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A Game Theoretical Approach for Interference Mitigation in Body-to-Body Networks

Amira Meharouech*, Jocelyne Elias*, Stefano Paris*† and Ahmed Mehaoua*

***Abstract*—In this paper, we consider a dynamic system composed of several Wireless Body Area Networks (WBANs) interacting with the surrounding environment, forming Body-to-Body Networks (BBNs). In this dynamic BBN system, we analyze the joint mutual and cross-technology interference problem due to the utilization of a limited number of channels by different transmission technologies (i.e., ZigBee and WiFi) sharing the same radio spectrum. To this end, we propose a game theoretical approach to address the problem of Interference Mitigation in BBNs. Our approach considers a two-stage channel allocation scheme: a BBN-stage for inter-WBANs' communications and a WBAN-stage for intra-WBAN communications. We demonstrate that the proposed BBN-stage and WBAN-stage games admit exact potential functions and develop best response algorithms that converge fast to Nash equilibrium points. Finally, numerical results show that the proposed approach is indeed efficient in optimizing the channel allocations in BBNs while using different transmission technologies.**

Index Terms*—Body-to-Body Networks, 2.4 GHz ISM band, Interference Mitigation, Cross-Technology Interference, Channel Allocation, Game Theory, Nash Equilibrium.

I. Introduction

Body-to-Body Networks have recently emerged as promising solutions for the monitoring of people behavior and their interaction with the surrounding environment [1]. BBNs may represent a number of scenarios: (i) rescue teams in a disaster area, (ii) groups of soldiers on the battlefield, and (iii) patients in a healthcare center, whose Wireless Body Area Networks (WBANs) interact with each other. The BBN consists of several WBANs, which in turn are composed of sensor nodes that are usually placed in the clothes, on the body or under the skin [2]. These sensors collect information about the person and send it to the sink (i.e., a Mobile Terminal (MT) or a PDA), in order to be processed or relayed to other networks.

Due to the scarce wireless channel resources, many existing wireless technologies, like IEEE 802.11 (WiFi), IEEE 802.15.1 (Bluetooth) and IEEE 802.15.4 (ZigBee), are forced to share the same unlicensed 2.4 GHz Industrial, Scientific and Medical (ISM) band. Hence, mutual as well as cross-technology interference may occur between these technologies. Furthermore, since WiFi transmission power can be 10 to 100 times higher than that of ZigBee, ZigBee communication links can suffer significant performance degradation in terms of data reliability and throughput. In addition to the previously mentioned challenging issues, the mobility of WBANs in their surrounding environment and their interactions with each other make the interference mitigation in body-to-body networks a very interesting and mandatory problem to address. This is indeed the focus of the paper.

Whilst a number of previous interference-aware studies have been based upon power considerations [3], [4], others have chosen alternative approaches [5], [6] to deal with this challenging problem in the design of WBANs. In [4] the authors propose a distributed power control algorithm representing the best tradeoff between energy and network utility. However, they have not envisaged transmissions among WBANs and have not considered precise assumptions concerning the used transmission technology. Furthermore, several works have investigated the interference mitigation problem with detailed specifications of wireless technologies, especially WiFi and ZigBee which are the most widespread ones in the WBAN industry [7], [8]. The proposed solutions enable ZigBee links to achieve high performance levels in the presence of heavy WiFi interference, but almost all of them do not consider the mobility feature of WBANs neither propose an SIR-based utility functions for mutual and cross-technology interferences.

In [9], we have analyzed the interference mitigation issue in a dynamic BBN system. The problem is formulated as an optimization problem, proposing an extended interference graph to model cross-technology conflicts. However, in the present work, we address the interference mitigation problem using concepts and mathematical tools from Game Theory, while this problem has been tackled in [9] in a completely centralized way.

Yet, to the best of our knowledge, this paper is the first to propose a game theoretical approach for an interference-aware channel allocation in BBNs. In our model, multiple WBANs can interact with each other within a BBN, as well as with other coexisting networks/BBNs, involving different access technologies; this can lead to severe interference, which is instead consistently mitigated by our proposed approach. The main contributions of our work can be summarized as follows:

- We propose a novel game theoretical approach that consists of two nested games (inter- and intra-WBANs), for interference mitigation in BBNs.
- A detailed expression of *Signal-to-Interference Ratio* is proposed to define the payoff function of the players, showing the different interference components, namely the co-channel, the mutual, and the cross-technology interferences.
- We demonstrate that our games admit at least one pure strategy Nash Equilibrium (NE) since the games have

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exact potential functions and we develop best response algorithms to compute the channel allocations, that converge fast to NE solutions.
- We perform a thorough performance analysis of the BBN- and WBAN-stage SIM games under different system parameters.

