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Algorithm to Differentiate Indoor MTC Devices

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Abstract

Typical machine type communication (MTC) applications require the MTC devices to be located in enclosed spaces, such as the cars or basement. These indoor MTC devices would experience an additional 20 dB penetration loss on the radio interface with respect to normal LTE devices. To guarantee the coverage of these indoor MTC devices, it is necessary to differentiate them from normal LTE devices and adopt dedicated compensation mechanisms. In this paper, we develop a unified differentiating algorithm suitable for any fading channels which are characterized by the probability distribution functions of receiving envelopes. Taking Rayleigh fading channel as an example, we carry out the performance analysis of this algorithm. The influences of additional penetration loss and proportion of indoor MTC devices on the error rate of discrimination is given out. In addition, we also proposed a dedicated power compensation mechanism with TTI bundling for indoor MTC devices to evaluate the link performance of this algorithm. Numerical results show that the proposed algorithm works well under Rayleigh fading and has a good ability to adapt the fast fading environment with profound stability.

Keywords: *Machine Type Communications; penetration loss; coverage improvement*

1. Introduction

Machine type communications (MTC) is defined as machine to machine communications over cellular mobile networks. It is an important revenue stream for operators and has a huge market potential from the perspective of operators [1, 2]. Typical application scenarios of MTC include smart metering like smart grid and smart home, Internet of vehicles, Internet of things, wireless sensor networks, etc. Most of these applications require the MTC devices to be installed in enclosed spaces, such as the basements of residential buildings or locations shielded by foil-backed insulation, metalized windows or traditional thick-walled building construction. These indoor MTC devices would experience a significantly higher penetration loss on the radio interface than normal LTE devices. According to the measurements of Vodafone, on average the additional loss is about 20dB [3]. Therefore, coverage improvement techniques both in uplink and downlink dedicated to this kind of MTC devices are needed, as conventional mobile networks are not intended to cover these areas with high penetration loss.

Prior to any coverage improvement, how to differentiate these indoor MTC devices with higher penetration loss from normal LTE devices is of prime important. This is because additional 20 dB penetration loss is always beyond the compensation scope of most of conventional mobile cellular networks. It needs some dedicated power compensation mechanisms, such as TTI bundling [4]. Dedicated mechanism requires preliminary user identification. Therefore, instead of focusing on the power compensation mechanism, in this paper, we develop a unified algorithm to differentiate the indoor MTC devices from normal LTE devices under fading channels and set the foundations for further design of dedicated power compensation mechanisms. This kind of different treatment on indoor MTC devices and normal LTE devices helps to improve the power

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efficiency of the compensation mechanisms as it avoids blindly using the same compensation mechanism to all devices.

The remainder of the paper is organized as follows. In Chapter II, we present the layout of the problem and elaborate on the necessary to differentiate indoor MTC devices from normal LTE devices. In Chapter III, we present the theoretical analysis of the proposed differentiating algorithm and give out the optimum threshold of partition. In Chapter IV, we evaluate the performance of the proposed differentiating algorithm under Rayleigh fading channel for verification and illustration. Numerical simulations show that it has a good ability to adapt the fast fading environment with profound stability. Accompanying with a power compensation mechanism with TTI bundling, reduced bit error rate (BER) of indoor MTC devices is achieved. Chapter V concludes this paper.

2. Layout of Problem

Here we consider a simple but realistic application scenario. MTC devices coexist with normal LTE devices and they share the same carrier network. Both MTC devices and normal LTE devices distribute uniformly within the coverage area of evolve node base (eNB). The coverage area of eNB is a circular area with radius R that has received power above a given threshold which depends on transmitted power, carrier frequency, propagation environment, receiver sensitivity and *etc*. [5]. The maximum allowable propagation loss of MTC devices is the same as that of normal LTE devices. However, indoor applications induce additional 20 dB penetration loss for MTC devices which causes the coverage of eNB for indoor MTC devices to reduce from R to R_1, as shown in Figure 1.

