WIMAX SYSTEM PERFORMANCE IN HIGHLY MOBILE SCENARIOS WITH DIRECTIONAL ANTENNAS

George Zaggoulos, Andrew Nix and Angela Doufexi
Centre for Communications Research, University of Bristol
Bristol, United Kingdom

ABSTRACT

This paper presents a performance evaluation of a WiMAX system (802.16-2004) employing directional antennas in highly mobile applications. A WiMAX physical layer simulator is used together with an appropriate mobile channel model to perform the analysis. Results show that mobile performance is significantly improved when directional antennas are utilised at the mobile end of the link. These antennas reduce the resulting Doppler spread, which in turn increases the channel's coherence time. In a time varying channel, irreducible errors occur as a result of an aging channel estimate. The structure of the channel estimation pilots has a strong impact on performance. Analysis reveals that results are relatively insensitive to the shape of the Power Doppler Profile, but strongly related to the value of the Doppler spread.

Keywords: WiMAX, Directional Antennas, Doppler Power Spectrum

I. INTRODUCTION

WiMAX technology was first standardised in 2002. The initial standard offered a fixed wireless broadband connection for metropolitan area networks (MAN) in frequency bands ranging from 10-66 GHz [1]. Later, support for the 2-11GHz band was added to the standard. In 2004, the 802.16 standard was updated to 802.16-2004 [2]. The enhanced standard focused on better support for fixed and nomadic applications and introduced two new physical layer (PHY) schemes. Orthogonal frequency division multiplexing (OFDM) with 256 sub-carriers and OFDMA with up to 2048 sub-carriers were introduced to support services in line-of-sight (LoS) and non-line-of-sight (NLoS) conditions. WiMAX systems conforming to the 802.16-2004 standard can support a limited degree of mobility. Motion results in a Doppler shift, which for a given path is proportional to the carrier frequency and the relative speed between the transmitter and receiver. In a multipath channel, each path experiences a unique Doppler shift, and this results in a Doppler spread. Unless the Doppler spread is successfully mitigated, this results in an irreducible error rate.

More recently, the IEEE 802.16e working group has produced a further amendment to the 802.16-2004 standard to allow enhanced mobility and support for handoff. The 802.16e standard has been developed for speeds of up to 120 km/h at 3.8 GHz [3]. This paper examines the possibility of using directional antennas with the WiMAX standard to reduce the impact of Doppler spread, and hence improve the performance of a mobile WiMAX communications link. The use of directional antennas improves performance without the need for increased digital signal processing at the receiver.

The maximum Doppler spread in a mobile channel is equal to twice the maximum Doppler shift f_m. This worst case value is observed when multipaths arrive directly in front, and directly behind, the direction of motion. The maximum Doppler shift is given by:

$$f_m = u / \lambda \tag{1}$$

where u represents the relative velocity between the receiver and transmitter, and λ is the wavelength of the carrier frequency. A signal path arriving at the receiver at an azimuth angle θ relative to the direction of the motion experiences a Doppler shift given by:

$$f_\theta = f_m * \cos(\theta) \tag{2}$$

The Power Spectral Density (PSD) shows the relationship between the signal power and the Doppler shift for a given channel. The PSD depends on the distribution of received power in the azimuth plane. This is normally characterised by the channel's Power Azimuth Spectrum (PAS).

A number of theoretic PSDs are commonly assumed in the literature. These are, 1) a flat power spectrum, 2) a Gaussian power spectrum, and 3) a Jake's (or Clarke's) power spectrum [4]. The first two models are normally used to describe a fixed wireless channel. The third model is used to describe a mobile channel. The Jake's PSD is used in this paper and is defined mathematically in [5].

$$S(f) = \begin{cases} \dfrac{\sigma_0^2}{\pi f_m \sqrt{(1 - f / f_m)^2}}, & |f| < f_m \\ 0, & |f| > f_m \end{cases} \tag{3}$$

Fig. 1 shows the corresponding PSD for different mobile velocities.