The paper is structured as follows: Section II presents the BBN system model. Section III details the two-stage socially-aware interference mitigation game theoretical approach, while Section IV presents the best response algorithms. Section V analyzes numerical results for the proposed games in several BBN scenarios. Finally, Section VI concludes this paper.

II. Body-to-Body System Model

In this section, we consider a multi-BBN scenario (as illustrated in Figure 1) composed of a set $\mathcal{N}$ of WBANs distributed over a set of coexisting BBNs, which are located in the same geographical area (i.e., a medical center, a rest home or a care home), and share the same unlicensed 2.4 GHz ISM band. Let $\mathcal{C}^w$ and $\mathcal{C}^z$ denote, respectively, the set of WiFi and ZigBee channels in this band. Each WBAN is equipped with a wearable Mobile Terminal (MT)[1], that uses both the 802.15.4 protocol (i.e., ZigBee) to communicate with the sensor nodes within its WBAN, and the IEEE 802.11 wireless standard (i.e., WiFi) to create a backhaul infrastructure for inter-WBANs' communications.

Since we are assuming that WBANs can move and interact with their surrounding environment, we decide to divide the operating time of the whole system into a set T of consecutive epochs, and during each epoch $t \in T$ we suppose that the network topology and environment conditions do not change. The set $\mathcal{L}^w(t)$ represents all WiFi unidirectional links established by mobile terminals during the epoch $t \in T$; $\mathcal{L}^w(t)$ may vary between two consecutive epochs due to WBANs' mobility. On the contrary, the set $\mathcal{L}^z$, which represents the ZigBee unidirectional links used for intra-WBAN communication does not change with time.

To summarize, our network model will focus on the following relevant elements:

- Every single WBAN's MT, muniequipped with one WiFi antenna and one ZigBee antenna, should dispose of non overlapping WiFi and ZigBee channels.
- No interference is present within a WBAN; we assume a TDMA-based medium access control implemented in each WBAN to deal with collisions.
- The interference between overlapping WiFi and ZigBee channels is represented by the matrix A, of size $|\mathcal{C}^w| \times |\mathcal{C}^z|$, whose element $a_{c_1 c_2}$ is a binary value: $a_{c_1 c_2} = 1$ if WiFi channel c_1 overlaps with ZigBee channel c_2 (0 otherwise).
- The degree of interference between overlapping WiFi channels is represented by the matrix $\mathcal{W}$, of size $|\mathcal{C}^w| \times |\mathcal{C}^w|$, whose element $w_{c_1 c_2} \in [0, 1]$ is a fractional value, defined in [10] as the ratio of the power spectral density functions of the band-pass filters for channels c_1 and c_2.
- To preserve the network connectivity within the BBN, a unique WiFi channel is required by each *connex component*, i.e., the set of connected WBANs over WiFi links of the same BBN referred to as *sub-BBN*. Such connectivity is represented using the $|\mathcal{L}^w| \times |\mathcal{L}^w|$ matrix B, whose element b_{ij} is a binary value: $b_{ij} = 1$ if WiFi links i and j belong to the same sub-BBN (0 otherwise).
- Finally, the magnitude between WiFi and ZigBee transmission power is large enough (i.e. $p^w >> p^z$) that it could be used to compute algorithmic approximations.

[1]The *WBAN* and his corresponding *Mobile Terminal* will be used interchangeably throughout the paper.

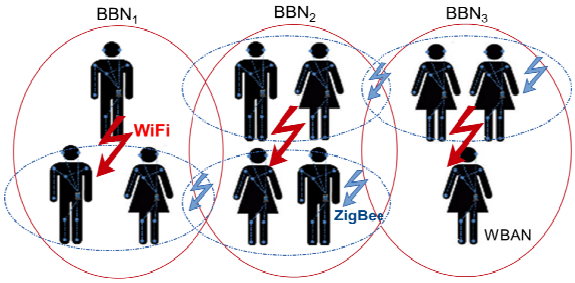


Figure 1: Three-BBN interfering scenario in the unlicensed 2.4 GHz ISM band

We use the *extended conflict graph* $G_c(V_c(t), E_c(t))$ introduced in our previous work [9], to model the mutual and cross-technology interfering wireless links, such as:

- $V_c(t)$: set of vertices corresponding to WiFi and ZigBee communication links in the network, $V_c(t) = \mathcal{L}^w(t) \cup \mathcal{L}^z$.
- $E_c(t)$: set of edges corresponding to the interference relationship among pairs of links.

