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New combined WiMAX/DSRC infrastructure design for efficient vehicular networking

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Abstract

In this article, a new infrastructure of a combined Worldwide Interoperability for Microwave Access (WiMAX) and Dedicated Short-Range Communications (DSRC) link layer is proposed with the purpose of reducing simultaneous WiMAX connections. WiMAX offers wide area connectivity of vehicles to ground-based base stations, while DSRC offers relatively shorter communication that allows for vehicles in proximity of each other to communicate directly. The proposed design uses the fact that WiMAX amendments support the concept of a WiMAX relay node, and substitutes the WiMAX relay nodes with nodes that are capable of both WiMAX and DSRC communications. This change allows for the number of WiMAX connections to be concentrated while supporting more subscribing users via WiMAX tunnelled over DSRC relay. The focus of this design is on the use case of providing broadband Internet access to a large number of DSRC capable vehicles in a WiMAX served region. The design uses DSRC as a WiMAX tunnel, but with changes to the WiMAX protocol, specifically network entry and handover processes are redesigned to have different behaviour only when operating over DSRC. Network entry over DSRC modifications are described and illustrated with comparison to existing WiMAX standards. Handover process facilitated over both WiMAX and DSRC layers are described, illustrated and are also standard compliant. Unified modeling language is used to assist with the explanations of the components to improve understanding of the design in relation to existing WiMAX standards. In addition to standard WiMAX operability, the design can also support WiMAX data subscription using a software-defined WiMAX radio via DSRC relay connectivity. This proposed design improves WiMAX communication by reducing the number of WiMAX connections between vehicles. We plotted the throughput of various cluster sizes of WiMAX only mobile relay, versus our proposed DSRC-enabled WiMAX mobile relay in order to show the efficiency benefit of our design. We also provide a simulated curve of percentage improvement efficiency for varying amount of active users. We show that as the total number of users in the system increases, our proposed system significantly improves the overall system efficiency, especially in heavily congested traffic.

Keywords: Broadband communication, Dedicated short-range communications, Metropolitan area networks, Mobile communication, Multiaccess communication, IEEE 80211 Standards, IEEE 80216 Standards, Vehicular and wireless technologies, WiMAX, Wireless communication, Pseudo-linear

Introduction

Ubiquitous wireless Internet seems to be the trend towards the future in our social media, video streaming, and Voice-over-IP (VoIP) calling culture. The advent of high-speed data broadband networking such as Worldwide Interoperability for Microwave Access (WiMAX), Long-Term Evolution, or other mobile communication standards do not appear to be a "one solution fits all" scheme. Even as the next generation of handheld wireless broadband solutions are being released, they are being released in a way that does not have full broadband coverage, but rather small pockets of high-speed data network within larger regions of lower speed data networking. These small pockets of high-speed network are not ideal for serving rich media applications to vehicles in vehicular ad hoc networking, due to frequent movements in and out of range of these high-speed areas. The metropolitan area WiMAX network is intended for blanketing a wide area with high-speed network capability, and correspondingly serves a relatively

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large number of users. We have previously shown in [1] that this high connection number seems to be Mobile WiMAX's weakness. We also show that by using an intermediate technology such as Dedicated Short-Range Communications (DSRC), concentrations of DSRC users can be served by a smaller number of WiMAX connections. At the same time, DSRC on its own does not lend itself well to serving high-speed broadband Internet without significant roadside infrastructure.

Mobile WiMAX [2] is the current revision of WiMAX, and is based on the 802.16-2009 revision [3] to the IEEE 802.16-2004 release of Wireless Wide Area Network. This system's physical layer (PHY) operates on frequencies between 2 and 11 GHz for non-line-of-sight applications and a Scalable Orthogonal Frequency Division Multiple Access (S-OFDMA) air interface. One important feature about the S-OFDMA system used in Mobile WiMAX is the easy scalability of the system to adapt to varying bandwidth configurations (1.25–20 MHz) in a cell, while keeping other system parameters such as frame size or sub-channel size constant. Adaptive modulation and coding allows each individual connection to adjust to changing channel conditions and provide an optimum balance between link throughput and robustness. Due to the fact that this scheme lends itself to the possibility of a large number of simultaneous streams, this increases the complexity of finding optimum coding and modulation due to more simultaneous transmissions. Therefore, the reduction of the number of simultaneous streams for the purpose of optimizing WiMAX transmissions is a significant motivation for our proposed system.

The IEEE 802.11p-2010 [4] amendment to the IEEE802.11-2007 standard provided support for highly mobile ad hoc vehicular communications and introduced important connection optimizations that dramatically reduced the amount of time it took to make a connection between one vehicle and another, and formed the physical layer for the DSRC standard. Additionally, the increase in symbol duration facilitated a reduction in errors at the PHY normally due to severe inter-symbol interference (ISI) under high relative velocities. This is an important problem to address when working with mobile nodes at high relative velocities, which is the case for vehicular networking. This improvement allows for data rates up to 27 Mbps per 10 MHz channel to be transferred from one vehicle to another. There are a total of seven 10-MHz channels defined in the current DSRC standard, of which only three are reserved for safety and control. This large bandwidth of DSRC can be multicast and shared between several users at once within the same channel, but do not necessarily have Internet connection without nearby roadside service providing the connection. With our system, the Internet source can be a vehicle with both WiMAX and DSRC antenna systems, acting as both client for its own Internet requirements, and server to other DSRC connected vehicles.

The rest of this article is organized as follows: The following section provides the related study discussion. Section "Proposed combined WiMAX/DSRC system" contains the proposed combined WiMAX/DSRC system general description including resource usage mapping, a detailed efficiency model for downlink and uplink of WiMAX and DSRC channels, WiMAX connection concentration, DSRC Clustering procedure, and proposed combined WiMAX/DSRC layout; Section "New combined WiMAX/DSRC link layer infrastructure design" presents the new combined WiMAX/DSRC link layer infrastructure design from a deployment diagram perspective from subscriber station (SS) to cluster head relay (CHR) to base station (BS), and describes the connection environment, relationship between node types, and goes into detail with respect to existing WiMAX standards to describe the interoperability of our design. In addition, the same section presents an expanded view of the deployment diagram, with specific descriptions of the new elements of our architecture that allows interoperation between WiMAX and DSRC, specifically the WiMAX network entry over DSRC process and WiMAX/DSRC handover processes as compared to standard WiMAX handover operations; Section "Simulation results" provides the simulation results; Finally, the last section offers concluding remarks.

Related study

All of the literature on IEEE 802.16j [5] amendment reviewed thus far concentrated on in-band relaying. As discussed in [6], the WiMAX subframes are further subdivided to provide the bandwidth for communications between the relay nodes and the subscriber nodes served by them. However, this is still subdividing the WiMAX bandwidth over multi-hop connections. The analysis done in [7] used the non-mobile or Fixed WiMAX standard with an OFDM frame structure. Mobile capable WiMAX described in the Mobile WiMAX standard [2] uses a somewhat different frame structure in order to preserve the robustness of the connection in highly mobile situations. Rather than OFDM, Mobile WiMAX uses an S-OFDMA frame structure [2]. Instead of dedicating all subcarriers to a single user, as is the case in OFDM, S-OFDMA defines bandwidth allocations both in terms of time and in terms of a subset of the available subcarriers.

DSRC is a technology for vehicle-to-vehicle communications that has seen much research. The DSRC standard only provides support for point-to-point communication. However, much research has investigated overlaying ad hoc routing network protocols on the physical layer. One scheme for ad hoc routing is clustering. Mobile nodes of physical proximity form groups, or clusters, with all traffic from within the clusters to other clusters being routed through a gateway node termed the cluster head node (CHR) [8]. In their proposed system, as nodes move, the clusters are independently controlled and dynamically reconfigured. Their architecture provides spatial reuse of the bandwidth due to node clustering, in each cluster, the sharing of the bandwidth is designed in a controlled fashion. Finally, and most importantly, their cluster algorithm is robust in the face of topological changes caused by node motion. Forming stable clusters of mobile nodes for ad hoc routing is an active research area with algorithms such as the Genetic Algorithm [9], a contention-based clustering algorithm [10] and the Distributed Clustering Algorithm [11], designed and tested to provide higher performance for generic mobile ad hoc networks (MANETs). The authors of [9] proposed a new clustering algorithm in MANET. Their resulting clustering algorithm provides a stable and generic cluster structure for the upper layer protocols. Hence, by applying the concepts of clustering to DSRC, which has been found in research to be realistic in heavily congested situations, the cluster head is in a position to concentrate the signals from all the cluster members. Authors of [12] investigated the concept of combining cellular backbone infrastructure with ad hoc relaying known as the iCAR project. The authors' iCAR system increases the conventional system's capacity cost effectively, and show that with a limited number of ad hoc relaying stations and some increase in the signalling overhead (as well as hardware complexity), the call blocking/dropping probability in a congested cell and the overall system can be reduced.

Authors of [13] investigated relatively stable clusters of moving airplanes. The authors referred to these systems as being "pseudo-linear", as they formed a relatively linear routing network, and had relatively constrained movement [14]. This study was subsequently granted a patent [15]. We propose extending this technique and lay the groundwork for applying this extension to congested highways and major roads for WIMAX and DSRC integrated system. For the described system, an optimized clustering and cluster head selection protocol will be investigated in detail through studies of real-world congested vehicle scenarios, using a test platform such as that described by Roccetti et al. [16]. Hence, in this manuscript, all the nodes are configured to have both DSRC and WiMAX system. To maximize network stability (and minimize the overhead of node handovers), the CHR selection protocol will have to factor in vehicle parameters such as relative speed and vehicle destination. Compared to the previous work, this clustering protocol will be specific for vehicles traveling on a road using a wide-area backbone network (WiMAX). This will simplify routing and allow an emphasis on speed and stable latency, as opposed to simple connectivity in a purely ad hoc system. Since the main contribution of this paper is to introduce a new and complete link layer infrastructure design for the WiMAX/DSRC system, network entry and handover processes are designed to have different behavior only when WiMAX operates over DSRC. The system described in this article assumes that all vehicles are equipped with both DSRC and WiMAX radios. These two systems for mobile nodes are available today, and as such the proposed system is capable of using either network.

The coexistence of WiMAX and DSRC in a heterogeneous environment has been discussed in [17], while this article is the first paper to design a new link layer protocol for the combined WiMAX and DSRC communication systems. There are many potential benefits to using this combined system rather than either WiMAX or DSRC on its own. Authors of [18] have found that using roadside stations for Internet access is impractical without a heavy investment in infrastructure. The improvement to the WiMAX system capacity minimizes the installation of costly WiMAX BS. On the other hand, one of the major problems with a DSRC-only system is the latency issues inherent with ad hoc routing systems. As the number of hops between the user and a network gateway is dynamic and the links can be fragile, it is difficult to provide bounds on the latency seen by the system. This can be a problem with Internet applications that are sensitive to latency, including voice communications and streaming media. A combined system also offers the ability to revert to WiMAX-only service, eliminating the sparse node problems seen in an ad hoc network where nodes are not dense enough to allow for continuous routing. This flexibility allows for rapid adaptation to changing system conditions such as exiting a busy highway onto a non-busy side road, without requiring the disruptive reestablishment of application-layer connections. Clustering and ad hoc routing becomes more effective as the road conditions become more congested, which are the conditions where traditional WiMAX routing is demonstrated to become ineffective. As such, the proposed system is far more robust to a wide variety of operating conditions, and provides bounds on the number of hops in the network, providing much more predictable latency conditions. Determining the conditions under which to run flat routing and when to cluster, as well as the size of the clusters and which vehicles to include in clusters, will be part of the cluster selection protocol through studies of real-world congested vehicle scenarios, using a test platform such as that described by Roccetti et al. [16]. In essence, this article extends the WiMAX protocol across DSRC for the purpose of providing broadband Internet access to DSRC connected clients, using a new link layer design.

Proposed combined WiMAX/DSRC system

Figure 1 shows the structure of a Mobile WiMAX frame and illustrates some of the sources of overhead. System overhead is produced by fields in the frame not being used to transmit user data. The most important are the DL_MAP and UL_MAP fields, specifying the user bandwidth allocations for the frame in the downlink and uplink directions. As the number of active connections increase, so does the number of entries in each of these fields. Other system components, including the preamble and the ranging slot (in the uplink subframes), further reduce the system efficiency. Further system overhead comes from unused allocations. It is conceivable that not all of a user's allocated bandwidth will be used. This may be due to a user not having sufficient data to transmit, or when the user's data do not fill the entire allocation. This inefficiency adds up over multiple connections. A conservative estimate would be to assume that half of the last allocated slot is empty, and therefore contributing to the overhead. If the traffic is burstier in nature (such as VoIP), the losses due to this unused allocation could be much greater.

The analysis method used in this section to calculate the system overhead present in a Mobile WiMAX system is based on the works done in [11], but it is substantially modified to accommodate the differences in frame structure. In S-OFDMA, the available bandwidth is broken into a series of orthogonal (non-interfering) subcarrier frequencies, called subcarriers. Some of the subcarriers are dedicated to data transmission, while others are used for tasks such as pilots and guard bands. Groups of subcarriers are put together to form a channel, the smallest bandwidth allocation for a user.

The number of available channels (and thus users) is limited by the available channel bandwidth. S-OFDMA allows for flexible allocation of bandwidth depending on licensed bandwidth and allocation schemes. The four main bandwidth sizes described in IEEE 802.16 are 1.25, 5, 10, and 20 MHz [3]. S-OFDMA allows for a variety of bandwidth configurations, while all other system parameters (frame length, symbol length, etc.) remain the same. This was a design decision made to simplify the hardware in mobile devices, which were not anticipated to be very powerful. Mobile WiMAX uses Time Division Duplexing, dividing the frame into downlink and uplink subframes.

