Mobility Support for IEEE 802.16d Wireless Networks

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Abstract – **The IEEE 802.16d standard (now called 802.16-2004) has been proposed to provide last-mile connectivity to fixed locations by radio links. Despite this original objective, we study in this paper whether mobility can be supported by the 802.16d network without any change in the specification. Mobility enhancements are considered in a later standard (IEEE 802.16e). However we expect that 802.16d devices will be widely deployed in the field before the 802.16e standard is finalized. Thus our proposed techniques can be useful regardless of the final acceptance of the new 802.16e standard. Mobility capability involves two main issues: connection handoff and correct reception for moving terminals. We find that seamless connection handoff can be achieved within the 802.16d standard by: 1) applying some of the existing functionalities defined for the terminal initialization process, 2) devising a set of protocols for message exchanges for handoff, and 3) forwarding some of the operational parameters from the current base station to a new one via the backhaul network, instead of over the radio link. As for reception at moving terminals, our analysis of bit error rate for the 802.16d OFDMA mode shows that under typical radio conditions, the 802.16d link can provide satisfactory error performance for terminal speed up to tens of kilometers per hour. As a result we show that the current 802.16d standard with our proposed technique can support user mobility.**

Keywords – **Bit error rate, connection handoff, IEEE 802.16d standard, mobility support, network protocol, performance analysis.**

I. INTRODUCTION

Wireless local-area-networks (WLAN) based on the IEEE 802.11 standards have been widely deployed and used in airports, offices and homes. Building on this success, the IEEE 802.16 standard [EMS02, KR02, FAF04] approved in 2001 specifies the air interface and medium-access-control (MAC) protocol for wireless metropolitan area networks (MANs). The idea there is to provide broadband wireless access to buildings through external antennas communicating with radio base stations (BSs). The wireless MAN thus offers an alternative to fiber optic link, cable modem, and digital subscriber loop. Using the new standard, home and business users can be connected via radio links directly to telecommunication networks and Internet.

To overcome the disadvantage of the line-of-sight requirement between transmitters and receivers in the 802.16 standard, the 802.16a standard was approved in 2003 to support non-line-of-sight links, operational in both licensed and unlicensed frequency bands from 2 to 11 GHz, and subsequently revised to create the 802.16d [I04a] standard. With such enhancements, the 802.16d standard has been viewed as a promising alternative for providing the last-mile connectivity by radio link. As a result, many large and small companies are actively developing and testing 802.16d products. However, the 802.16d specification was devised primarily for fixed wireless users. The 802.16e committee [I04b] was subsequently formed with the goal of extending the 802.16d standard to support mobile terminals. Based on its current progress, it is expected that the 802.16e standard will not be approved until 2005, so products based on the new standard will not be generally available on the market until a couple of years later.

The primary objective of this paper is as follows. Although the 802.16d standard is devised for fixed terminal locations, we explore whether the existing specification itself, *without any changes or modifications*, can be applied to support terminal mobility. Our results in this paper reveal that it is indeed possible for 802.16d without changes to support mobility. There are two aspects of the mobility support. First, the quality of service (QoS) requirements between a mobile terminal and its base station (BS) should be satisfied, while the terminal is moving within the coverage area of the BS. Secondly, when the terminal moves from one BS to the next, the network should be capable of handing off the connection from the original BS to the new one, with an objective of minimizing data loss and delay in the handoff process. Correspondingly, we establish the feasibility of mobility support for the 802.16d standard by: 1) devising a set of protocols for exchanges of signaling messages for connection handoff from a BS to a neighboring one, and 2) showing reasonable performance in terms of bit error rate under typical radio and user-mobility conditions.

Besides providing new insights into whether the existing 802.16d standard with its original intent to serve fixed locations can indeed support mobility, this work may also have significant commercial implications. First, the 802.16e equipment for mobile environments will not be widely available for at least a couple of years. On the other hand, the 802.16d products will become commonly available very soon (e.g., Intel has promised such with their “Rosedale” chip). Therefore, service providers could start to realize revenue right away by applying the techniques in this paper to support mobility using existing 802.16d standard. Furthermore, since 802.16d-enabled devices will be widely available soon, our proposed techniques can be applied to support mobility capabilities for the ‘legacy’ 802.16d devices, regardless of the final acceptance of the new 802.16e standard.

