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Interference Mitigation Using Adaptive Schemes in Body Area Networks

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Abstract Considering the medical nature of the information carried in body area networks (BANs), interference from coexisting wireless networks or even other nearby BANs could create serious problems on their operational reliability. As practical implementation of power control mechanisms could be very challenging, link adaptation schemes can be an efficient alternative to preserve link quality while allowing more number of nodes to operate simultaneously. This paper proposes several interference mitigation schemes such as adaptive modulation as well as adaptive data rate and duty cycle for BANs. Interference mitigation factor is introduced as a measure to quantify the effectiveness of the proposed schemes. These schemes are relatively simple and well-suited for low power nodes in BANs that might be operating in environments with high level of interference.

Keywords Body area networks · Link adaption · Interference mitigation · Adaptive modulation

1 Introduction and Background

Body area networks (BANs) which consist of RF-enabled wearable and implantable sensory nodes are poised to be a promising interdisciplinary technology with novel uses in pervasive healthcare, personal entertainment and consumer electronics. Radio-enabled implantable sensor nodes offer a revolutionary set of applications among which we can point to smart pills for precision drug delivery, glucose monitors and eye pressure sensing systems. Similarly, wearable sensor nodes offer an attractive set of applications such as medical/physiological monitoring (e.g., electrocardiogram, temperature, respiration, heart rate, and blood pressure), disability assistance and human performance management. Integration of BAN with the existing information infrastructure will create a truly pervasive environment for many of these critical applications with great impact on improving the quality of life. Some recent advances in microelectronics indicate that the technology to achieve ultra-small, and ultra-low power devices for these applications are within reach. However, numerous technical challenges including energy efficiency, reliability, coexistence and security issues still need to be resolved.

Considering the mobile nature of BANs along with their proposed operational frequency bands, these networks are expected to coexist with other wireless devices that are operating in their proximity [1]. Therefore, interference from coexisting wireless networks or even other nearby BANs could create a serious problem on the reliability of the network operation. Similarly, rapid movements of body parts are another reason that could greatly affect the quality of a link between a sensor node and the controller.

The interference among nodes of a single BAN can be avoided by using multiple access techniques, e.g., time-division multiple access (TDMA). However, when several individuals wearing BAN are within close proximity of each other, interference may occur since no coordination across separate networks exists in general. Therefore, the increasing number of such BANs in short proximity of each other could result into performance degradation of the communication link. Even when there are a small number

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of adjacent BANs, the received signal strength from nearby interfering BANs may be too high, resulting in overwhelming of the desired signal within a particular BAN; and therefore, causing performance degradation in detecting or decoding the desired signal.

To maintain the link quality [e.g., desired received signal strength level or signal to interference and noise ratio (SINR)] in such varying communication channels, efficient power control mechanisms have been proposed [2–4]. However, practical implementation of such mechanisms for BAN applications could be very challenging, particularly in fast changing scenarios when the SINR is varying due to the movement of multiple nearby BANs. In these scenarios, controlling the transmit power in order to keep the desired link quality (i.e., power control) might not be effective. Moreover, the effectiveness of the power control to keep the desired link quality may be even worse when interference is significant; for example, in a scenario with high transmit power from other coexisting wireless networks. Another scenario highlighting the possible problem with power control will be described in Sect. 3.

Advanced signal processing using interference cancellation techniques [5, 6] has also been proposed to minimize the impact of interference. However, there are two main problems with such techniques especially when it comes to their application in BAN. First is the high complexity of the receiver which makes the implementation of interference cancelation impractical unless the number of nodes is very small. Complexity is especially a critical issue for nodes in BANs. As they mainly rely on battery power, prolonging the lifetime of these nodes are of prime importance. The second problem is that some interference cancellation schemes require knowledge of the channel condition (such as attenuation, phase, and delay) between each of the interferers and the receiver. Obtaining accurate estimates of the channel condition is extremely difficult for BANs.

Due to the possible inefficiency of power control and the stated problems with interference cancellation, interference mitigation techniques [6] can be an attractive alternative, particularly in an environment with high interference level. Some interference mitigation techniques require complex advanced signal processing. However, in this paper, we focus on techniques such as adaptive modulation as well as adaptive data rate and duty cycle, which involve low computational complexity. The proposed schemes represent suitable candidates for mitigating interference in BANs.

