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Bit-error-rate performance improvement of mobile dual-hop relaying systems using directional antennas

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Abstract: The bit-error-rate (BER) performance of orthogonal frequency division multiplexing (OFDM) systems in mobile multi-hop relaying (MMR) system is severely degraded by the effect of Doppler shift and the severity of this degradation increases with the number of hops traversed by the OFDM signal. In this study, the authors propose a method to mitigate the effect of Doppler shift in MMR system (such as the IEEE 802.16j system) using directional antennas. It is shown that the effect of the resulting inter-carrier interference (ICI) because of the phase noise generated by the Doppler shift over multi-hop relaying channels, can be reduced by employing directional antennas at both the mobile and relay stations. Consequently, the BER performance of MMR system is significantly enhanced. Analysis and simulation results show that the BER enhancements using the proposed approach are strongly related to the orientation and beamwidth of the directional antenna employed. As the antenna beamwidth is reduced, the BER enhancement increases for both the perpendicular and parallel antenna orientations, and comparing these two orientations, the parallel orientation case provides slightly better BER enhancements.

1 Introduction

Broadband wireless access networks (BWANs) such as long-term-evolution advanced (LTE-advanced) and the Worldwide Interoperability for Microwave Access (WiMAX) [1–3] have gained tremendous attention lately for leveraging the support of a wide range of applications with different quality of service (QoS) requirements. Despite the support for such range of applications, satisfying the different QoS requirements, whereas maximising the network capacity and extending the network coverage are still major issues in these networks. Multi-hop relaying has been adopted in several BWANs such as LTE-advanced and WiMAX as a cost-effective means of extending the reach and/or capacity of these wireless networks. The emerging mobile multi-hop relaying (MMR) extension enhances the conventional BWANs to enable support of multi-hop communication between a mobile station (MS) and a base station (BS) through intermediate relay stations (RSs).

BWANs based on orthogonal frequency division multiplexing (OFDM) has also gained tremendous attentions lately. OFDM provides an efficient broadband data transmission by sending parallel data over a number of closely spaced subcarriers. For high data rate, it is desirable to increase the number of subcarriers per OFDM symbol. As the number of subcarriers increases for a fixed symbol size however, the frequency spacing between the subcarriers in the OFDM symbol is reduced. This makes the OFDM system more sensitive to frequency shift which destroys the orthogonality of the subcarriers, causing inter-carrier interference (ICI). One of the main issues causing frequency shift in OFDM systems is the Doppler effect. Relative speed between the transmitter and receiver in a mobile wireless channel, introduces Doppler shift in the received frequencies, causing ICI. This effect poses significant problem in MMR systems as the end-to-end Doppler shift increases with the number of hops traversed by the transmitted signal when the AF relaying option is considered. Thus the cascade effect of the multiple relaying channel dramatically amplifies the frequency shift problem for the underlying OFDM system [4]. Doppler shift effect should therefore be given because of considerations in the design of broadband MMR systems, where the OFDM symbols typically traverse several hops from source to the destination nodes.

Directional antennas have been employed for spatial filtering in the literature [5–8], traditionally in the context of single-hop transmissions. In [5], directional antennas was employed for spatial filtering in a single-hop transmission in WiMAX networks. In [6], the deployment of directional antenna at the MS or receiver side was investigated, where it was shown that the multipath components can be significantly mitigated. The effect of directional antennas on the ICI power in an OFDM system was analysed in [7]. It was shown that the ICI power can be reduced substantially when directional antenna is employed at the MS. In [8], the probability density function (pdf) of the angle-of-arrival (AOA) of the multipath components is derived and the effects of directional antennas at the BS on the Doppler shift was studied. All these works were conducted in the context of single-hop communications. For the multi-hop case, the works in [9] examines the throughput gain achievable using directional antenna in multi-hop wireless networks, where it was inferred that low power consumption because of lower interference when using directional antenna can lead to throughput gain. In [10, 11] respectively, scheduling and routing schemes that rely on directional antenna in multi-hop systems were developed, using simulation studies. To the best of our knowledge however, no work has thus far presented error rate performance results to illustrate the behaviour of directional antenna solution in mobile OFDM relaying system.

Contribution of paper: A major requirements in 4G systems (LTE-advanced and WiMAX) is the provisioning of services at certain data rate and certain QoS. Thus, for every scheme deployed in 4G such as multi-hop relaying, service providers must have documented works not only on the potential impact of the scheme on data rate (or throughput) for various SNR, but also on the corresponding error rate performance at different SNR since the latter significantly impact wireless QoS. In this paper, we present the first documented work in the literature, on the effect of directional antenna on the error rate performance of MMR systems employing directional antennas. We derive the bit-error-rate (BER) performance of MMR system employing directional antennas and evaluate the effectiveness of this solution in MMR channels, analytically and by simulation.

The remainder of this paper is organised as follows. Section 2 presents the system model. Section 3shows the analysis of the Doppler effects [4], as well as the benefits of deploying directional antenna at the MS and RS. Section 4 presents the BER improvement using directional antenna at both the MS and RS. Section 5 describes the simulation parameters and the obtained results. Finally, Section 6 concludes the paper.