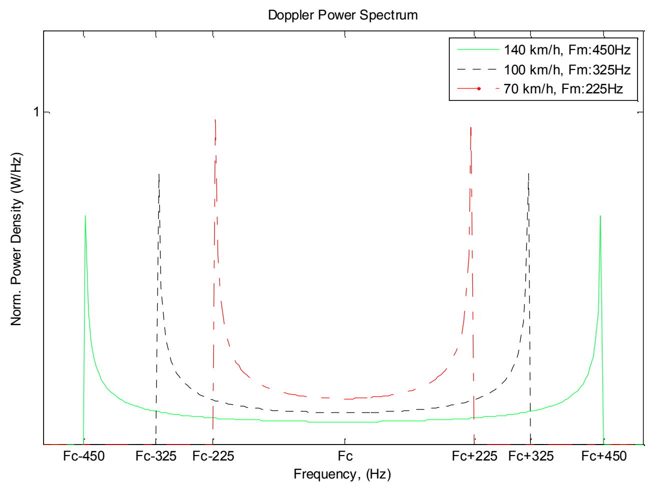

Figure 1: Jake's PSD for different mobile velocities

The Jake's PSD is derived on the assumption of an infinite number of scatters in a 2D plane. The scatters are of equal power and are uniformly distributed in the azimuth plane. In its standard form, the Jake's PSD cannot be used for systems with directional antennas.

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For a mobile communications system, the spaced-time autocorrelation function (see Fig. 2) is important since it enables the channel correlation to be determined as a function of time-shift Δt . For example, if a channel estimate is acquired at time *t*, the autocorrelation function determines the correlation between this estimate, and the channel at some time $t+\Delta t$ in the future. The coherence time is defined as the time period over which the channel remains highly correlated (with a correlation coefficient of 0.9 or 0.5 commonly used). The spaced-time autocorrelation function is related to the PSD through an inverse Fourier transform [6].

$$R(\tau) = FT^{-1}\{S(f)\} \tag{4}$$

Fig. 2 shows the spaced-time autocorrelation function for the Jake's PSD at three different values of maximum velocity. As the mobile speed increases, the channel's coherence time is seen to decrease.

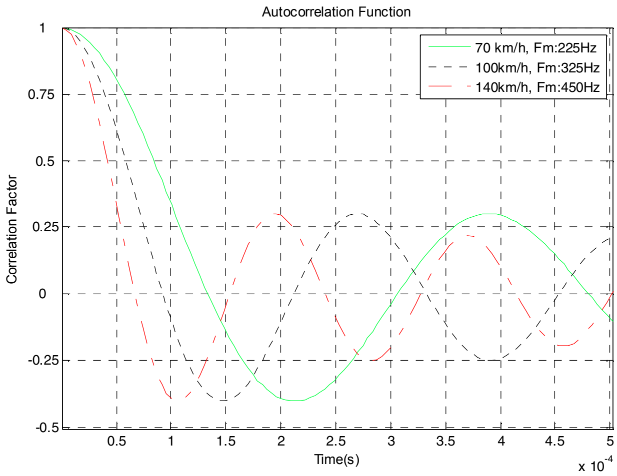

Figure 2: Autocorrelation Function for mobile channels with different velocities

The coherence time can also be approximated [7, 8] using the following expression:

$$T_c = \frac{\lambda/2}{u} = \frac{0.5}{F_m} \tag{5}$$

The use of directional (or sectorized) antennas is desirable in a mobile channel for a number of reasons. In particular, if correctly aligned, they enable:

- Enhanced signal levels,
- Reduced Doppler spread,
- Reduced delay spread,
- Reduced co and adjacent channel interference.

A directional antenna is said to perform spatial filtering [9]. When used at the receiver, the antenna significantly enhances the gain of multipaths over a specific range of azimuth angles. As a result, the characteristics of the channel, such as the received power, the RMS delay spread, the RMS Doppler spread, and the signal to interference (SIR) ratio can be improved dramatically. For channels where power is received over a wide range of azimuth angles, a highly directional antenna can result in some degree of signal loss (since multipaths outside the main beam of the antenna are suppressed). Nevertheless, this power loss is normally more than compensated for by the directional antenna gain.

The 802.16-2004 WiMAX standard defines the use of preambles, which are spaced every 8 OFDM symbols [2]. However, the latest amendment of the mobile WiMAX standard [10] allows the use of preambles every 4 symbols. Although the simulations in this paper are based on the 2004 WiMAX standard, the packet structure of the new amendment is considered.