The smallest allocation that can be made in the OFDMA scheme is called a slot, which defines the allocation in bandwidth and time. In the downlink direction, it consists of one channel and two symbols in time. In the uplink direction, it is one channel and three symbols in time. Table 1 shows the number of data carriers available for each bandwidth configuration.

The number of channels in the uplink and downlink directions is defined in the IEEE 802.16 standard (8.4.6.1.2.2 for downlink, 8.4.6.2 for the uplink). A channel consists of a number of data carriers, which are a set of frequencies that can send encoded user data.

Concentration and WiMAX

Concentration of connections is one of the items addressed by the IEEE 802.16j amendment [5]. As defined in [6,7], the IEEE 802.16j amendment [5] introduces the relay station (*RS*) node. This node has some of the functionality of a BS and provides access to the WiMAX network for a number of users. While operating under the control of a single BS node, this node appears to end users as an independent *BS*. A new class of connection is defined between the *RS* nodes and the

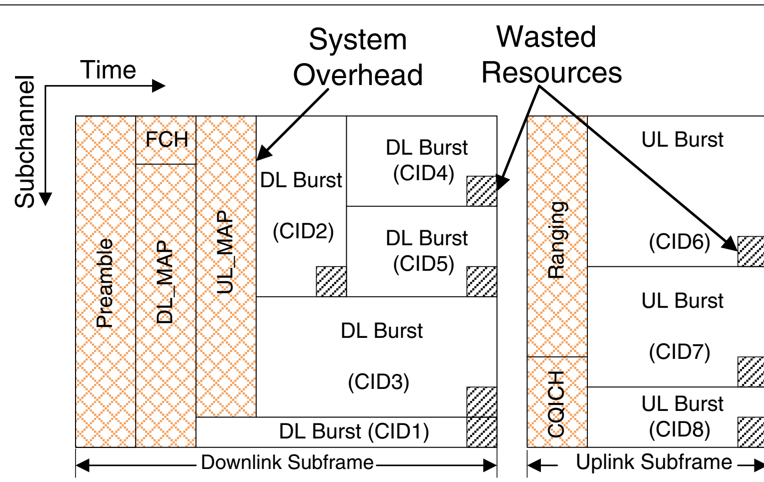

Figure 1 Mobile WiMAX frame.

Table 1 WiMAX channels by available bandwidth

Channel bandwidth (MHz)	FFT size (bits)	Channels (down/up)	N_{SD}—data carriers per symbol (down/up)
1.25	128	3/4	72/64
5	512	15/17	360/272
10	1024	30/35	720/560
20	2048	60/70	1440/1120

BS called a tunnel. These connections allow concentration of the connections for all SS nodes being serviced by the RS, transmitting this traffic across a single connection. This reduces the number of active connections in the system, improving system efficiency while servicing the same number of users.

All of the literature on IEEE 802.16j amendment [5] reviewed thus far concentrated on in-band relaying. As discussed in [6], the WiMAX subframes are further subdivided to provide the bandwidth for communications between the relay nodes and the subscriber nodes served by them. However, this is still subdividing a scarce resource (the WiMAX bandwidth). Furthermore, as the RSs are using the same frequencies with one another, interference starts becoming a problem (particularly if the RSs are moving and close to each other). In addition, particularly if non-transparent relaying is used, the RSs produce an additional set of system header messages. The WiMAX link can be identified as the scarcest bandwidth link in the system, and the one that must be optimized as much as possible.

Although not investigated in literature on multi-hop WiMAX thus far, the IEEE 802.16j standard also offers support for out-of-band relaying—that is, relaying using a separate set of frequencies. This will be the basis of the proposed network structure. By using a separate set of frequencies for relaying, the full bandwidth of the cell remains un-fragmented. Rather than use WiMAX for short-range relaying, this article proposes to use another technology. This will be better suited for short-range communications, allowing for better frequency reuse. This is a technology designed (and tested) specifically for vehicle-to-vehicle communications. As will be explained in the following section, this also allows for ad hoc clustering, which makes sense for mobile vehicle networking.

DSRC system

In 1999, the U.S Federal Communication Commission (FCC) allocated a 75-MHz spectrum at 5.9 GHz for DSRC system for services that involve vehicle-to-vehicle and vehicle-to-roadside communications [19]. The DSRC spectrum is structured into seven 10-MHz wide channels. One of these is a control channel and restricted to safety communications, two of these are reserved for critical safety of life and high power public safety, and the remaining four are service channels available for both safety and non-safety usage [19]. DSRC is a popular ad hoc protocol and is based on the popular IEEE 802.11 Wireless Local Access Network (WLAN) standards [20]. The main purpose of its establishment is for improving road safety, however, it is now considered for commercial purposes. The DSRC system is a short to medium range communication system, i.e., the distance range between the transmitter and the receiver should be around 1000 m. The IEEE 802.11p Wireless Access in Vehicular Environments (WAVE) amendment [4] makes WLAN suitable for vehicle communications [21].

DSRC is also known as the IEEE 802.11p [4] Wireless Access in Vehicular Environment (WAVE) [19], and was based on the IEEE 802.11a standard. The main difference between these two standards is the increase of the symbol duration in DSRC that resulted from the 10 MHz reduction in the channel spacing compared to the IEEE 802.11a standard, with 20-MHz channel spacing. IEEE 802.11a is one of the standards used in WLAN, and was designed for time-invariant channels suitable for stationary indoor environments with low delay spread; hence it makes sense to extend the symbol duration in DSRC, which was justified in [22]. The DSRC PHY employs the well-known orthogonal frequency division multiplexing (OFDM) PHY technique [23], which is popular for its ability to mitigate ISI through the use of sufficient guard interval.

DSRC PHY is defined by a partitioning of a signal across many low-symbol-rate orthogonal subcarriers. The message is encoded with a convolution encoder for forward error correction. The convolution encoder uses a generator [133_8, 177_8], and a constraint length of 7. The message is then interleaved. This interleaved message is now digitally modulated using one of four Gray-coded constellations: binary phase-shift keying, quadrature phase-shift keying (QPSK), 16-point quadrature amplitude modulation (16QAM), and 64QAM [4]. The OFDM packet is split into 64 subcarriers: 4 pilots, 48 data carriers, and 12 for padding. The symbol duration is 8.0 μs with 1.6 μs guard interval and signal bandwidth of 10 MHz. The subcarrier frequency is 0.15625 MHz (10 MHz/64). For phase tracking and frequency estimation purposes, the four pilot subcarriers are spaced apart at 1.875 MHz. These symbols are then multiplexed into a 64-point (inverse fast Fourier transform or IFFT) using the OFDM modulation scheme. The resulting symbol is transformed into an 80-point length vector after the addition of the guard interval, and then serially transmitted over the channel. The data rate is calculated as $R_d = \frac{R_c \log_2(m) N_{SC}}{T_S}$, where N_{sc} is the number of subcarriers, R_c is the code rate, T_s is the symbol period, and m is the number of constellation points in the digital modulation scheme being used. Hence, the data rates depend on the code rates and modulation schemes for DSRC, which result in the following: 3, 4.5, 6, 9, 12, 18, 24, and 27 (Mbps).

At the receiver end, the reverse of the transmitter takes place. Hence, after converting the received signal to parallel signals and removing the guard interval, the signal is transformed back into a frequency-domain signal using the FFT algorithm. Then two training symbols are used to obtain the estimated channel response for the first OFDM symbol over the first two received symbols. The conventional DSRC system uses the same channel response estimated for the first OFDM symbol throughout the entire packet. The received data symbols of the packet are then compensated by the estimated channel response. Finally, the compensated data are deinterleaved and then Viterbi decoding takes place to recover the "message".

Combined WiMAX/DSRC approach

The proposed system is to use ad hoc vehicular networking based on DSRC technology to form clusters of vehicular nodes, with the cluster head functioning as an IEEE 802.16j relay node in order to concentrate connections across the wide-area WiMAX link to the *BS*. The highly congested system conditions where WiMAX overhead becomes an issue is also the situation where clustering of DSRC nodes becomes most effective. Figure 2 shows the suggested system layout. The smaller circles represent the short-range DSRC clusters, with one node identified as the cluster head (*CHR*). The different patterns represent the different clusters, using different frequencies. The identified *CHR* is then used to communicate over WiMAX to the *BS*. WiMAX is used to cover a relatively large geographic area with network coverage.

There are many potential benefits to using this combined system rather than either WiMAX or DSRC on its own. The improvement to the WiMAX system capacity minimizes the installation of costly WiMAX BS. In addition, we have shown in Figure 1 that the structure of a Mobile WiMAX frame, and have also shown in Figure 3 that the system efficiency is reduced with increased number of connections or users due to the fact that not all of a user's allocated bandwidth is used. This inefficiency adds up over multiple connections. Also, the proposed system solves one of the major problems with a DSRC-only system, which is the latency issue inherent with ad hoc routing systems. However, the use of the separate set of DSRC frequencies negates the need to divide the scarce WiMAX bandwidth for relaying, which will in turn solve the reduction of the system efficiency with increased number of connections problem seen in WiMAX systems. The benefit of frequency reuse in DSRC compared to the frequency reuse of a WiMAX-based relay system is also clearly seen due to the fact that a WiMAX system will have to reserve bandwidth for the relays over the entire cell size (possibly kilometres), so the bandwidth gets used up pretty quickly. A DSRC cluster, on the other hand, is going to cover a very small area. As such, especially in light of our pseudo-linear structure, we will be able to reuse DSRC frequencies regularly. For example, clusters separated by a few hundred metres can use the same frequencies and not interfere with each other, while the WiMAX system will allow these clusters to communicate with infrastructure over a wide coverage area.

Finally, this system will help encourage the adoption of DSRC, which is desired for its safety and Intelligent Transportation System (ITS) applications. The combined network also offers ITS systems an alternative to expensive [18] DSRC roadside equipment for data collection, electing instead to use the combined DSRC/WiMAX network to report ITS information such as traffic conditions [24]. An

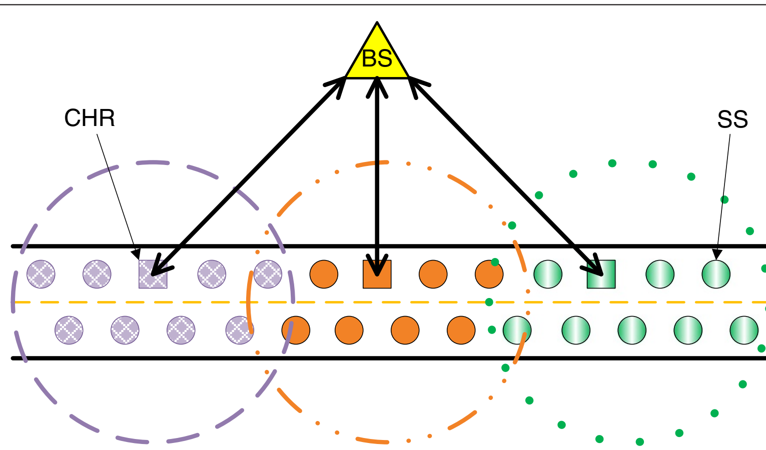

Figure 2 Proposed DSRC/WiMAX system structure.

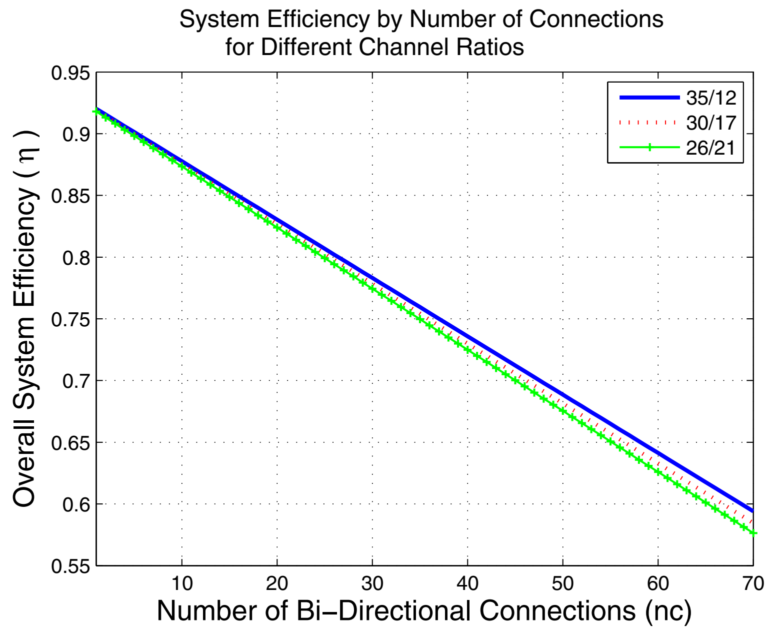

Figure 3 System efficiency by number of connections.

example structure of a combined WiMAX/DSRC system is shown in Figure 2. The CHR nodes relay information with each other via Mobile WiMAX network, while the SS nodes relay information via each other via DSRC network.

In the proposed system, all subscriber nodes connected to the WiMAX network through the DSRC *CHR* are full members of the WiMAX network. In other words, *CHR* is not simply acting as an Internet access proxy. In this way, all *SS* nodes are registered onto the WiMAX network and are individually addressed by the system. By doing this, all nodes are better authenticated and audited by the system. This system is also more robust in mobility by taking advantage of WiMAX's built-in handover support. Finally, by registering all users on the WiMAX network, it further eases the switch between a direct WiMAX connection and a combined WiMAX/DSRC connection without resetting active connections, and allows for easier handovers between RS nodes. The switch between a direct WiMAX connection and a WiMAX/DSRC connection does not break the session that the user has with the *BS*.

