Joint Energy Harvesting and Internetwork Interference Mitigation amongst Coexisting Wireless Body Area Networks

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ABSTRACT

This paper investigates simultaneous transfer of information and energy for interference mitigation amongst multiple coexisting Wireless Body Area Networks (WBANs). We propose to utilize interference that falls into the network as a source of energy, which is mainly discarded in conventional interference mitigation schemes. More specifically, in each time slot, a single sensor node is scheduled to receive information whilst the remaining sensor nodes opportunistically harvest the ambient radio frequency energy. We develop a novel opportunistic scheduling scheme, which offers a significantly high network lifetime through a tradeoff between a sensor's spectral efficiency and average amount of energy harvested. Simulation results show that the proposed energy harvesting with smart channel allocation (E-SCA) scheme can achieve optimal spatial reuse and good energy harvesting. We also show that the proposed approach is robust to variations in channel conditions, density of sensor nodes in each WBAN and increase in number of coexisting WBANs.

Keywords

Wireless Body Area Networks, WBANs, IEEE 802.15.6, Interference Mitigation, Energy Harvesting

1. INTRODUCTION

Wireless body area networks (WBANs) have evolved rapidly in recent years due to advancements in wireless communications, integrated circuits and Micro-Electro-Mechanical Systems (MEMs). These networks have addressed potential collaboration amongst miniaturized, intelligent, low power micro and nano-technology sensors that are strategically placed in or on the human body. However, numerous challenges need to be addressed to allow for efficient usage of the limited and stringent requirements of WBANs [1]. Since a WBAN is most likely to coexist with other WBANs, inter-WBAN interference is of utmost importance. Generally, interference occurs when no coordination exists amongst multiple coexisting WBANs (Inter-WBAN Interference) [2, 3].

Based on the proposed IEEE 802.15.6 standard, nodes in a single WBAN can avoid interference by using multiple access techniques such as TDMA [2]. However, due to the nature of WBANs and their high mobility, it is unfeasible to allocate a global coordinator to control coexistence amongst multiple WBANs [4]. In cases where co-located WBANs use the same channel (e.g., similar frequencies), transmissions can conflict; as the active periods can overlap [5]. Moreover, with the increase in the number of WBANs that can coexist in short proximity of each other, the communication link can suffer performance degradation. Even in cases where small number of WBANs are deployed in each other's vicinity, the received signal strength of the interfering signal can be quite high, which affects the performance of a particular WBAN [2]. Additionally, the IEEE 802.15.6 task group requires the system to function properly within the transmission range of up to 3 meters when up to 10 WBANs are co-located, with each WBAN consisting of up to 256 nodes [6].

Energy is the most valuable resource of a WBAN, which can be easily wasted by inter-network interference. This can reduce the signal to interference plus noise ratio (SINR)

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value and leads to throughput degradation. In fact, energy-constrained networks like WBANs have fixed energy resources, i.e., batteries, which have a limited network lifetime. Even though the network lifetime can be extended by replacing or recharging the batteries of the sensor nodes, the procedure can be costly, uncomfortable and even impossible; specifically in the case of sensors implanted in the human body. Therefore, it is crucial for WBANs to have a long network lifetime to avoid constant recharging and replacement of nodes attached to a person. Energy harvesting is a promising solution by scavenging energy from the environment. On the other hand, as WBANs are becoming increasingly pervasive, their coexistence will become a major issue in the years to come. Eleven million active units were estimated to be used in 2009 and are predicted to reach 420 million by 2014 [4].

Literature [7–12] states interference mitigation or interference avoidance techniques proposed for other wireless networks cannot be directly deployed in WBANs due to the stringent characteristics of these networks. In [13], a smart spectrum allocation scheme with high spatial reuse and low complexity has been proposed for interference mitigation in WBANs, where partially orthogonal channel assignment was proposed for sensor nodes amongst coexisting WBANs to mitigate inter-WBAN interference. This approach allows for higher spatial reuse than other proposed interference mitigation schemes for WBANs by allowing simultaneous transmission within coexisting WBANs, without imposing interference on one another. Although this scheme increases spatial reuse, it has not considered the scenario where the energy of all nodes in the network deplete.