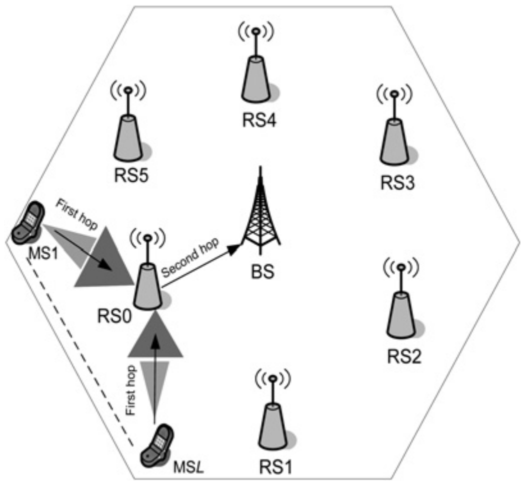

Fig. 1 *Mobile multi-hop relaying system*

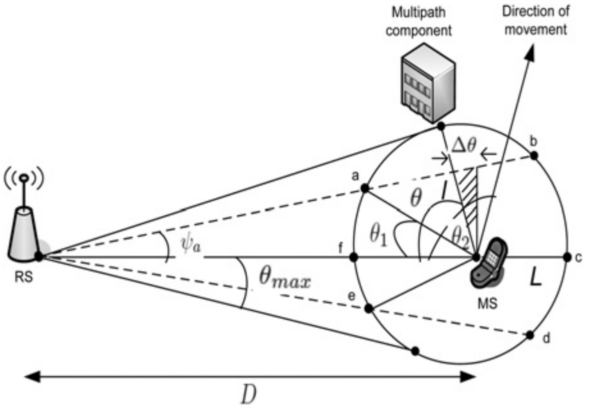

Fig. 2 *AOA of signals at mobile station with respect to the direct LOS component*

2 System model

Consider a broadband wireless network employing OFDM transmission over multi-hop relaying channels, with each OFDM symbol consisting of N_c subcarriers. The transmitted signal from a MS originating the data, passes through a number of RSs enroute to the BS. We assume that there are U users equipped with directional antennas, uniformly distributed in the coverage area of the BS, and that each user can be associated with the BS or an RS whichever provides stronger signal-to-noise ratio (SNR). An example of this model for the case $R = 2$ (two-hops relay network) is illustrated in Fig. 1 for a cellular deployment, in which each cell is serviced by a BS, located at the centre of the cell, and six RSs ($N = 6$) equipped with directional antennas, each equidistant from the BS and located at the center of each side of the hexagon as shown.

We assume that the amplify-and-forward (AF) relay option is employed at the relay nodes, where RSs simply AF the OFDM symbol at the radio frequency (RF) stage, without decoding its content. The RS demodulates the OFDM symbol, then amplifies all subcarriers separately.

BWAN terminals that experience high Doppler effects are most likely to be highly mobile, therefore the scenario studied in this paper assumes a BWAN 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 scatterers in the azimuth plane, then for a given directional antenna orientation, relative to the direction of motion, the resulting Doppler shift can be computed as illustrated in Fig. 2. This figure demonstrates the situation when a directional antenna with a beamwidth $2\psi_a$ is deployed at the RS. If the scatterers are assumed to be placed in a circle around the MS, then the AOA of the signal is limited to a region of $2\theta_{\max}$, therefore two cases can be considered: First, when $\psi_{\rm a} \geq \theta_{\max}$, then the directional antenna at the RS will eliminate all the scatterers, and the pdf of the AOA will be uniform. Second, when $\psi_{\rm a} < \theta_{\max}$, then the directional antenna at the RS will eliminate some of the scatterers, and the pdf of the AOA will not be uniform [8]. Through out this paper, the symbol ϖ is used to denote the case when antenna orientation is parallel to the direction of the motion, whereas $-\varpi$ is used to denote the case when antenna orientation is perpendicular to the direction of the motion.

3 Doppler shift effect

Since the BWANs terminals are usually highly mobile, the transmitted signal is shifted by Doppler effect $\Phi_{{\rm Dop},r}(n)$ as a result of the movement of the MS, which is given by $2\pi f_d T_s$, where $n = 1, \ldots, N_c$ is the subcarrier index, $T_{\rm s}$ is the OFDM symbol duration and f_d denotes the frequency offset between the transmitter and the receiver which can be expressed as

$$f_d = f_m \cos(\theta_2 - \theta_1) \tag{1}$$

The parameter θ_1 is the AOA of the received signal, whereas θ_2 denotes the angle of the motion. Both θ_1 and θ_2 are measured with respect to the direct line-of-sight (LOS) component, as illustrated in Fig. 2. In this figure, the parameter f_m denotes the Doppler shift, which can be observed when the signal arrives directly in front or behind the direction of motion, whereas L is the radius of the coverage area and D is the distance from the RS to the MS.