This paper is organized as follows: The operational scenario is described in section II. In section III the simulation structure and configuration are discussed, and the system parameters are given. Results are presented in section IV, and conclusions are drawn in section V.

II. Operational Scenario

WiMAX terminals that experience high Doppler spreads are most likely to be deployed on vehicles or trains. The scenario studied in this paper assumes a WiMAX terminal placed in a moving vehicle. In this situation, the orientation of the directional antenna is aligned toward the motion of the vehicle.

If we assume a uniform distribution of scatters in the azimuth plane, then for a given directional antenna orientation (relative to the direction of motion), the resulting Doppler spread can be computed. The symbol '//' is used to mean parallel to the direction of motion, while '|-' is used to mean perpendicular to the direction of motion. The numeric value in the antenna description represents the ideal 3dB beamwidth of the antenna. Table 1 tabulates the resulting Doppler spread for five antenna configurations. From table 1 it can be observed that for all types of directional antenna, the value of Doppler spread is considerably reduced.

Table 1: Doppler spread for different antenna beamwidths and orientations

#	Antenna description	Doppler spread (Hz)		
		at 70 km/h	at 100 km/h	At 140 km/h
1	Omni	458	650	900
2	90 //	66	95	133
3	120 //	113	162	227
4	60 |-	227	324	458
5	90 |-	324	458	650

More generally, a directional antenna with a beam-width α reduces the Doppler spread from $2f_m$, to $(1-\cos(\alpha/2))*f_m$ if the boresight is aligned straight ahead or behind the vehicle [4] (assuming the vehicle moves in a forward or backward direction). This first case corresponds to the '//' condition. On the other hand, if the same antenna is rotated such that its bore-sight is pointing to the side of the car, then the Doppler spread is reduced to $2*f_m*\sin(\alpha/2)$. This second case corresponds to the '|-' condition. Furthermore, the shape of the resulting PSD in the first case will be similar to the left or right-hand edge of the Jake's PSD (see Fig. 3a), depending on whether the antenna is orientated directly in-front or behind the vehicle. For the second case the resulting PSD is quite flat, since it is derived from the central section of the Jake's PSD (see area 2 in Fig. 3a). From our simulations we have concluded that the shape of the PSD does not strongly influence the resulting error performance (assuming a constant Doppler spread). In the literature [6], we note that the shape of the power delay profile (PDP) has been shown not to strongly influence the resulting bit error rate (BER) in a time dispersive channel (assuming a constant RMS delay spread). It is well known that delay dispersion and frequency dispersion are duals of one another. By analogy, we conclude that the error performance in a time-varying channel is strongly related to the RMS Doppler spread. While the shape of the PSD will impact the RMS Doppler spread, for a given RMS Doppler spread, the particular PSD shape is not significant. These conclusions are easy to be verified by taking the inverse Fourier transform of different PSDs and comparing the corresponding autocorrelation functions (see Fig. 3b). Since the system performance is determined by correlation values of 0.5 or higher, any differences in the shape of the lower correlation values are immaterial.

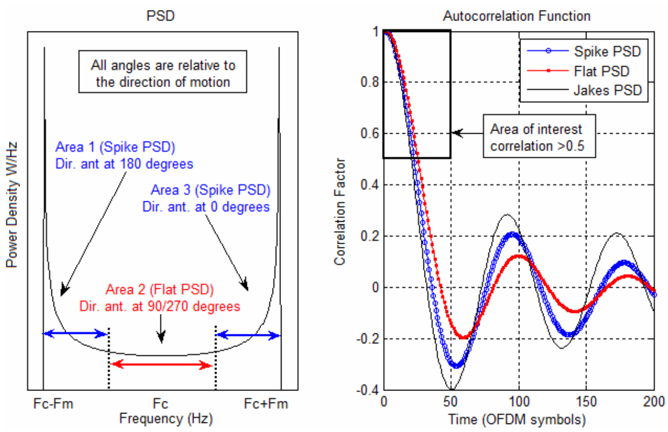

Figure 3: a) PSDs with directional antennas and different relative orientations, b) Autocorrelation functions for different PSDs, but for the same Doppler spread (225 Hz)