In this paper, we consider joint node-level interference mitigation and energy harvesting to achieve optimum spatial reuse as well as significantly increasing the network lifetime. More specifically, we allow nodes from different WBANs with lower interference levels to transmit on the same channel while high interference nodes transmit orthogonally. At the same time, the remaining sensor nodes harvest the wireless broadcast energy from the transmission of other sensor nodes. Our proposed approach reveals an interesting phenomenon due to both capturing the interference signal to be used as a source of energy, and mitigating the interference at the same time. We refer to the smart spectrum allocation scheme and show that the higher the spatial reuse, the higher the average amount of energy harvested at the expense of higher outage probability. We further propose a probabilistic approach to reduce the outage probability at the cost of a very small reduction in spatial reuse and harvested energy. To the best of our knowledge, there is no prior work on joint energy harvesting and interference mitigation for WBANs.

The rest of the paper is organized as follows. Section 2 describes the system model. The proposed interference mitigation scheme is presented in Section 3. Section 4 presents mathematical analysis for the proposed scheme. Simulations results are provided in Section 5 and finally Section 6 concludes the paper.

2. SYSTEM MODEL

We consider N_c WBANs to be collocated in a $d_{max} \times d_{max}$ area, where the minimum distance between two WBANs is assumed to be d_{min}. We then define the channel between the sensors and the coordinator in each WBAN (intra-WBAN) to be modeled with gamma fading and the channel between the sensors and coordinators of different WBANs (inter-WBAN) to be modeled with Rayleigh fading.

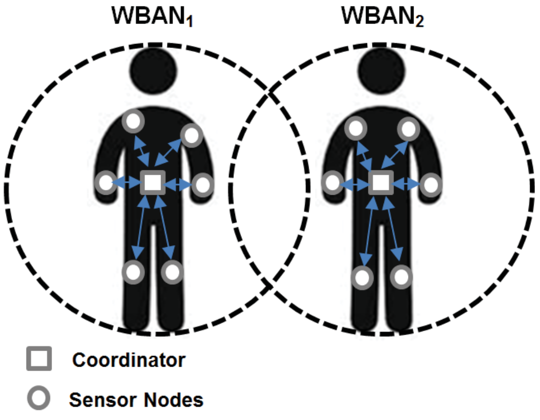

Figure 1: System Model

We consider a one-hop star topology within each WBAN, where N_s sensor nodes aim to transmit their data to a common destination which is a single central processing node, known as the coordinator, that collects various vital signs from the sensor nodes (Fig. 1). The coordinator conveys all the collected data to an access point or base station. The nodes in each WBAN are coordinated by the coordinator using a Time Division Multiple Access Scheme (TDMA). For simplicity, we model each WBAN by a circle of radius r, where the coordinator is located at the center while sensor nodes are uniformly located at random within the circle. According to the path loss model, the received power from a sensor node in WBAN$_i$ at WBAN$_0$ is as follows:

$$P_{r,dB} = P_{t,dB} - 10\log\left(\frac{4\pi d_i f}{c}\right)^2 + 10\log\left({h_i}^2\right) - X_{i,dB}, \tag{1}$$

where $P_{t,dB}$ is the transmit power, h_i is the rayleigh fading coefficient between WBAN$_i$ and WBAN$_0$, d_i is the distance between the sensor of WBAN$_i$ to WBAN$_0$ and $X_{i,dB}$ is the shadowing offset that for simplicity we consider to be constant for the whole network. Accordingly, we increase the path loss related to shadowing in varied amount from 0 dB (No shadowing) to 20 (partial shadowing) and then 40 dB (full shadowing).

3. JOINT ENERGY HARVESTING AND INTERFERENCE MITIGATION

3.1 Energy Harvesting with Smart Channel Allocation (E-SCA)

Existing proposals for interference mitigation in WBANs, assign fully orthogonal channels to all sensors in their network to avoid inter-WBAN interference. More specifically, in a system consisting of N_c WBANs, each with N_s sensor nodes, the whole channel (bandwidth) is divided into N_cN_s time slots where each sensor node is allocated a single time slot. Thus, the average transmission rate of each sensor node will be divided by N_cN_s compared to the single WBAN transmission. However, a sensor in a specific WBAN may cause a higher interference level on its surrounding WBANs whilst other sensors of that WBAN may have a very low interference on its coexisting WBANs, which implies that sensor nodes with lower level of interference are not required to transmit orthogonally. Therefore, we take a step forward and consider node-level interference mitigation to maximize the spatial reuse. More specifically, we allow nodes from different WBANs with lower interference level to transmit on the same channel while high interference nodes transmit orthogonally. In addition, the remaining sensor nodes harvest the energy they hear from information transfer between the sensor node of interest and its coordinator, which is referred to as interference.