The rest of this paper is organized as follows. Section II discusses the objective of connection handoff, application of certain functionalities defined in the 802.16d standard for connection handoff, and handoff protocols. We also identify an existing message in the 802.16d standard that can be used to enable handoff. Then, we analyze and show in Section III the feasibility of the 802.16d physical layer for supporting hard handoff and mobility. Section IV concludes our paper.

II. PROTOCOLS FOR CONNECTION HANDOFF

A. *Handoff Objective and Mobility Management*

As the quality of an established radio link between a subscriber station (SS) (or terminal) and its BS deteriorates due to mobility, the objective of handing off the connection to a neighboring BS is to maintain the IP connectivity between the SS and the corresponding host. A major goal is to minimize packet loss and delay induced by the handoff process. Since the 802.16d standard defines only the physical (PHY) and MAC layers, without loss of generality, suppose that the network under study employs the hierarchical mobile IP (HMIP) algorithm [GJP02] for micro-mobility management. (Similar observations apply to other mobility management algorithms such as [CGK02] and [RVS02].) Using the common terminology for mobile networks, Figure 1 shows the architecture of the HMIP for the 802.16 network under consideration. Specifically, one router is designated the Primary Foreign Agent (PFA) and serves as the “anchor point” for each SS (or connection). That is, data from and to a given SS always goes through the corresponding PFA. In addition, the PFA also keeps track of the operational parameters for the 802.16d connections associated with the SS. As shown in the figure, the communication path consists of multiple IP tunnels and packets are forwarded by tunneling.

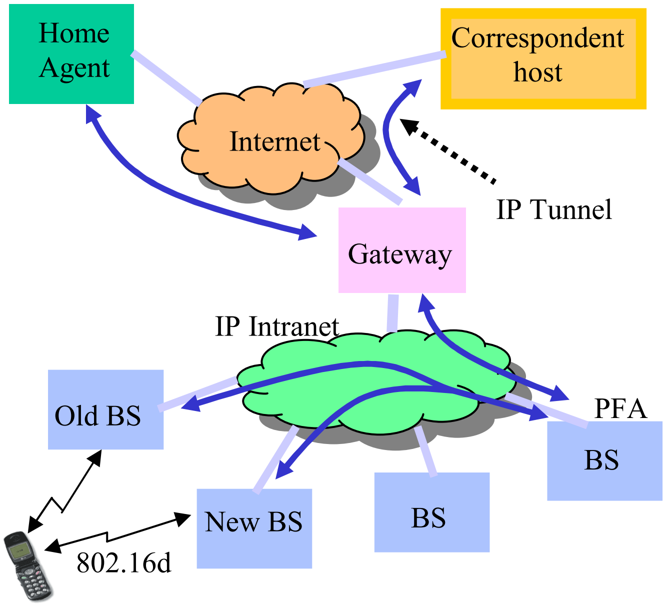


Figure 1. Hierarchical Mobile IP for 802.16d Network

B. *Initialization Process*

Since our objective is to support mobility without standard change, we have to use the features and protocols defined in the existing 802.16d standard. We observe that in the most basic sense, handoff is to tear down the existing connection with the current BS and to set up a new connection with a neighboring BS with better link quality. Let us ignore the delay in setting up the new connection *for a moment*. The key functionalities for handoff are quite similar to the initialization process of a SS when registering with a BS upon power up. This is the starting point of our approach. Namely, we attempt to re-use some of the functionalities of the initialization process defined in the 802.16d standard to assist connection handoff. Toward this goal, it is instructional to first review the initialization process. Then, we identify a set of required functionalities for connection handoff.

