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Stochastic Geometry Analysis of IEEE 802.15.6 UWB WBAN Performance with Game Theoretical Power Management

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***Abstract*—Inter-network interference in ultra-wideband (UWB) wireless body area networks (WBANs) is analyzed using stochastic geometry with the objective of quantifying the inherent interference tolerance of UWB WBANs in terms of the bit error probability. Such networks are expected to be common in the IoT segment of 5G networks and our methodology may be extended to other network configurations. Our results show that the amount of interference that can be tolerated depends on the node density of a Poisson point process and the transmission power. Moreover, decreasing the number of pulses per burst while transmitting a bit may increase the interference tolerance. On the other hand, UWB WBANs cannot tolerate significant amounts of interference in networks of ultra-densely deployed nodes. In these situations, there will be a significant amount of inter-network interference, and it is essential to adjust the power levels of all the nodes. With this objective, the transmission power of all nodes is decreased and their levels are determined by using a game theoretical approach; specifically with a non-cooperative continuous-kernel game. These optimized power levels not only reduce interference but also enhance the energy efficiency, which is of critical importance for WBANs.**

***Index Terms*—WBANs, stochastic geometry, error probability, game theory.**

I. Introduction

The presence of densely distributed wireless nodes is expected to result in significant interference within 5th generation (5G) mobile networks. Although a centralized control mechanism for all nodes may coordinate the users and prevent the interference, this results in very high complexity. Indeed, it is not realistic to completely eliminate the interference, so there will always be some remaining interference. It is crucial to determine this interference power level in wireless networks, because such interference is the main impediment that limits performance. However, obtaining the appropriate amount of interference power is very challenging for heterogeneous networks due to ultra-dense deployment of nodes. Modeling the interference statistically is more appropriate especially for densely distributed nodes in which the number and locations of nodes are not known precisely. For this purpose, stochastic geometry is a good tool to analyze the interference statistically [1]. Stochastic geometry can be used to obtain the statistical properties of interference by considering the wireless nodes as a random collection of points.

One basic network architecture within the 5G/IoT family, that is especially vulnerable to interference is wireless body area networks (WBANs). The IEEE 802.15.6 WBAN standard defines low power, reliable communication that can be employed as a health and fitness tracker, among other applications. Although the sensors within WBANs have a short range, different WBANs can adversely affect each other such as in a hospital, concert hall or stadium in which people are in close proximity with each other. Although there are three operating modes including narrowband, ultra-wideband (UWB) and human body communications, we consider UWB communications since UWB systems are inherently more tolerable to interference [2] than the other modes.

IEEE 802.15.6 UWB WBANs have been recently studied for energy efficiency see, e.g., [3]-[7]. However, none of these studies consider the interference among different WBANs and determine the tolerance of UWB systems to the level of interference. Although the range of a WBAN is several meters [8], interference will occur whenever there are many people in close proximity. Although a plethora of recent studies working on inter-network interference for WBANs exists [9]-[12], they do not model the interference using stochastic geometry. In [13]-[14] the inter-WBAN interference problem is modeled using stochastic geometry, however, these references do not take into account the UWB communication within WBANs. Of course, reducing the interference is even more important than modeling the interference. One technique for efficient interference mitigation is based on game theory and there are some studies that utilize game theory to control inter-WBAN interference, but without a stochastic geometry analysis [15]-[16].

The contributions of this paper are the following: (1)-Obtaining a closed form expression of bit error probability for UWB WBANs by using stochastic geometry to determine the impact of inter-WBAN interference. (2)-Characterizing the performance loss in terms of symbol error rate (SER) with the node density around a hub and determining the trade-off between the processing gain and the interference tolerance of UWB communication, and (3)-Implementation of a non-cooperative game theoretical solution based on power management among nodes to compensate for the large performance loss of UWB WBANs when there is a high node density in the medium by using the results of our stochastic geometry analysis.