3.1.1 Step-1. Orthogonal Transmission

In the first transmission round of the proposed interference mitigation scheme, the coordinators of collocated WBANs negotiate to assign orthogonal channels for each WBAN. Therefore, the shared channel has to be divided evenly into N_cN_s for each sensor node to be allocated a unique time slot for its transmissions. We assume that the ℓ^{th} sensor of $WBAN_i$ transmits at time slot $T_{i,\ell}$. At the same time, the coexisting coordinators compute the interference level of the transmission of that sensor on its own sensors from the received signal power. Let $\gamma_{i,j,\ell}$ denote the received power from the ℓ^{th} sensor of $WBAN_j$ at $WBAN_i$. When all sensors have transmitted orthogonally in the first round, each coordinator is able to create a table consisting of the received power from each sensor of all WBANs.

3.1.2 Step-2. Formation of the Interference Set

Then, in the *second round of transmission*, each coordinator finds the minimum received power from its sensors and compares it to the received power from sensors of other WBANs. Let us consider that the minimum received power of sensors in $WBAN_i$ at its coordinator is $\gamma_{min,i}$, then $\gamma_{min,i} = \min\{\gamma_{i,i,\ell}\}$. If the received power of a sensor from other WBANs is larger that $\gamma_{min,i} - \gamma_{Th}$, that sensor is added to the Inter-Interference list; otherwise, it is considered as a low interference node. We show the interference list of $WBAN_i$ by $\mathcal{I}_i$, where $\mathcal{I}_i = \{(j,\ell)|\gamma_{i,j,\ell} > \gamma_{min,i} - \gamma_{Th}\}$.

3.1.3 Step-3. Exchanging Information

Each coordinator broadcasts its interference list at this stage. Therefore, each coordinator can determine which of its sensors significantly interfere on the transmission of other WBANs. Also, each coordinator can verify which sensors of other WBANs have significant interference on itself. Each coordinator then creates a set,known as the interference set, consisting of all sensors which have a significant interference level. More specifically, the interference set of $WBAN_i$ is $\mathcal{S}_i = I_i \cup \{(i,\ell)|(i,\ell) \in \mathcal{I}_j,\ j \neq i\}$.

3.1.4 Step-4.Spectrum Allocation

Then each WBAN will assign channels for its sensors as shown in Fig. 3. This figure shows that two time slots have been assigned for node a of $WBAN_1$, which shows twice more spatial reuse compared to the fully orthogonal channel assignment, where only one time slot is assigned for each sensor. Also, as clearly seen in Fig. 3, nodes in the interference sets are not transmitting at the same time, which ensures that the interference level is kept as low as possible.

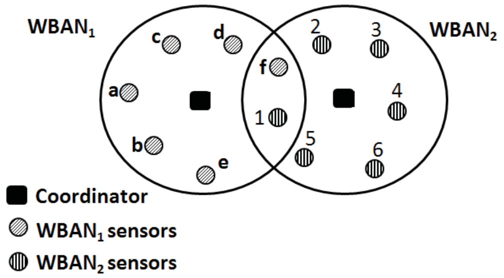

Figure 2: An example of distribution of nodes amongst two WBANs and their Interference Region

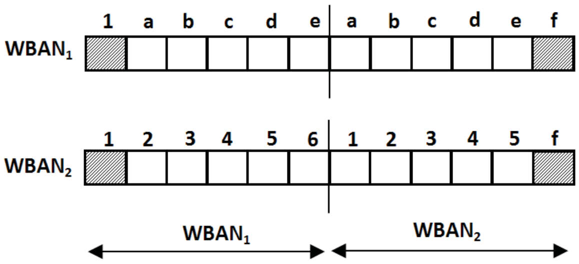

Figure 3: Proposed channel assignment for nodes in Fig. 2.