The studies reported in this paper are based on two different sectorised antenna structures. The first antenna consists of four directional elements, each with a beamwidth of 90 degrees. The second sectorised antenna consists of 2 sectors with a 60-degree beamwidth (pointing to the sides of the vehicle), and 2 with a 120-degree beamwidth (pointing in-front and behind the vehicle). Both of the sectorised antennas are mounted on top of the vehicle, such that the bore-sight of the front facing sector is aligned with the direction of the vehicle, as shown in Fig. 4.

a) Equal beamwidth sectors b) Different beamwidth sectors

Figure 4: Sectorised antennas mounted on the top of a vehicle

As mentioned previously, when the orientation of a directional antenna is locked relative to the direction of motion, the Doppler spread can be predicted assuming a uniform distribution of equal power scatters (as with the Jake's PSD).

The Doppler spreads simulated in this paper are shown in table 1. Fig. 5 shows the maximum Doppler spread for a 90-degree beamwidth antenna for different antenna orientations as a percentage of the Doppler spread for an omni-directional receiving antenna.

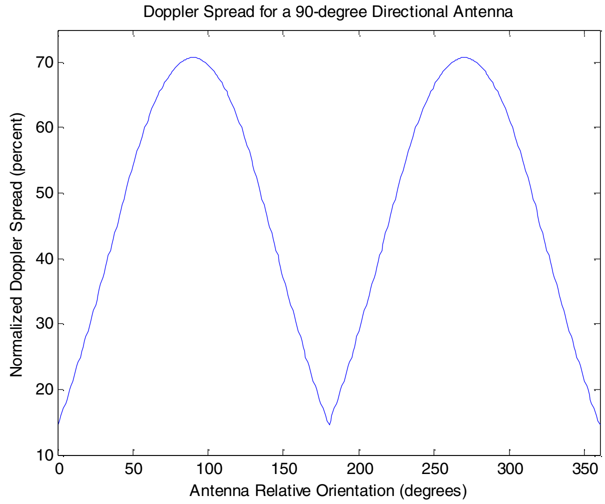

Figure 5: Doppler spread for a 90-degree directional antenna centred at different azimuth angles relative to the direction of the motion

III. SIMULATION CONFIGURATION

The results presented in this paper are produced using a WiMAX physical layer simulator. The simulator is designed in accordance with the 802.16-2004 standard. Using a Jake's PSD, a 3-tap Tapped Delay Line (TDL) channel model is developed for different user velocities using the Doppler filtering method described in [11]. The parameters used in the simulations are given in tables 2 and 3.

Table 2: WiMAX simulator parameters

Operating Frequency	3.5 GHz
Bandwidth	5 MHz
FFT Size	256
Useful Sub-carriers	192
Guard Interval Length	64
Sub-carrier Spacing	22.5 KHz
Useful Symbol Duration	44.4 µs
Total Symbol Duration	55.5 µs
Channel Coding	Punctured 1/2 rate convolutional code, constraint length 7, $\{133,171\}_{octal}$
Mode	BPSK ½

Table 3: Channel parameters
(Assumed: Fc = 3.5GHz, Relative speed = 140 km/h)

	Tap 1	Tap 2	Tap 3
K-factor	0	0	0
Delay (ns)	0	500	1000
Power (dB)	0	-10	-20
Max. Doppler Spread (Hz)	450	450	450
PSD	Jakes	Jakes	Jakes

The packet structure follows the latest published amendment [10] of the mobile WiMAX standard and consists of five OFDM symbols as shown in Fig. 6. The first symbol in each packet is used as a preamble, and the remaining four symbols contain payload data. No interpolation is performed from one packet to another (since packet rather than continuous transmission is assumed).

Preamble	Data 1	Data 2	Data 3	Data 4

Figure 6: Proposed packet structure with dense preamble

The simulated speeds are 70, 100 and 140 km/h, which result in a maximum Doppler spread of approximately 450, 650 and 900 Hz respectively at a carrier frequency of 3.5 GHz when an omni-directional antenna is used at the receiver. Based on equation 5, the coherence time for the simulated speeds is approximately 2.22, 1.54 and 1.11ms respectively. The coherence time can also be expressed normalised to the symbol or packet duration. Using an OFDM symbol period of 55.5µs (inc. guard interval), the above values are listed with normalised values in table 2 for each of the simulated maximum Doppler shifts f_m.