In case of this, indoor MTC devices within the radius of R_1 can still communicate effectively to eNB with the conventional power compensation mechanism applying to normal LTE devices, while the ones in the radius of R_1 to R may suffer from a serious deterioration of signal quality and lose connection to the network. So, how to guarantee the coverage of the MTC devices in the radius of R_1 to R? Current solutions require either an increased densification of sites or remedial solutions at the receiver such as small home area networks, meshes or external antennas with additional antenna feeds [6-8]. These solutions are often impractical, may require additional spectrum, and will lead to greater expense. In addition, without taking the different coverage radius of indoor MTC devices and normal LTE devices into account, this also makes them quite power inefficient. This is because normal LTE devices in the radius of R_1 to R would not suffer from additional 20dB penetration loss. They do not need additional power compensation, but the indoor MTC devices within this area definitely need. This implies it is not a good idea to adopt the same mechanism for indoor MTC devices and normal LTE devices. Therefore, a cost effective and power efficient compensation mechanism dedicated to indoor MTC devices in the radius of R_1 to R is needed.

To implement dedicated power compensation mechanism for indoor MTC devices, we must recognize them first. This is a classical bivariate classification problem which has been studied for a long time. However, the bivariate classification problems under different propagation environments have not been studied by former statisticians. Therefore, in this paper, we develop a unified algorithm to differentiate indoor MTC devices with higher penetration loss from normal LTE devices under fading channels. Besides this, we also propose a power compensation mechanism with TTI bundling and verify the effectiveness of the proposed differentiating algorithm.

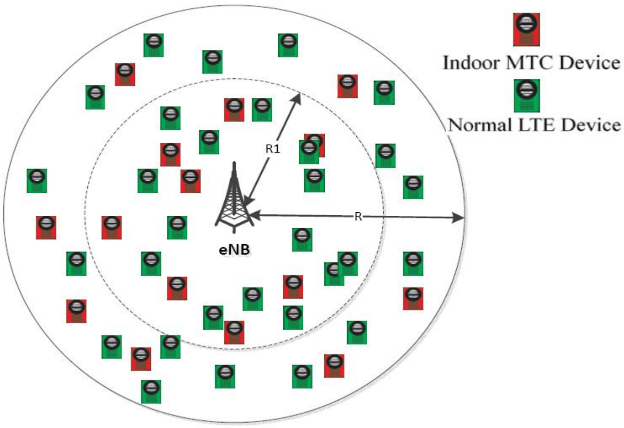

Figure 1. Layout of the Problem

3. Theoretical Analysis

Propagation loss along the radio path is predicted by propagation models and can be divided into three distinct parts: path loss, the slow variation due to shadowing and the rapid variation in the signal due to multipath effects [9-11]. Typical path loss prediction models include free space propagation model, Okumura's and Lee's model for macro cell, COST model for outdoor microcell and etc. The slow variation due to shadowing can be well approximated by log-normal distribution. The probability distribution functions (PDF) account for the receiving envelopes of the sum of multipath component includes Rayleigh distribution, Rice distribution, Nakagami-m distribution and etc.

Here we adopt Lee's model to obtain the optimal threshold that discriminates indoor MTC devices from normal LTE devices with minimum misjudgment rate. Lee model is one of the most commonly used propagation models because of its aptitude to achieve good prediction accuracy and still remains relatively simple and intuitive [12]. The median loss at a distance d is given by [10]

$$L = L_0 + \gamma \log d + F \tag{1}$$

where, L_0 is the median transmission loss at a range of 1km; d is the distance from base station to mobile terminals; γ is the slope of the path loss curve, the unit is dB/decade; for free space, $\gamma = 20$; $F = 20\log r$ is an adjustment factor depending on fading environment and r is the envelope of the receiving signal at mobile terminal, the PDF of which could be any ones given in [13].