3.2 Example

In Fig.2 we show an example of channel assignment in our proposed method for a typical network with two coexisting WBANs known as WBAN$_1$ and WBAN$_2$. The interference region amongst them is shown as the intersection of the coverage range of the WBANs. The inter-interference set of each WBAN is as follows, $\mathcal{I}_1 = \{(2,1)\}$ and $\mathcal{I}_2 = \{(1,f)\}$; where the first component is the ID of the WBAN that is interfering with the specified WBAN and the second component is the ID of the node of that WBAN which is interfering with our WBAN of interest. These WBANs broadcast their inter-interference sets, and then create the interference set as follows, $\mathcal{S}_1 = \{(1,f),(2,1)\}$ and $\mathcal{S}_2 = \{(1,f),(2,1)\}$.

3.3 Average Transmission Rate

The average transmission rate of the i^{th} sensor node in WBAN$_i$ is then calculated as follows:

$$\mathcal{R}_{j,i} = \frac{1}{N_cN_s}\sum_{t\in\mathcal{T}_{j,i}}\log_2\left(1+\frac{\gamma_{j,j,i}}{1+\sum_{(\ell,m)\in\mathcal{S}_t}\gamma_{j,\ell,m}}\right), \tag{2}$$

where $\mathcal{T}_{j,i}$ is the set of time slots which are allocated to sensor node (i,j) and $\mathcal{S}_t$ is the set of sensor nodes that are simultaneously transmitting at time instant t.

As the sensor nodes use a portion of the battery energy for each of their transmissions, each sensor node can transmit so long as its energy level does not exceed its minimum critical battery capacity. Accordingly, since the sensor nodes in all WBANs are associated with an energy harvesting model, we propose for each sensor to harvest energy in all of the slots that the sensor is not transmitting. The higher the interfering signal from simultaneous transmissions of a sensor in another WBAN, the higher the amount of harvested energy. Additionally, our proposed scheme adds no complexity to the sensor nodes as all the calculations are carried out by the coordinators.

As the coordinator is not as energy critical as the sensor nodes, our focus in mainly on the sensor nodes within each WBAN. Each sensor node is associated with a rechargeable battery and an energy harvesting device. We adopt the energy harvesting model described in [14], where the amount of harvested energy for a unit-length time slot can be calculated as follows:

$$E_h = \zeta_i P_r, \tag{3}$$

where $(0 < \zeta_i < 1)$, $i = 1, ..., K$ is the energy harvesting efficiency at the receiver and P_r is the received power at the sensor. For convenience, we consider $\zeta_1 = ... = \zeta_K = \zeta$ in the sequel of this paper. More specifically, the average harvested energy at sensor node (j, i) can be calculated as follows:

$$\mathcal{E}_{j,i} = \zeta \sum_{t \notin \mathcal{T}_{j,i}} \sum_{(\ell,m) \in \mathcal{S}_t} \gamma_{j,\ell,m}, \tag{4}$$

3.4 Probabilistic Approach

Let $P_{out,i}$ denote the probability that the total interference at time instant i is larger than γ_{th} at $WBAN_0$. Then $P_{out,i}$ can be calculated as follows:

$$P_{out,0} = p\left(\sum_{j=1}^{N-1} \gamma_j > \gamma_{th}\right). \tag{5}$$

Here, we propose a probabilistic approach to effectively reduce the outage probability and then we analytically prove that the proposed probabilistic approach achieves a lower outage probability. As stated before, WBAN$_0$ places a sensor node in the interference region if the received SNR from that sensor is higher than a threshold. Let γ_j denote the received SNR from a sensor node in WBAN$_j$ at WBAN$_0$. It is clear that if $\gamma_j > \gamma_{th}$, then those sensor nodes will each be assigned an orthogonal channel. Otherwise, if $\gamma_j < \gamma_{th}$, we propose to assign an orthogonal channel for that sensor with a certain probability which is a function of $\frac{\gamma_j}{\lambda\gamma_{th}}$, where λ is the predefined probability factor. The average interference level at time instant i by using the proposed probabilistic approach can then be calculated as follows:

$$\gamma_i = \sum_{j=1}^{N-1} \gamma_j \left(1 - f(\frac{\gamma_j}{\lambda\gamma_{th}})\right), \tag{6}$$

which arises from the fact that by using the probabilistic approach, a sensor is assigned with an orthogonal channel with probability $\frac{\gamma_j}{\gamma_{th}}$. The following gives the outage probability for the proposed probabilistic approach.