The maximum Doppler shift is given by

$$f_m = \frac{f_c * V_{S,D}}{c} = \frac{V_{S,D}}{\lambda} \tag{2}$$

where f_c is the transmitted frequency, $V_{S,\ D}$ is the velocity of the transmitter relative to the receiver (m/s), c is the speed of light (3×10^8(m/s)), and $\lambda = c/f_c$ is the wavelength. Therefore substituting (2) into (1) gives

$$f_d = \frac{V_{S,D}}{\lambda}\cos(\theta_2 - \theta_1) \tag{3}$$

Using the second term in (2), (3) can be rewritten as

$$f_d = \frac{f_c V_{S,D}}{c}\cos(\theta_2 - \theta_1) \tag{4}$$

Typically, the Doppler effect can be reduced from $2f_d$ to $(1 - \cos(\psi_a/2))f_d$ using a directional antenna with a beam-width ψ_a if the bore-sight is aligned in either direction, straight ahead or behind the MS [5]. If the bore-sight is aligned straight ahead, this case corresponds to the ϖ condition. On the other hand, if the antenna is rotated such that its bore-sight is pointing to either side, right or left of the MS, then the Doppler shift is reduced to $2f_d\sin(\psi_a/2)$, and this case corresponds to the $-\varpi$ condition[5].

3.1 Using directional antenna at relay station

Deploying directional antenna at the RS mitigates the effect of Doppler shift introduced as a result of MSs movement. From Fig. 2, the region of scatterers that can be successfully mitigated by the deployed directional antenna at the RS is a, b, c, d, e, f. Because of the symmetry, considering the region a, b, c, MS, f, where $0 < \theta \leq \pi$, the pdf of AOA of the received signal, $p_{(\theta)}$ at the MS, when $\psi_a < \theta_{\max}$ can be derived by measuring the area of the small shaded portion in Fig. 2. The area defined by θ, and $\theta + \Delta\theta$ can be calculated as [8]

$$C = \frac{1}{2}\int_{\theta}^{\theta+\Delta\theta} l^2 \mathrm{d}\theta \tag{5}$$

Therefore the value of l is given by

$$l = \begin{cases} L, & \text{if } 0 < \theta \leq \theta_1 \\ \dfrac{D\tan(\psi_a)}{\sin(\theta) + \cos(\theta)\tan(\psi_a)}, & \text{if } \theta_1 < |\theta| \leq \theta_2 \\ L, & \text{if } \theta_2 < |\theta| \leq \pi \end{cases} \tag{6}$$

Using the geometry in Fig. 2, gives

$$\theta = \cos^{-1}\left[\frac{D}{l}\sin^2(\psi_a) \pm \frac{\cos(\psi_a)}{l}\sqrt{l^2 - D^2\sin^2(\psi_a)}\right] \tag{7}$$

Recall that, assuming the scatterers are uniformly distributed in the region a, b, c, d, e, f, the density area can be given by

$$f_{\text{dens}.} = \frac{1}{L^2(\pi + \theta_1 - \theta_2) + 2D\sin(\psi_a)\sqrt{L^2 - D^2\sin^2(\psi_a)}} \tag{8}$$

Using (5) and (8), the cumulative distribution function (cdf) of the AOA, $F(\theta)$ can be calculated as

$$F_{(\theta)} = \int_0^{\theta}\frac{f_{\text{dens}.}l^2}{2}\mathrm{d}\alpha \tag{9}$$

Considering the derivative of (9) and α as a dummy variable, the pdf of AOA, $p_{(\theta)}$ can be expressed as

$$p_{(\theta)} = \begin{cases} \dfrac{L^2}{A}, & \text{if } -\theta_1 < \theta \leq \theta_1 \\ \dfrac{[D\tan(\psi_a)]^2}{A[\sin(\theta) + \cos(\theta)\tan(\psi_a)]^2}, & \text{if } \theta_1 < |\theta| \leq \theta_2 \\ \dfrac{L^2}{A} & \text{if } \theta_2 < \theta \leq -\theta_2 \end{cases} \tag{10}$$

where

$$A = 2L^2(\pi + \theta_1 - \theta_2) + 4D\sin\left(\psi_a\sqrt{L^2 - D^2\sin^2(\psi_a)}\right) \tag{11}$$

3.2 Using directional antenna at both RS and MS

Considering the deployment of directional antenna at the RS and MS helps to reduce the Doppler effect, consequently improves the BER performance. The pdf of AOA of the received signal, $p_{(\theta)}$, when a directional antenna is deployed at the MS and pointing to the RS [10, 11] is given by

$$p_{(\theta)} = \begin{cases} \dfrac{1}{2\psi_m}, & \text{if } |\theta| < \psi_m \\ 0, & \text{otherwise} \end{cases} \tag{12}$$

where ψ_m is the beamwidth of the directional antenna at the MS. When using directional antennas at both the RS and MS sides, the pdf of AOA of the received signal, $p_{(\theta)}$, is derived by multiplying (10) and (12), which can be written as

$$p_{(\theta)} = \begin{cases} \dfrac{Q}{2\psi_m}\dfrac{L^2}{A}, & \text{if } |\theta| < \theta_2 \\ \dfrac{Q}{2\psi_m}\dfrac{[D\tan(\psi_a)]^2}{A[\sin(\theta) + \cos(\theta)\tan(\psi_a)]^2}, & \text{if } \theta_2 < |\theta| < \psi_m \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

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where Q is a constant and $p_{(\theta)}$ is the pdf of AoA of the received signal.