The *Interference issue* and the *SINR metric* are tightly related. A few recent studies have dealt with SINR and employed it as interference metric [4], [6] for WBANs, though, the noise component is ever assimilated to the background white noise power, which is insufficient for a BBN context since numerous environmental and human parameters are involved. Thus, we prefer investigate the noise component in a future work, and in this paper, we focus only on the interference metric (SIR).

III. Two-Stage Socially-aware Interference Mitigation (SIM): a Game Theoretical Approach

In this section, we first define the basic notation and parameters used hereafter, and then we describe in detail the proposed socially-aware interference mitigation game theoretical approach.

The lack of a centralized control and access priority to the radio spectrum, in addition to the restricted knowledge of network information, motivate us to employ at WBAN-stage local interaction games, in which players (or WBANs) consider their own payoffs as well as those of their neighbors, so as to optimize their strategies while relying on their surrounding network information. Besides, at the BBN-stage game, each group of WBANs (i.e., each sub-BBN) is represented by a special player (a delegate or a leader of the group) who decides which WiFi channel to choose. Indeed, to ensure network connectivity all WBANs within the same sub-BBN

should be tuned to the same WiFi channel. Therefore, we consider this special player that acts on behalf of the entire sub-BBN. To this end, we consider in this work a two-stage socially-aware interference mitigation scheme. Each player is represented by a couple of links (l, h), such that $l \in \mathcal{L}^w(t)$ and $h \in \mathcal{L}^z$ are a WiFi and a ZigBee link corresponding to a given WBAN $i \in \mathcal{N}$ assimilated to its MT. At time epoch $t \in T$, each player chooses a couple of strategies $(x^l_{c_1}(t), y^h_{c_2}(t)) \subset S^l(t) \cup S^h(t)$, such as $x^l_{c_1}$ is the strategy to allocate a WiFi channel $c_1 \in \mathcal{C}^w$ to WiFi link l, and $y^h_{c_2}$ is the strategy to allocate a ZigBee channel $c_2 \in \mathcal{C}^z$ to ZigBee link h. $S^l(t)$ and $S^h(t)$ are the sets of the channel allocation strategies of links l and h of WBAN i, respectively.

A. BBN-stage SIM Game

In order to assign a single WiFi channel to each sub-BBN, we opt for a BBN-stage SIM game so that each set of communicating WBANs, forming a sub-BBN, are represented by a specific WiFi link. The representative WiFi link is situated in the center of the sub-BBN and plays the role of the *delegate*, and the other WBANs belonging to the same sub-BBN will be allocated the same WiFi channel.

We build the extended conflict graph and we assume that each WBAN has information only about his sub-BBN underlying WBANs, through the exchange of polling messages. Thus, we can identify for each WBAN, the set of interfering neighbors at time epoch $t \in T$ (i.e., the set of edges between a link of such WBAN and transmission links of the others). Let W_l denote the set of links interfering with WiFi link l:

$W_l(t) = \{k \in L^w(t) : (l, k) \subset E_c(t)\} \cup \{j \in L^z : (l, j) \subset E_c(t)\}$

Thereby, we can define the BBN-stage game as follows:

- *Players:* the set of BBNs represented by their delegates, the player is assimilated to its WiFi link l.
- *Strategies/actions:* $s^l(t) = x^l_{c_1}(t)$, strategy to choose a WiFi channel c_1 to WiFi link l from $\mathcal{C}^w$.
- *Utility function:* To ensure a realistic representation of the game, we use the worst SIR values perceived by the two radio interfaces, WiFi and ZigBeeIn Equation (1), we extend the SIR expression of the player $l \in \mathcal{L}^w$ to consider interfering transmitters using different technologies:

$$SIR^w(x^l_{c_1})(t) = 10log(\frac{g_{ll}p^l_w}{I^w_{c_1}(x^l_{c_1}) + I^w(x^l_{c_1}) + I^{wz}(x^l_{c_1})}), \quad (1)$$

where

$I^w_{c_1}(x^l_{c_1})$: Co-channel interference from WiFi links of other sub-BBNs ($b_{kl} = 0$) sharing channel c_1 with WiFi link l.

$$I^w_{c_1}(x^l_{c_1}) = \sum_{\substack{k \in \mathcal{L}^w \\ b_{kl}=0}} x^l_{c_1} x^k_{c_1} g_{lk} p^k_w \quad (2)$$

$I^w(x^l_{c_1})$: Mutual interference from WiFi links of other sub-BBNs ($b_{kl} = 0$) using WiFi channels that overlap with c_1.