Suppose the propagation loss of normal LTE devices and indoor MTC devices are

$$A = L_0 + \gamma \log d \ \text{ and } \ B = L_0 + \gamma \log d + m \tag{2}$$

respectively, where m is the additional penetration loss of indoor MTC devices. As shown in Figure 2, the ratio of error discrimination is

$$\min \ \ E = \alpha \int_{10^{(L_T - A)/20}}^{+\infty} p(r)dr + (1\text{-}\alpha) \int_{0}^{10^{(L_T - B)/20}} p(r)dr \tag{3}$$

where, $p(r)$ is the PDF of the envelope r of the receiving signal at mobile terminal, L_T is the optimum threshold to differentiate indoor MTC devices from normal LTE devices and α is the proportion of normal LTE devices.

By using Lagrange formula, the optimum threshold L_T is

$$\frac{p\left(10^{(L_T-B)/20}\right)}{p\left(10^{(L_T-A)/20}\right)}=\frac{\alpha}{1-\alpha}10^{\frac{m}{20}} \tag{4}$$

As long as the PDF of r is known, L_T is obtainable. Thus, Equation (4) could be applicable under any fading channels. However, the analytical solution of Equation (4) is not always possible except for some simple fading distributions. The main reason is the complexity and nonlinearity of $p(r)$. Therefore, in most cases, such as composite multipath/shadowing channel model, we have to resort numerical algorithms to obtain L_T.

Fortunately, a description of channel in terms of Rayleigh distributed fast fading and lognormal-distributed shadow fading is usually adequate for the evaluation of most communication systems. And the analytical solutions of L_T exist. If $p(r)$ follows Rayleigh distribution, then

$$L_T=A+10\log_{10}\left(\frac{2\sigma^2\ln\left(\frac{\alpha}{1-\alpha}10^{\frac{m}{10}}\right)}{1-10^{-\frac{m}{10}}}\right) \tag{5}$$

If $p(r)$ follows log-normal distribution, then

$$L_T=\frac{A+B}{2}+\frac{2\cdot\ln\left(\frac{\alpha}{1-\alpha}\right)\cdot(20\sigma\log_{10}e)^2}{m} \tag{6}$$

Equation (6) can easily be explained as that if $\ln(r)$ is normally distributed with zero mean and variance σ^2, then $F=20\log r$ is also normally distributed with zero mean and variance $(20\sigma\log e)^2$, the optimal threshold equals the classical bivariate classification problem with Gaussian noise.

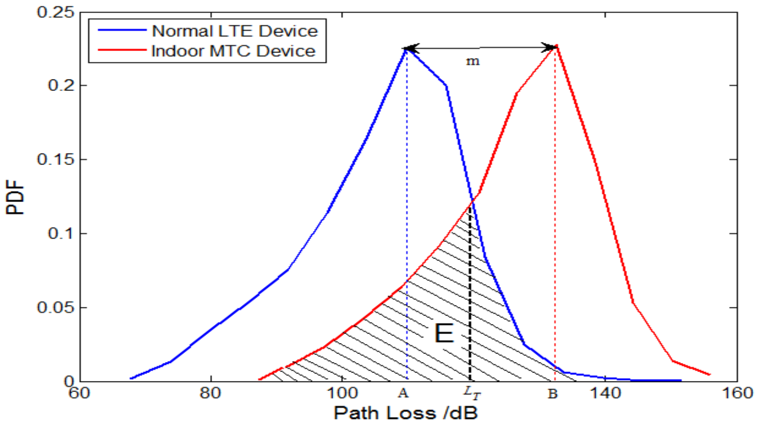

Figure 2. Ratio of Error Discrimination

4. Numerical Analysis

In Chapter III, we present the method to calculate the optimal threshold, which depends on the distance between base station and mobile terminals, penetration loss, the depth of fading and proportion of normal LTE devices, to differentiate indoor MTC devices from normal LTE devices. In this chapter, taking Rayleigh fading channel as an example, we propose a power compensation scheme for indoor MTC devices to demonstrate how to incorporate the above analysis into the design of dedicated compensation mechanism. This scheme first discriminates indoor MTC devices by usage of the aforementioned optimal threshold as a reference and then adopts a dedicated power control mechanism by usage of TTI bundling. The reason why we choose TTI bundling is that the low cost requirements of MTC devices forbid the use of other effective but expensive methods, such as space diversity with multi-antenna or frequency diversity with larger bandwidth.