The paper is organized as follows. In Section II, the system model is presented and the problem is formulated in Section III. The impact of inter-WBAN interference is analyzed by stochastic geometry with its numerical results in Section IV. After observing the interference impediment, a game theoretical solution is given in Section V. The paper ends with the concluding remarks in Section VI.

II. System Model

In this section, a one-hop star network topology of a WBAN is considered, which has one hub and a number of nodes, which is similar to the model in [3]-[4]. According to this scenario, every node contends with other nodes to transmit and the hub decides who will transmit. The fundamental difference of the model in this study from the prior art is the fact that there are many WBANs and the sensors of different WBANs are in close proximity. This results in inter-WBAN interference, as exemplified in Fig. 1 by the dashed lines.

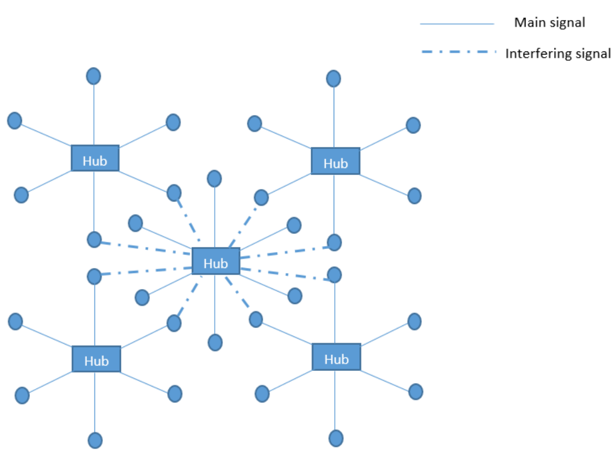


Fig. 1. Many WBANs that are close to each other

Energy efficiency is one of the primary concerns for WBANs, therefore binary pulse position modulation is generally preferred in the IEEE 802.15.6 UWB PHY [17], since it minimizes complexity and ensures low power operation. Note that symbols and bits are the same thing for binary pulse position modulation and can be used interchangeably throughout this work. There are N_w pulse positions for each symbol time T_{sym} such that the duration of a pulse position T_w is calculated as $T_w = T_{sym}/N_w$. Moreover, there are N_{cpb} number of pulses per burst, i.e., $T_p = T_w/N_{cpb}$ where $N_{cpb} \in \{1, 2, 4, 8, 16, 32\}$. Notice that the processing gain can then becomes $N_{cpb}N_w$ [18]. N_{cpb} is utilized to adjust the processing gain, because $N_w = 32$ is fixed in the standard [17].

Pulses are generated at 499.2 MHz yielding a receiver front end whose equivalent noise bandwidth W_{rx} is 499.2 MHz. The pulse energy is $\epsilon_p = \epsilon_b/N_{cpb}$ where ϵ_b is the bit energy. A non-coherent energy detector is considered with equally likely bits. Accordingly, the energy is collected within a time and frequency window, and a decision is made with an appropriate detector threshold [19]. The performance metric for the evaluation of interference tolerance is the bit error probability at the output of this detector as in [3]

$$P_b = Q\left(\sqrt{\frac{1}{2}\frac{(h\epsilon_b/N_0)^2}{h\epsilon_b/N_0 + N_{cpb}T_wW_{rx}}}\right) \tag{1}$$

where N_0 is the noise power spectral density and h is the channel gain, which is a complex Gaussian distributed random variable.

III. Problem Statement

Sensors placed on around or inside the human body that constitutes a WBAN can be coordinated in a one-hop star topology with appropriate protocols. Accordingly, there are many sensors connected to one hub such that each sensor can transmit its own data to the hub. In this model although every node contends for the medium, the hub works as a controller and prevents intra-WBAN interference. On the other hand, there can be many different WBANs, i.e., many people in a limited area that are close to each other. In this paper, each of those WBANs is considered to be acting individually instead of cooperating and coordinating with other networks, thus the hub of one WBAN can interfere with other sensors located on other WBANs, so inter-WBAN interference is inevitable. The situation becomes even worse in a crowded area such as hospital, concert hall or stadium where the sensors pertaining to one person may interfere with a number of other sensors.