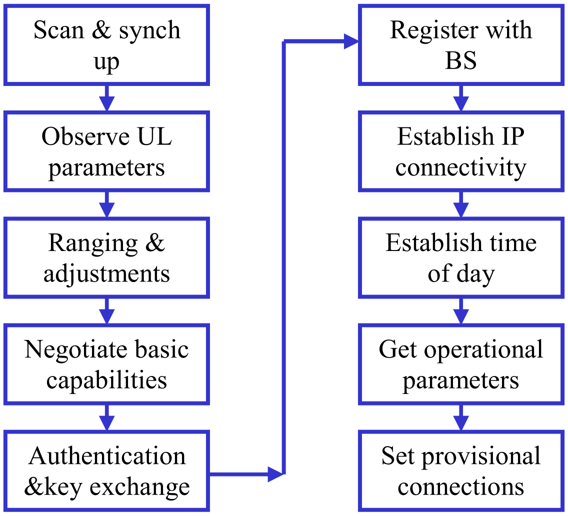


Figure 2. Initialization steps for 802.16d

A schematic diagram of steps in the initialization process is given in Figure 2, which is a simplified version of Fig. 55 in Section 6.3.9 of the draft standard [I04a]. In the first step of the process, an SS begins scanning its frequency list to identify an operating channel (or it may be programmed to log on with a specified BS). After deciding on the channel to attempt communication, the SS tries to synchronize to the downlink transmission by detecting the periodic frame preambles. Once the physical layer is synchronized, the SS in Step 2 looks for the periodically broadcast downlink channel descriptor (DCD) and uplink channel descriptor (UCD) messages, from which the SS learns the modulation and forward-error-control information for the chosen channel.

With the channel parameters known, the SS identifies a transmission opportunity from the uplink (UL) Medium Access Protocol (MAP) to send ranging message(s) to the target BS. Based on the range-response message from the BS, the SS can adjust its transmission power and timing. Furthermore, the message also provides the SS with the basic and primary management connection identities (CIDs). After the ranging process is completed, the SS and BS exchange two messages to inform each other of their capabilities.

The next step is for the SS to go through the authentication procedure and exchange of encryption keys with the BS. The step involves several messages exchanged between the SS and BS. It starts with the SS sending its X.502 digital certificate (MAC address and SS public key), cryptographic algorithm and basic CID to the BS. At the end of the step, both the SS and BS agree upon the authorization and traffic-encryption keys and their associated life-times.

In the registration step, the SS sends the BS a request message to register with the network. The BS returns a response message to indicate success or failure of the registration and, if successful, a secondary management CID. Then, the SS acquires an IP address and related parameters via dynamic host communication protocol (DHCP). In the next step, the SS sends a request for time and receives a response from a time server. The DHCP server also provides the address of the TFTP (Trivial File Transfer Protocol) server from which the SS can obtain a configuration file containing operational parameters. As a final step, connections are set up for service flows between the SS and BS. There are alternative ways to set up the connections. One way is for the BS to send a dynamic service addition (DSA) message to the SS. The request message contains service flow IDs, possibly CIDs and their QoS parameters. The connection setup is completed after the SS returns a DSA response to the BS and the BS sends an acknowledgment.

C. *Functionalities for Connection Handoff*

We obtain the functionalities required by connection handoff by eliminating unnecessary steps in the initialization process. As a result, the schematic diagram in Figure 2 can be reduced to Figure 3 for connection handoff.

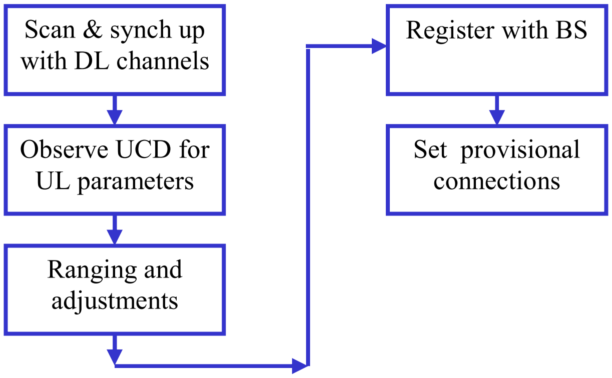


Figure 3. Functionalities for Connection Handoff

Let us discuss why the functionalities (with over-the-air message exchanges) in the above figure are sufficient for connection handoff. First, it is assumed that the current BS and the new BS involved in the handoff have identical capabilities, so the negotiation of basic capabilities in step 4 in Figure 2 becomes unnecessary. User re-authentication can be achieved by exchange of control messages in the backhaul network. In addition, encryption keys and their associated parameters can be forwarded from the current BS to the new BS also via the backhaul network. Thus, messages exchanged over the radio link for steps 5 and 6 can be avoided. (How authentication and forward of encryption keys can be done via the backhaul network is discussed in the following subsection.)