$$I^w(x^l_{c_1}) = \sum_{\substack{k \in L^w \\ b_{kl}=0}} (\sum_{\substack{c \in C^w \\ c \neq c_1}} w_{c_1 c} x^l_{c_1} x^k_c) g_{lk} p^k_w, \quad (3)$$

$I^{wz}(x^l_{c_1})$: Cross-interference from ZigBee links, using ZigBee channels other than c_2, overlapping with c_1.

$$I^{wz}(x^l_{c_1}) = \sum_{\substack{k \in L^z \\ k \neq h}} (\sum_{c \in C^z} a_{c_1 c} x^l_{c_1} y^k_c) g_{lk} p^k_z; \quad (4)$$

g_{ll} is the channel gain of link l, g_{lk} the link gain from the transmitter k to the receiver l, p^k_w and p^k_z are the WiFi and ZigBee transmit power, respectively.

Note that in expression (4) we use the binary parameter $a_{c_1 c_2}$ to model the cross-technology interference instead of the fractional $w_{c_1 c_2}$ used in Equation (3) for mutual WiFi interference. In fact, although in the literature the interference of the IEEE 802.11b has been modeled as an additive white Gaussian noise (AWGN) to the ZigBee signal, the authors in [11] measured a packet loss of $99,75\%$ up to 100% in WBANs used for blood analysis and ECG sensing when a video streaming is executed over an interfering WiFi channel. Therefore, due to the tight constraints on WBANs' transmissions reliability, we consider the worst effect caused by WiFi interference on ZigBee communications, using the binary parameter $a_{c_1 c_2} \in \{0, 1\}$.

1) Convergence of BBN-stage game: Nash Equilibrium

Having defined the BBN stage of the SIM game, we then demonstrate that such game indeed admits at least one pure-strategy Nash equilibrium. Thus, we first define the utility function of player l as follows:

$$U_w(x^l_{c_1}) = 10log(g_{ll}p^l_w) - 10log(IF^w_l(x^l_{c_1}))$$

where $IF^w_l(x^l_{c_1})$, denoted as the WiFi Interference Function of player l, is the total interference suffered by link l when playing strategy $x^l_{c_1}$, and is expressed as follows:

$$\begin{aligned} IF^w_l(x^l_{c_1}) &= I^w_c(x^l_{c_1}) + I^w(x^l_{c_1}) + I^{wz}(x^l_{c_1}) \\ &= \sum_{k \in W_l \cap \mathcal{L}^w} \sum_{c \in \mathcal{C}^w} f(x^l_{c_1}, x^k_c) + \sum_{j \in W_l \cap \mathcal{L}^z} \sum_{\substack{c \in C^z \\ c \neq c_2}} g(x^l_{c_1}, y^j_c) \end{aligned}$$

or function of the strategies:

$$IF^w_l(s^l) = \sum_{k \in W_l \cap \mathcal{L}^w} f(s^l, s^k) + \sum_{j \in W_l \cap \mathcal{L}^z} g(s^l, s^j)$$

where:

$$f(s^l, s^k) = \begin{cases} 0, & s^l \neq s^k \text{ and WiFi channel } c_1 \text{ of link } l \\ & \text{does not overlap with WiFi channel of link } k. \\ g_{lk}p^k_w, & s^l = s^k \\ w_{c_1 c} g_{lk} p^k_w, & s^l \neq s^k \text{ and WiFi channel } c_1 \text{ of link } l \\ & \text{overlaps with WiFi channel of link } k. \end{cases}$$

and:

$$g(s^l, s^j) = \begin{cases} 0, & \text{WiFi channel } c_1 \text{ of link } l \text{ does not overlap} \\ & \text{with ZigBee channel of link } j. \\ g_{lj}p^j_z, & \text{WiFi channel } c_1 \text{ of link } l \text{ overlaps with} \\ & \text{ZigBee channel of link } j. \end{cases}$$

Due to the property of *monotone transformation*, if the modified game with utility IF^w is a potential game, then the original BBN-stage SIM game with utility U_w is also a potential game with the same potential function. Then, the BBN-stage SIM game ($\mathcal{G}_1$) is expressed as follows: $(\mathcal{G}_1)$: $\min_{x^l_{c_1} \in S^l(t)} IF^w_l(x^l_{c_1}, x^{-l}_{c_1}) \quad \forall l \in \mathcal{L}^w$

$$s.t. \sum_{c \in \mathcal{C}^w} x^l_c = 1 \qquad \forall l \in \mathcal{L}^w(t) \quad (5)$$

$$x^l_{c_1} \in \{0, 1\} \quad \forall l \in \mathcal{L}^w(t), c_1 \in \mathcal{C}^w, \quad (6)$$

For convenience, we designate by -l all the players belonging to W_l. Constraint (5) forces the assignment of a single WiFi channel for a single WiFi link for each player. The convergence of the BBN-stage SIM game to a Nash equilibrium is given by the following theorem:

Theorem 1: The BBN-stage SIM game $\mathcal{G}_1$ is an exact potential game.