Detailed efficiency model derivation

This article includes the first comprehensive and detailed mathematical derivation for the system's efficiency model. Efficiency is defined by the ratio of Medium Access Control (MAC) data transmitted to the total data transmitted. We start with calculating the number of data carriers (N_{SD}) in the downlink and uplink directions (and thus the data throughput capacity).

Calculating N_{SD} for the downlink subframes

The channels for downlink communications are defined by structures known as clusters. A cluster consists of 14 subcarriers spread over two symbols. Over the two symbols, this represents 24 data carriers and 4 pilot symbols. A channel consists of two clusters, for a total of 48 data carriers over 2 symbol times. An illustration of the OFDMA cluster structure is provided in Figure 4.

Using a 10-MHz channel as an example, the number of data carriers per symbol (N_{SD}) for the downlink subframes can be calculated to be:

$$\frac{30_{\text{subchannels/symbol}} \times 24_{\text{data carriers/cluster}} \times 2_{\text{clusters/subchannel}}}{2_{\text{symbols/cluster}}} = 720_{\text{data carriers/symbol}} \quad (1)$$

Calculating N_{SD} for the uplink subframes

In recognition of the less robust nature of a mobile client, the uplink communications uses a different allocation structure. As shown in Figure 5, the available carriers are broken into tiles made up of four subcarriers and three symbol times. More of the carriers are dedicated to pilot signals for increased robustness. A channel consists of six of these tiles, for a total of 48 data carriers over 3 symbol times.

This can consist of six consecutive tiles, or a more dispersed allocation for robustness against subcarrier

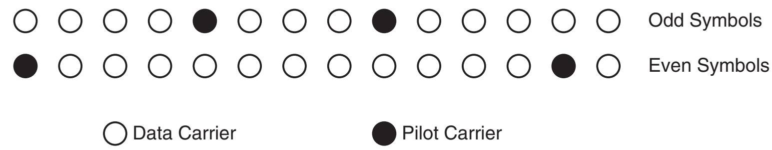

Figure 4 OFDMA cluster structure (downlink).

specific interference. Furthermore, the allocated tiles can be changed between frames for more robustness.

Again, using a 10-MHz channel example, the number of data carriers per symbol (N_{SD}) for the uplink subframes can be calculated to be:

$$\frac{35_{subchannels} \cdot 6_{titles/subchannel} \cdot 8_{data\ \ carriers/title}}{3_{symbols/title}} = 560_{data\ \ carriers/symbol} \quad (2)$$

According to the IEEE 802.16 and Mobile WiMAX specifications for the OFDMA modulation scheme, the following modulation/coding rates are defined. Table 2 is adapted from the one in [25], but updated to the different block size used in OFDMA.

The selection of modulation and coding rate is a factor of the channel condition, with more complex modulation and lower coding rates improving the channel throughput, but decreasing the resistance against noise and interference. The modulation and coding rate will be dynamically adjusted to provide the best throughput for the channel condition, aided by the fast feedback mechanism defined in Mobile WiMAX. The physical mode (m) is an indication of which combination of modulation and coding rate was selected. The coding rate indicates the number of bits which will contain redundant information for channel robustness. The number of bits encoded per subcarrier is represented by $\log_2 M$. The term block refers to a group of 48 data carriers, which is the basic unit of data transmission over either two (for downlink) or three (for uplink) symbols. The coded channel block size is the number of bits that will be encoded in a block. The un-coded channel block size (BpS_m) is the number of user data bits that will be encoded in the block and is defined as:

$$BpS_m = N_{sc} \cdot R_C \cdot \log_2 M, \quad (3)$$

where N_{sc} is the number of data carriers per channel, R_C is the code rate, and M represents the number of constellation points in the digital modulation scheme used.

The overall efficiency of the system can be defined by the ratio of MAC data transmitted over the air interface to the total data transmitted [1,25]:

$$\eta = \frac{\theta_{Net/MAC}}{\theta_{Phy/symbol}} \quad (4)$$

where

$$\theta_{\text{Net/MAC}} = \frac{\sum \text{Payload}}{T_{\text{frame}}} \quad (5)$$

and

$$\theta_{Phy/symbol} = \frac{N_{SD} \cdot R_C \cdot \log_2 M}{T_{symbol}} \quad (6)$$

The payload is the total number of data bits transmitted, and T_{symbol} is the frame duration (5 ms for Mobile WiMAX), while T_{symbol} is the symbol duration (102.9 μs for Mobile WiMAX including guard band).

Mobile WiMAX incorporates different effective symbol times and number of data carriers for the downlink and

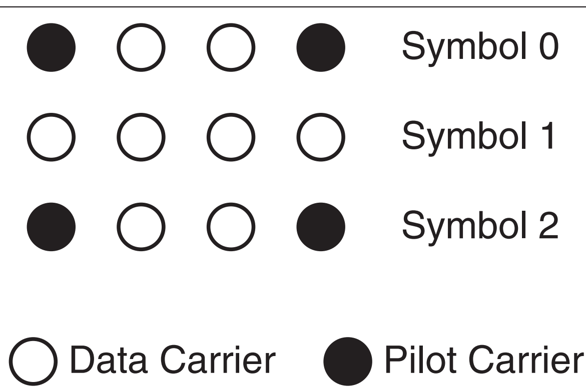

Figure 5 OFDMA tile structure (uplink).

Table 2 Coded and un-coded block size by modulation

PHY mode (m)	Modulation and coding rate	Coding rate Rc	$\text{Log}_2 M$	Un-coded channel block size (bits) (BpS_m)	Coded channel block size (bits)
1	QPSK 1/2	1/2	2	48	96
2	QPSK 3/4	3/4	2	72	96
3	16-QAM 1/2	1/2	4	96	192
4	16-QAM 3/4	3/4	4	144	192
5	64-QAM 2/3	2/3	6	192	288
6	64-QAM 3/4	3/4	6	216	288
7	64-QAM 5/6	5/6	6	240	288

uplink subframes, as well as a variable ratio of symbol allocation. Therefore, the physical transmission rate can be further defined as:

$$\theta_{\text{Phy/symbol}} = \frac{[(N_{\text{DL Symbols}})\cdot(N_{\text{DL SD}}\cdot R_C\cdot \log_2 M)] + [(N_{\text{UL Symbols}})\cdot(N_{\text{UL SD}}\cdot R_C\cdot \log_2 M)]}{(N_{\text{DL Symbols}} + N_{\text{UL Symbols}})T_{\text{symbol}}} \quad (7)$$

where $N_{\text{DL Symbols}}$ and $N_{\text{UL Symbols}}$ are the total symbols dedicated to the downlink and uplink and $N_{\text{DL SD}}$ and $N_{\text{UL SD}}$ are the number of data subcarriers in the downlink and uplink, respectively. This calculation does not take into account the overhead of the preamble, as well as the guarding between the transmit and receive portions of the frame, as they do not contribute to MAC level system overhead.

To calculate the payload, total slots available for data transmission are calculated as follows:

$$N_{Slots\ \ DL} = [((N_{DL\ \ Symbols} - 1)/2)\cdot N_{DL\,SC}] \quad (8)$$

and

$$N_{Slots\ \ UL} = [(N_{UL\ \ Symbols}/3)\cdot N_{UL\ \ SC}] \quad (9)$$

where $N_{\text{DL SC}}$ and $N_{\text{UL SC}}$ are the number of channels in the downlink and the uplink, respectively. One symbol is removed from the downlink subframes to account for the preamble.

The number of slots available for payload (user data) is defined as:

$$N_{Payload} = N_{Slots} - \sum Overhead \quad (10)$$

This can be further be defined for the downlink and uplink subframes through the specification of the system overhead components specific to each direction as:

$$\begin{aligned} N_{\text{Payload DL}} = N_{\text{Slots DL}} - N_{\text{FCH}} - N_{\text{DL-MAP}} \\ - N_{\text{UL-MAP}} - N_{\text{DCD}} - N_{\text{UCD}} \end{aligned} \quad (11)$$

and

$$\begin{aligned} N_{Payload\ \ UL} = N_{Slots\ \ UL} - N_{Ranging} - N_{ACK} \\ - N_{CQICH} - N_{Padding} \end{aligned} \quad (12)$$

The system overhead takes the form of the preamble, the Frame Control Header (*FCH*), the *DL - MAP*, the *UL - MAP* on the downlink, and contention channels for ranging, bandwidth request, and fast feedback on the uplink. The preamble is one symbol long and allows for synchronization of all clients.

The *FCH* contains channel configuration information, including *MAP* message length, sub-channels, coding scheme, etc. The *DL - MAP* and *UL - MAP* messages provide the per-user bandwidth allocations in the downlink and uplink directions, respectively. The *FCH* consumes six slots, while the *DL - MAP* and *UL - MAP* are dependent on the number of connections. Each consists of a standard MAC header and ends with a CRC, for a total of 10 bytes. Furthermore, each message consists of the standard *DL - MAP* and *UL - MAP* message, with an information element (*IE*) for each connection. The length of the *DL - MAP* and *UL - MAP* messages (in bytes) is defined as:

$$\begin{aligned} L_{\text{DL-MAP}} &= L_{\text{Header+CRC}} + L_{\text{DL-Map Header}} \\ &\quad + L_{\text{PHY Sync}} + L_{\text{DL-MAP-IE}} + L_{\text{Padding}} \\ &= 80 + 72 + 32 + n_c\cdot 60 + 4 \\ &= 188 + n_c\cdot 60 \end{aligned} \quad (13)$$

Similarly for the uplink,

$$\begin{aligned} L_{\text{UL-MAP}} &= L_{\text{Header+CRC}} + L_{\text{UL-Map Header}} + L_{\text{UL-MAP-IE}} \\ &\quad + L_{\text{Padding}} \\ &= 80 + 64 + n_c\cdot 48 = 144 + n_c\cdot 48 \end{aligned} \quad (14)$$

where n_c is defined to be the number of bidirectional connections active in the system. While connections are allocated on a directional basis, a bidirectional model makes sense for the kind of traffic being investigated in this article. The upload and download maps are modulated using 1/2 QPSK, the most robust modulation available.

The remaining variables from Equations (11) and (12) are defined as follows:

$$N_{DL-MAP} = \frac{L_{DL-MAP}}{BpS_1} \ \ and\ \ N_{UL-MAP} = \frac{L_{UL-MAP}}{BpS_1} \quad (15)$$

The Mobile WiMAX specification specifies a 6-slot channel for ranging and bandwidth requests. A 6-slot channel is used for channel quality information (*CQI*) requests, part of the fast feedback mechanism used for mobile systems to adapt modulation based on changing channel conditions. Hence from Equation (12):

$$N_{Ranging} = 6\ \ and\ \ N_{CQICH} = 6 \quad (16)$$

Finally, overhead is introduced by each connection, as the *MAC PDU* will not perfectly align to the *MAC SDU* and padding will be added. It is reasonable to assume that this adds up, over time, to half of a slot in each direction per bidirectional connection. This is making the conservative estimation that nodes have information to transmit all the time. If the transmissions are burstier in nature, much more bandwidth will be lost in the form of unused allocations.

Using the conservative estimate, the overhead due to this unused bandwidth is found to be:

$$N_{Padding} = n_c \cdot 0.5 \tag{17}$$

With this information, the MAC data bit rate in the downlink and uplink directions are calculated to be:

$$\begin{aligned} N_{Payload\ \ DL} &= N_{Slots\ \ DL} - \left[\left(\frac{6 + 188 + n_c \cdot 60 + 144 + n_c \cdot 48}{BpS_1}\right) + n_c \cdot 0.5\right] \\ &= N_{Slots\ \ DL} - \left[\left(\frac{388 + n_c \cdot 108}{BpS_1}\right) + n_c \cdot 0.5\right] \end{aligned} \tag{18}$$

and

$$\begin{aligned} N_{Payload\ \ UL} &= N_{Slots\ \ UL} - (6 + 6 + n_c \cdot 0.5) \\ &= N_{Slots\ \ UL} - (12 + n_c \cdot 0.5) \end{aligned} \tag{19}$$

Finally, the MAC data transmission rate is calculated to be:

$$\theta_{Net/Mac} = \left[\frac{(N_{Payload\ \ DL} + N_{Payload\ \ UL}) \cdot BpS_m}{T_{Frame}}\right]. \tag{20}$$

The formulas derived above allowed testing of different configurations of the system, including the number of active connections, the ratio of uplink symbols to downlink symbols and the modulation and coding used for the data being sent. We have shown in [1] that the system efficiency decreased from 92% with a single active bi-directional connection to 58–59% with 70 active bi-directional connections. These results are also shown in Figure 3. The channel ratio was also adjusted, using the WiMAX specification downlink:uplink ratio limits of 35:12 and 26:21 and a median value of 30:17. It can be seen that as more resources are dedicated to the uplink, a slight increase in the amount of overhead is produced. In addition, the results show that the system efficiency suffered when the systems were congested. Hence, these results found an overhead problem with the OFDMA system in Mobile WiMAX, which was similar to that found with Fixed WiMAX in [7].

This inefficiency is stemmed from the bandwidth allocation information included within each frame, coupled by unused parts of allocated bandwidth due to nodes not being able to fill their allocated bandwidth, and is multiplied by the number of link allocations within the system. By reducing the number of individual connections within the system, more of the bandwidth can be used for actual data transmission.

The following sections discuss methods to approach this issue. The concept of concentration of connections, introduced by the IEEE 802.16j amendment [5], is discussed as a possible solution. Network clustering and vehicular ad hoc networks are then investigated. Finally, the two techniques are combined and proposed as a solution to the issue of system overhead in WiMAX systems.

New combined WiMAX/DSRC link layer infrastructure design

System structure description and design of proposed system

Figure 6 shows the overall structure of the proposed system. Three node types are identified, as well as the communication medium between one another. The three nodes SS, CHR, and BS provide the combined WiMAX/DSRC system.