Functions	Message exchanged		Delay (for 7 ms/frame)	
	SS	BS	Number of frames	msec
Synch up with DL channels	-	-	5	35
Observe UL parameters	-	-	5	35
Ranging & adjustment	2x RNG-REQ	2x RNG-RSP	4	28
Registration	REG-REQ	REQ-RSP	2	14
Establish connections	DSA-RSP	DSA-REQ, DSA-ACK	3	21
Total handoff latency			19	133

Table 1. Estimated latency for the ‘short’ initialization

Furthermore, since the same IP connectivity is maintained by use of HMIP in spite of handoff, one can avoid the need for re-establishing a new IP connection. As the existing IP connection remains unchanged, there is no need for the SS to receive new operational parameters. In addition, as it is reasonable to assume that BSs are synchronized, say by the

Global Positioning System (GPS), it is unnecessary for the SS to re-establish time of day as part of the handoff process. Based on all these observations, the functionalities required by the handoff process are thus obtained, as shown in Figure 3.

It is worth noting that by comparing Figures 2 and 3, the handoff procedure actually represents a "short" initialization process. This not only enables handoff to reuse existing functionalities but also helps keep the handoff latency satisfactorily low.

We now estimate the latency for the handoff functionalities. Table 1 shows the messages involved in the functionalities and their estimated latency by assuming: 1) 7 msec per frame (which is a medium frame length) and 2) transmission of DCD and UCD every 5 frames, and 3) messages can be processed and responding messages can be sent in the next frame. Note that delay incurred in channel synchronization and observation of UL parameters can be reduced if a second radio chain is used to perform the task while the first one continues its normal operations.

D. *Handoff Protocol and Message Exchanges*

Figure 4 shows the sequence of message exchanges for connection handoff. We note that as a SS can stay silent (with no transmission) at times, its BS may not recognize the need of handoff when the SS moves away for the BS. So SS initiated handoff is more appropriate than that initiated by BS. When a SS realizes a need for handoff (e.g., by checking error rate for the MAPs periodically broadcast from BS on the downlink or by measuring the received signal strength), it sends a handoff request (HO-REQ) to its current BS (denoted as the old BS). In turn, the BS returns with a handoff acknowledgment (HO-ACK) message to signify that the SS can start the handoff process. It is important to note that both HO-REQ and HO-ACK messages are *not* defined in the 802.16d standard. We include them here mainly to illustrate the handoff protocol and discuss later how one can replace these messages by an existing one defined in the standard.

Soon after the old BS responds to the SS's request for handoff, the old BS sends the BN-MSG1 (Backhaul Network message 1) to inform the PFA, which is the "anchor" point for the SS, of the MAC address, CIDs, encryption keys and other service parameters associated with the SS. Upon receiving the MSG1, the PFA forwards BN-MSG2 messages, which contain information about the SS's MAC address, connections and operational parameters, via the backhaul network to alert all BS's surrounding the old BS, to look out for the possible handoff of the SS. This list of neighboring BSs, which are the likely candidates for handoff, is maintained at the PFA, and is analogous to the neighbor list in CDMA systems.

Following the reception of the HO-ACK message, the SS proceeds to execute the functionalities in Figure 3. That is, it scans and synchronizes with a new channel of a neighboring BS (denoted as the new BS in the diagram). Then, it obtains the uplink transmission parameters, completes the ranging and adjustment procedure, registers and sets up provisional connections with the new BS. Once the "short initialization process" is completed, the new BS sends the BN-MSG3 to inform the PFA of the completion of the handoff. In turn, the PFA sends the BN-MSG4 to reset PHY and MAC associated with the SS on the old BS. As the new connections are established between the SS and the new BS, the PFA starts to tunnel data to the new BS for forwarding to the SS.