Proof: we construct the potential function as follows:

$$\Phi^w(s^i, s^{-i}) = \frac{1}{2}\sum_{i\in L^w}\sum_{k\in W_i\cap L^w} f(s^i, s^k) + \sum_{i\in L^w}\sum_{j\in W_i\cap L^z} g(s^i, s^j)$$

Therefore, when player $l \in \mathcal{L}^w$ changes its action at time epoch $t \in \mathcal{T}$, from s^l to $\hat{s}^l$, the variation of the potential function subsequent to this player's strategy change is given by:

$$\Phi^w(s^l, s^{-l}) - \Phi^w(\hat{s}^l, s^{-l}) =$$

$$\frac{1}{2}\sum_{\substack{i\in L^w\\ i\neq l}}\sum_{k\in W_i\cap L^w} f(s^i, s^k) + \sum_{\substack{i\in L^w\\ i\neq l}}\sum_{j\in W_i\cap L^z} g(s^i, s^j) \tag{7}$$

$$-\frac{1}{2}\sum_{\substack{i\in L^w\\ i\neq l}}\sum_{k\in W_i\cap L^w} f(s^i, s^k) - \sum_{\substack{i\in L^w\\ i\neq l}}\sum_{j\in W_i\cap L^z} g(s^i, s^j) \tag{8}$$

$$+\frac{1}{2}\sum_{\substack{i\in L^w\\ i\neq l}} f(s^i, s^l) - \frac{1}{2}\sum_{\substack{i\in L^w\\ i\neq l}} f(s^i, \hat{s}^l) \quad (k = l)$$

$$+\frac{1}{2}\sum_{k\in W_l\cap L^w} f(s^l, s^k) + \sum_{j\in W_l\cap L^z} g(s^l, s^j) \quad (i = l)$$

$$-\frac{1}{2}\sum_{k\in W_l\cap L^w} f(\hat{s}^l, s^k) - \sum_{j\in W_l\cap L^z} g(\hat{s}^l, s^j) \quad (i = l)$$

We can easily see that (7)+(8)=0. On the other hand, since each player has only interference with his neighboring set, then $\{i \in L^w : i \neq l\} = \{k \in W_l \cap L^w\}$, and we assume that function f is symmetric so as we consider symmetric channel gains ($g_{lk} = g_{kl}$ if $b_{kl} = 0$), therefore:

$$\Phi^w(s^l, s^{-l}) - \Phi^w(\hat{s}^l, s^{-l}) = \sum_{k\in W_l\cap L^w} f(s^l, s^k) + \sum_{j\in W_l\cap L^z} g(s^l, s^j)$$
$$- \sum_{k\in W_l\cap L^w} f(\hat{s}^l, s^k) - \sum_{j\in W_l\cap L^z} g(\hat{s}^l, s^j) = IF_l^w(s^l, s^{-l}) - IF_l^w(\hat{s}^l, s^{-l})$$

Accordingly we prove that, when a delegate $l \in \mathcal{L}^w$ deviates from a strategy s^l to an alternate strategy $\hat{s}^l$, the change in the *exact potential function* Φ^w exactly mirrors the change in l's utility. Therefore the SIM game is an exact potential game. ■

Thereby, we can rely on the following theorem [12] to confirm the existence of a Nash equilibrium to our game.

Theorem 2: Every potential game has at least one pure Nash equilibrium, namely the strategy s^l that minimizes $\Phi^w(s^l)$.

B. WBAN-stage SIM Game

We now consider the WBAN-stage game, where each WBAN will be assigned a ZigBee channel that guarantees the minimal interference with his neighbors.