4.1. Work Procedure and Parameters Setup

Figure 3 illustrates the work procedure of the proposed scheme. And Table I illustrates the necessary parameters to carry out the following Monte-Carlo simulation. It represents the typical application scenario of LTE in the context of MTC.

The proposed scheme consists of two separate processes, namely, the discrimination process and the compensation process. The discrimination process is a simple comparing process. Suppose all mobile terminals are able to receive the reference signal from eNB successfully. Mobile terminals measure instantaneous path loss based on CRS (cell-specific reference signal) or DRS (dedicated reference signal) and feed it back to eNB through CQI (channel quality indication). eNB calculates the optimal path loss threshold L_T which is derived from Equation (5) and broadcast it in the cell. If the measured path loss of mobile terminal is smaller than L_T, the legacy power control of LTE is adopted. Otherwise, dedicated power compensation mechanism with TTI bundling is adopted. Here, we only consider the uplink power compensation, as most MTC applications are uplink-centric and draw more attentions of operators [12].

The dedicated power compensation process with TTI bundling works as follows. When transmitted power of MTC devices $P_t < P_{c\max}$ ($P_{c\max}$ is the upper limit of transmit power of mobile terminals), the volume of compensation depends on the number of NACK and retransmission times $N_{i,TimeOut}$, which partly presents the depth of channel fading. When the transmitted power of MTC device $P_t = P_{c\max}$, it is of no use to increase the transmission power. In case of this, TTI bundling is adopted to get additional time diversity gain without introducing any extra costs. It is a technique bundling a set of consecutive TTIs (transmission time interval) and transmit them simultaneously.

Prior to implementation, another two issues should be considered. The first is that as the depth of fading can reach up to 20-40 dB, normal LTE device may be misjudged as indoor MTC device in the duration of deep fade. To eliminate the influence of deep fast fading, it is better to take the AND operation on the decision of several successive intervals. The final decision on whether the *i*th mobile terminal is an indoor MTC device becomes as

$$D_i(t) = I_i(t) \text{ and } I_i(t-T) \text{ ... and } I_i(t-nT) \tag{7}$$

where, T is the period of channel measurements (0.5ms), n is the number of AND operation and

$$I_i(t) = \begin{cases} 1, \text{ if } L_i(t) > L_T \\ 0, \text{ otherwise} \end{cases} \tag{8}$$

is the decision on a single round. When $D_i(t) = 1$, it indicates that the *i*th mobile terminal is an indoor MTC device and the dedicated power compensation scheme should be triggered.

The second is that the optimal threshold decided form Equation (4)-(6) is a constant and remains unchanged, which cannot tune its value timely to adapt these time-variant channels. To obtain adaptive optimal threshold of L_T, mobile terminals feedback $L_i(t)$

and $D_i(t)$ to eNB with CQI, eNB updates the optimal threshold L_T by means of calculating the quantile of $\{L_i(t)\}$. The quantile is determined as

$$p(t) = \frac{N_p}{N} = \frac{\sum D_i(t)}{N} \tag{9}$$

where, N_p is the number of indoor MTC devices in this decision round, N is the number of total terminals. The key idea is to use the instantaneous proportion of indoor MTC device to rectify L_T. In simulation, the threshold eNB broadcasted is the rectified L_T.