The SS node represents the component containing the end user's applications in the system. In the context of a WiMAX system, the SS node is an agent in a mobile vehicle accessing Internet services through the network. In our proposed architecture, the SS node is a member of a DSRC network and communicates through the CHR cluster-head node. The CHR node is responsible for relaying information between the DSRC and the WiMAX networks. This configuration allows the CHR node to function as a pseudo BS to SS nodes operating under it. Data from these SS users is routed to the region's BS across a tunnelled WiMAX link. The BS node performs the functions of the BS node outlined in the IEEE 802.16j standard specification [5]. Within a WiMAX coverage region (WiMAX cell), the BS node is responsible for allocation of resources and handling authentication and handovers.

Overview of proposed system

The SS in our combined WiMAX/DSRC design is a mobile node equipped with both a DSRC transmitter/receiver and a WiMAX transmitter/receiver. However, instead of the WiMAX transmitter/receiver transmitting into the channel, it transmits and receives the WiMAX transmissions through DSRC transmissions and a cluster head/relay (CHR) station. The WiMAX network entry process has the required operations of Ranging, Registration, Security, and Service Provisioning WiMAX transmissions. The SS nodes can complete these operations by encapsulating them in DSRC packets for transmission through DSRC PHY. An SS can be elected to become a CHR station if the current CHR comes out of range, or a new CHR can be chosen from the group of in-range SS. When a reply message is received by the DSRC receiver, it must be processed by encapsulation and the reply processed appropriately. If no other SS

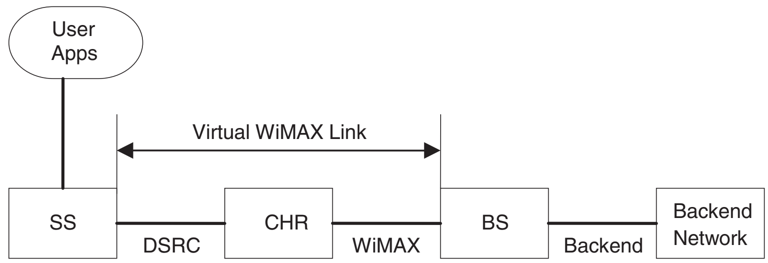

Figure 6 System structure.

nodes are in DSRC range, the SS node will become its own CHR station and communicate directly with WiMAX BS. This is particularly important because purely ad hoc systems suffer when there is not enough node density to ensure constant routing. Therefore, in situations where node density does not allow for clustering, SS nodes can therefore use the WiMAX radio to connect with the BS node directly. Through the use of the protocols described in this article, it will be possible for nodes to switch between being served in a DSRC cluster and being served through a direct connection and still maintain their network connections.

The CHR is a mobile node like the SS, but this node serves as a relay for multiple SS nodes to pass WiMAX transmissions that has been tunnelled through DSRC to roadside WiMAX BS. CHR nodes are elected from clusters of vehicles, and handovers can be made to ensure that SS nodes maintain connection with WiMAX BS, as will discussed later in this article. The CHR node essentially acts like a WiMAX multi-hop system, but with the subscriber side of the WiMAX relay being tunnelled through DSRC to an SS. This leads to some certain optimizations, that is, due to the fact that the SSs do not need to transmit over the WiMAX channel, the connection information setup is more efficient and is replaced on the DSRC side with an SYNC message that tells the SS stations how busy the WiMAX channel is. This is so that the SS nodes know when and how fast to transmit to the CHR stations. It is recommended that each mobile node have two MAC addresses to readily distinguish between traffic intended for the node itself while operating in SS mode, and traffic intended for other nodes connected to it while operating in CHR mode. Some WiMAX tunnelled traffic is pre-processed at the CHR, especially during a handover session.

WiMAX BS are spread out across a coverage area. Each BS can serve and receive WiMAX data traffic from/to multiple mobile nodes. Additionally, a BS should directly be or indirectly connected to Backend Network, as seen in Figure 6, to be able to provide Internet services to WiMAX connected subscribers. Our detailed proposed backend network or Internet Access Gateway (IAG) design and its functionality is presented in [26].

Figure 7 shows the relationship between SS and CHR nodes, without showing the BS node. The notation 1..* represents relative multiplicity of more than one. The SS node uses a single network link to communicate with the cluster head (the CHR node) in the DSRC network across a DSRC link. The details of this link are described in Section "Overview of proposed system". The network entry process between the SS node and the CHR and BS nodes is described in Section "Architecture interoperation and behavior". Figure 7 also shows the CHR node which is based on the RS described in the IEEE 802.16j specification [5]. However, rather than relying on in-band or out-of-band WiMAX for relaying the messages, the CHR node uses DSRC as the relaying medium. The CHR and the SS nodes are identical in construction, with the CHR node simply being an SS node that was elected to being a relay over the underlying DSRC protocol. Similarly, as shown in Figure 8, a CHR node (on the DSRC interface) can accept connections from multiple SS users, while on the WiMAX interface (BS side), a CHR node establishes an uplink connection with the BS node.

Due to the CHR node's dual PHY interface capabilities, two distinct communications occur. First, it is connected directly across the WiMAX network to the servicing BS

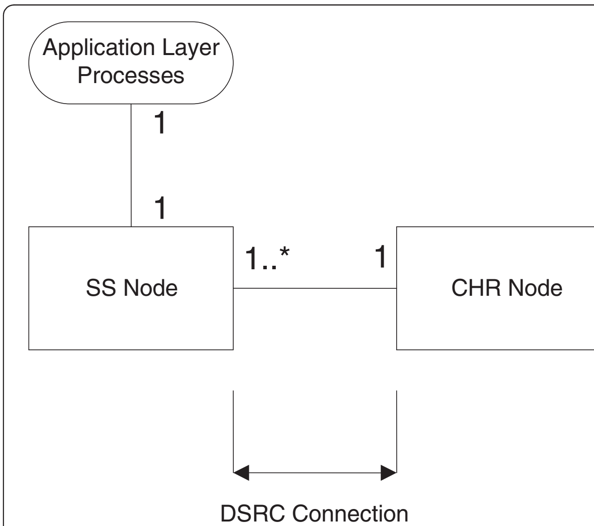

Figure 7 Overall SS node structure.

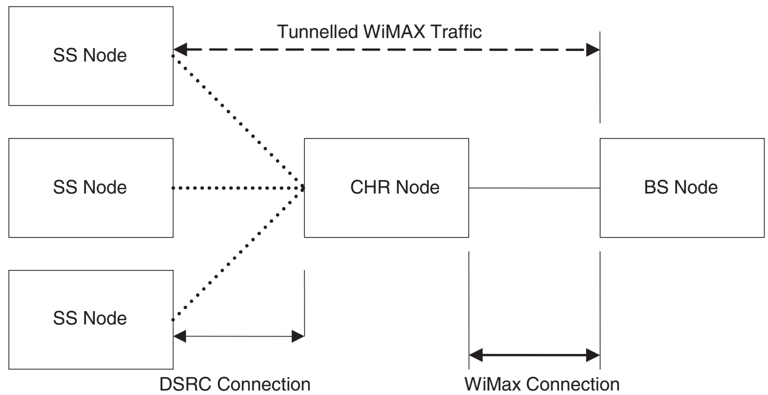

Figure 8 Overall CHR node structure.

node in the WiMAX cell. This link is described in detail in Section "Overview of proposed system", and is used to communicate both configuration networks for the CHR node, as well as for tunnelling traffic to and from the SS nodes served by the CHR node. The connection establishment process between the CHR node and its serving BS node is described in Section "Establishing CHR-BS connection over WiMAX PHY". Second, each individual SS node within its cluster establishes a connection with the CHR node over the DSRC link.

The overall BS node structure is shown in Figure 9. It is responsible for the allocation of resources in the WiMAX network, authentication and accounting of users, and coordinating network handovers between BS. The BS node is also responsible for forwarding application layer data to the responsible application providers. Within the context of the proposed system, this includes forwarding Internet access data to the agent responsible for coordinating the network access. As described in the IEEE 802.16j specification [5], the BS node manages connections from RS nodes, as well as direct connections from SS nodes. As the primary controller for the WiMAX cell, it also accepts relayed connections from SS nodes. The BS node is also connected to the backend network set up by the WiMAX service provider. This network is used for many purposes, such as coordination between BS nodes for handovers and to authenticate users against a master authentication server. Another purpose for this connection is to provide services to the user, such as Internet access. The services that are involved in the BS nodes connecting with the fourth node, the Backend, or the IAG are described in our backend network proposal in [26].

The communication between the BS node and connected CHR nodes is described in the next section, which is important for understanding the appropriate handling of this communication when it comes to extending WiMAX services to DSRC connected SS nodes.

WiMAX communication details

As defined in the IEEE 802.16 specification [3], there are two main classes of communications: management messages and user data. The management messages are used to establish communications and update the link as circumstances change. The user data messages are used

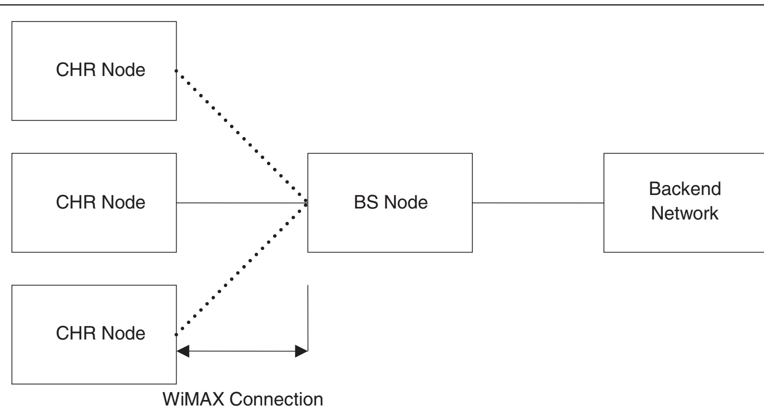

Figure 9 Overall BS node structure.

to transmit application layer data on behalf of the clients using the system. Within the context of the proposed system, this represents Layer 3 Network protocol [26] packets and Internet traffic. The IEEE 802.16j specification [5] adds another class of messages for traffic between the RS and the BS called relay messages. Relay messages allow an RS to group together traffic to and from the BS by SS nodes served by the RS, and transmit them using a single connection, represented by a connection identifier (CID), making more efficient use of the WiMAX bandwidth.

Both management and user data PDUs use a common MAC header. As defined in the IEEE 802.16 specification, this header is shown in Figure 10. The details on the different fields in this header are shown in Table 3. The different message types are identified by the CIDs used in the message. During the initial connection process, nodes will be assigned several CIDs. Some (the basic and primary management CID—PMCID) are used for management messages. RS nodes get assigned CIDs for tunnelling, while SS nodes will request CIDs for service flows. The details on management messages can be found in the IEEE 802.16 specifications [5]. The main purpose of management messages are to manage the user sessions on the WiMAX network. This includes tasks such as network entry, ranging (initial and periodic), bandwidth requests, and handover requests. Specific CIDs are assigned to each user within a WiMAX cell for management purposes. These include the assigned basic CID (BCID) and the assigned PMCID, as well as a default CID (usually 0) used during the original network entry. The structure of management messages is shown in Figure 11. Some of the management messages used heavily during a typical WiMAX session (and in the proposed system) include the ones listed in Table 4.

User data messages are transmitted across the WiMAX system in structures known as service data units (SDUs). This data come from applications operating at a higher protocol level, such as network layer traffic. The Layer 3 Tunnelling Protocol frame is an example of this kind of traffic. Frames containing SDUs are structured like the one in Figure 12. User data are transmitted across service flows. IEEE 802.16 defines these as “a MAC transport service that provides unidirectional transport of packets either to uplink packets transmitted by the SS or to downlink packets transmitted by the BS”. During the connection establishment process with the BS node, the SS node will be assigned a Service Flow CID associated with this service flow. This flow will be linked to a network service and both the SS and the BS nodes will forward it properly. In the case of the proposed system, the SS and BS nodes will transmit data from the upper layer network protocol using this service flow. The BS node will forward these SDUs on to the IAG for processing. The SS node will forward service flow traffic to the upper layer process, which will be responsible for providing Internet access for user applications. This process will be described in more detail in Section “Simulation results”.

LSB

<table>
<tr><td>HT
(1)</td><td>EC
(1)</td><td>Type
(6)</td><td>ESF
(1)</td><td>CI
(1)</td><td>EKS
(2)</td><td>Rsv
(1)</td><td>LEN
(MSB)
(3)</td></tr>
<tr><td colspan="3">LEN (LSB)
(8)</td><td colspan="5">CID (MSB)
(8)</td></tr>
<tr><td colspan="3">CID (LSB)
(8)</td><td colspan="5">HCS
(8)</td></tr>
</table>

Figure 10 Generic WiMAX MAC header.

Table 3 Generic MAC header fields

Name	Length (bits)	Description
CI	1	CRC Indicator
		1 = CRC is appended to the end of the PDU
		0 = No CRC is used
CID	16	CID
EC	1	Encryption Control
		1 = Payload is encrypted
		0 = Payload is not encrypted
EKS	2	Encryption key sequence
ESF	1	Extended subheader
		1 = Using extended subheader
		0 = Extended subheader absent
HCS	8	Header check sequence
HT	1	Header type (use 0 for generic header)
		1 = Bandwidth request header
		0 = Generic MAC header
LEN	11	Length
		Length of the MAC PDU in bytes (including header and CRC, if used)
Rsv	1	Reserved for future use. Set to 0
Type	6	Flags to indicate the type of payload attached

Relay frames are special frames defined in the IEEE 802.16j amendment. They allow an RS to group protocol data units (PDUs), which are WiMAX frames in this context, from multiple users into a single connection between the RS and the BS. This reduces the number of active connections in the system, which in turn lowers the system overhead produced by controlling the individual connections. Likewise, the BS will group PDUs destined for users served by the RS into this single connection. According to the 16j specification, the relay frames take the format of Figure 13. The relay header itself is shown in Figure 14. The fields in the WiMAX Relay Header are described in more detail in Table 5.