The remainder of this paper is organized as follows. Section 2 describes the SINR in BANs. Section 3 provides an outline of link quality and adaption using a simulation scenario for a single BAN. The proposed techniques of interference mitigation for multiple BANs are presented in Sect. 4. Simulation results and conclusions are discussed in Sects. 5 and 6 respectively.

2 Overview of the System

In a BAN, several nodes form a network with a star topology as shown in Fig. 1. These nodes could share the same spectrum in a TDMA manner based on the proposed IEEE 802.15.6 standard. Therefore, there is no interference among the nodes within a single BAN. However, interference may come from other sources, such as other nearby BANs or other coexisting non-BAN wireless networks. Let's assume that there are M networks in the system, including one desired BAN and $M-1$ interferers. In the analysis, we focus on the performance at the controller (or master) node of the desired BAN. The Signal to Interference plus Noise Ratio (SINR) [7] at the controller node of BAN i is defined as:

$$SINR_i = \frac{S_i}{N + \sum_{j \neq i} S_j} \tag{1}$$

where S_i is the desired received power at controller node of BAN i, S_j is undesired received power from interferer j, and N is additive noise power. The interference signal may come from any place or any coexisting wireless network including other BANs that are not coordinated with the BAN i. Analyzing a special scenario with pre-specified locations will not provide sufficient information in order to judge effectiveness of mitigation schemes. Here, we assume that the desired signal power and total interference plus noise power information are available at the controller node of the desired BAN. Based on the available SINR, the controller node may command other nodes to select appropriate interference mitigation schemes.

3 Link Quality in a BAN

Several statistical channel models for BANs have been considered in the IEEE 802.15.6 standard group. These

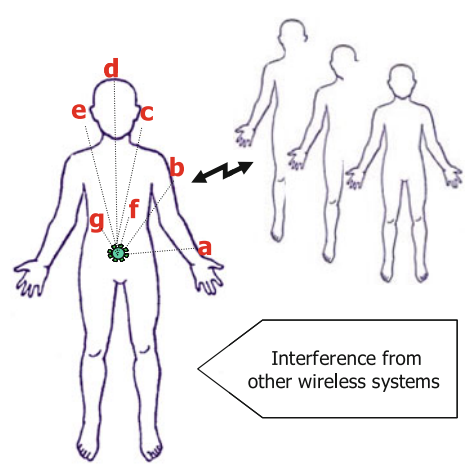

Fig. 1 A BAN with other potential interferers

Table 1 S_{21} for the seven communication links displayed in Fig. 1

Location	d (mm)	S_{21} (dB)	$P_{rx}^{\max}$ (dBm)	P_{tx}^{req} (dBm)
a: left hand	388.3	−52.6	−36.2	−32.4
b: left arm	369.9	−55.9	−39.5	−29.1
c: left ear	683.2	−62.6	−46.2	−22.4
d: top head	700.3	−65.7	−49.3	−19.3
e: right ear	686.0	−69.3	−52.9	−15.7
f: right chest	409.2	−61.1	−44.7	−23.9
g: left chest	210.2	−62.8	−46.4	−22.2

models are applicable to different usage scenarios in various frequency bands [7]. Measurement data for specific scenarios are also available in the literature [8, 9]. In this paper, we have chosen not to use the statistical models to calculate the path loss. Instead, we focus on a specific scenario that covers most likely usage locations for wearable nodes in a BAN. We then perform simulation to obtain the path loss. Figure 1 shows the simulation scenario, where a controller node is located in front of the body around the waist (green circle) and seven sensor nodes are located at different locations labeled a, b,…, g. All transmit or receive antennas are operating at the 2.4 GHz frequency and are located 14 mm above body surface. Considering dielectric properties of human body, the mean values of S_{21} for the seven links between the transmitter and the receivers are calculated using the platform described in [10]. The S_{21} (in linear scale) is defined by Eq. 2 and the results of the simulation are listed in the third column of Table 1.