THEOREM 1. *Let $P_{out}^{(prob.)}$ denote the outage probability for the proposed probabilistic approach, and P_{out} is the outage probability for the original scheme. Then, $P_{out}^{(prob.)} < P_{out}$. Moreover, if R_0 and $R_0^{(prob.)}$ are the average reuse factor for the proposed scheme with and without probabilistic channel assignment, respectively, then $R_0^{(prob.)} < R_0$.*

PROOF. According to the definition of outage probability, we have:

$$\begin{aligned} P_{out}^{(prob.)} =& p\left(\sum_{i=1}^{N-1} \gamma_i(1 - \frac{\gamma_i}{\gamma_{th}}) > \gamma_{th}\right) \\ =& p\left(\sum_{i=1}^{N-1} \gamma_i > \gamma_{th} + \sum_{i=1}^{N-1} \frac{{\gamma_i}^2}{\gamma_{th}}\right) \\ <& p\left(\sum_{j=1}^{N-1} \gamma_j > \gamma_{th}\right) = P_{out}, \end{aligned}$$

where the last step arises from the fact that the cumulative probability distribution function is an increasing function of its argument.

Let $P_{I,i}^{(prob.)}$ denote the probability that a sensor node of WBAN$_i$ is in the interference region of WBAN$_0$ after deploying the probabilistic approach. Then we have

$$P_{I,i}^{(prob.)} = P(\gamma_i > \gamma_{th}) + P(\gamma_i < \gamma_{th})\frac{\gamma_i}{\gamma_{th}},$$

which is clearly larger than $P_i = P(\gamma_i > \gamma_{th})$. Therefore, the average reuse factor for this approach can be calculated as follows:

$$\begin{aligned} R_0^{(prob.)} =& N - \sum_{i=1}^{N-1} P_{I,i}^{(prob.)} \\ =& N - \sum_{i=1}^{N-1} P_I - \sum_{i=1}^{N-1} p(\gamma_i < \gamma_{th})\mathrm{E}\left(\frac{\gamma_i}{\gamma_{th}}\right) \\ <& N - \sum_{i=1}^{N-1} P_I = R_0. \end{aligned}$$

This completes the proof. □

4. ANALYSIS OF THE PROPOSED SCHEME

We calculate the average reuse factor for the WBAN of interest (WBAN$_0$) in this section. This result that can be applied to other WBANs because of symmetry. Let P_I denote the probability that the received power is above the threshold value γ_{th}. The following gives the average reuse factor for WBAN$_0$:

THEOREM 2. *Let R_0 denote the average reuse factor for $WBAN_0$ and $P_{I,i}$ as the probability that a sensor node of $WBAN_i$ exists in the interference region of $WBAN_0$. Then R_0 can be calculated as follows:*

$$R_0 = N_c - \sum_{i=1}^{N_c-1} P_{I,i} \tag{7}$$

PROOF. Since $P_{I,i}$ is the probability that a sensor node of WBAN$_i$ exists in the interference region of WBAN$_0$, then on average $N_s P_{I,i}$ sensors of WBAN$_i$ exist in the interference region of WBAN$_0$, for $i = 1, 2, ..., N$. Due to symmetry,

$N_s P_{I,i}$ sensors of WBAN$_0$ exist in the interference region of WBAN$_i$. The total number of available channels is $N_c N_s$, which among them $2\sum_{i=1}^{N-1} N_s P_{I,i}$ channels will be allocated orthogonally. The remaining channels will be uniformly assigned to the sensor nodes of WBAN$_0$. The number of the sensor nodes of WBAN$_0$, which are in the interference region is $\sum_{i=1}^{N-1} N_s P_{I,i}$, and so the average reuse factor can be calculated as follows:

$$R_0 = \left(\frac{1}{N_s}\Big(\sum_{i=1}^{N-1} N_s P_{I,i}\Big) \times 1 + \frac{(NN_s - 2\sum_{i=1}^{N-1} N_s P_{I,i})}{N_s - \sum_{i=1}^{N-1} N_s P_{I,i}} \times \Big(N_s - \sum_{i=1}^{N-1} N_s P_{I,i}\Big) \right).$$