1) ZigBee local interaction game

Similarly to the BBN stage, denote Z_h as the set of neighbors of ZigBee link h, using the conflict graph:

$$Z_h(t) = \{j \in L^z : (h, j) \subset E_c(t)\} \cup \{k \in L^w(t) : (h, k) \subset E_c(t)\}$$

Hence, we can define the local interaction game of the WBAN stage as follows:

- *Players:* set $\mathcal{N}$ of WBANs. For the WBAN-stage, the player is assimilated to his ZigBee link h.
- *Strategies/actions:* $s^h(t) = y^h_{c_2}(t)$, strategy to choose a ZigBee channel c_2 to ZigBee link h from $\mathcal{C}^z$.
- *Utility function:* is, similarly to BBN stage, function of the SIR considering the ZigBee interface which is used for intra-WBAN communications, given by:

$$SIR^z(y^h_{c_2})(t) = 10log(\frac{g_{hh}p^h_z}{I^{wz}(y^h_{c_2}) + I^z(y^h_{c_2})}), \tag{9}$$

$I^{wz}(y^h_{c_2})$ represents the *cross-technology* interference caused by mobile terminals using WiFi channels that interfere with the ZigBee channel c_2 on which WBAN link h is tuned.

$$I^{wz}(y^h_{c_2}) = \sum_{\substack{k\in\mathcal{L}^w\\ b_{kl}=0}}\sum_{c\in\mathcal{C}^w} a_{cc_2}x^k_c y^h_{c_2} g_{hk} p^k_w(t). \tag{10}$$

$I^z(y^h_{c_2})$ accounts for the *co-channel interference* of nearby WBANs sharing the same ZigBee channel c_2 of player h.

$$I^z(y^h_{c_2}) = \sum_{k\in\mathcal{L}^z} y^k_{c_2} y^h_{c_2} g_{hk} p^k_z(t). \tag{11}$$

Conversely to the BBN stage (Equation (1)), in Equation (9) only cross and co-channel interference components are considered at the denominator, since all ZigBee channels are completely orthogonal among each other, i.e. no mutual interference is there. In case of sharing the same ZigBee channel, i.e., expression (11), the corresponding experimental scenario in [11] measures 18% of packet losses. Therefore, we model our game so that selecting different and non-overlapping ZigBee channels for intra-WBAN communications emerges as the best strategy for all players. Yet, we consider local interaction behaviors among players interacting within the same neighboring set, which is translated in the utility function by a local cooperation quantity as a tradeoff to the player selfish attitude. Thus, we define the utility function of player h for the WBAN-stage game as follows:

$$U_z(y^h_{c_2}) = SIR^z(y^h_{c_2}) + \sum_{k\in Z_h} SIR^z(y^k_c)$$
$$= 10log(g_{hh}p^h_z) + \sum_{k\in Z_h} 10log(g_{kk}p^k_z) - IF^z_h(y^h_{c_2})$$

where: $IF^z_h(y^h_{c_2}) = I_h(y^h_{c_2}) + \sum_{k\in Z_h} I_k(y^h_{c_2})$
and: $I_k(y^h_{c_2}) = 10log(I^{wz}(y^k_c) + I^z(y^k_c)) \quad ,\forall c \in C^z : y^k_c = 1$

$I_k(y^h_{c_2})$ is the total interference suffered by link k of a neighboring WBAN when link h plays strategy $y^h_{c_2}$.

As in [13], using the monotone transformation property, the WBAN-stage SIM game is expressed as follows:

$$(\mathcal{G}_2) : \min_{y^h_{c_2}\in S^h(t)} IF^z_h(y^h_{c_2}, y^{-h}_{c_2}) \quad \forall h \in \mathcal{L}^z$$

$$s.t. \sum_{c\in\mathcal{C}^z} y^h_c = 1 \qquad \forall h \in \mathcal{L}^z(t) \tag{12}$$

$$y^h_c \in \{0, 1\} \quad \forall h \in \mathcal{L}^z, c \in \mathcal{C}^z \tag{13}$$

Constraint (12) forces the assignment of a single ZigBee channel for a ZigBee link, for each player.

2) Convergence of WBAN-stage game: Nash Equilibrium

The property of the proposed local interaction game is characterized by the following theorem:

Theorem 4: $\mathcal{G}_2$ is an exact potential game which has at least one pure strategy NE, and the optimal solution of his potential function constitutes a pure strategy NE.