$$S_{21} = \frac{P_{rx}}{P_{tx}} \tag{2}$$

In the simulation, a transmit power of one watt is used to calculate S_{21}. Note that S_{21} is independent of the transmit power. After the simulation, we find out the maximum local specific absorption rate (SAR) is 36.73 W/kg. To meet the FCC regulation limit of 1.6 W/kg [11], the source transmit power should be reduced to $1.6/36.73 = 0.0436$ W (or 16.4 dBm). The maximum local SAR value is a function of the gap between the transmit antenna and the body surface [12]. When the gap becomes smaller, the SAR value increases and the maximum transmit power should be reduced. Using the maximum transmit power of 16.4 dBm, the received power is calculated as below and listed in the fourth column of Table 1.

$$P_{rx}^{\max}(\text{dBm}) = P_{tx}^{\max}(\text{dBm}) + S_{21}(\text{dB}) \tag{3}$$

To save battery life and to minimize interference level, the transmit power may be limited to a certain level in order to maintain a minimum acceptable link quality. For example, to maintain the received signal level at −85 dBm without considering any interference and noise, the power may be transmitted only at the level listed in the fifth column of Table 1. Those values can be calculated by using the following equation.

$$P_{tx}^{req}(\text{dBm}) = P_{rx}^{req}(\text{dBm}) - S_{21}(\text{dB}) \tag{4}$$

As mentioned before, a practical and efficient transmit power control might be difficult to achieve particularly in a fast changing BAN channel (e.g., body motion and posture change). Moreover, in a multi-BAN situation, the following scenario could occur and further degrade signal quality at a receiver. When the signal fades at the intended receiver, the power control mechanism will boost the power of the associated transmitter to maintain the appropriate link quality. At the same time, the boosted signal causes more interference to other networks in the vicinity. Due to elevated interference levels, the nodes at the surrounding BANs also need to increase their transmit power to maintain their link qualities. This, in turn, adversely affects the signal quality at the original receiver; forcing higher transmit-power by the associated transmitter and similarly in all nearby networks. Eventually, none of the links will be able to operate with an acceptable quality.

To avoid this phenomenon, simple interference mitigation schemes could play an important role to reduce the impact of elevated ambient interference. The principle of the interference mitigation scheme is basically to reduce transmit power by using link adaption schemes in order to maintain minimum link quality. Operating at lower transmit power will decrease interference to other adjacent networks; therefore, resulting in better coexistence of more number of BANs in the vicinity of each other. One should keep in mind that using interference mitigation schemes may cause other performance degradation, such as lower throughput or data rate. Our proposed interference mitigation schemes include adaptive modulation as well as adaptive data rate and adaptive duty cycle.

4 Interference Mitigation for Multiple Adjacent Bans

The purpose of interference mitigation is to lower the average transmit power using link adaption schemes while maintaining link quality at the cost of lower throughput or data rate. However, it may allow for more simultaneously active networks to coexist in an interference rich environment. During a normal or low interference scenario, all networks may operate in their normal mode. Once the interference level is evaluated, one of the interference mitigation schemes needs to be activated. Here, we propose interference mitigation factor (IMF) as a measure of the effectiveness of such schemes. The IMF is defined as the

reduction of transmit power level using a mitigation scheme compared with the normal (i.e., original) operation mode. In the next section, we will describe algorithms and IMF measures for adaptive modulation, data rate, and duty cycle.

4.1 Adaptive Modulation

In this paper, a set of MPSK schemes (such as BPSK, QPSK and 8PSK) for adaptive modulation have been considered due to their similar detection mechanism at the receiver. These modulation schemes can be easily implemented with minor modifications for link adaption. Given a pre-specified BER, the required SINR may be determined based on channel conditions. For higher SINR in normal operation, the 8PSK scheme is chosen to obtain higher bit rate. With power control, if SINR decreases, the transmit power needs to increase to maintain the same BER at 8PSK data rate. Instead, with an adaptive modulation scheme, QPSK or BPSK may be used to maintain the same BER. This will lower the required transmit power level, which will result in less interference to all other nodes across multiple BANs in the system.