One intrinsic interference avoidance property of IEEE 802.15.6 is inherent in the UWB PHY layer. Since the average interference power P_{int} can be written as

$$P_{int} = \epsilon_{int}R_{data} \tag{2}$$

where ϵ_{int} is the average interference level that affects each bit and R_{data} is the data rate, the interference level per transmitted bit energy decreases with increasing bandwidth or data rate. The same idea can be simply justified in the frequency domain by Parseval's theorem

$$\int_{-\infty}^{\infty}|x(t)|^2dt = \frac{1}{2\pi}\int_{-\infty}^{\infty}|X(\omega)|^2d\omega \tag{3}$$

where $X(\omega)$ is the Fourier transform of $x(t)$. Then, interference can spread among frequencies for a constant interference power $\int_{-\infty}^{\infty}|x(t)|^2dt$. Therefore, it can be interesting to observe the impact of inter-WBAN interference on the performance of the error probability of IEEE 802.15.6 UWB WBANs or the interference tolerance of UWB WBANs.

There can be many wireless nodes that interfere with each other in a wireless medium and determining the exact interference power on the received signal is impossible. Even predicting the number and location of terminals is challenging. Therefore, it is reasonable to model the interference statistically and stochastic geometry is a good tool for this task [1]. Poisson point processes, which are one of the basic building blocks of stochastic geometry, can model the number of people around a person or the number of inter-network interferers around one WBAN. In this direction, the average interference power of inter-WBAN interference is found by using fundamental principles of stochastic geometry and its effect is observed in the symbol error probability of a non-coherent energy detector.

In a densely deployed wireless medium, it is nearly impossible to completely mitigate the interference while simultaneously satisfying the low latency requirement. Therefore, efficient techniques are highly desirable in order to reduce the interference in the medium modeled by stochastic geometry. One remedy used for reducing the interference comes from the game theory [20]. In this study, a non-cooperative continuous-kernel game based on power management of nodes is applied to reduce the interference in IEEE 802.15.6 UWB WBAN.

IV. Interference Analysis

Assuming that network nodes are distributed as a homogeneous Poisson point process the total interference power measured at a hub $y \in R^2$ can be shown as

$$I(y) = \sum_{x \in \Phi} P_x h_x l(||y - x||) \tag{4}$$

where P_x is the transmission power, h_x is the channel gain, $l : R^2 \to R$ is the path loss function and Φ represents the set of all transmitting nodes. Notice that without loss of generality our focus is on two-dimensional Euclidean space R^2 depending on the locations of wireless nodes in the real world and can be easily extended to three dimensions. Due to the spatial stationarity of the interference, it is not important where the interference is measured and the index y can be simply omitted while taking expectation

$$E[I] = E[\sum_{x \in \Phi} P_x h_x l(||x||)] \tag{5}$$

where $l(||x||) = \min\{1, ||x||^{-\alpha}\}$. Since channel fading and the Poisson point process are independent processes, (5) can be expressed as

$$E[I] = \sum_{x \in \Phi} P_x E[h_x] E[\min\{1, ||x||^{-\alpha}\}]. \tag{6}$$

Assuming constant transmit power and $E[h_x] = 1$ for all $x \in \Phi$ yields

$$E[I] = P \sum_{x \in \Phi} E[\min\{1, ||x||^{-\alpha}\}]. \tag{7}$$

By the Campbell theorem, (7) becomes

$$E[I] = Pq \int_0^{2\pi} \int_1^{\infty} x^{1-\alpha} dx \tag{8}$$

which is equal to

$$E[I] = 2\pi q P \left(\frac{x^{2-\alpha}}{2 - \alpha} \right) |_1^{\infty}. \tag{9}$$