LSB

Generic MAC Header	Management Message Type	Management Message Payload	CRC (If Used)
(See Figure 10)	(1 byte)	(Variable Size)	(4 bytes)

Figure 11 WiMAX management message format.

The virtual WiMAX link is a key component to the proposed system. The system allows out-of-band relaying of a WiMAX signal across another technology, in this case DSRC link, which is more appropriate technology for vehicles. The virtual WiMAX link will attempt to implement as much of the WiMAX protocol as possible. This allows SS nodes to function as full members of the WiMAX network. The virtual WiMAX frames follow the WiMAX frame structure as closely as possible. Communications between the BS and CHR nodes will consist of WiMAX packets encapsulated within the underlying protocol, as shown in Figure 15.

In the proposed system, we assume that the clusters are successfully formed and that the cluster members know which node is the cluster head and can communicate with them. The nodes communicate using TCP/IP, where all nodes in the system have an IP address. The allocation of the addresses is done by the underlying DSRC protocol. SS nodes are aware of the IP address of the serving CHR node. The CHR node offers a WiMAX service at a known port. When an SS node wants to communicate with the WiMAX network, it will connect to the service on the CHR node. Once this TCP/IP connection is established, WiMAX messages in the packet structure form described in the next subsection are sent across the connection.

Connection differences with WiMAX

The WiMAX over DSRC system attempts to replicate the WiMAX system as close as possible for the sake of compatibility. However, due to differences in network topology, a few minor changes have to be made. During a network entry using a standard WiMAX channel, system configuration parameters (such as the Base Station ID) are obtained by passively listening to the channel and reading the Frame Control Header (FCH). Since the point-to-point nature of WiMAX over DSRC precludes this, a new WiMAX command called SYNC is created to provide system configuration information. Using a management message of type 255, a SYNC message provides the BSID of the CHR node and the WiMAX over DSRC protocol version. This message is sent from the CHR node to the SS automatically upon establishment of a connection. The message has the structure seen in Figure 16, with the fields described in more detail in Table 6.

The WiMAX over DSRC system uses an abbreviated ranging process, as physical ranging is handled by the underlying DSRC layer. The ranging command is only used once and the reply is used to supply all the important information supplied in a WiMAX ranging session, including the basic and PMCIDs. Finally, no bandwidth allocation is used, and the WiMAX frames are transmitted as a series of messages across the underlying DSRC connection.

Architecture interoperation and behavior

In this section, we provide details regarding the interoperation and behavior of the components within SS, CHR, and BS nodes. The interconnections between

Table 4 WiMAX management message types

Message name	Type	Spec definition	Description
RNG-REQ	4	6.3.2.3.5	A message from an SS/RS node requesting ranging information
RNG-RSP	5	6.3.2.3.6	The reply from the BS/RS with ranging information and basic/PMCID parameters
REG-REQ	6	6.3.2.3.7	A request from an SS/RS node to finalize registration on the WiMAX network
REG-RSP	7	6.3.2.3.8	A reply from the BS node confirming or denying registration. Tunnel CIDs for RS nodes are provided at this point as well
PKM-REQ/PKM-RSP	9/10	6.3.2.3.9	Key sharing for authentication and securing of the connection
DSA-REQ	11	6.3.2.3.10	A request from an SS node to open a service flow with the BS node
DSA-RSP	12	6.3.2.3.11	The BS reply. If successful, includes the CID for the service flow
DSA-ACK	13	6.3.2.3.12	Acknowledgement by SS of the new service flow
MOB_BSHO-REQ	56	6.3.2.3.52	A request from the BS node to an SS node to initiate a handover process
MOB_MSHO-REQ	57	6.3.2.3.53	A request from the SS node to initiate a handover process
MOB_BSHO-RSP	58	6.3.2.3.54	A reply from the BS node confirming initiation of the handover process
MOB_HO-IND	59	6.3.2.3.55	Indication from the SS node that the handover process is complete

LSB

Generic MAC Header (See Figure 10)	Service Flow Data (Variable Size)	CRC (If Used) (4 bytes)

Figure 12 WiMAX user data message.

components are presented in unified modeling language (UML) deployment diagram format and are intended to show a high level view that can be referred to when implementing our proposed design. It is important to note that although we show the SS node and CHR node as being separate entities, they are in fact simply two different states of the same system. This is because the SS node can change to a CHR operating node and vice-versa. Also, there is potential for many active SS nodes and CHR nodes for each BS. The UML deployment diagram in Figure 17 uses the notation by the use of 1..* to indicate a one-to-many relationship between SS, CHR, and BS nodes. In this diagram, the operation mode is assumed to be SS nodes accessing WiMAX over DSRC through CHR nodes for accessing a WiMAX facilitated services through BS nodes. Components are drawn within the nodes, and important subcomponents appear inside of other components. Dashed line arrows are used to represent the flow of control information between components. Interestingly, because we are modeling a communication system, control information generally flows in the same direction as data because the information is stored in headers attached to the data. Relationships between the nodes are shown with a solid line, and the communication physical interface between the nodes is shown with the stereotypes <<DSRC>> for OFDM-based DSRC connection, <<WiMAX>> for OFDMA-based WiMAX connection, or <<Backend Connection>> for reliable backend data connection.

In Figure 17, the locations of various important components are documented showing their relationship between each other. The WiMAX network entry processes in the CHR node include registration, security, service provisioning, and ranging, which are the same operations from standard WiMAX network entry [3]. The virtual WiMAX tunnel processing is similar to multi-hop WiMAX amendment [5] except that the client side of the tunnel is connected to a DSRC transmitter/receiver instead of a WiMAX transmitter/receiver. The network entries over DSRC processes in the SS node are modified versions of the WiMAX network entry processes, and

Relay Header	User PDU #1	User PDU #2	…

Figure 13 WiMAX relay frame structure.

HT (1)	Rsv (1)	RMI (1)	Rsv (7)	Priority (3)	LEN (MSB) (3)
LEN (LSB) (8)			CID (MSB) (8)		
CID (LSB) (8)			HCS (8)		

Figure 14 WiMAX relay header.

are described in detail in the following section with accompanying UML diagrams. The interconnection between the two CHR and SS nodes operate over the DSRC interface, but the SS nodes look like multi-hop WiMAX nodes to the WiMAX BS node. Handover operations are very important to proper system operation, where the occurrence of handovers are influenced by the physical environment, relative positions of other nodes, and other factors as covered in Section "Handover process". The connectivity of each process/component is provided to illustrate interoperation of the components to aid in understanding of internal system structure. The role change processes in the SS and CHR nodes are used to transition the node's operation mode when a handover occurs, i.e., SS nodes changing its role to become a CHR node, or vice-versa. The next section begins the descriptions of the processes that are distinct in our system from Figure 17, with additional functional descriptions presented in UML diagrams.

Network entry process

The network entry process is important because it informs the BS node of which WiMAX connected nodes it is responsible for serving and receiving communication content. As mentioned earlier, network entry is the process of establishing connection between a BS and a

Table 5 WiMAX relay header fields

Name	Length (bits)	Description
RMI	1	Relay mode indication
		1 = Use relay MAC header
		0 = Use GMH
CID	16	CID
		Tunnel CID or BCID of the RS
Priority	3	Priority of the tunnelled MPDU
HCS	8	Header check sequence
HT	1	Header type (use 0 for relay header)
		1 = Bandwidth request header
		0 = Relay header
LEN	11	Length
		Length of the MAC PDU in bytes
Rsv		Reserved for future use. Set to 0
Type	6	Flags to indicate the type of payload attached

LSB

DSRC MAC Header	TCP/IP Headers (If Used)	Encapsulated WiMAX Packet	
		WiMAX MAC Header	Message Body

Figure 15 Virtual WiMAX frame structure.

WiMAX node, which consists of Registration (REG), Ranging (RNG), Get Link Information, Provisioning of Service Flow, and Private Key Management (PKM). In respect to our proposed system, the network entry over DSRC must still perform these same operations to be able to communicate with a BS node, but must do so using the CHR node as a man-in-the middle for connection tunnelling. In Figure 17, we saw how the processes interacted in the actual deployment, but it is also important to see the direct relationship between the processes that are similar to each other because the DSRC network entry processes are cousins to their WiMAX only version.

The use case diagram of Figure 18 shows the relationship between the standard network entries that a node would use when communicating directly with a BS, and a network entry that would be performed by an SS over a DSRC connection with a CHR node. It is clear that the network entry over DSRC is directly a tunnelled version of the WiMAX network entry. The following section goes into detail of the network entry over DSRC processes with full description, and importantly highlights the differences between the tunnelled and non-tunnelled versions. Before getting into full detail, the general network entry operations for CHR to BS, and SS to CHR to BS network entries, over both WiMAX and DSRC are presented.

Establishing CHR-BS connection over WiMAX PHY

The connection handshake process follows the process laid out in IEEE 802.16j. This process authenticates CHR nodes with the WiMAX network and sets them up to accept connections with SS nodes, which will be tunnelled and processed by the network. The entry process is shown in Figure 19 in the form of a sequence diagram, and the important operations of network entry are described in subsequent paragraphs. The BS node maintains a routing table of active connections within the WIMAX cell. This includes SS and CHR nodes connected directly through the WIMAX interface, as well as

LSB

Generic MAC Header (See Figure 10)	**0xFF** (Message Type for SYNC)	**System Version** (2-4 bytes – TBD)	**BSID** (4 bytes)

Figure 16 Virtual WiMAX frame structure.

Table 6 SYNC management message fields

Field	Description
Version	The protocol version of the "Virtual WiMAX" system. This ensures that the client software is compatible with the protocol used by the RS node
BSID	The base station ID of the RS node. Used for the network entry messages, etc.

SS nodes connected indirectly through CHR nodes registered with the BS. Each entry stores the current status of the connection and encryption information for secure communication.

Figure 19 presents the network entry sequence diagram which contains the required procedures as shown in Figure 17 for connecting a CHR node to a BS over WiMAX. The BS nodes use Get Link Information operation, which includes broadcast of its BSID. This operation is the traditional method of entry for WIMAX nodes over an S-OFDMA air interface. This process is used to passively retrieve channel parameters about the WiMAX cell. The CHR node scans to find the closest BS node. It then synchronizes with the WiMAX frames and listens for the channel MAPs and channel descriptors. The BSID of the BS is determined and it indicates the appropriate location within the frame to send the initial registration message. CHR nodes can issue a Range (RNG) request (REQ), for determining signal quality between the BSIDs in its region. The ranging process is the first communications between the CHR node and the BS node it is registering with. This process is conducted according to the normal access process specified in IEEE 802.16 and IEEE 802.16j. One of the parameters transmitted with the "RNG REQ" message is the CHR's MAC address. It is in this process that the concept of the CHR node having two MAC addresses becomes important. This is useful because the CHR node can tunnel its own traffic through the same connection as the SS traffic it is tunnelling through to the BS station. The response of the BS node to the RNG REQ is a range response (RNG RSP). After this response, security keys are exchanged using PKM. The "PKM" process performs the initial authentication of the BS node using public keys. It also establishes the session keys for encrypted communications between the CHR and BS nodes. This will be used by the CHR node to secure communications of tunnelled information. Afterwards, registration request (REG REQ) by the CHR node, and registration response (REQ RSP) by the BS node take place. This is the final step in the network entry for the CHR node. At some stage, it was determined that the node is a CHR. The BS node provisions three values required for the CHR role at this stage. The first is a valid BSID to be used by the gateway for accepting clients. This is the effective "BS" that each client will