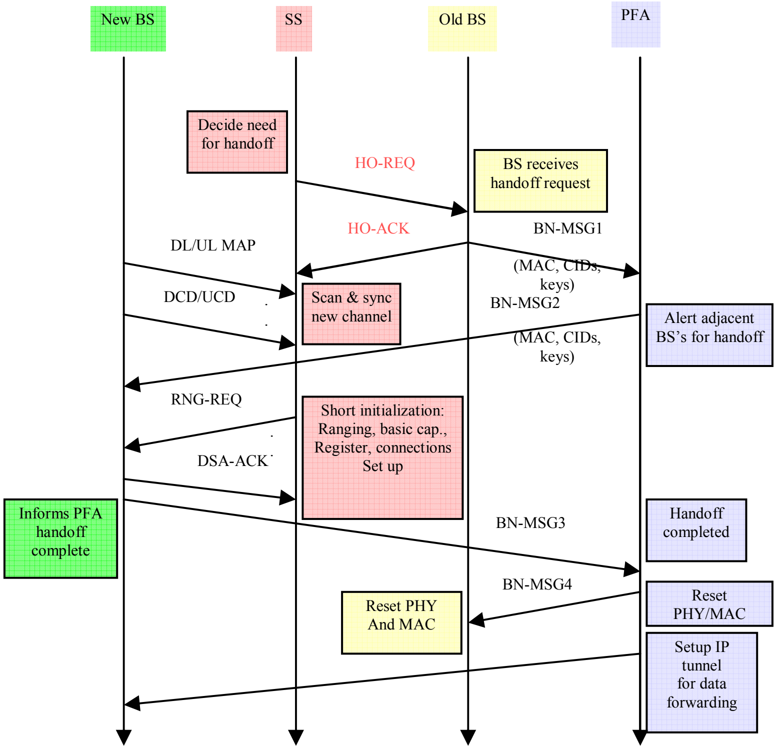


Figure 4. Handoff protocol

Before continuing, we note that there is a key delay requirement for the handoff protocol to work properly. That is, the BN-MSG2 sent from the PFA must be received and processed by all BSs surrounding the old BS before the first ranging (RNG-REQ) message from the SS arrives. This is so because without receiving the BN-MSG2 message, the neighboring BSs will not be aware of the handoff, and thus follow the rest of the steps for the normal initialization process, instead of those of the "short" process for handoff. (On the other hand, the SS knows that it has to follow the short process because it has been told to do so by receiving the HO-ACK message from the old BS.) Since the scanning and synchronization with a new channel may take at least tens of msec to complete, the delay requirement does not appear to be a stringent one. Rather, with a typical high-speed IP backhaul network, it is expected that the BN-MSG2 message can reach and be processed by the neighboring BSs within a couple of tens of msec, which should be short in comparison with the delay incurred in channel scanning and synchronization.

E. Use of Existing Message to Request and ACK Handoff

As mentioned earlier, the HO-REQ and HO-ACK messages have not been defined in the 802.16d standard and defining the new messages in the standard is not our goal either. In order to avoid a change to the standard, we observe that it is possible to re-use an existing message, namely the De-registration Command (DREG-CMD) with action code of 03, to serve the place of the HO-REQ and HO-ACK messages. That is, when the SS initiates the handoff, it sends a DREG-CMD (code=03) message to its BS. If the BS agrees to the handoff, it returns another DREG-CMD (code=03) to the SS. When the latter is received by the SS, it signifies that the handoff process is started. The rest of the protocol and message exchanges presented in Figure 4 are carried out.

We now explain why the DREG-CMD (code=03) message can be applied as such. The standard specifies [I04a, Sec. 6.3.2.3.26] that "the DREG-CMD message shall be transmitted by the BS on an SS's basic CID to force the SS to change its access state. Upon receiving a DREG-CMD, the SS shall take the action indicated by the action code." If the action code is 03, the "SS shall return to normal operation and may transmit on any of its active connections." First of all, BS does not expect to receive the DREG-CMD (code=03) message from its SSs. If it is indeed received, how the BS would interpret the message has not been specified in the standard. Thus, it is acceptable if the BS chooses to interpret the message as a request for handoff (HO-REQ). After the SS sends the first DREG-CMD (code=03) message, the SS intends to begin a handoff, thus has a context to interpret the returned DREG-CMD from the BS as an ACK (HO-ACK).

The choice of the DREG-CMD (code=03) message has an additional advantage. Namely, the message simply asks the SS to resume normal operations, thus it does not cause any adverse effects to the SS if it does not interpret the message in such a special way for supporting handoff. Furthermore, the message also enables correct operations for mixed SSs and BSs with or without the new handoff capability. For example, suppose that the SS has the handoff capability, but its BS does not. In this case, after receiving the first DREG-CMD (code=03) from the SS, the BS will not send the second DREG-CMD (code=03) to acknowledge (or approve) the handoff. Without the returned DREG-CMD, the SS simply continues its operations as defined in the original standard. In short, by initiating the handoff process from the SS, and by re-using the DREG-CMD (code=03) message, we ensure that there are no problems arising from misinterpretation of a message that arrives at an unexpected time due to a failure of synchronization, for example.