Two thresholds $\{\gamma_H, \gamma_L\}$ are introduced to determine the range of adaption for the set of modulation schemes. When SINR is higher than the higher threshold, 8PSK scheme is used. Likewise, BPSK is chosen when SINR is lower than the lower threshold. QPSK is used when the SINR is between the two thresholds. Since SINR may be changing rapidly in practice, a weighting factor α_M is introduced to maintain a running average of SINR over a fast changing channel. The algorithm for adaptive modulation scheme is described below.

Algorithm 1: Adaptive Modulation

Require: Modulation schemes $S = \{BPSK, QPSK, 8PSK\}$
Require: γ (measured SINR), thresholds $\{\gamma_H, \gamma_L\}$
Initial: $S = 8PSK$, $\bar{\gamma}$
1. $\bar{\gamma} \leftarrow \alpha_M \cdot \gamma + (1 - \alpha_M) \cdot \bar{\gamma}$
2. if $\bar{\gamma} < \gamma_L$, **then** $S = BPSK$,
3. if $\bar{\gamma} > \gamma_H$, **then** $S = 8PSK$,
4. else $S = QPSK$,
5. end if
6. γ (measured SINR)
7. **Go Back to** 1.

For adaptive modulation, the IMF, when 8PSK is used as normal mode, is defined as:

$$IMF(\text{dB}) = P_{8PSK}(\text{dBm}) - P_S(\text{dBm}) \tag{5}$$

where P_{8PSK} and P_S are the required transmit power for 8PSK and the chosen modulation scheme, S, respectively. The IMF is a function of SINR and channel condition.

4.2 Adaptive Data Rate

The second mitigation scheme is adaptive data rate. The data rate is divided into M steps between maximum and minimum values $R_{\max}$ and $R_{\min}$. The data rate is operated at $R_{\max}$ in the normal mode and is changed by comparing a weighted sum of SINR and target SINR. The weighted sum of SINR may smoothly reduce significant variation of SINR by selecting an appropriate value of α_R between 0 and 1. Also, a hysteresis factor of Δ_R is used to minimize possible ping-pong effect between the two data rates. The algorithm for interference mitigation using adaptive data rate is proposed below.

Algorithm 2: Adaptive Data Rate

Require: M data rates $\{R_1 = R_{\max} > R_2 > \cdots > R_M = R_{\min}\}$
Require: $\hat{\gamma}$ (target SINR), γ (measured SINR)
Initial: $R_1, \bar{\gamma} = \hat{\gamma}$
1. $\bar{\gamma} \leftarrow \alpha_R \cdot \gamma + (1 - \alpha_R) \cdot \bar{\gamma}$
2. if $\bar{\gamma} < \hat{\gamma} - \Delta_R$, **then**
$R_f \leftarrow \begin{cases} R_{m+1} & \text{if} \quad m < M \\ R_M & \text{if} \quad m = M \end{cases}$
3. **else if** $\{\bar{\gamma} > \hat{\gamma} + \Delta_R\}$, **then**
$R_f \leftarrow \begin{cases} R_{m-1} & \text{if} \quad m > 1 \\ R_1 & \text{if} \quad m = 1 \end{cases}$
4. **else** $R_f \leftarrow R_m$
5. **end if**
6. $R_m \leftarrow R_f$, γ (measured SINR)
7. **Go Back to** 1.

The relationship between the transmit power (S) and data rate (R) is:

$$\frac{E_b}{I_o + N_o} = \frac{S}{I_o + N_o}\frac{1}{R} \tag{6}$$

where E_b, I_o, and N_o are bit energy, interference and noise spectral density, respectively. To keep the same required $E_b/(I_o + N_o)$, the transmit power and the data rate must be proportional. The higher the data rate, the more transmit power is required. Therefore, the IMF, when R_1 is the data rate in the normal mode, is defined as:

$$IMF = 10\log\frac{S_1}{S_f} = 10\log\frac{R_1}{R_f}(\text{dB}) \tag{7}$$

where S_1 and S_f are the corresponding transmit powers for data rates R_1 and R_f, respectively.