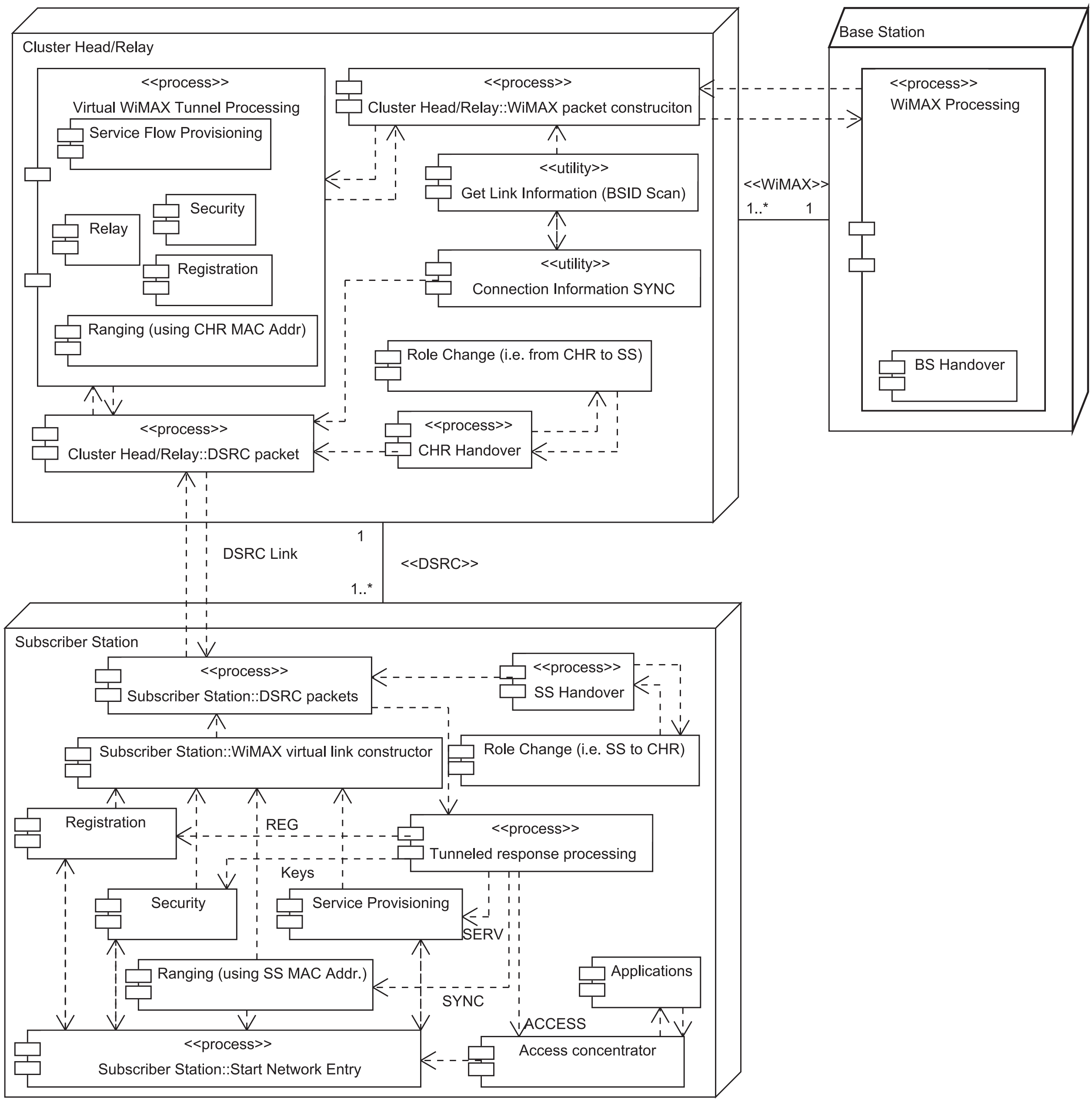

Figure 17 Deployment diagram.

be using, even though all traffic is ultimately forwarded by the CHR to the BS node responsible for controlling a cell. This BSID is unique within the WiMAX system. The other two values are the management tunnel connection identifier (MT-CID) and tunnel CID (T-CID). These values are specified by IEEE 802.16j to provide the functionality for tunnelling of SS traffic data between the CHR and BS nodes. These CIDs will indicate to the BS that encapsulated traffic is being transmitted (as opposed to management messages between the BS and CHR nodes). At the completion of the handshaking process, the CHR node has been assigned a number of parameters. From the initial ranging, it has a BCID and PMCID number. After the network registration, it is also assigned a BSID value, as well as the tunnel and management tunnel CIDs.

Establishing SS-CHR-BS connection over DSRC and WiMAX PHY

This section details how an SS node enters the WiMAX network across a DSRC connection and using a CHR node as its network entry point. This process is shown

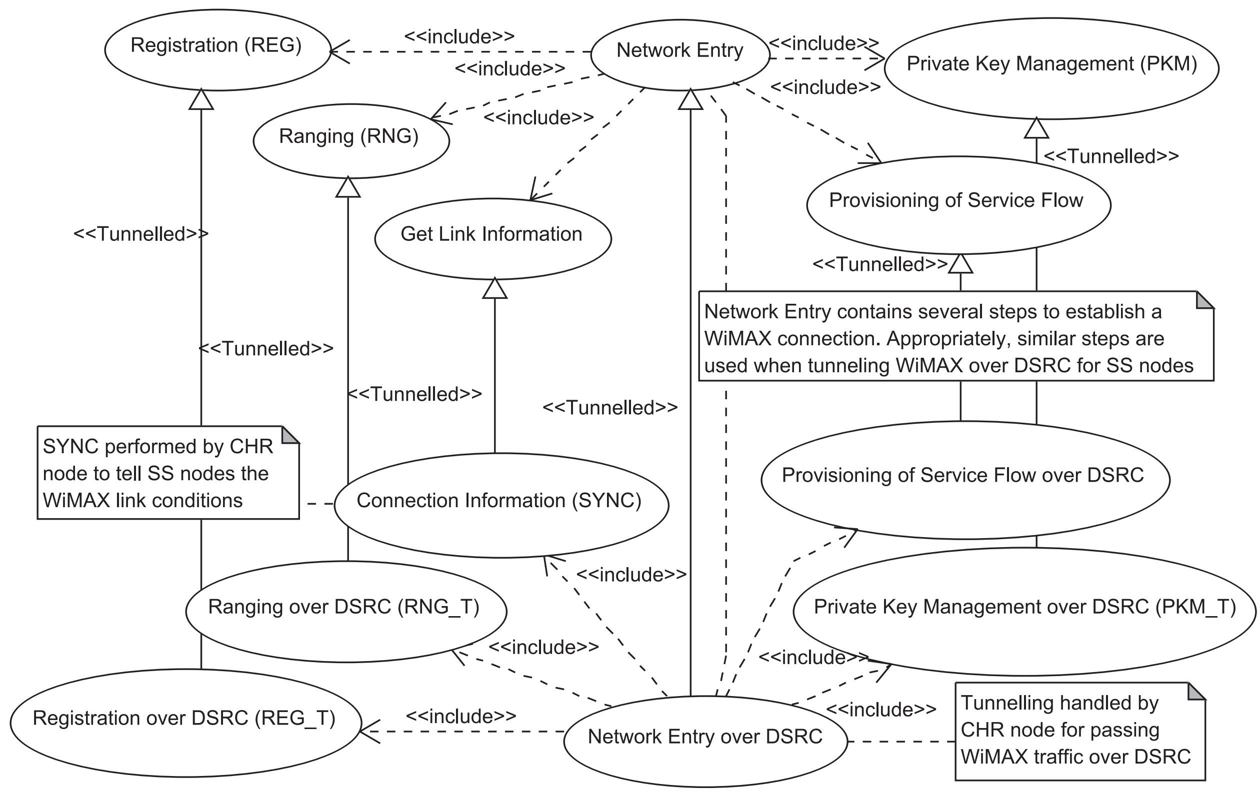

Figure 18 **Network entry use case diagram.**

in Figure 20 in the form of a sequence diagram, and the important operations for WiMAX network entry over DSRC are described in subsequent paragraphs. This is based on the client network entry process described in IEEE 802.16j [5]. The CHR node maintains a forwarding table to track the connections across the WiMAX/DSRC gateway interface. This enables the CHR node to properly route traffic as it crosses through the gateway interface, as well as tracking the status of the connections. The BS node maintains a table of all SS connections in the system, including the CHR node currently serving each one. The virtual WiMAX connection uses a substitute message SYNC to obtain initial connection information from the CHR node. This message is sent upon initial connection between the SS node and the CHR service on the CHR node. A new entry in the CHR routing table is also created. Upon initial connection, this connection is empty (other than perhaps physically connection information, version number, physical address, etc.).

Next, ranging over DSRC operation is conducted. This process is similar to the ranging process described in IEEE 802.16j, except the information is not being transmitted across a physical WIMAX link, and message fields such as power control can be ignored. This difference effectively shortens the ranging process, which normally requires several iterations across a WiMAX physical layer. In the ranging request message, the SS prepares a WIMAX control packet with a CID of 0. Within the RNG request, a random ranging code is selected. Other information transmitted includes the WIMAX MAC address of the SS node. This is the MAC address of the WIMAX radio, which is not being used for the DSRC communications but will be used if the node later directly connects with the BS node. When this packet is received at the CHR, it is recognized as a ranging packet by the CID of 0 (as well as the command message packet header). The CHR updates the routing table entry with the ranging code, and then forwards it along in a tunnelled connection. The packet is received at the BS and is processed like any SS entering the system, as defined in the IEEE 802.16j specification. As the packet is forwarded, message fields such as power settings are once again ignored. The BS provisions a B-CID and PM-CID and creates a new entry for the SS in its internal routing table, as is the assigned CHR for that node. The reply message (RNG RSP) is sent back across the management tunnel to the CHR. When the reply is received at the CHR, the entry is looked up in the routing table by the ranging code value. The ranging code

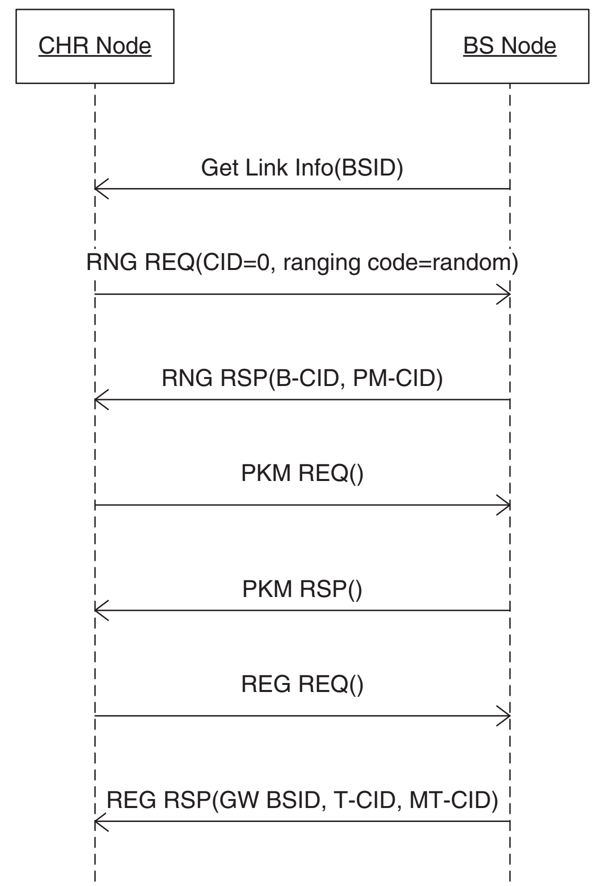

Figure 19 CHR network entry sequence diagram.

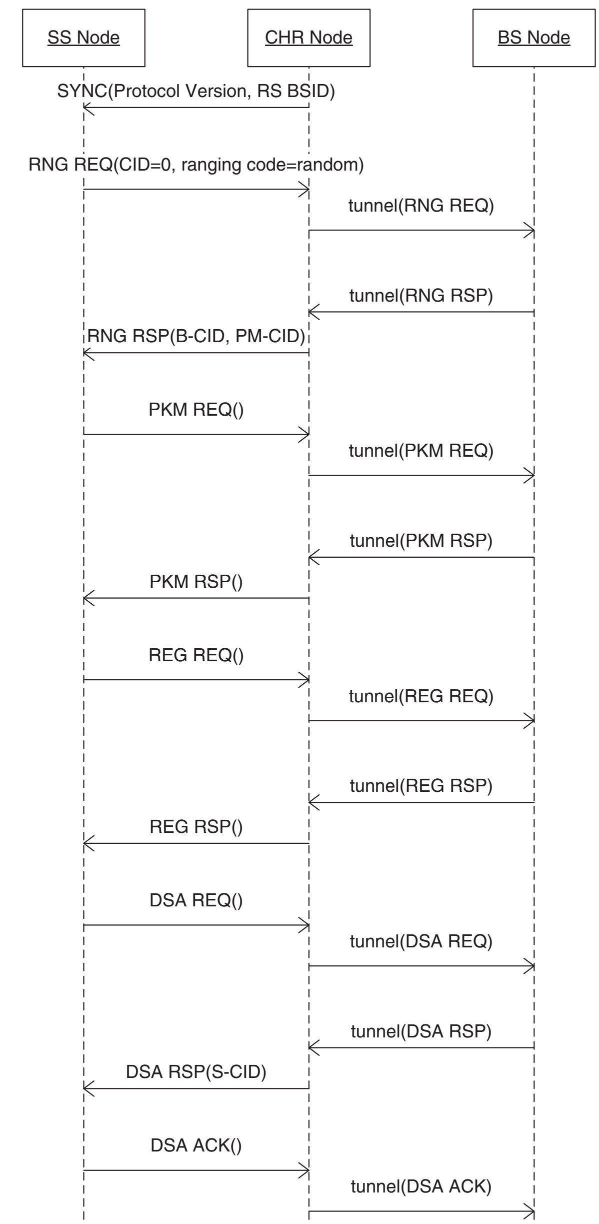

Figure 20 SS network entry.

value is removed and replaced with the B-CID and PM-CID values in the ranging reply. The message is then forwarded along to the SS node. The message is finally received back at the SS node. The B-CID and PM-CIDs are used for further communications.

This stage ensures that the SS node is authorized to use the system. It involves a security key exchange between the SS and BS node. If the authentication is accepted, the BS node replies back with an authentication reply message. This includes the session key, sequence number, and timer information, encoded in the SS's public key. Encryption is important because data traffic from SS nodes is tunnelled through CHR nodes, which may contain sensitive information. After being authenticated, the node registers on the WiMAX network using the REG commands by tunnelling a REG REQ through its CHR node to the BS. The CHR node relays the REG RSP to the SS node over DSRC. This finishes the initial handshake process. At this point, the node is ready to send and receive traffic across the WiMAX network.

Once the system is registered, it needs to obtain a service flow for transporting the higher level network data. There are two methods that this can be accomplished with WiMAX. WiMAX systems can support "managed connections", where IP support is intrinsic to the connection. This IP configuration is not optimized for mobility, where users will get a new IP upon handing over, and existing IP connections are broken. The other option is to provide unmanaged connections. From an Internet access perspective, this unmanaged connection can be made to resemble a simple serial-like link layer. The service flow is provisioned using the dynamic service add (DSA) series of commands. These specify the QoS/service parameters describing the Internet access link service requested. After the DSA handshake is complete, the node will be assigned a service CID (S-CID), which is then ready for use for Internet access. Upon receipt of the DSA RSP message (with the assigned CID), the CHR node will update its routing table with the S-CID value. It also updates the status of the connection to indicate that the SS node is registered and ready to handle user traffic. At this point, communications between the individual SS nodes and the BS node through the CHR node has been established. Now that the methodology of establishing a connection has been described, we can now go into detail on how to maintain that connection in the vehicular ad hoc network scenario.