In order to prevent "ping-ponging" of an SS between an old and new BS, we propose the usual solution of a hysteresis threshold, such that a handoff will only be requested by the SS if the received signal strength from the new BS exceeds that from the old BS by at least this threshold. However, since the handoff scheme uses a "short" version of the initialization process, and in particular omits the authentication and key exchanges and request/grant of connection IDs (which are retained by the old BS and transmitted over the backhaul to the new BS), it is possible for the SS to abort the handoff at any stage before the MAC and PHY are reset at the old BS with BN-MSG4 in Fig. 4, simply by sending another DREG-CMD (code=03) to the old BS.

III. FEASIBILITY OF SUPPORTING HARD HANDOFF

In this section, we show that the physical (PHY) layer of 802.16d standard can support terminals moving with moderate speed. In particular, we present a simple analysis leading to an expression for the bit error rate (BER) on a wireless link between a BS and an SS with the OFDMA air interface as specified in 802.16d. It is reasonable to assume [S02, p.254] that such a link is limited by inter-carrier interference (ICI), rather than by interference between OFDMA users. This is because the latter is averaged over multiple users and, for universal or low frequency reuse, may be taken to be small and relatively constant over time, and thus absorbed into the Gaussian thermal noise. (On the other hand, for the OFDM with TDMA PHY mode, this assumption may be problematic for systems with high frequency reuse. This is so because the lack of fast power control and the bursty nature of interference in a TDMA system implies that the out-of-cell interference is more accurately modeled by a lognormal distribution [DV04].) In addition, we assume no fast or soft handoff (so that the terminal of interest remains supported by the given BS over the duration of the following analysis). Further, we assume no or slow power control, so that the transmitted symbol energy stays the same over the time interval of interest.

The link is subject to both fast and slow fading, the latter assumed to be almost unchanged over the duration of observation and hence absorbed into the average symbol energy at the receiver. The fast fading is assumed to be Rayleigh, given by the Clarke-Jakes model [J95]. Then, it can be shown [S02, p.255] that the average received symbol energy-to-noise ratio is given by

$$\bar{\gamma}_{\mathrm{s}} = \frac{1}{1-\frac{1}{N^2}\left[N+2\sum_{i=1}^{N-1}(N-i)J_0\left(2\pi f_{\mathrm{m}}T_{\mathrm{s}}i\right)\right]+\frac{NT_{\mathrm{s}}}{E_{\mathrm{s}}/N_0}}$$

where N is the number of OFDM sub-carriers, T_{s} is the duration of each M-ary QAM symbol transmitted on a subcarrier, N_0 is the noise power, E_{s} is the average transmitted symbol energy, and $f_{\mathrm{m}} = f_{\mathrm{c}}\left(v/c\right)$ is the Doppler frequency, where f_{c} is the carrier frequency, v the terminal speed, and c the speed of light. The corresponding average received bit energy-to-noise ratio is given by $\bar{\gamma}_{\mathrm{b}} = \bar{\gamma}_{\mathrm{s}}/\log_2 M$, or

$$\bar{\gamma}_{\mathrm{b}} = \frac{1/\log_2 M}{1-\frac{1}{N^2}\left[N+2\sum_{i=1}^{N-1}(N-i)J_0\left(2\pi f_{\mathrm{m}}T_{\mathrm{s}}i\right)\right]+\frac{NT_{\mathrm{s}}}{\log_2 M}\left(\frac{1}{E_{\mathrm{b}}/N_0}\right)}$$

for M-ary QAM modulation (e.g., M=4 for QPSK and M=16 for 16-QAM). Note that $E_b = E_s/\log_2 M$ is the average transmit energy per bit.