4.3 Adaptive Duty Cycle

The third mitigation scheme is adaptive duty cycle. The duty cycle (η) of a BAN (Eq. 8) may be adjusted by controlling the window of active (T_{active}) and inactive (T_{inactive}) periods while keeping the sum of the two periods constant. Longer inactive periods will cause less average interference level to other networks in the neighborhood. The duty cycle can be controlled based on the interference level from other BANs.

$$\eta = \frac{T_{\text{active}}}{T_{\text{active}} + T_{\text{inactive}}} \tag{8}$$

The duty cycle is divided into K steps between maximum and minimum values $\eta_{\max}$ and $\eta_{\min}$. The duty cycle is normally operated at $\eta_{\max}$ and is changed by comparing a weighted sum of SINR and target SNIR. The weighted sum of SINR may smoothly reduce significant variation of SINR by selecting appropriate values of α_C between 0 and 1. Again, a hysteresis factor of Δ_C is introduced to minimize possible ping-pong effect between two duty cycles. The algorithm for interference mitigation using adaptive and discrete duty cycle is proposed below.

Algorithm 3: Adaptive Duty Cycle

Require: K duty cycles $\{\eta_1 = \eta_{\max} > \eta_2 > \cdots > \eta_K = \eta_{\min}\}$
Require: $\hat{\gamma}$ (target SINR), γ (measured SINR)
Initial: $\eta_1, \bar{\gamma} = \hat{\gamma}$
1. $\bar{\gamma} \leftarrow \alpha_C \cdot \gamma + (1 - \alpha_C) \cdot \bar{\gamma}$
2. if $\bar{\gamma} < \hat{\gamma} - \Delta_C$, **then**
$$\eta_f \leftarrow \begin{cases} \eta_{k+1} & \text{if} \quad k < K \\ \eta_K & \text{if} \quad k = K \end{cases}$$
3. **else if** $\{\bar{\gamma} > \hat{\gamma} + \Delta_C\}$, **then**
$$\eta_f \leftarrow \begin{cases} \eta_{k-1} & \text{if} \quad k > 1 \\ \eta_1 & \text{if} \quad k = 1 \end{cases}$$
4. **else** $\eta_f \leftarrow \eta_k$
5. **end if**
6. $\eta_k \leftarrow \eta_f$, γ (measured SINR)
7. **Go Back to** 1.

For adaptive duty cycle method, the IMF, when η_1 is the duty cycle in the normal mode, is defined as:

$$IMF = 10 \log \frac{\eta_1}{\eta_f} (\text{dB}) \tag{9}$$

5 Results

In the simulation, the channel models [7] of body surface to body surface and body surface to external nodes at 2.4 GHz band are adopted. The simulation scenario is a star topology as shown in Fig. 1. The mean path loss of the desired signal is set to 60 dB obtained from Table 1. The shadowing is a lognormal distribution with standard deviation of 3.80 and 6.89 dB for a hospital room and an anechoic chamber, respectively [7]. The interference sources may be from many coexisting BANs or non-BANs networks. Let's assume that there exists co-channel interference from three other BANs and from one non-BAN. The non-BAN interferer may employ technologies like WiFi, Bluetooth, etc. Due to higher transmit power; the non-BAN interferer usually has higher interference level than the BAN ones. Under the same environment, we also assume that the shadowing of all interferers is log-normally distributed with the standard deviation of 6.84 dB [7]. Then, the SINR values may be generated based upon the above lognormal distributions. Note that the distribution of interference plus noise is not log-normally distributed after summing noise and interference power. However, an approximation of lognormal distribution may be made if one of interference signals is dominated compared with others. The average IMF performance will be evaluated in terms of signal to BAN interference ratio plus noise, S/I_{BAN} and non-BAN to BAN interference ratio, $I_{non-BAN}/I_{BAN}$.

5.1 Adaptive Modulation

In the simulation, adaptive modulation schemes include BPSK, QPSK, and 8PSK. To select the thresholds of γ_H and γ_L, BER performance of modulation schemes over AWGN channel is used. At BER = 0.1 %, the required SNR values are 6.8, 9.8 and 14.8 dB for BPSK, QPSK and 8PSK, respectively [13]. Therefore, we choose $\gamma_H = 12$ dB, $\gamma_L = 8$ dB.

