSIDERATIONS IN THE DESIGN OF THE INTER-UE LINK IN WIMAX

For a WiMAX based V-MIMO system, the IL could be developed using a different technology. A benefit of such an approach is that the technology can be optimized for short-range communication, i.e., for a range of not more than a few meters. An example of such a technology could be UWB.

Another possibility for the IL, which is what we investigate here, is the re-use of WiMAX technology. Here, there are some obvious drawbacks. Some of these, and some means of addressing them, are discussed in this section.

We first look at the improvement in data rates that are attainable through V-MIMO if re-use of WiMAX is used for the IL, with the currently supported coding and modulation schemes.

Next, we discuss some issues and features that are of interest in the design of such systems.

Finally, we propose some amendments to the WiMAX standard that would enable efficient inter-UE communication.

A. Attainable speed-up factors

We define a ‘speed-up factor’ for V-MIMO operation, as the factor by which the system data rate goes up through the use of the technology.

Let one ‘resource’ be defined as one subcarrier over one symbol duration.

Let the number of UEs in the V-MIMO UE cluster be M, and let

S_{BU} = no. of resources given to the BS-UE link,
S_{UU} = no. of resources given to the UE-UE link,
$R_{UU\text{-}BU} = S_{UU} / S_{BU}$,

For pure spatial multiplexing, the speed-up factor without spatial re-use of the inter-UE link would be:

$$SF = M / (1 + R_{UU\text{-}BU}).$$

In practice, the UE-UE link is likely to be re-used within the cell. For computing the speedup with re-use of the inter-UE link, the following scenario is considered. K users at well-separated points within the WiMAX cell all use the same resources for the UE-UE link. In other words, the UE-UE link re-use factor is K. The speed-up factor with re-use is

$$SF_r = M / (1 + R_{UU\text{-}BU} / K).$$

We first consider the Uplink with V-BLAST [36] used as the MIMO technology and Decode-and-Forward relaying on the inter-UE link.

For this case, the speedup that can be obtained would be dependent on the coding and modulation schemes supported by WiMAX.

The best scenario for V-MIMO would be the cell edge, where the UE-UE distance is only a small proportion of the BS-UE distance. The BS-UE distance is such that the most robust coding and modulation scheme is being used on this link, and the UE-UE distance is such that the least robust coding and modulation scheme is being used on it.

The worst scenario for V-MIMO would be the cell interior, where the BS-UE and UE-UE distances would be comparable. Here, both the BS-UE and UE-UE links make use of the same coding and modulation scheme, which is likely to be the least robust.

The speedup factors for three coding and modulation schemes are indicated in Table 1 below, for 4-UE and 2-UE clusters.

The speedup factors for data transfer on either the UL or DL with Amplify-and-Forward relaying would correspond to cases 3 and 6 in Table 1, where the same coding and modulation scheme is used on the main link and the BS-UE link. In the absence of re-use, no speedup would be available. However, with the use of suitable compression techniques, it should be possible to obtain speed-ups even without re-use.

B. Limitations of the coding and modulation schemes

While the figures in Table 1 indicate that the re-use of WiMAX for the inter-UE link, with the existing coding and modulation schemes, can potentially give good improvement in spectral efficiency, we look at what better can be done.

The channel between two UEs a couple of meters apart would have a very high capacity compared to typical cellular channels. The coding and modulation schemes in WiMAX have not been designed to work at the rates that such a channel can support.

Indeed, the highest order modulation supported in 802.16 is 64 QAM. The reference sensitivity for rate ¾ 64-QAM is –68 dBm for a 10 MHz channel. We consider a case as in [32], where the operating frequency is 2.5 GHz, the channel bandwidth is 10 MHz, and the UE has a maximum transmit power capability of 23 dB and an antenna gain of –1 dBi. At a separation of 5m with LOS, if the transmission is at the maximum power, the power received at a neighboring UE would be about –40 dBm, i.e., about 28 dB above reference sensitivity. Hence, there is considerable capacity going to waste here.