Table 1. Parameters Setup For Monte-Carlo Simulation

Parameter	Value
Cell type	Urban Macro cell (Inter-site distance = 500 m)
Channel model	Extended Typical Urban Channel
Max number of MTC devices	18000
Max number of normal LTE devices	2000
Max Doppler shift	10 Hz
System bandwidth	10 MHz
Carrier frequency	2 GHz
Type of modulation	QPSK
Max transmit power of eNB	23 dBm or 200 mW
Max transmit power of terminals $P_{c\max}$	14 dBm
Max retransmission time of HARQ	8
Size of TTI bundling	4
Round Trip Time (RTT)	8 ms
Median transmission loss (L_0)	128.1
Slope of path loss (γ)	37.6
Penetration loss	1-20 dB

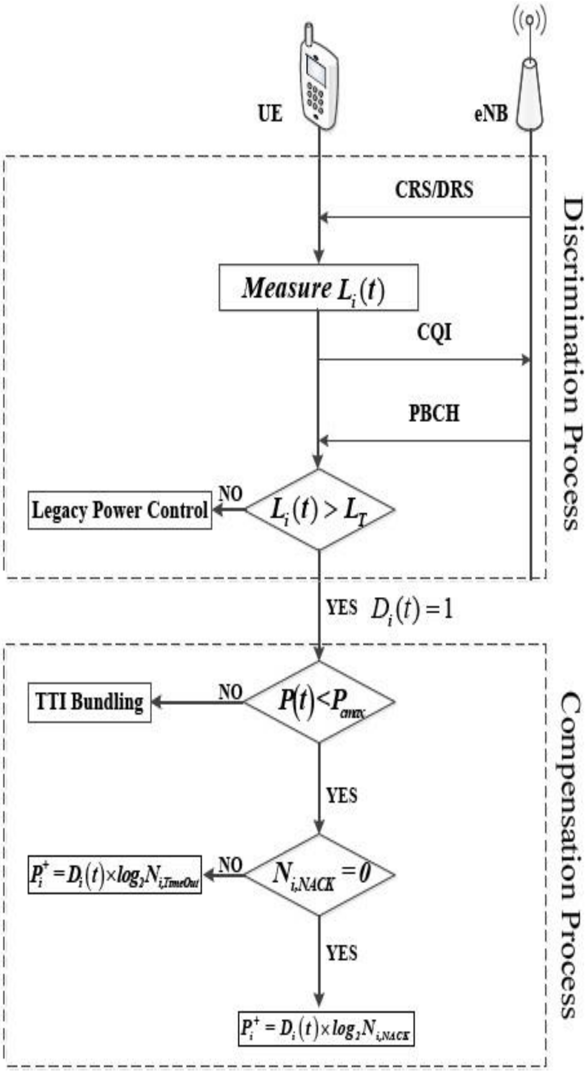

Figure 3. Work Proceduare of Proposed Scheme

4.2. Numerical Results

Figure 4 shows the influence of penetration loss m and the proportion of indoor MTC devices $1-\alpha$ on the misjudgment rate of the discrimination process. It shows that: 1) The misjudgment rate is a convex function of the proportion of indoor MTC devices $1-\alpha$ and when $1-\alpha=0.5$, it reaches the maximum. 2) The increase of penetration loss m tends to reduce the misjudgment rate. This is because the larger the path loss gap between normal LTE devices and indoor MTC devices, the easier the discrimination process. When the penetration loss reaches up to 20 dB or higher, the misjudgment rate levels off and the influence of m and $1-\alpha$ can be neglected. 3) In practice, it is predicted that the ratio of MTC traffic to H2H service will be 10-30 in 2020 [4]. Thus, the proportion of indoor MTC devices is between 0.91 and 0.97. It is observed that in this range the misjudgment rate is around 0.05. Hence, the proposed algorithm to differentiate indoor MTC devices can offer a good performance under realistic scenario of mixed MTC and H2H services.