The interferers include three BAN interferers and one non-BAN interferer, where each of the interference signals is log-normally distributed in either a hospital room or an anechoic chamber in Figs. 2 and 3. As expected, given the same S/I_{BAN}, the more non-BAN interference level, the more average IMF where BPSK is better candidate than others since BPSK requires lower transmit power for a given BER. To compare the environment between a hospital room and an anechoic chamber, the hospital room, which has lower standard deviation of shadowing, has higher average IMF at lower S/I_{BAN} values. On the other hand, at higher S/I_{BAN} values, the anechoic chamber has higher average IMF.

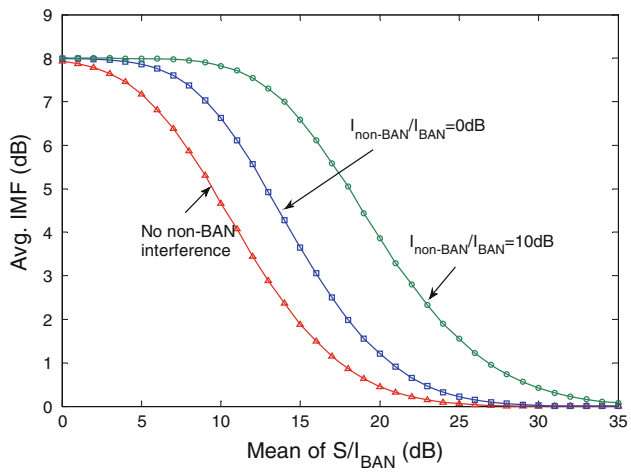

Fig. 2 Interference mitigation using adaptive modulation at $\alpha_M = 0.8$ (hospital room)

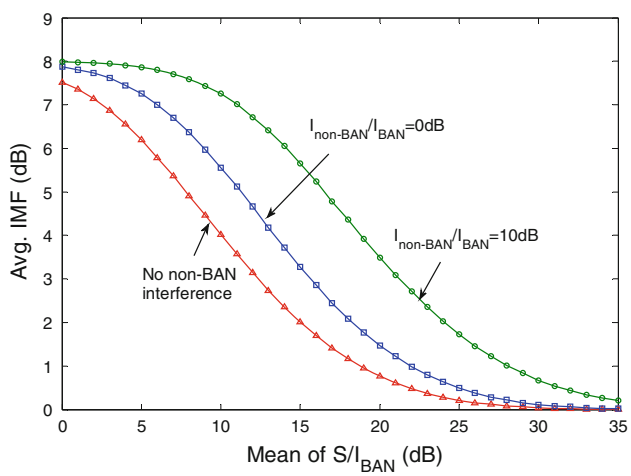

Fig. 3 Interference mitigation using adaptive modulation at $\alpha_M = 0.8$ (anechoic chamber)

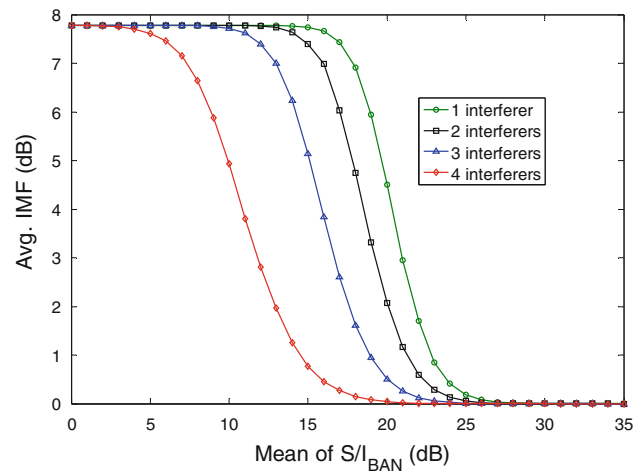

Fig. 4 Interference mitigation using adaptive data rate (hospital room)