Table 4: Normalised Channel Coherence time for all simulated maximum Doppler shifts

Fm (Hz)	Tc (ms)	Tc (symbols)	Tc (packets)
40	12.5	225.2	45.0
50	10.0	180.2	36.0
60	8.3	149.5	29.9
70	7.1	127.9	25.6
80	6.3	113.5	22.7
115	4.3	77.5	15.5
165	3.0	54.1	10.8
225	2.2	39.6	7.9
325	1.5	27.0	5.4
450	1.1	19.8	4.0

A zero-forcing (ZF) algorithm is used in the simulator for channel estimation, and the estimate is then applied to the remaining payload. For simplicity, no attempt to track the channel is performed. For the packet structure shown in Fig. 6, this results in a channel estimate update every 0.2775 ms.

IV. RESULTS

Results are presented in this section according to the speed of the vehicle. Each figure includes the performance of the five considered antenna configurations. It should be noted that the 90-degree antenna element, which is simulated for two different orientations, is expected to result in different PER depending on whether it is perpendicular or parallel to the direction of motion. This occurs since the Doppler shifts are non-linearly related to the relative AoA and the direction of motion. Additionally, and to aid discussion, we assume that the maximum PHY layer PER is 10^{-2}. MAC layer ARQ can be used as an option in WiMAX, and this can be selected during connection establishment [12] to retransmit errored packets.

Fig. 7 shows the PER for all simulated antenna beamwidths and orientations at a speed of 70 km/h. This speed translates to a maximum Doppler spread of 458 Hz. However, the use of sectorised antenna can reduce this spread to as little as 66 Hz as shown in table 1. Given the reduction in Doppler spread, a gain of between 5 and 8 dB can be seen at a PER of 10^{-2}. This gain increases if a lower PER threshold is selected. For the perpendicular elements it is interesting to note that the irreducible PER is lower when a more directional antenna is used. For parallel elements, the irreducible error is completely removed, and the link becomes power limited. In general, at a speed of 70 km/h, both sectorised antenna structures give the same average performance. However, if we assume that the signal arrives from the front and back of the vehicle (instead of a uniform distribution), then the sectorised antenna with four equal-beamwidth elements should be chosen.

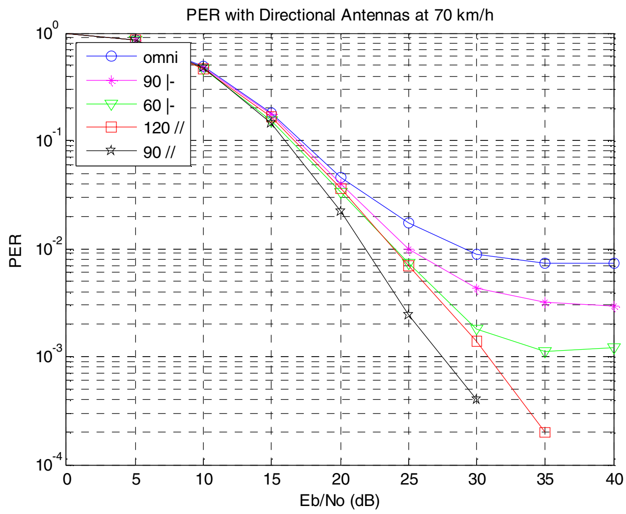

Figure 7: PER with different directional antenna configurations (vehicular speed = 70 km/h)

By increasing the simulated vehicle speed to 100 km/h, it can be observed from Fig. 8 that the performance of the 90-degree perpendicular sector has dropped closer to the maximum acceptable PER (10^{-2}).

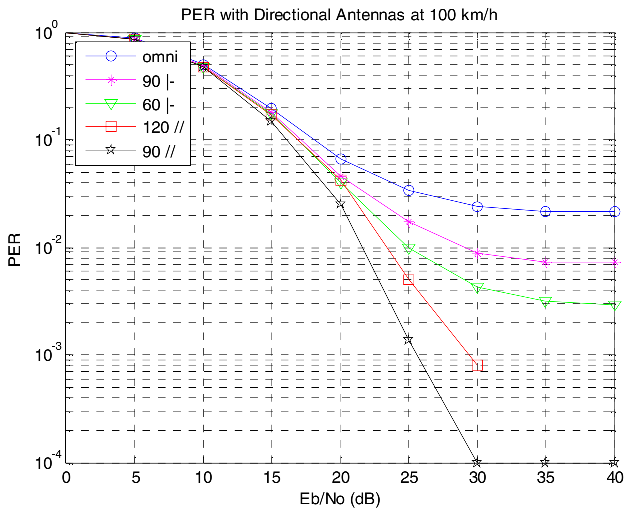

Figure 8: PER with different directional antenna configurations (vehicle speed = 100 km/h)