We assume symbol-by-symbol detection at the receiver. Let $P_b(\gamma_b)$ be the probability of bit error (BER) when the received bit energy-to-noise ratio is γ_b. Then we have

$$P_b = \int_0^\infty P_b(\gamma) f_{\gamma_b}(\gamma)\,\mathrm{d}\gamma \tag{1}$$

where $f_{\gamma_b}(\gamma)$ is the probability density function (pdf) of the bit energy-to-noise ratio under the chosen fading model. For the case of Rayleigh fading, we have

$$f_{\gamma_b}(\gamma) = \frac{\exp(-\gamma/\bar{\gamma}_b)}{\bar{\gamma}_b}, \quad \gamma \ge 0. \tag{2}$$

Finally, we make the assumption that the inter-carrier interference (ICI) may be approximated by additive white Gaussian noise (AWGN). As shown in [S02, p.254], this approximation is very accurate for $N = 256$ and virtually exact for $N \ge 1024$. This approximation allows for the reuse of well-known expressions for the probability of bit error on an AWGN channel. For QPSK modulation, the exact expression for bit error probability is available:

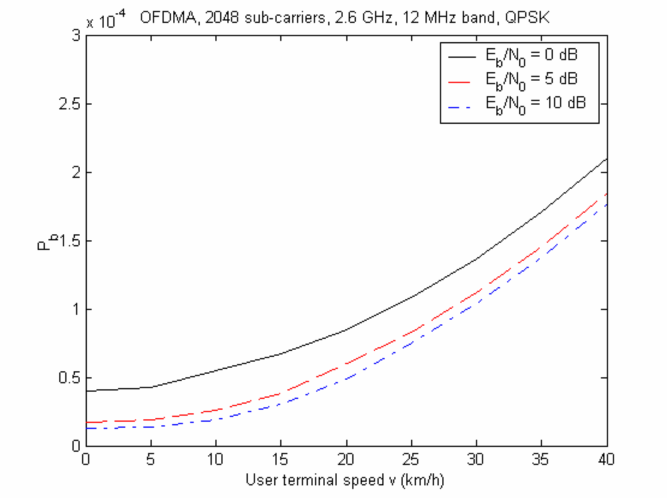
$$P_b(\gamma_b) = Q\left(\sqrt{\gamma_s}\right) = Q\left(\sqrt{2\gamma_b}\right) \tag{3}$$

whereas for general M-ary QAM, we only have the approximation (which applies to Gray coding)

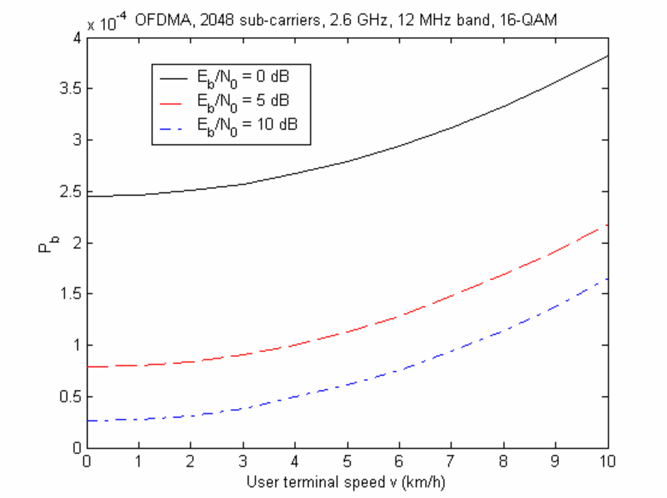
$$P_b(\gamma_b) \approx \frac{P_M(\gamma_s)}{\log_2 M} \tag{4}$$

where P_M is the symbol error probability. For example, the symbol-error probability for 16-QAM is

$$P_M(\gamma_s) = 3Q\left(\sqrt{\frac{\gamma_s}{5}}\right)\left[1 - \frac{3}{4}Q\left(\sqrt{\frac{\gamma_s}{5}}\right)\right]. \tag{5}$$



(a)



(b)

Figure 5. BER versus terminal speed for an MMDS OFDMA link with Rayleigh fading, 2048 sub-carriers, 2.6 GHz carrier frequency, and 12 MHz bandwidth, for (a) QPSK and (b) 16-QAM modulation.