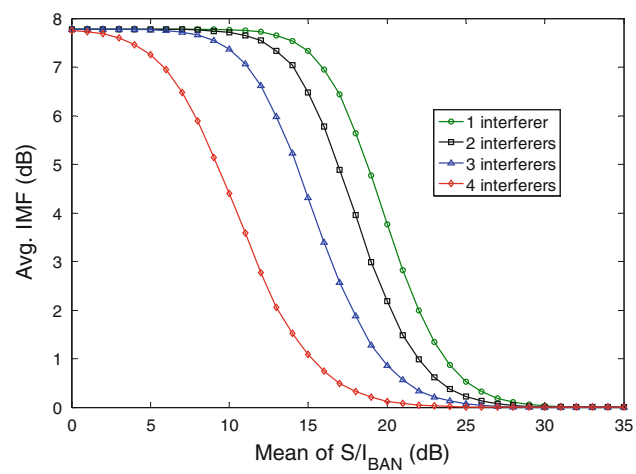

Fig. 5 Interference mitigation using adaptive data rate (anechoic chamber)

5.2 Adaptive Data Rate

IMF in terms of mean of SINR and number of BAN interferers using adaptive data rate scheme in either hospital room or anechoic chamber are shown in Figs. 4 and 5. The mean of SINR at x-axis is the ratio of signal to one BAN interference plus noise. All the BAN interfering signals have the statistics with the same mean and standard deviation. The total interference power is calculated by summing total interference power, where the number of BAN interferers is from 1 to 4. The set of data rates is assumed to be {600, 400, 200, 100} kbps while $\alpha_R = 0.5$, $\Delta_R = 2.0$ and $\hat{\gamma} = 12$ dB. The data rates may be chosen in accordance with the quality of service (QoS) requirements. As expected, the more number of BAN interferers, the more the average IMF, which requires lower data rate. For lower mean of SINR cases, higher average IMF values are observed. Also, for a given average SINR, the average IMF value at an anechoic chamber is smaller than that at a hospital room, where the standard deviation of SINR at a hospital room is smaller. This effectively means a lower data communication rate for the link at a hospital room.

5.3 Adaptive Duty Cycle

Figure 6 depicts the IMF results versus the choices of weighting and hysteresis parameters when adaptive duty cycle is used. The selected duty cycles are 20, 10, 5 and 3 % and the target SINR is 12 dB. Again, these values may be selected based on the QoS requirements. As observed in Fig. 6, the IMF value does not heavily rely on the values of weighting and hysteresis parameters even in a wide range of non-BAN interference level. However, the selection of the weighting factor of $\alpha_C = 1$ may result in frequent changes of the duty cycle.

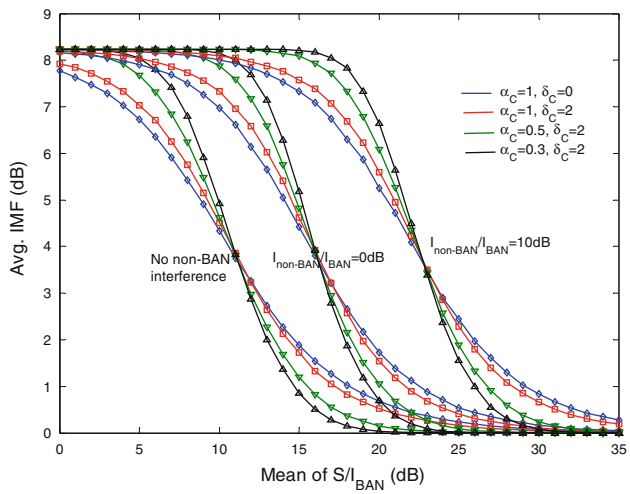

Fig. 6 Interference mitigation using adaptive duty cycle at anechoic chamber

6 Concluding Remarks

In this paper, we have proposed several interference mitigation schemes including adaptive modulation as well as adaptive data rate and duty cycle. A quantitative measure called IMF was used to evaluate the effectiveness of these schemes in BANs application. These schemes are relatively simple and well-suited for very low power nodes in BANs that might be operating in environments with high interference level. Theoretical study and modeling in assessing the performance of these schemes for multiple BAN scenarios and also their implementation complexity is necessary in the future.

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