4 BER performance analysis

In this section, we derive the BER performance of OFDM systems in two-hop relaying system employing quadrature amplitude modulation (QAM) signals over Rayleigh fading channels in the presence of Doppler shift, $\Phi_{\text{Dop},r}$ impairment. The improvement in BER performance when directional antennas are employed at both the RS and the MS sides is then evaluated. The received signal on the kth subcarrier after passing through the first wireless relay hop, $r = 1$, can be expressed as [12]

$$Y_r[k] = H_r[k]X[k]\Phi_{\text{Dop},r}[0] + \beta_r[k] + W_r[k]$$

where $H_r[k]$ denotes the frequency-domain channel coefficients on the kth subcarrier, $k = 0, 1, \ldots, N_c - 1$, $X[k]$ is the frequency-domain transmitted signal, $\Phi_{\text{Dop},r}[0]$ is the Doppler shift impairments, and $W_r[k]$ is the additive white Gaussian noise (AWGN), which can be considered as a Gaussian random variable with zero mean and variance $\sigma^2_{W_r}$. $\beta_r[k]$ is the ICI signal with variance $\sigma^2_{\beta_r}$ and is given by

$$\beta_r[k] = \left(\sum_{m=0, m\neq k}^{N_c-1} H_r[m]X[m]\Phi_{\text{Dop},r}[m-k]\right) \tag{14}$$
$$m = 0, 1, \ldots, N_c - 1$$

The received signal at the end of the second-hop transmission, $r = 2$, can be expressed as [4]

$$Y_r[k] = H_r[k]Y_{r-1}[k]\Phi_{\text{Dop},r}[0] + \beta_r[k] + W_r[k]$$

which can be expressed, after substituting the received signals on the kth subcarrier, $k = 0, 1, \ldots, N_c - 1$, in the $(r-1)$th hop, $Y_{r-1}[k]$, as

$$\begin{aligned} Y_r[k] = {} & H_{r-1}[k]H_r[k]X[k]\Phi_{\text{Dop},r-1}[0]\Phi_{\text{Dop},r}[0] \\ & + H_r[k]\beta_{r-1}[k]\Phi_{\text{Dop},r}[0] + H_r[k]W_{r-1}[k]\Phi_{\text{Dop},r}[0] \\ & + \beta_r[k] + W_r[k] \end{aligned} \tag{15}$$

where $H_r[k]$ and $H_{r-1}[k]$ are the frequency-domain channel coefficients on the kth subcarrier, $k = 0, 1, \ldots, N_c - 1$ for the first- and second-hop, respectively. $W_r[k]$ and $W_{r-1}[k]$ are the corresponding complex Gaussian noise with variances $\sigma^2_{W_r[k]}$ and $\sigma^2_{W_{r-1}[k]}$, respectively. $\beta_r[k]$ and $\beta_{r-1}[k]$ are the ICI terms caused by the loss of orthogonality between subcarriers as a result of Doppler shift in the first- and the second-hop as expressed in (14).

We assume that the data symbol $X[.]$ has an average power E_s normalised to one, and the phase rotation imposed by the channel $\Phi_{\text{Dop},r}[0]$ can be accurately estimated at each hop receiver, therefore (15) can be simplified as

$$\begin{aligned} Y_r[k] = {} & H_{r-1}[k]H_r[k]X[k] + H_r[k]\beta_{r-1}[k] \\ & + H_r[k]W_{r-1}[k] + \beta_r[k] + W_r[k] \end{aligned} \tag{16}$$

The signal-to-interference-plus-noise ratio (SINR) $\gamma_{r[k]}$ at the receiver side can be obtained using (16) as

4.1 Pdf of SINR

Considering the received signal at the end of the rth-hop transmission, $Y_r[k]$ above, the SINR expression for the case when $r = 1$ (first-hop) in (17), can be rewritten as

$$\gamma_{r[k]} = \frac{E\left[z^2\right]}{\sigma^2_{\beta_r[k]} + \sigma^2_{W_r[k]}} \tag{18}$$

$\gamma_{r[k]}$ is considered to be an exponential random variable, which have the pdf and the cdf defined, respectively, as

$$f_{\gamma_{r[k]}}(\gamma) = \frac{1}{\overline{\gamma}_{r[k]}} \mathrm{e}^{-\left(\gamma/\overline{\gamma}_{r[k]}\right)} \tag{19}$$

$$F_{\gamma_{r[k]}}(\gamma) = 1 - \mathrm{e}^{-\left(\gamma/\overline{\gamma}_{r[k]}\right)} \tag{20}$$

where $\overline{\gamma}_{r[k]} = E[\gamma_{r[k]}]$, and may be different for all k. The SINR is considered to be static when $\overline{\gamma}_{r[k]}$ is same for all k. On the other hand, frequency selectivity can be achieved by allowing different $\overline{\gamma}_{r[k]}$ for different k. The two-hop channel case can be modelled as an equivalent single-hop channel case whose SINR equivalent $\gamma_{eq[k]}$ is approximated as [13]

$$\gamma_{\text{eq}[k]} \simeq \min_{r=1,\ldots,R} \gamma_{r[k]} \tag{21}$$

Using the assumption that the hops are subject to independent but not necessarily identically distributed gives the cdf and pdf of $\gamma_{\text{eq}[k]}$ as

$$\begin{aligned} F_{\gamma_{\text{eq}[k]}}(\gamma) &= 1 - P\left[\gamma_r > \gamma, \ldots, \gamma_R > \gamma\right] \\ &= 1 - \prod_{r=1}^{R}\left[1 - F_{\gamma_{r[k]}}(\gamma)\right] \end{aligned} \tag{22}$$