When $\alpha \leq 2$, the mean interference power does not converge, otherwise it converges. Since $\alpha > 2$ for urban microcells and urban macrocells [2], (9) becomes

$$E[I] = \frac{2\pi q P}{\alpha - 2}, \alpha > 2. \tag{10}$$

In a non-coherent detector with equally likely bits for a bit energy of ϵ_b and N_{cpb} number of pulses, the error probability becomes as in (1). When inter-network interference is considered, and the mean interference power level in (9) is used as an interference power measure, (1) becomes

$$P_b = Q\left(\sqrt{\frac{1}{2} \frac{(h\epsilon_b/(N_0 + I_{avg}))^2}{h\epsilon_b/(N_0 + I_{avg}) + N_{cpb} T_w W_{rx}}} \right) \tag{11}$$

where

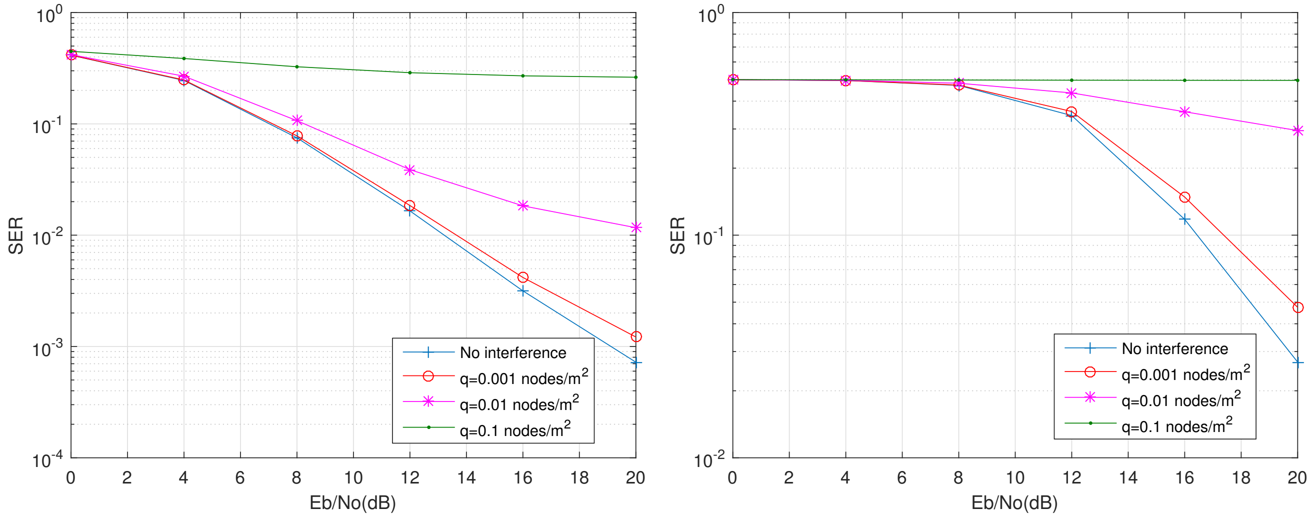
$$I_{avg} = \frac{2\pi q P}{(\alpha - 2) R_{data}}, \alpha > 2. \tag{12}$$

A Monte Carlo simulation is performed with 10000 runs to numerically evaluate the equation (11). For this purpose a single tap channel with Rayleigh fading is considered and the path loss factor α is taken as 3.5, which is usual in urban microcells [2]. First, the impact of node density that creates inter-WBAN interference on one hub terminal is determined in terms of SER when $N_{cpb} = 1$. As can be observed in Fig. 2(a), the performance decreases gradually with increasing node density. Indeed, the UWB PHY shows some tolerance to interference up to 8dB when the node density is not greater than 0.01. On the other hand, the SER of the system is significantly disturbed for larger values of node density. Similar results are observed in case of $N_{cpb} = 16$ as shown in Fig. 2(b). One point that is important to emphasize is that the SER performance is more robust to incremental interference level with a fewer number of pulses per burst.