Proof: we construct the potential function as follows:

$$\Phi^z(s^h, s^{-h}) = \sum_{k \in L^z} I_k(s^h, s^{-h})$$

if we compute the variation of the utility function when player $h \in \mathcal{L}^z$ changes its action at time epoch $t \in T$, from s^h to $\hat{s}^h$, we obtain:

$$IF_h^z(s^h, s^{-h}) - IF_h^z(\hat{s}^h, s^{-h}) = \\ I_h(s^h, s^{-h}) - I_h(\hat{s}^h, s^{-h}) + \sum_{k \in Z_h} [I_k(s^h, s^{-h}) - I_k(\hat{s}^h, s^{-h})]$$

On the other hand, the variation of the potential function subsequent to this player's strategy change is given by:

$$\Phi^z(s^h, s^{-h}) - \Phi^z(\hat{s}^h, s^{-h}) = \sum_{k \in L^z} I_k(s^h, s^{-h}) - \sum_{k \in L^z} I_k(\hat{s}^h, s^{-h}) \\ = I_h(s^h, s^{-h}) - I_h(\hat{s}^h, s^{-h}) + \sum_{k \in Z_h} [I_k(s^h, s^{-h}) - I_k(\hat{s}^h, s^{-h})] \\ + \sum_{\substack{k \in L^z \setminus Z_h \\ k \neq h}} [I_k(s^h, s^{-h}) - I_k(\hat{s}^h, s^{-h})]$$

Yet, with the local cooperative nature of WBAN-stage game, h player's action only affects players in its interference range, thus we have:

$$I_k(s^h, s^{-h}) - I_k(\hat{s}^h, s^{-h}) = 0 \quad \forall k \in L^z \setminus Z_h, k \neq h$$

This leads to the following equation:

$$IF_h^z(s^h, s^{-h}) - IF_h^z(\hat{s}^h, s^{-h}) = \Phi^z(s^h, s^{-h}) - \Phi^z(\hat{s}^h, s^{-h})$$

Accordingly we prove that, when a player $h \in \mathcal{L}^z$ deviates from a strategy s^h to an alternate strategy $\hat{s}^h$, the change in the exact potential function Φ^z exactly mirrors the change in h's utility. Therefore the WBAN-stage SIM game is an exact potential game.

IV. Best-Response BBN/WBAN-stage SIM Algorithm (BR-SIM)

In this section, we propose an iterative algorithm that implements a best response dynamics for our proposed SIM game theoretical approach. Indeed, potential games have two appealing properties: they admit at least one pure-strategy NE which can be obtained through a best-response dynamics carried out by each player, and they have the Finite Improvement Property (FIP) [14], which ensures the convergence to a NE within a finite number of iterations.

BR-SIM is processed at time epoch $t \in \mathcal{T}$: it starts by forming the coalitions of sub-BBNs whose delegates are representative WiFi links situated in the center with symmetric gains. The delegates and the underlying WBANs are initialized to random WiFi and ZigBee channels with respect to the connectivity criterion within BBNs. Then, the algorithm iteratively examines whether there exists any player that is unsatisfied, and in such case a greedy selfish step is taken so that such player l changes his current strategy $s^l(\tau)$, $\tau < t$, to a better strategy $s^l(\tau + 1)$ with respect to the current action profile of all other players, as follows:

$$s^l(\tau + 1) = \underset{s^l \in C^w}{\arg\min}\, IF_l^w(s^l, s^{-l}) \quad s.t. \tag{14}$$
$$s^{-l} = \{s^1(\tau + 1), s^2(\tau + 1), ..., s^{l-1}(\tau + 1), s^{l+1}(\tau), ..., s^{|L^w(t)|}(\tau)\}$$

where $s^1, s^2..., s^{l-1}$ have been updated to their best-responses at iteration $\tau + 1$ and do not change from their selected strategies during the current iteration.

Alike the WiFi Best-response procedure, players update iteratively the ZigBee channels that minimize their Interference Functions, with respect to their WiFi channels selected at the BBN- (or WiFi-) stage step. Thus, for a ZigBee player h, the strategy domain of the ZigBee channel selection process is delimited to the set of available ZigBee channels $C_h^z(t)$, i.e., not overlapping with his assigned WiFi channel at time epoch t. Therefore, the best-response strategy of ZigBee player h is expressed by:

$$s^h(\tau + 1) = \underset{s^h \in C_h^z(t)}{\arg\min}\, IF_h^z(s^h, s^{-h}) \quad s.t. \tag{15}$$
$$s^{-h} = \{s^1(\tau + 1), s^2(\tau + 1), ..., s^{h-1}(\tau + 1), s^{h+1}(\tau), \ldots, s^{|L^z(t)|}(\tau)\}$$

Due to the FIP property, such algorithm is guaranteed to converge in a finite number of iterations to a BBN-stage NE, and then to a local interaction ZigBee NE where no player has an incentive to deviate from his best-response choice.