Therefore the joint pdf of $\gamma_{\text{eq}[k]}(\gamma)$ for $R = 2$ hops is given by differentiating (22) as

$$f_{\gamma_{\text{eq}[k]}}(\gamma) = \sum_{r=1}^{R} f_{\gamma_{r[k]}}(\gamma) \prod_{j=1, j\neq r}^{R}\left[1 - F_{\gamma_{j[k]}}(\gamma)\right] \tag{23}$$

Substituting (19) and (20) into (23), the joint pdf of $\gamma_{\text{eq}[k]}$

$$\gamma_{r[k]} = \frac{E\left[\left|H_r[k]\right|^2\right]E\left[\left|H_{r-1}[k]\right|^2\right]}{E\left[\left|H_r[k]\right|^2\right]P_{\beta_{r-1}[k]} + E\left[\left|H_r[k]\right|^2\right]\sigma^2_{W_{r-1}[k]} + P_{\beta_r[k]} + \sigma^2_{W_r[k]}} \tag{17}$$

can be expressed as

$$f_{\gamma_{\mathrm{eq}[k]}}(\gamma) = \sum_{r=1}^{R}\left(\frac{1}{\overline{\gamma}_{r[k]}}\mathrm{e}^{-\gamma/\overline{\gamma}_{r[k]}}\right)\prod_{j=1, j\neq r}^{R}\left[1-\left(1-\mathrm{e}^{-\gamma/\overline{\gamma}_{j[k]}}\right)\right] \tag{24}$$

which can be simplified as

$$f_{\gamma_{\mathrm{eq}[k]}}(\gamma) = \sum_{r=1}^{R}\left(\frac{1}{\overline{\gamma}_{r[k]}}\mathrm{e}^{-\gamma/\overline{\gamma}_{r[k]}}\right)\prod_{j=1, j\neq r}^{R}\mathrm{e}^{-\gamma/\overline{\gamma}_{j[k]}} \tag{25}$$

After some manipulations, (25) can be rewritten as

$$f_{\gamma_{\mathrm{eq}[k]}}(\gamma) = \sum_{r=1}^{R}\left(\frac{1}{\overline{\gamma}_{r[k]}}\mathrm{e}^{-\gamma\sum_{j=1}^{R}\overline{\gamma}_{j[k]}^{-1}}\right) \tag{26}$$

This can be simplified as

$$f_{\gamma_{\mathrm{eq}[k]}}(\gamma) = G\mathrm{e}^{-\gamma G} \tag{27}$$

where

$$G = \textstyle\sum_{r=1}^{R}\overline{\gamma}_{r[k]}^{-1}$$

4.2 Probability of error expression analysis

The probability of error $P_e(k)_r$ expression of the system over Rayleigh fading channels for M-ary QAM modulation scheme [14] can be written as

$$P_e(k)_r = \int_0^{\infty}\frac{1}{\sqrt{M}\log_2\sqrt{M}} \times \sum_{j=1}^{\log_2\sqrt{M}}\sum_{n=0}^{v_j}p_n^j\,\mathrm{erfc}\left(\sqrt{g_n\gamma}\right)f_{\gamma_{\mathrm{eq}[k]}}(\gamma)C\left(T_s\right)\mathrm{d}\gamma \tag{28}$$

where

$$v_j = \left(1-2^{-j}\right)\sqrt{M}-1,$$

$$p_n^j = (-1)^{\left\lfloor\frac{n2^{j-1}}{\sqrt{M}}\right\rfloor}\left(2^{j-1}-\left\lfloor\frac{n2^{j-1}}{\sqrt{M}}+\frac{1}{2}\right\rfloor\right),$$

$$g_n = \frac{(2n+1)^2 3\log_2 M}{2M-2},$$

M is the constellation order, erfc is the complementary error function (see [15, Eq. (4A.6)]), and $\lfloor . \rfloor$ is the floor. The correlation function $C(T_s)$ of the Rayleigh fading channel with the pdf of AOA, $p_{(\theta)}$ [16, 17] can be expressed as

$$C(T_s) = \int_{-\pi}^{+\pi}p_{(\theta)}\mathrm{e}^{\mathrm{j}2\pi f_d T_s\cos\theta}\mathrm{d}\theta \tag{29}$$

Equation (29), can be rewritten as

$$C\left(T_s\right) = \int_{-\pi}^{+\pi}p_{(\theta)}\mathrm{sinc}^2(f_d T_s\cos\theta)\mathrm{d}\theta \tag{30}$$