The same numerical evaluation is performed when the wireless transmission medium is an urban macrocell whose path loss factor is equal to $\alpha = 6.5$ [2]. From (12), it is evident that the higher the path loss factor, the lower the interference level will be. As illustrated in Fig. 3(a), IEEE 802.15.6 UWB PHY is somewhat tolerant to interference as long as the node density does not exceed a certain threshold. In particular, urban macrocells are more resistant to interference than urban microcells. Moreover, Fig. 3(b) illustrates that a higher number of pulses per burst makes the SER performance more vulnerable to interference. Therefore, it can be deduced that there is a trade-off between interference resistance and processing gain in terms of the number of pulses per burst.

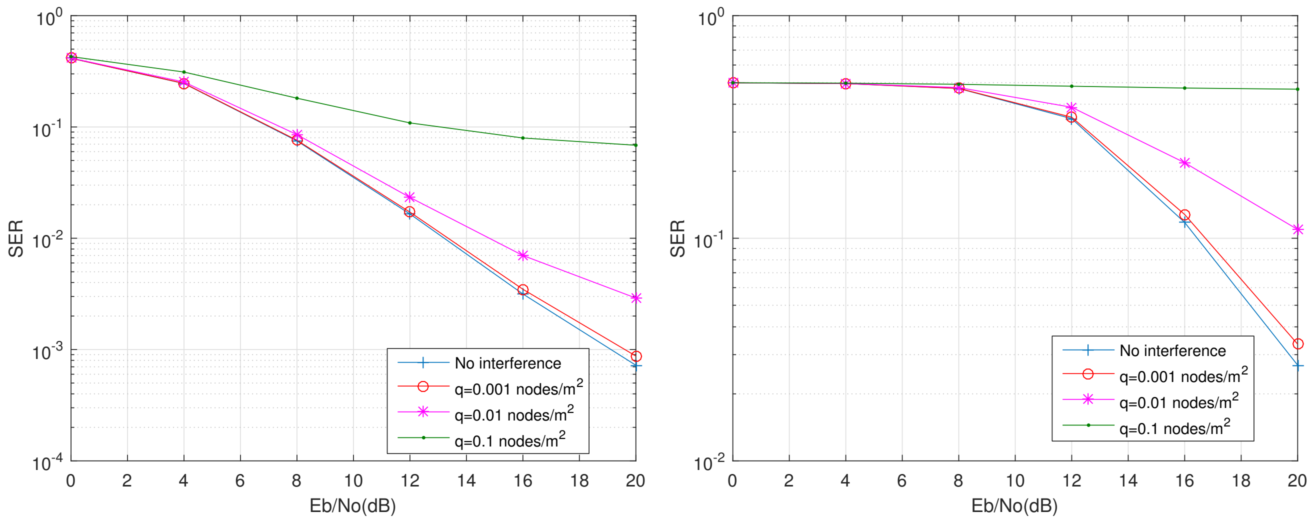
V. Game Theoretical Solution

In a crowded area, inter-WBAN interference dramatically degrades the bit error probability despite UWB communication. In particular, the IEEE 802.15.6 UWB PHY cannot tolerate the inter-network interference when the node density exceeds a certain threshold as shown in the previous sections. In this case it is necessary to find solutions that reduce the level of interference by creating a power control mechanism among the WBAN nodes. In this paper, a solution based on



(a) (b)

Fig. 2. The performance of SER depending on transmitted SNR for (a) $N_{cpb} = 1$ and $\alpha = 3.5$ (b) $N_{cpb} = 16$ and $\alpha = 3.5$



(a) (b)

Fig. 3. The performance of SER depending on transmitted SNR for (a) $N_{cpb} = 1$ and $\alpha = 6.5$ (b) $N_{cpb} = 16$ and $\alpha = 6.5$

a game theoretical approach is proposed. Using game theory, the power level of each node is determined depending on the transmission parameters and satisfies a Nash equilibrium [20].