One way of dealing with the issue would be to introduce higher order modulation and higher rate coding into the standard for inter-UE communication. The other way would be to transmit at lower power, thus enabling more spatial re-use of the IL resources, and consequently, improving spectral efficiency. However, if only a few users engage in V-MIMO communication at a particular time, the capability for such re-use is not of much use in improving efficiency.

C. Loss of efficiency due to the cyclic prefix

Another way in which WiMAX fails to meet the requirements of a very short range technology is in its being based on OFDM, which is a technology designed for scenarios with significant delay spread. If line of sight communication over a range of a few meters is considered for the IL, the delay spread would be small, and the cyclic prefix, which is typically 1/8 of the useful symbol duration, would lead to an unnecessary wastage of bandwidth.

D. Zones for inter-UE communication

One option for the inter-UE communication would be to accommodate it within the existing WiMAX frame structure [4, 5], consisting of DL and UL sub-frames, by allocating a few of the sub-channels for IL communication.

We consider a Time Division Duplex (TDD) system. For DL data transfer, all the UEs of a V-MIMO cluster need to listen to the DL continuously, and would not be able to transmit on it simultaneously. So, some sub-carriers of the UL sub-frame could be used for the IL communication. This kind of organization for DL data transfer is depicted in Fig. 3. Similarly, for UL data transfer, some sub-carriers of the DL sub-frame after the DL-MAP could be used for IL communication. Problems to be solved would include how UL ranging and MAC messaging would be carried out by the neigbour UEs in the first case and how a UE would be able to engage in a UL as well as a DL call at the same time.

Another problem with this scheme is that power control for both the short-range IL and the long-range DL/UL within the same OFDMA symbol can be problematic. For example, for DL data transfer at the cell-edge, a UE will need to transmit fairly high levels of power on the IL so as to maintain a balance with adjacent sub-carriers being used for the long-range UL communication by the UEs of the V-MIMO cluster or by other UEs in the vicinity. This could seriously hamper the ability to optimize spatial re-use of the IL.

Technically much simpler and more efficient than the above schemes would be the definition of a separate time zone or sub-frame for the IL communication. This kind of organization is depicted in Figs. 4 and 5.

Here, the power control for the inter-UE communication can be carried out without reference to the UL/DL communication and powers.

If a separate time zone is provided for the IL communication on the DL sub-frame, the BS would need to schedule the DL bursts such that the neighbor UEs of the V-MIMO cluster have time to turn around to transmit mode in the IL zone. Otherwise, neighbor UEs would be unable to simultaneously engage in a user-terminated call of their own. A new sub-frame for IL communication with time gaps separating them from the DL/UL sub-frames would help get round this problem.

Table 1. Speedup factors through the use of V-MIMO in WiMAX, for UL data transfer using spatial multiplexing (V-BLAST), and DF on the inter-UE link. Cases 3 and 6 also apply to UL/DL data transfer using AF on the inter-UE link.

S. No.	Coding and mod scheme		No. of UEs in cluster	Ratio of UE-UE to BS-UE resources (%)	Speedup without reuse	Speedup with reuse factor 5
	BS-UE	UE-UE				
1	½ rate, 6 rep, QPSK	5/6 rate 64-QAM	4	10	3.6	3.9
2	½ rate QPSK	5/6 rate 64-QAM	4	60	2.5	3.57
3	5/6 rate 64-QAM	5/6 rate 64-QAM	4	300	1	2.5
4	½ rate, 6 rep, QPSK	5/6 rate 64-QAM	2	3.3	1.94	1.99
5	½ rate QPSK	5/6 rate 64-QAM	2	20	1.67	1.92
6	5/6 rate 64-QAM	5/6 rate 64-QAM	2	100	1	1.67