Handover process

The handover process is an important part of the WiMAX over DSRC system because it must be handled properly in order to achieve reliable and robust connections across the two mediums. There are four types of handovers that can occur in our proposed architecture as shown in Figure 21, namely the standard WiMAX BS-BS handovers, CHR-BS handovers, CHR-CHR handovers, and BS-CHR handovers. The relationship between SS, CHR, and BS nodes in relation to the handovers are shown in the use case diagram Figure 21.

Due to the mobile nature of the proposed architecture, mobile nodes cannot remain connected to the same node for services. Figure 21 shows the use case diagram for achieving the four types of handovers encountered in our proposed architecture with respect to maintaining WiMAX connectivity. Handovers occur when a node leaves one service area and enters into another. When going through a handover, the node has to connect and authenticate with the new service area and then transfer its session from the old one. In the context of the described system, there are several kinds of handovers that will occur. These are divided up into SS node handovers and CHR node handovers. CHR node handovers are somewhat more complicated, as it involves the indirect handover of several different connections at the same time. The SS is subject to three handover conditions. The first is moving from one DSRC cluster to another (CHR–CHR). The other two involve entering a cluster mode (BS-CHR) or exiting cluster mode (CHR-BS). Finally, the CHR and BS nodes will experience a handover condition when a mobile CHR node hands over from one BS node to another (BS–BS). More specific detail regarding the network entry processes involved in the handovers are shown in the expanded use case diagram in Figure 22. This diagram is a more detailed form of Figure 21, with

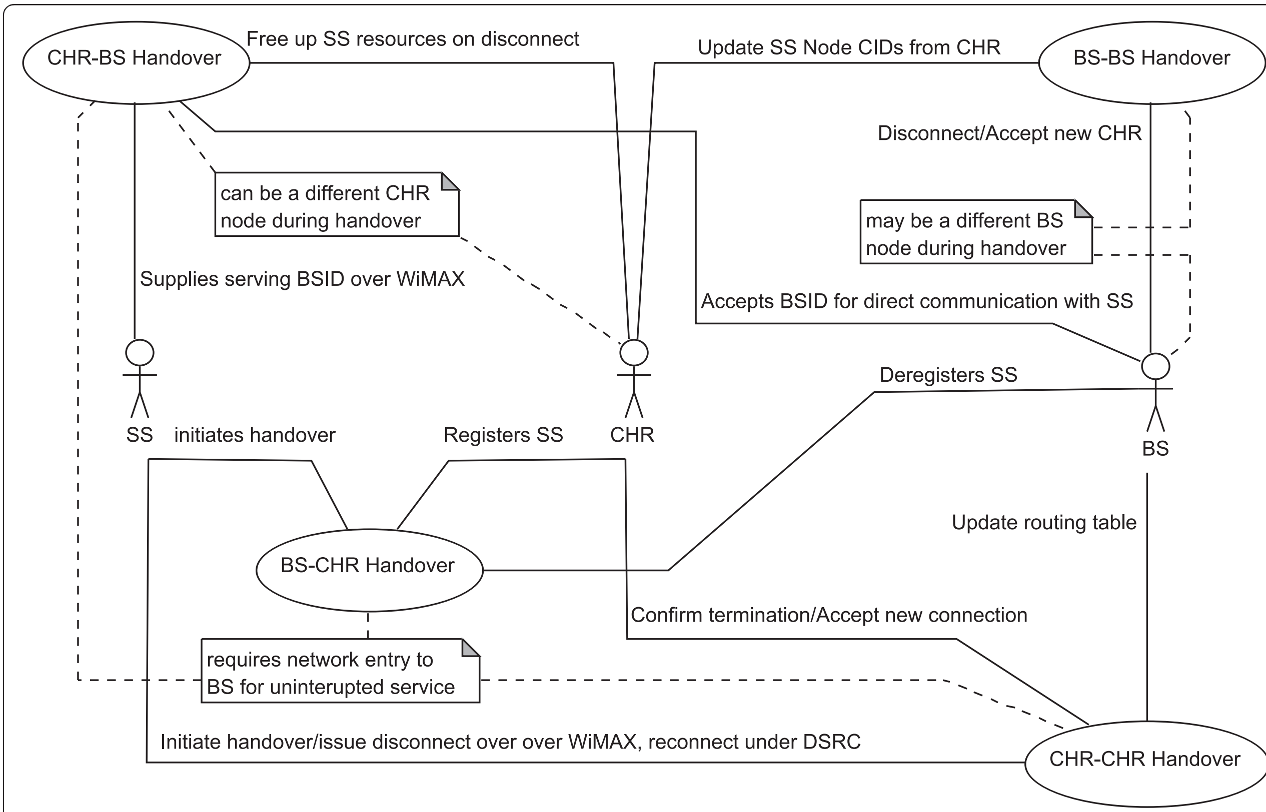

Figure 21 Handover use case diagram.

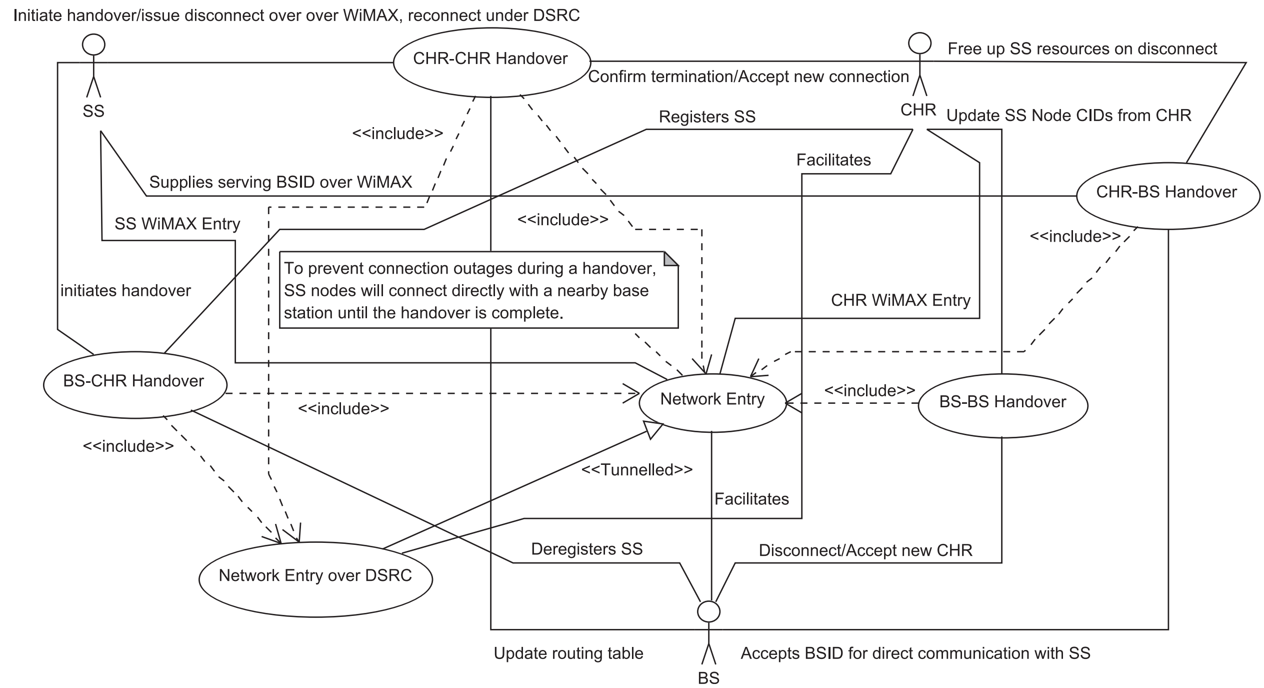

Figure 22 Detailed handover use case diagram.

the DSRC and WiMAX network entry included as required for each respective handover.

As can be seen, CHR-BS handover and BS–BS handover only require a WiMAX connection to perform the handover operation, while CHR–CHR and BS-CHR handovers require both WiMAX and DSRC connections to transition between each other. In all cases, we are assuming that cross-layer information is not available (i.e., the system is not aware of an impending handover situation), which will result in an abrupt termination of connections. The nodes will perform the appropriate handover process depending on its situation and environment. Detailed descriptions follow in the next sections for the four handovers, namely the CHR–CHR, BS-CHR, CHR-BS, and BS–BS handovers.

SS performing a CHR–CHR handover

This handover occurs when a node leaves one DSRC cluster and enters another. This can be a vehicle going faster or slower than the cluster head, or a new node is elected as the cluster head. Section 6.3.21.2 of the IEEE 802.16 standard discusses the way standard Mobile WiMAX performs a handover. This begins with an SS node issuing a MOB_BSHO-REQ command to alert the current BS node that it is leaving. In the DSRC link, this is not possible due to the assumption of no cross-layer information, and instead the link termination will be abrupt. On the other hand, the termination of the underlying link between the SS and CHR node will provide confirmation that the connection is terminated. When CHR–CHR handover occurs, the underlying connection between the SS and the CHR will be broken. Both nodes will be aware of the connection being terminated. Both nodes will go into a handover state and will start a timer. If the handover does not occur in a timely manner, the connection will be terminated. All connections will be terminated and all system resources (such as CIDs) will be returned to the pool for reallocation. When the SS node connects to the new CHR, it will go through the network entry process from the previous section. The difference is that the node supplies a “serving BSID” value in its RNG REQ message. This alerts the new CHR node that the SS node is handing over from another RS. This information is forwarded along to the serving BS node. If the serving BS node is the same (one CHR to another within the same BS cell), the information is updated in the BS’s routing tables. If the node is changing serving BS nodes, the new BS node will obtain session information from the old BS node, as the CHR node’s BSID is unique and routable to a specific BS node.

SS performing BS-CHR handover

There are two special cases in the client handover—a client that is directly connected to the BS joining the DSRC cluster system, and a client leaving the clustered system for a direct WiMAX connection. In realistic terms, this could represent a client entering or leaving the freeway or a major road for a less populated side road. When a node is entering a DSRC system, it performs the handover as described in Section 6.3.21.4 of the IEEE 802.16j proposal. However, instead of performing a full scan, it begins the connection with the CHR node while maintaining a connection with the BS node using the WiMAX radio. Once the connection with the CHR node is complete, it finishes the handover and terminates the direct WiMAX connection with the BS node.

SS performing CHR-BS handover

This handover occurs when the SS node leaves a cluster situation and starts direct communication with the BS. Similar to a CHR–CHR handover, this will likely be abrupt, giving the node no time to prepare for the handover. Much like a CHR–CHR handover, the node starts by establishing a connection with the BS node across the WiMAX interface using the network entry process described in Section 6.3.9 of the IEEE 802.16 specification. Similar to the CHR–CHR handover, the SS node supplies a "serving BSID" value in its RNG REQ. This allows the BS node to carry over the session and continue any established sessions uninterrupted.

CHR performing a BS–BS handover

As the CHR node itself is going to be mobile, it will also be subject to frequent handovers. This is probably the most frequent handover that will be seen in the proposed system. The mobile RS handover process is described in Section 6.3.21.4 of the IEEE 802.16j draft standard. The CIDs for the SS nodes will be updated according to the MS CID process which informs the new BS of its new CHR node(s) and accompanying SS nodes. Hence in our proposal, the CHR node swaps the CIDs of the SS nodes for new CIDs, and then forwards the MAC information over to the SS nodes over DSRC.

In summary, the goal of the system was to provide a similar experience to WiMAX (long range, managed latency, high bandwidth), while solving the efficiency issue when there are a high number of simultaneous connections. By utilizing DSRC over WiMAX, handovers are performed within the WiMAX system as simply a relay-to-relay or relay-to-BS handover, with CHR nodes functioning as IEEE 802.16j relay nodes. As the WiMAX connection does not have to be re-established, the complexity is going to be minimized and compatibility with the WiMAX system is maximized. DSRC-based ad hoc routing is notorious for wildly variable latency, as the connection paths are constantly changing and it's hard to fix the routing length. By using WiMAX as the backhaul technology, as compared to just DSRC and ad hoc routing, the number of hops (and latency) will be better controlled, while still benefiting from the increased capacity resulting from concatenated connections. The wide coverage area of WiMAX also ensures better reliability of service from a purely ad hoc system. This system has been demonstrated as a high-level prototype; hence, we presented the use cases listing the detailed steps/layout of the complete link layer infrastructure. The actual performance measurements will be confirmed once vehicle testing with real-world scenarios is started.

Simulation results

Since the proposed DSRC/WiMAX system has never been tested as one whole integrated system, the simulation section presented in this article is to demonstrate that it does in fact improve both efficiency and throughput relative to that of the current WiMAX-only system in use today. Another important use of these results will be as a benchmark for the building of the actual prototype. Using the mathematical model we presented in Section "Proposed combined WiMAX/DSRC system", we were able to test different configurations of the system, including the number of active connections, the ratio of uplink symbols to downlink symbols and the modulation and coding used for the data being sent. The simulation results of Figures 23, 24, 25, and Table 7 demonstrate the "System Efficiency by Cluster Size", "WiMAX Effeciency Improvement with DSRC Clustering Integration", "Proposed System's Percentage Throughput Improvement", and "System Throughput Per User", respectively. To evaluate the benefits of our proposed system, we use MATLAB to simulate our model with different cluster sizes and parameter values shown in Table 8. These values are taken from the Mobile WiMAX standard, presented in Tables 1 and 2. The number of clusters range from 1 to 70 clusters. The frame duration, T_{frame}, is 5 ms, while the symbol duration, T_{symbol}, is 102.9 μs. The data carriers per channel, N_{sc}, is 48. The total symbols dedicated to downlink and uplink, $N_{\text{DL Symbols}}$ and $N_{\text{UL Symbols}}$, and data subcarriers in the downlink and uplink, $N_{\text{DL SC}}$ and $N_{\text{UL SC}}$, and the data carriers/symbol, N_{SD}, are obtained for WiMAX channel bandwidth of 10 MHz.