Let us consider as an example the OFDMA mode in the MMDS band (carrier frequency $f_c = 2.6\,\mathrm{GHz}$), with a bandwidth of 12 MHz. As specified in the 802.16d standard, the number of sub-carriers is $N = 2048$ and the OFDM useful symbol period is $NT_s = 149.33\,\mu\mathrm{s}$. The raw bitrate for rate ½ coding is about 10 Mb/s for QPSK, and about 20 Mb/s for 16-QAM when the cyclic prefix duration is 1/32 of the useful symbol period. For this choice of parameters, in Figure 5(a), we plot the BER as obtained from (1) and (2) for QPSK modulation [$P_b(\gamma)$ given by (3)] as a function of the terminal speed v for several choices of the average bit energy to noise ratio E_b/N_0. In Figure 5(b), we repeat the plots for the case of 16-QAM modulation [$P_b(\gamma)$ given by (4) and (5)]. For QPSK, the lack of dependence of BER on E_b/N_0 supports the validity of the approximation that the system is ICI-limited and not noise-limited, while the accuracy of this approximation is lower for the 16-QAM case. Note that with QPSK modulation, we can maintain a BER of 0.002% or less for terminal speeds up to 40 km/h, and with 16-QAM, we can maintain this BER for terminal speeds up to about 10 km/h. Thus terminal mobility can be supported for these moderate speeds. It is important to note that these results correspond to cases without coding. So, it is expected that higher terminal speeds can be supported when coding techniques are used.

Finally, let us consider the handoff latency requirement. In a practical system, SSs anywhere in a cell could see the dominant pilot change or a new BS enter the set of candidates for handoff. The frequency of this event, which could potentially trigger a handoff request, depends upon the speed of the SS. For slowly-moving SSs, the channel quality to the old BS does not change rapidly, so the maximum latency possible for the handoff is given by the decorrelation distance of the shadow fading from the old BS, which is several tens or even hundreds of meters. For slowly-moving SSs, the time taken to cover this distance is much larger than the time taken to complete the handoff. For a fast-moving SS in the interior of the cell, the channel quality changes rapidly over a short time interval. Thus the introduction of a time hysteresis for the handoff request, i.e., requiring that a new BS should have a better channel for at least some length of time before a handoff request is initiated, is likely to remove the need to perform handoffs arising from the majority of such events. In general, for a fast-moving SS, the time hysteresis requirement is likely to be met when the SS is moving toward the periphery of the cell and into a new cell. We now focus on this case.

Assume that the cell radius (covered and served by one BS) is 1 km and that there is a 5% overlap in the coverage area of two adjacent cells. Modeling these cells as circles of radius 1 km each, with distance d km between the bases, the fractional area of overlap is given by

$$\frac{2}{\pi}\left[\cos^{-1}\left(\frac{d}{2}\right)-\left(\frac{d}{2}\right)\sqrt{1-\left(\frac{d}{2}\right)^{2}}\right]$$

which is 5% when $d = 1.75$ km. This in turn implies that the overlapping area extends 250 m into each cell. Consider a user terminal moving from one cell to the next in a straight line with constant velocity. To simplify the analysis, let us assume that if the terminal has not been handed off to the adjacent cell (BS) when it has passed the common overlapping coverage area of the current cell, then the connection is dropped. Then the maximum total distance over which the handoff must be completed is 250 m. For the maximum supported mobile speed of 40 km/h (with a BER of 0.002% or less and QPSK modulation) we see that the handoff must be completed within 22.5 sec. Such a requirement can be easily met when compared to latency estimates in Table 1 plus the typical delay in tens of msec incurred in the message exchanges in Figure 4.

IV. CONCLUSION

We have studied in this paper whether the 802.16d standard can intrinsically support terminal mobility without any change in the specification, although its original intent is to provide the last-mile connectivity to fixed locations. We have shown that mobility capability can be achieved for the 802.16d by: 1) applying some of the existing functionalities defined for the initialization process, 2) devising a new set of protocols for connection handoff, and 3) forwarding some of the operational parameters from the current BS to the handoff BS via the backhaul network, instead of over the radio link. Our link-performance study shows that under typical radio conditions, the 802.16d link can provide satisfactory bit error performance for terminal speed up to tens of kilometers per hour. Therefore, we conclude that our proposed techniques can be applied to support mobility using the existing 802.16d specification without waiting for the approval of the new 802.16e standard for mobile environments. As the 802.16d devices will be widely available in the near future, our proposed techniques can be applied to enable mobility capabilities for the 'legacy' devices, regardless of the final acceptance of the new 802.16e standard.

ACKNOWLEDGMENT

The authors would like to thank T.E. Klein and H. Viswanathan for their helpful discussions.

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