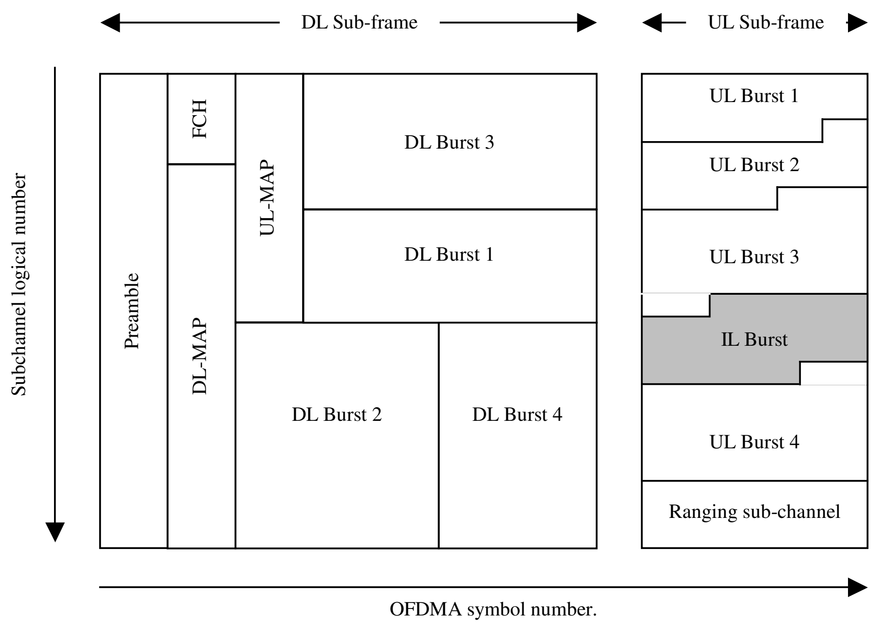

Fig. 3. IL communication in WiMAX using sub-channels of the UL sub-frame for DL data transfer.

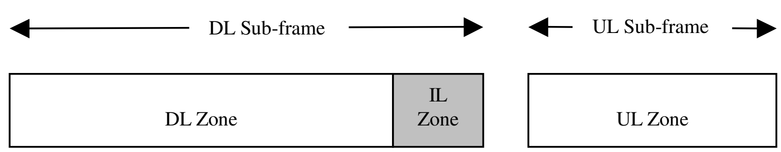

Fig. 4. IL communication in WiMAX on a separate time zone.

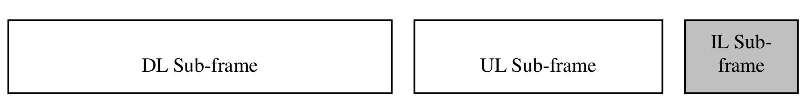

Fig. 5. IL communication in WiMAX on a separate sub-frame.

E. *Proposed amendments to the standard*

Hence, for enabling efficient re-use of WiMAX for short-range communication, the following are some of the possible ways in which the standard can be amended.

- A separate time-zone or sub-frame for the IL communication, with adaptable length.
- Introduction of higher order and higher rate coding and modulation schemes.
- The use of OFDM symbols with highly reduced cyclic prefix length in the IL sub-frame.
- A CSMA based protocol for communication on the IL sub-frame, that would enable re-use of resources without centralized allocation.
- A means of estimating relative positions of UEs, which would enable re-use of IL resources through centralized scheduling.

Some of these amendments would require significant changes to the standard. However, such changes can be justified if they are looked at as enablers not just for Virtual MIMO communication, but for efficient short-range communication of other kinds as well.

Indeed, a UE today is often at the hub of two kinds of communication – a long range communication with a base station, and many kinds of short range communication with local devices. Introducing an efficient short-range sub-system into WiMAX could, for instance, enable the replacement of a WiMAX + Bluetooth handset with a purely WiMAX handset, thus reducing the need for an additional baseband and RF. It could also enable combining the advantages of mesh and point-to-point communication, which WiMAX does not support at once. The system could use long range centralized resource allocation and synchronization for the short range data transfer, and enable the use of licensed bands for the short-range communication, which would be an asset in many scenarios.

From the above perspective, it could be useful to introduce significant changes of the kind proposed here for the evolution to 802.16m.

V. CONCLUSION

Several issues and challenges involved in the introduction of V-MIMO systems in WiMAX, and in the implementation of practical V-MIMO systems, were discussed. We considered the re-use of WiMAX technology for the inter-UE link. It was shown that this can deliver good improvement in spectral efficiency even with the currently supported coding and modulation schemes in WiMAX. Some amendments to the standard were proposed that would enable the re-use of WiMAX for the inter-UE link, and for short-range communication of other kinds as well.

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