Figure 23 shows the effect of clustering on system efficiency with various levels of loading. Regardless of the amount of active users, the system showed an improvement with an introduction of clustering. However, the greatest improvement with clustering is shown with the heavily loaded systems (ones with higher numbers of active nodes).

Figure 24 shows the proposed system's percentage improvement in efficiency over the current WiMAX system for varying amount of active users. We have tested the efficiency using the parameters shown in Table 8; however, the efficiency results did not present a difference with different coding rate and modulation scheme, so we show the results for $R_c = 1/2$ and for

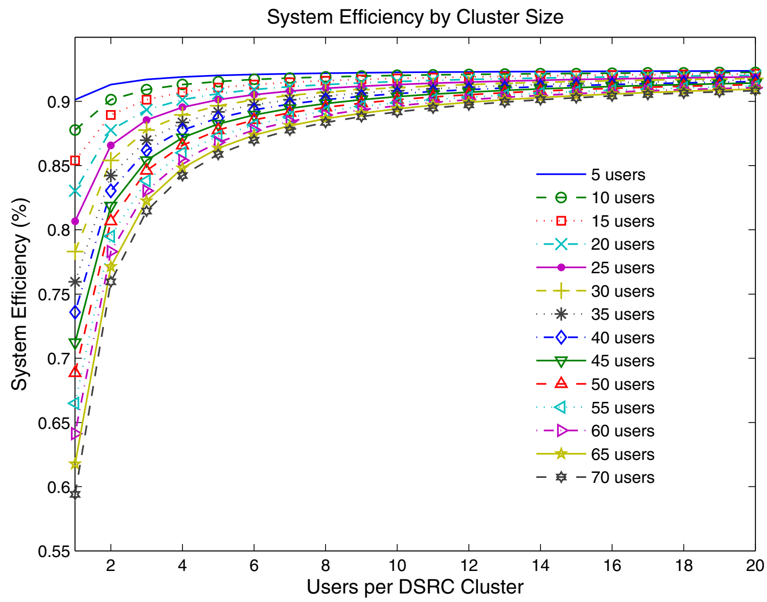

Figure 23 **System efficiency by cluster size.**

QPSK modulation scheme. The greatest improvement is seen with introducing clusters of 2 to 4-users per cluster, and eventually converges to a constant gain. The main reason lies in the explanation discussed in Section "Proposed combined WiMAX/DSRC system" about the overhead problem found in the frame structure of WiMAX (shown in Figure 1). With this overhead problem, as we increase the number of connections, the WiMAX-only system decreases in efficiency. This is also confirmed in Figure 23 simulation result. It is observed from Figure 24 that the proposed system yields a significant improvement in overall system efficiency.

More specifically, Figure 24 shows what will be the projected improvement when DSRC link is used with clustering for out-of-band relaying compared to WiMAX-only links used by nodes. For example, on the horizontal comparison, where the number of users in a cluster is not fixed but with the total number of users being fixed, and if we look at 60 active users scenario and look at two example users per cluster scenarios; 5

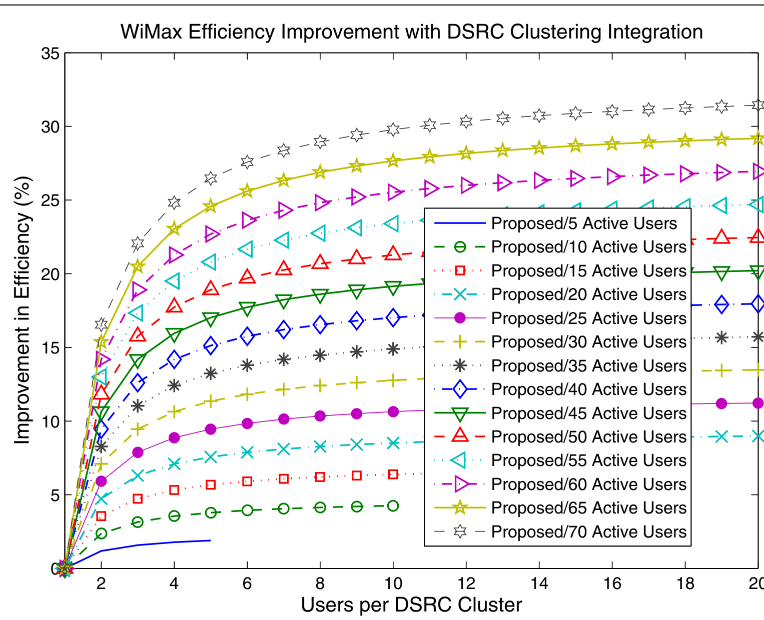

Figure 24 **WiMAX efficiency improvement with clustering.**

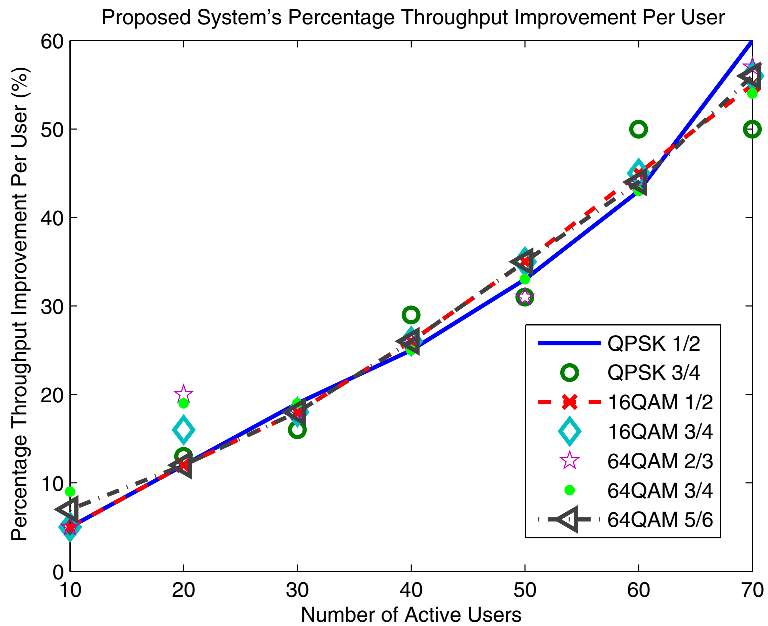

Figure 25 System throughput per user.

users per cluster in this scenario (12 clusters of 5 users each) improves the efficiency by 23%, whereas 10 users per cluster (6 clusters of 10 users each) provides an efficiency increase of around 25% over WiMAX-only system. This concludes that for any given active users, having more users per cluster improves the system efficiency, again for the same overhead problem reason that exists in WiMAX-only system with an increased number of connections. A problem not found in the proposed system.

On the vertical comparison of the same figure, namely when we fix the number of users per cluster, the scenarios that have more active users in the system yield the better performance. For example, if there are 70 active users in the system with 10 users per cluster, our proposed system exhibits an improvement of around 30% in efficiency relative to the same amount of active users for WiMAX-only system; whereas for 30 active users, an improvement of around 14% is observed. This is due to the same reason, i.e., as the number of users is increased, the more the overhead problem is evident, which in turn the use of the proposed WiMAX/DSRC integration result in the most efficiency improvement.

Table 7 contains the parameters used to obtain the throughput results for WiMAX-only and our proposed WiMAX/DSRC clustered network systems *per user*, as well as the percentage throughput improvement of our proposed system relative to that of WiMAX. The channel bandwidth is 10 MHz, hence the number of data subcarriers in the downlink and uplink, $N_{\mathrm{DL\ SC}}$ and $N_{\mathrm{UL\ SC}}$ will be 30 and 35, respectively. The total symbols dedicated to the downlink and uplink, $N_{\mathrm{DL\ Symbols}}$ and $N_{\mathrm{UL\ Symbols}}$, is 35 and 12, respectively. We have shown in Figure 3 that this ratio outperforms the remaining downlink to uplink ratios. The frame duration, T_{frame}, is 5 ms. The data carriers per channel, N_{sc}, is 48.

Table 7 System throughput per user

Modulation and coding rate	Number of bidirectional active connections n_c	WiMAX throughput (Mbps)	Proposed system throughput (Mbps)	Percentage throughput improvement (%)
QPSK 1/2	[10 20 30 40 50 60 70]	[0.55 0.26 0.16 0.120.09 0.07 0.05]	[0.58 0.29 0.19 0.15 0.12 0.10 0.08]	[5 12 19 25 33 43 60]
QPSK 3/4	[10 20 30 40 50 60 70]	[0.83 0.39 0.25 0.17 0.13 0.1 0.08]	[0.87 0.44 0.29 0.22 0.17 0.15 0.12]	[5 13 16 29 31 50 50]
16-QAM 1/2	[10 20 30 40 50 60 70]	[1.1 0.52 0.33 0.23 0.17 0.13 0.11]	[1.16 0.58 0.39 0.29 0.23 0.19 0.17]	[5 12 18 26 35 46 55]
16-QAM 3/4	[10 20 30 40 50 60 70]	[1.66 0.78 0.49 0.35 0.26 0.20 0.16]	[1.75 0.87 0.58 0.44 0.35 0.29 0.25]	[5 16 18 26 35 45 56]
64-QAM 2/3	[10 20 30 40 50 60 70]	[2.2 1.0 0.65 0.46 0.35 0.27 0.21]	[2.3 1.2 0.77 0.58 0.46 0.39 0.33]	[5 20 18 26 31 44 57]
64-QAM 3/4	[10 20 30 40 50 60 70]	[2.4 1.10 0.73 0.52 0.39 0.30 0.24]	[2.62 1.31 0.87 0.65 0.52 0.43 0.37]	[9 19 19 25 33 43 54]
64-QAM 5/6	[10 20 30 40 50 60 70]	[2.70 1.30 0.82 0.580.43 0.34 0.27]	[2.90 1.46 0.97 0.73 0.58 0.49 0.42]	[7 12 18 26 35 44 56]

Table 8 Simulation parameters

Coding rate Rc	Modulation schemes (bits) $\log_2 M$	Channel block size (bits) (BpS_m)	Number of bidirectional active connections n_c	Total symbols dedicated to downlink and uplink $N_{DL\ Symbols}$: $N_{UL\ Symbols}$	Data subcarriers in downlink and uplink $N_{DL\ SC}$: $N_{UL\ SC}$	Data carriers/symbol (down/up) N_{SD}
1/2	2	48	[10 20 30 40 50 60 70]	35:12	30:35	720/560
3/4	2	72	[10 20 30 40 50 60 70]	35:12	30:35	720/560
1/2	4	96	[10 20 30 40 50 60 70]	35:12	30:35	720/560
3/4	4	144	[10 20 30 40 50 60 70]	35:12	30:35	720/560
2/3	6	192	[10 20 30 40 50 60 70]	35:12	30:35	720/560
3/4	6	216	[10 20 30 40 50 60 70]	35:12	30:35	720/560
5/6	6	240	[10 20 30 40 50 60 70]	35:12	30:35	720/560

It can be seen from Table 7 that the proposed system's throughput outperforms that of the WiMAX system in all cases. It is important to note that the throughput in Mbps is obtained for only one user. Hence, the total throughput for all users in the proposed system is more significant, which is desired in vehicular ad hoc systems. Additionally, Table 7 shows that as the number of active users increases, so does the throughput improvement per user for our proposed system relative to the WiMAX system. For a better visual, this percentage throughput improvement due to our proposed system is provided in Figure 25. It is noted that the proposed system has shown an increase of around 60% for the 70 active users' case. This improvement will become more significant as we increase the number of active users.

Conclusion

This article proposed a novel link layer infrastructure for vehicular ad hoc networks for the purpose of enabling WiMAX network service to a large number of vehicles using both WiMAX and DSRC networking. Having a large number of active WiMAX connections created a bottleneck in the system because of the amount of overhead associated with OFDMA reservation scheme. In order to more effectively address this problem in vehicular ad hoc networks, our proposed system using DSRC link relay by employing CHR nodes as mobile RSs to SS nodes allowed WiMAX to maintain its full bandwidth without subdivision. This article provided the complete link layer infrastructure details that are important in ensuring standard compliance with the two existing technologies, while illustrating the functionality of the combined system. Simulation results provided the performance of the proposed system, and have shown to achieve its goal of reducing the number of simultaneous WiMAX connections with an increase of overall throughput performance. An increase in WiMAX efficiency by over 30% was observed. The proposed system performed the best under high load scenarios where it reduced the number of connections the most, where individual users' throughput can be improved by more than 60%. A detailed handover mechanism is provided for the DSRC and WiMAX systems' transitions between each other; great consideration was taken into providing this seamless operation. In order to aid in design and understanding, we separated the traditional WiMAX network entry into two parts, namely the WiMAX network entry, and WiMAX network entry over DSRC, of which the differences were explained.

Quantifying the pseudo-linear nature of congested vehicular traffic and development of a CHR selection protocol, based on real-world traffic data will allow us to model the overhead introduced by cluster handovers under a variety of traffic conditions and determine the situations where clustering will be more efficient than flat network architecture, the appropriate cluster size, and determine which nodes should be included in clustering. Combination of other road data (such as destination information from an onboard GPS unit) could allow for even more efficient clustering. In addition to simulation, physical test beds will allow evaluation of the system under real-world conditions, and allow optimization of the combined WiMAX/DSRC system.

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