Assume that there are N different WBANs, each of which has a single active node at a time and the transmission of one node affects the other hubs as well as its own hub. The users on different networks seek to adjust power levels in a non-cooperative game to reduce interference. This problem is similar to adjusting the power levels of users in a single cell uplink CDMA network and accordingly, our cost function that will be minimized for a power level p_i of any user i is [21]

$$J_i(p_i, \mathbf{p}_{-i}) = \rho_i p_i - \beta_i \log(1 + \gamma_i), \forall p_i \geq 0 \tag{13}$$

where $\mathbf{p}_{-i}$ is the power of all users except i^{th} user, ρ_i is the linear price that each user pays for their power consumption, β_i represents the benefit parameter and γ_i is the SINR, which is equal to

$$\gamma_i = N_{cpb} N_w \frac{h_i p_i}{\frac{2\pi q \sum_{j \neq i} p_j}{(\alpha-2)(N-1)} + N_0 W_{rx}} \tag{14}$$

or

$$\gamma_i = N_{cpb} N_w \frac{h_i p_i (\alpha - 2)(N - 1)}{2\pi q \sum_{j \neq i} p_j + N_0 W_{rx} (\alpha - 2)(N - 1)}. \tag{15}$$

Notice that $N_{cpb} N_w > 1$, since N_w is fixed to 32 [17] and we further assume that the data rate of all users is the same. In our formulation the interference power is specified in an average sense by using stochastic geometry, whereas [21] calculates the interference by receiving the total nodes' power from the base station in the downlink with a heavy overhead.

Having these parameters, a theorem in [21] proves that there exists a unique Nash equilibrium for the following power levels

$$p_i^* = \frac{1}{h_i} \frac{N_{cpb} N_w}{N_{cpb} N_w - 1} \left(a_i - \frac{\sum_{j \in N^*} a_j}{N_{cpb} N_w + N^* - 1} \right) \quad (16)$$

for $i \in N^*$ and $N^* \leq N$ provided that

$$a_{\tilde{N}} > \frac{1}{N_{cpb} N_w + \tilde{N} - 1} \sum_{i=1}^{\tilde{N}} a_i \quad (17)$$

where $\tilde{N}$ is the largest integer which is smaller than N and satisfies (17), and

$$a_i = \frac{\beta_i h_i}{\rho_i} - \frac{N_0 W_{rx}}{N_{cpb} N_w}. \quad (18)$$

There exists a unique Nash equilibrium such that p_i^* is as stated in (16) for $i = 0, 1, \cdots, N^*$ and $p_i^* = 0$ for $i = N^* + 1, \cdots, N$. It can be deduced that some nodes must stay at idle state in order to reduce the interference. That is, consuming less energy, which is quite important in WBANs, attains more efficient performance. The question of how the nodes will know that they need to be idle can be handled as follows. The hub can continuously calculate how many nodes are active among the N-nodes by using (17), so that the average number of active nodes at a time can be found. Sending this information to every nodes will reduce their power by the amount of the average percentage of active users, so that the Nash equilibrium is achieved in the average sense. As a result, using stochastic geometry each user can determine the Nash power level based upon its own observations and knowledge.

VI. Conclusions

Inter-network interference can become one of the major impediments degrading WBAN performance. An intrinsic solution to the interference problem is inherent in the IEEE 802.15.6 standard is the use UWB communication. Deterministically, it is impossible to know the interference environment around a person, and hence the cumulative interference, whereas the interference can be statistically analyzed. Since the number of people around a person can be well modeled by a Poisson point process, we used stochastic geometry as a tool to analyze the impact of inter-network interference statistically for WBANs.

In this paper, we measured the inter-network interference in the mean sense and observed its impact on the SER. Our results show that when node density is not higher than 0.01 nodes/m^2, the interference can be tolerated up to 8dB transmitted SNR. Furthermore, the tolerance can be improved by decreasing the number of pulses per burst. On the other hand, increased node density or transmitted SNR leads to performance loss. In particular, the loss becomes unacceptable when the node density grows, i.e., in crowded areas. For this kind of medium, the nodes should adjust its power levels that are specified by a continuous-kernel game theory solution that is based on a stochastic geometry analysis. In this way the users can enhance their energy consumption as well as reducing interference.

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