Therefore, at this higher speed it becomes clear that the second sectorised antenna solution (which uses different beamwidths) should be used since the 120-degree parallel sector has an approximate 2dB loss compared to the 90-

degree parallel device, whereas the perpendicular 60-degree element offers a 5 dB gain compared to the 90-degree device at a PER of 10^{-2}. It is worth noting that an omni-directional antenna gives a PER of 2 x 10^{-2} at a speed of 100 km/h. Therefore, this is the maximum speed at which an omni-directional antenna can be used at 3.5 GHz.

Finally, Fig. 9 shows PER results for a vehicle speed of 140 km/h. The difference in the performance between the parallel and perpendicular oriented sectors is further increased. At high speeds it becomes clear that the directional antennas give better performance if their orientation is parallel to the direction of motion. This agrees with theory, since based on this orientation the Doppler spread is lower, and thus the channel is more correlated over the data packet. As a result, the channel estimation is accurate across the entire packet. However, as the coherence time approaches the packet length, the use of a single preamble at the start of the packet will no longer suffice. Consequently, an irreducible PER is introduced at higher Doppler spreads (this can be observed in fig. 9, where the 120-degree parallel antenna element experiences an irreducible PER of approximately 10^{-3}).

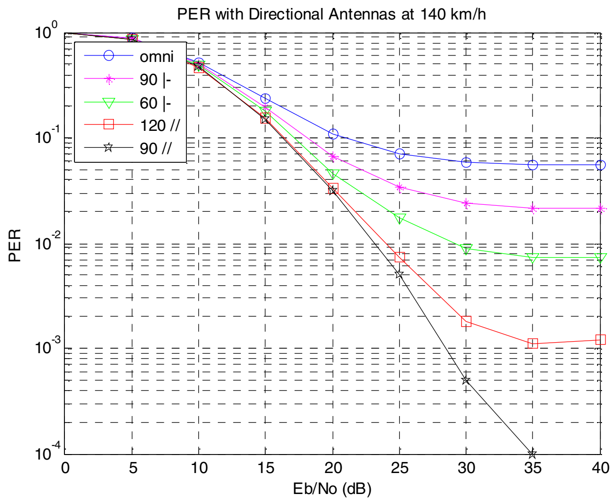

Figure 9: PER with different directional antenna configurations (vehicle speed = 140 km/h)

Referring back to table 4, the normalised coherence time for the corresponding maximum Doppler shift (115 Hz) is around 68 OFDM symbols; which means that the channel begins to show significant change over a packet. Therefore, in order to remove this error floor, either a higher density of pilots must be used, or some degree of channel tracking must be introduced.

In general, from the simulation results we conclude that there is no irreducible packet error floor (at least above a PER threshold of 10^{-4}) as long as the coherence time is at least approximately 20 times the packet length.

V. CONCLUSIONS

In this paper a study of high mobility within the context of the WiMAX standard was presented. Various vehicle speeds and antenna structures were explored, with the channel based on a worst case Jake's PSD. It was deduced that the shape of the PSD is much less important than the value of the RMS Doppler spread. We demonstrated via computer simulation that the beamwidth and orientation of a directional antenna can limit the Doppler spread; and hence the channel fading rate, for a given velocity. For a fixed packet length and preamble structure, the use of directional antennas was seen to facilitate higher vehicle speeds for a given irreducible PER. For an omni-directional antenna, it was shown that speeds of up to 100 km/h are possible, although an irreducible error floor was observed (PER=$2\text{x}10^{-2}$). Two different sectorised antenna arrays were compared, and it was found that uneven beamwidths result in better performance at high speeds. In particular, a broader beamwidth (120 degrees) was preferred on the front and back facing sectors, with a narrower beamwidth (60 degrees) used on the side facing sectors.

ACKNOWLEDGMENTS

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