This completes the proof. □

The average transmission rate of each sensor node can then be calculated as follows:

$$\bar{\mathcal{R}} = \frac{R_0}{NcNs} \log_2\left(1 + \gamma_{avg}\right), \tag{8}$$

where γ_{avg} is the average SINR of each sensor node. Also, the average harvesting energy can be calculated as follows:

$$\bar{\mathcal{E}} = (NcNs - R_0)\gamma_{avg}. \tag{9}$$

5. SIMULATION RESULTS

We consider that N_c WBANs are randomly deployed in a $10m \times 10m$ area, where the minimum distance between two coexisting WBANs is considered to be $0.5m$. We model each WBAN with a circle of radius $0.5m$, where N_s sensor nodes are randomly positioned within this circle. We also consider that all sensor nodes excluding the coordinator in a WBAN have similar transmit power (P_t). We consider different WBAN densities of low, middle, high and extremely high by considering N_s to be 12, 25, 50 and 100, respectively. We have also evaluated our proposed scheme for different channel conditions: *No Shadowing* (0 dB), *Partial Shadowing* (20 dB) and *Full Shadowing* (40 dB).

The achievable rate versus N_c for all WBANs with variations in the shadowing offset from no shadowing to partial shadowing and full shadowing is shown in Fig. 4. As can be seen in this figure, a higher rate is obtained for different shadowing offsets compared to the fully orthogonal scheme, where the higher the shadowing offset the better the achievable rate. In fact, the achievable rate in these scenarios is approximately 4 times the conventional orthogonal approach. The higher the number of coexisting WBANs the higher the interference and the lower the achievable rate. We have also evaluated the amount of harvested energy of each sensor node versus variations in the number of coexisting WBANs in Fig. 5; where a higher number of coexisting WBANs corresponds to a higher amount of harvested energy obtained when the number of coexisting WBANs is increased.

Fig. 6 demonstrates the amount of harvested energy with the probabilistic approach for different probability factors. As can be clearly seen in this figure, the probabilistic approach harvests a higher amount of energy for higher probability factors. In fact, the higher the probability of existence of nodes in the interference set, the more the harvested energy. Also, Fig. 6 shows variations in channel condition for the probabilistic approach, where a higher amount of energy is harvested with a lower shadowing offset which is due to the fact that the lower the shadowing offset, the higher the interference from the coexisting neighbors and the higher amount of harvested energy.

In addition, as can be seen in Fig. 7, when the probability factor reaches zero, the proposed scheme will achieve its highest achievable rates in terms of spatial reuse. Accordingly, in higher shadowing offsets a better rate will be achieved due to the fact that less interference is imposed. In fact, there is a tradeoff between the amount of harvested energy and the achievable rate which is shown in Fig. 8. Accordingly, a higher amount of energy is harvested when the

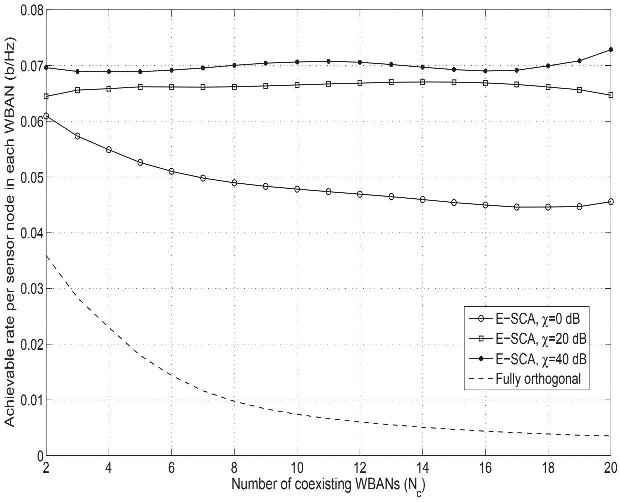

Figure 4: Achievable rate versus density of coexisting WBANs

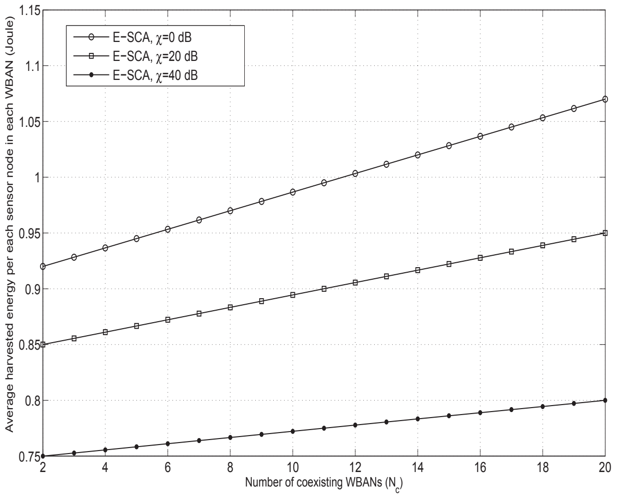

Figure 5: Amount of harvested energy in each sensor node versus the number of coexisting WBANs