Substituting (26) and (30) into (28) gives

$$P_e(k)_r = \int_0^{\infty}\int_{-\pi}^{+\pi}\frac{1}{\sqrt{M}\log_2\sqrt{M}}\sum_{j=1}^{\log_2\sqrt{M}}\sum_{n=0}^{v_j}p_n^j\,\mathrm{erfc}\left(\sqrt{g_n\gamma}\right) \times \sum_{r=1}^{R}\overline{\gamma}_{r[k]}^{-1}\mathrm{e}^{-\gamma\sum_{r=1}^{R}\overline{\gamma}_{r[k]}^{-1}}p_{(\theta)}\mathrm{sinc}^2(f_d T_s\cos\theta)\mathrm{d}\gamma\mathrm{d}\theta \tag{31}$$

which can be rearranged as

$$P_e(k)_r = \frac{1}{\sqrt{M}\log_2\sqrt{M}}\sum_{j=1}^{\log_2\sqrt{M}}\sum_{n=0}^{v_j}p_n^j \times \int_0^{\infty}\int_{-\pi}^{+\pi}\mathrm{erfc}\left(\sqrt{g_n\gamma}\right)\sum_{r=1}^{R}\overline{\gamma}_{r[k]}^{-1}e^{-\gamma\sum_{r=1}^{R}\overline{\gamma}_{r[k]}^{-1}} \times p_{(\theta)}\mathrm{sinc}^2\left(f_d T_s\cos\theta\right)\mathrm{d}\gamma\mathrm{d}\theta \tag{32}$$

Performing the first integral with respect to γ and using $G = \sum_{r=1}^{R}\overline{\gamma}_{r[k]}^{-1}$, the $P_e(k)_r$ formula can be expressed as

$$P_e(k)_r = \frac{1}{\sqrt{M}\log_2\sqrt{M}}\sum_{j=1}^{\log_2\sqrt{M}}\sum_{n=0}^{v_j}p_n^j\left(1-\sqrt{\frac{g_n G^{-1}}{1+g_n G^{-1}}}\right) \times \int_{-\pi}^{+\pi}p_{(\theta)}\mathrm{sinc}^2\left(f_d T_s\cos\theta\right)\mathrm{d}\theta \tag{33}$$

Consequently, the average SER can be expressed as [18]

$$\mathrm{SER}_r = \frac{1}{N_c}\sum_{k=0}^{N_c-1}P_e(k)_r \tag{34}$$

Finally, the BER in a two-hop relaying system can be estimated using the derived SER_r expression as

$$\mathrm{BER}_r = \frac{\mathrm{SER}_r}{\log_2(M)} \tag{35}$$

Table 1 Parameters of the BWAN simulated

Parameter	Value
N_c	256
bandwidth	20 MHz
operating frequency	3.5 GHz
data subcarriers	192
guard subcarriers	64
total symbol duration	55.5 µs
modulation scheme	QAM

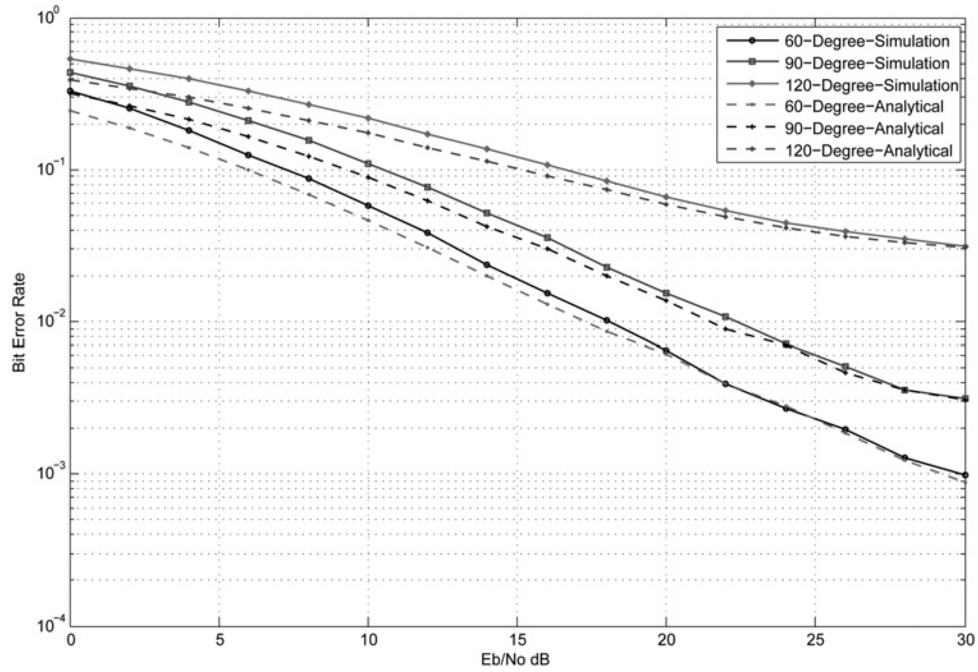

Fig. 3 *BER performance with perpendicular directional antenna configuration,* $-\varpi$, $R = 2$, *speed = 50 km/h (city traffic)*

5 Simulation results

In this section, we present simulation results to verify the effects of directional antennas on the BER performance of OFDM systems in MMR channels. We consider a two-hop relaying system and adopt the network model presented in Fig. 1. The channel between each transmitter and receiver is modelled as a Rayleigh fading channel. The simulated MS speeds are 50 and 100 km/h which results in Doppler shift values, $f_d = 320$ and 650 Hz. The antenna configurations used in the simulations are 60°, 90° and 120°, parallel and perpendicular orientations to the direction of the motion. The BER performance of MMR system with directional antennas are then obtained for different MS speeds. The parameters of the BWAN used in the simulation are listed in Table 1.

We obtain representative BER performance curves for both the perpendicular and parallel antenna orientation, for each and every one of the antenna configurations 60°, 90° and 120° used, thus depicting the most possible scenarios for directional antenna deployments in broadband MMR systems.