Figure 5 shows the theoretical L_T of the proposed differentiating algorithm when $m=20$ dB and $\alpha=0.1$. The blue and red circle represents the path loss of normal LTE devices and indoor MTC devices derived from Equation (2). The dotted red line is the L_T derived from Equation (5). It shows that L_T has the shape of log function and successfully differentiates indoor MTC devices from normal LTE devices. With the result of Monte-Carlo simulation, we get to know that misjudgment rate is around 0.03. In practice, the continuous measurement of the distance between eNB and mobile terminals would increase the implementation complexity of the proposed algorithm. Furthermore, as most of MTC devices have the characteristics of low mobility. Therefore, we organize the mobile terminals into K groups according to their distance from eNB to approximate the mathematical expression of the optimal threshold L_T. Namely, we divide the cell into K concentric circles with different but appropriate radius. The decision on the radius of each circle is to reduce the error of fitting the step curve in Figure 6 to the log curve in Figure 5. Terminals belonging to the same group are assigned with the same threshold. Figure 6 gives an example to divide the cell into 9 areas. Although this may increase the misjudgment rate, it definitely reduces the complexity of implementation. In case of this, the adaptive adjustment of the thresholds introduced in Equation (9) now applies to these 9 areas. Monte-Carlo simulation shows that the instantaneous threshold is always around the optimal one. Figure 6 shows us a snapshot of the simulation process and proves the stability and flexibility of the proposed algorithm to adapt fast fading.

Figure7 shows that the performance of the cascaded power compensation mechanism. It shows that under the same bit error rate (BER), the signal to noise (SNR) difference between the mechanism with TTI bundling and the standard power compensation mechanism is about 2-3 dB. This implies 2-3dB improvement of the proposed mechanism.

In general, the proposed differentiating mechanism could effectively differentiate indoor MTC devices from normal LTE devices and can be easily incorporated in the design process of power compensation.