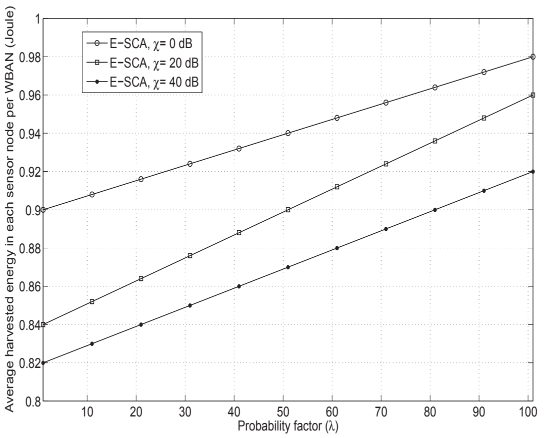

Figure 6: Amount of Harvested Energy versus the Probability Factor

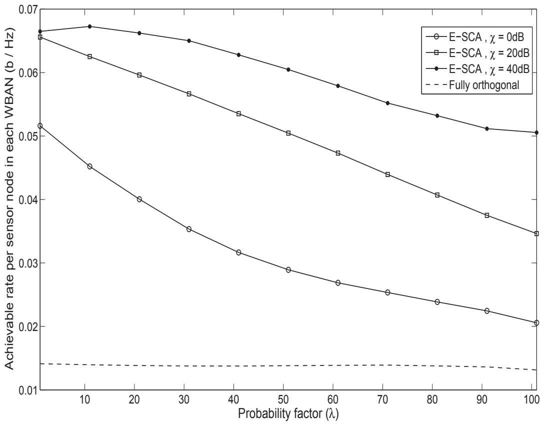

Figure 7: Achievable rate versus the probability factor

achievable rate is lower. In other words, when more sensor nodes are included in the interference set of each WBAN, interference is much higher which leads to a higher amount of energy to be harvested at the expense of lower achievable rate.

6. CONCLUSION

In this work, a novel approach for interference mitigation between coexisting WBANs in proposed that increases the channel reuse as well as increasing the energy level of each sensor node for future transmissions. In fact, the proposed internetwork scheduling scheme controls the tradeoff of spectral efficiency and amount of harvested energy for simultaneous transmissions of multiple coexisting WBANs. A partially orthogonal channel assignment was proposed for nodes amongst coexisting WBANs to mitigate inter-WBAN interference. In our proposed method, nodes that cause interference to other WBANs are allocated orthogonal channels whilst others are allowed to use the whole time slot until all are occupied. Meanwhile, sensor nodes are associated with an energy harvesting model which stores the ambient radio energy it collects from additive simultaneous transmissions of other coexisting WBANs. Our approach aims to Our proposed scheme has been evaluated by simulation showing 20 times higher spatial reuse as well as increasing its energy levels from harvesting the ambient radio energy related to transmissions from coexisting WBANs. Our results reveal that the higher the number of coexisting WBANs causing interference to the transmission of a sensor node, the higher the amount of harvested energy and the higher the network lifetime. This way, more efficient usage of the limited resources in WBANs is achieved which results in a higher network lifetime and much longer depletion time.

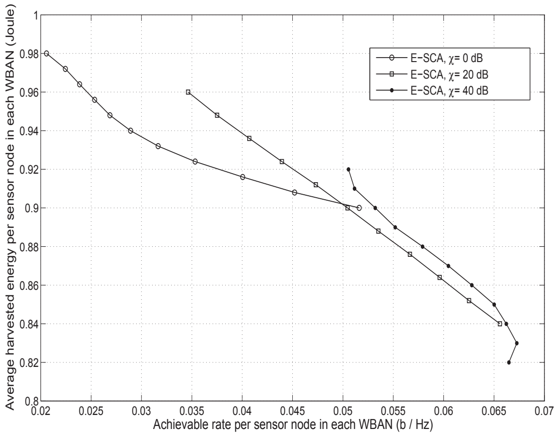

Figure 8: Amount of Harvested Energy versus the achievable rate

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