Figs. 3 and 4 illustrate the BER performance of MMR system (two-hop case) employing directional antennas with two different antenna orientations, perpendicular and parallel orientations, respectively. Both analytical and

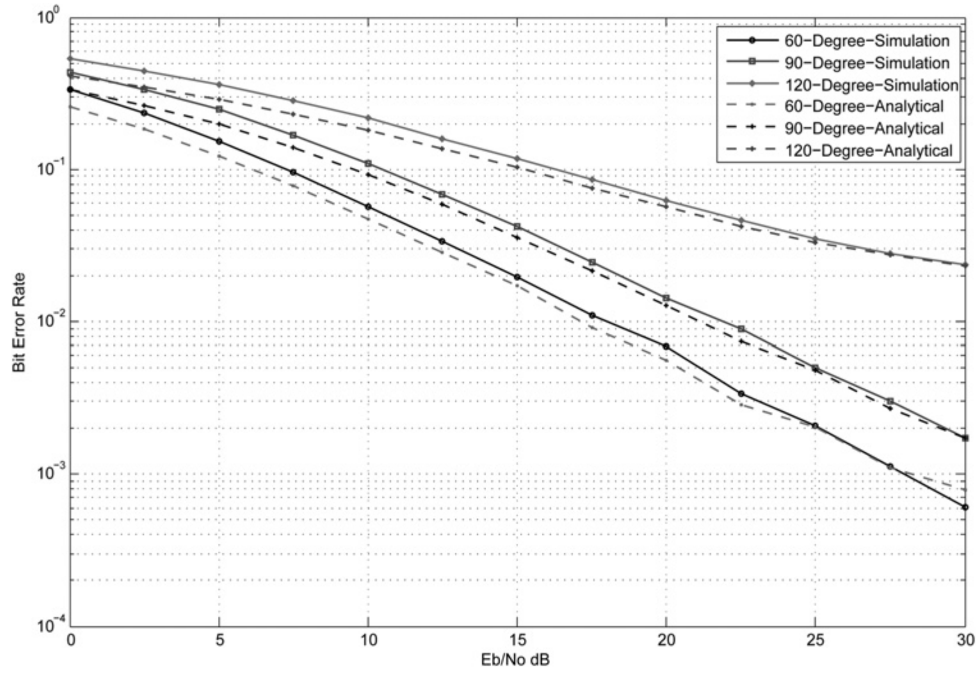

Fig. 4 *BER performance with parallel directional antenna configuration,* ϖ, $R = 2$, *speed = 50 km/h (city traffic)*

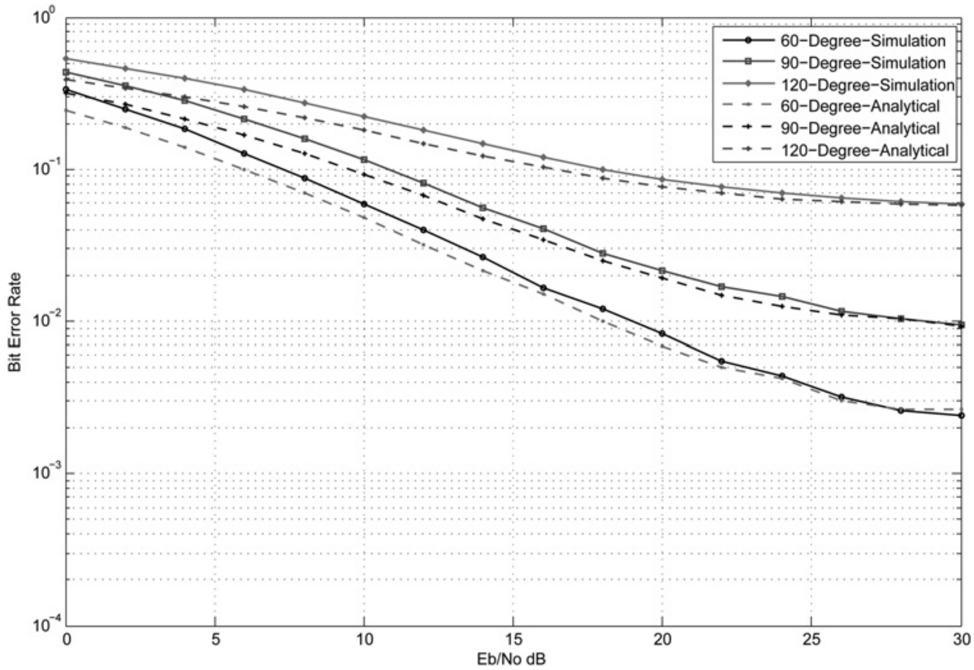

Fig. 5 *BER performance with perpendicular directional antenna configuration,* $-\varpi$, $R = 2$, *speed = 100 km/h (highway traffic)*

simulation results are included in these figures. The analytical results are not very tight at low-SNR because the approximation used in (21) is somewhat loose in low-SNR regimes, but they become more accurate in high-SNR allowing reasonable asymptotic estimates using the derived expressions. The MS speed used for these simulations is 50 km/h, representing city traffic. This speed translates to a maximum Doppler shift of $f_d = 320$ Hz. For the perpendicular elements (Fig. 3), it is interesting to note that when a directional antenna is used, the BER is significantly enhanced as the beamwidth of the directional antenna is reduced from 120° to 60°. For example at $E_b/N_0 = 30$ dB, whereas the BER of the MMR system with 120° beamwidth has reached an error floor around 10^{-1} because of the MMR channel impairments, the BER performance of the system for the case of 60° directional antenna has improved to 10^{-3} at same E_b/N_0, which means a two-hop transmission at practically acceptable error rate is achievable with directional antenna with beamwidth of 60° for the perpendicular antenna orientation. For parallel elements (Fig. 4), the BER performance of the MMR system is similarly enhanced for smaller antenna beamwidth compared to the larger ones. Comparing the respective results for the perpendicular and vertical antenna orientation cases in Figs. 3 and 4, we observe that the parallel antenna orientation case has better BER