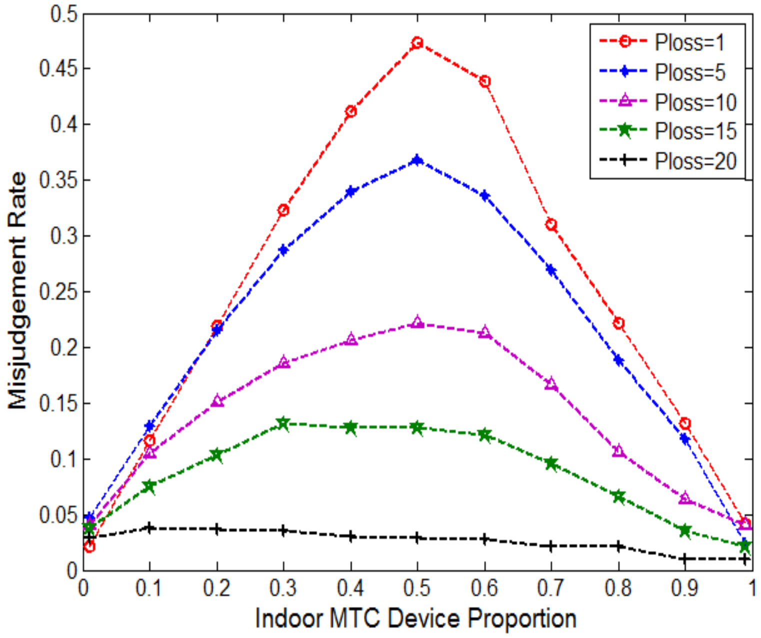

Figure 4. Misjudgment Rate of Proposed Differntiating Algorithm

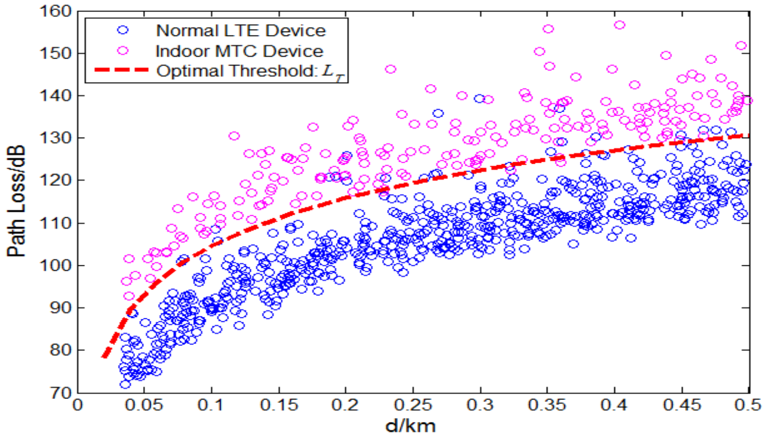

Figure 5. Theoretical L_T of Proposed Differentiating Algorithm

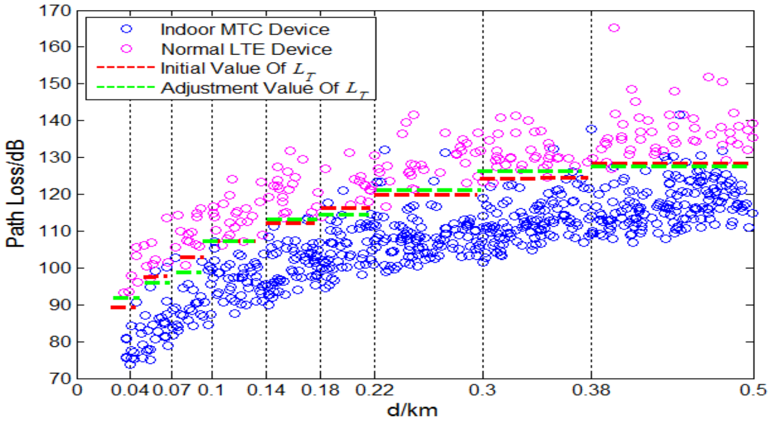

Figure 6. Grouping Techniques to Approximate Optimal L_T

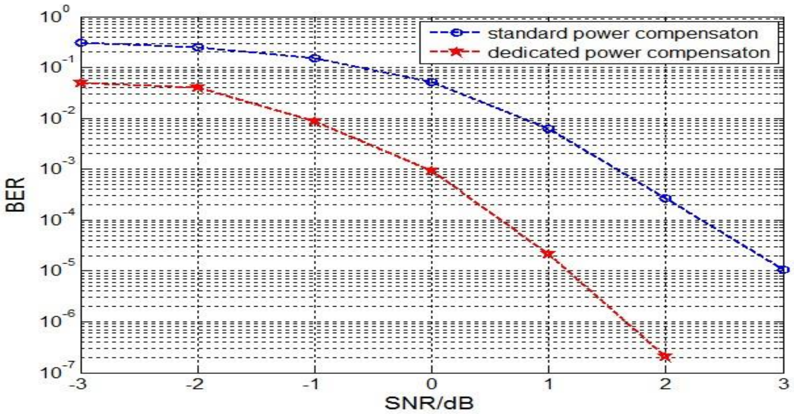

Figure 7. Bit Error Rate of Cascaded Power Compensation Mechanism

5. Conclusions

In this paper, we develop an algorithm suitable to differentiate indoor MTC devices from normal LTE devices under any fading channels which are characterized by the probability distribution functions of receiving envelopes. To verify the effectiveness of this algorithm, taking the Rayleigh fading as an example, we present the performance of this algorithm and the influences of additional penetration loss and proportion of indoor MTC devices on the error rate of discrimination. In addition, we also propose a dedicated power compensation mechanism with TTI bundling for indoor MTC devices to evaluate the link performance of this algorithm. Numerical results show that the proposed algorithm works well under Rayleigh fading and has a good ability to adapt the fast fading environment with profound stability.

Acknowledgements

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