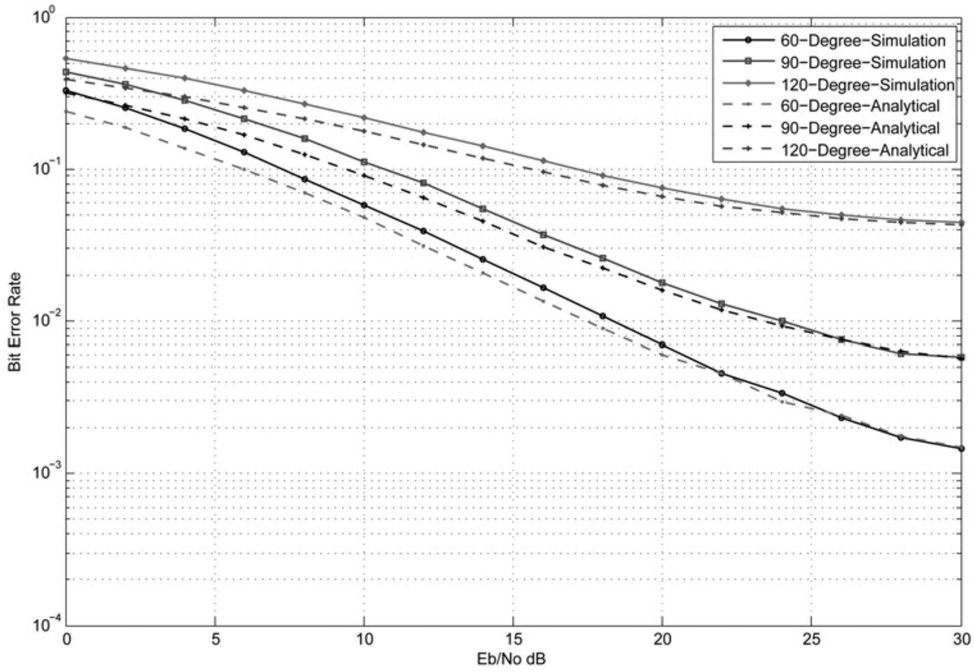

Fig. 6 *BER performance with parallel directional antenna configuration,* ϖ, $R = 2$, *speed = 100 km/h (highway traffic)*

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enhancements for the MMR system than the perpendicular orientation case. However in general, directional antennas can effectively enhance the performance of MMR system to practically acceptable error rate level in both cases, for a moderate vehicular speed such as 50 km/h (representing in intra-city traffic).

Figs. 5 and 6 present, respectively, the BER performance of MMR system employing directional antennas for the cases of perpendicular and parallel antenna orientations, after the simulated MS speed is increased to 100 km/h, representing highway traffic. Since the Doppler shift becomes larger as the MS's speed increases, the BER performance of the system in Figs. 4 and 5 are more degraded compared to their counterpart results for lower MS speed in Figs. 3 and 4. The general observation from Figs. 4 and 5 is that for both the parallel and perpendicular antenna orientations in high vehicular speed, directional antenna is still able to provide some BER performance enhancement for the MMR system as the antenna beamwidth is reduced from 120° to 60°. However, since the BER performance exhibit error floors somewhere above 10^{-3} for this case, additional BER performance enhancement techniques such as encoding schemes would need be combined with the directional antenna deployment in order to obtain practically acceptable BER performance in high vehicular speeds. Finally, comparing the analytical and simulation results in Figs 3–6, it is generally observed that the effects of approximating the equivalent multi-hop SINR as in (21) on the analytical results becomes less appreciable at high-SINR.

6 Conclusion

This paper investigates the possibility of deploying directional antennas at both the MS and RS sides in MMR systems, for mitigating the BER performance degradation caused by the Doppler shift experienced over MMR channels. A directional antenna at either side of the communication link eliminates some multipath components, therefore the narrower the beamwidth of the directional antenna, the more the multipath components that would be canceled. Different MS speeds and antenna orientations were used to evaluate the effectiveness of the proposed solution. We show that the proposed scheme generally enhances the BER performance of MMR system as the beamwidth of the directional antenna is reduced from 120° down to 60°, and that significant enhancements are possible for both the perpendicular and parallel antenna orientations, even though the latter is observed to provide better BER enhancement than the former. Also, we observed that significant BER enhancements are observed at low and high MS speeds using this solution. However for high vehicular speeds, the system exhibits significant error floor above 10^{-3} for all antenna beamwidth studied, which suggests that extra BER enhancements techniques will be required in addition to directional antenna technique to achieve practically acceptable BER for this case.

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