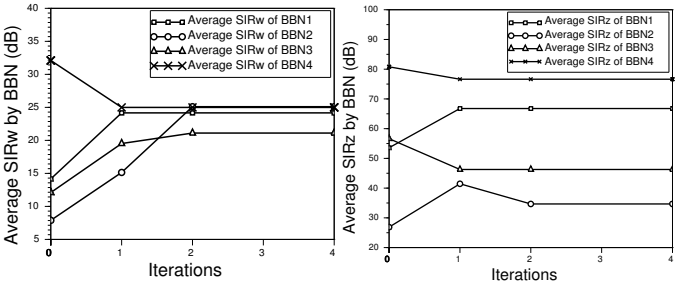
V. Performance Evaluation

This section illustrates and discusses the numerical results obtained in different network scenarios, using the INRIA Scilab software package. The mobile WBANs, which number varies in the range [20,40], are randomly deployed in a $1000 \times 1000m$ area, and divided into four overlapping BBNs. The mobility is simulated using the common *random waypoint model*. We consider the first five overlapping WiFi channels of the ISM band ($\mathcal{C}^w = \{1, 5\}$) and the whole band of ZigBee channels ($\mathcal{C}^z = \{11, 26\}$) in order to simulate the WiFi mutual interference and the cross-technology scenarios. To compute channel gains, we refer to the BBN-specific channel gain model in [15]. The WiFi and ZigBee transmission powers are set to 100 mW and 1 mW, respectively.

To show the effectiveness of our distributed solution, we evaluate the effect of the WBANs density on the dynamics of the BR-SIM channel selection algorithm. More specifically, we measure the WiFi and ZigBee signal-to-interference ratios for each BBN, proving that the BR-SIM algorithm guarantees a fair share of wireless resources.

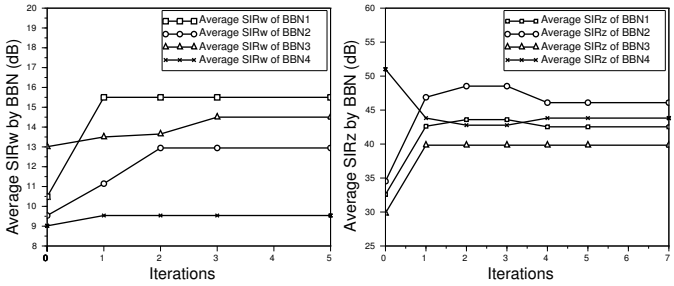
The curves on Fig.2 and Fig.3 illustrate respectively the dynamics of the BR-SIM algorithm for different BBN densities, namely for the number of WBANs N=20 and N=40. Each figure displays the evolution of the average signal-to-interference ratios for BBN and WBAN stages. As expected, increasing the BBN density results obviously in increasing the network overall interference and then the number of iterations to reach an equilibrium.

Besides, we notice at the Nash Equilibrium that the worst WiFi SIR (21 dB for N=20 and 9 dB for N=40), measured with the standard transmission power of 20 dBm (100 mW)



(a) Dynamics of average SIRw. (b) Dynamics of average SIRz.

Figure 2: Dynamics of BR-SIM algorithm by each BBN for a density of N=20 WBANs



(a) Dynamics of average SIRw. (b) Dynamics of average SIRz.

Figure 3: Dynamics of BR-SIM algorithm by each BBN for a density of N=40 WBANs

is always above the receiver sensitivity of most commercial cards (the lowest receiver sensitivity for the Atheros chipset is -95 dB), even considering other effects like fading and thermal noise. The same conclusions are observed for the worst ZigBee SIR measured by all four BBNs (i.e., the WBAN that experiences the worst SIR in a BBN), which varies between 25 and 30 dB for N=20 and N=40 respectively. Note that the worst SIR measured at the ZigBee receiver is higher than the value measured at the WiFi receiver due to the restricted number of overlapping WiFi channels used in the simulation in order to enable mutual and cross-technology interferences, thus resulting in conflicting transmissions using the WiFi technology. Naturally, within a BBN only WiFi transmissions coming from surrounding BBNs are considered in the computation of the WiFi interference, since we assume the utilization of a coordination scheme for intra-BBN communications, whereas the ZigBee interface of any WBAN experiences both intra-BBN and inter-BBN interference. Thereby, further experiments with non-overlapping WiFi channels would reverse the previous conclusions and assess higher values of WiFi SIR versus ZigBee SIR.

Yet, the performance of BR-SIM algorithm is ensured since it provides a rather fair, socially-aware channel allocation, so that both WiFi and Zigbee signal-to-interference ratios tend to be quite close to a mean value at the Nash Equilibrium. Nevertheless, a perceptible decrease in the range of SIR values (mainly SIRz), at the NE point, is observed when the density of the WBANs jumps to upper values, thus constant segments of the curves are tightly close. Indeed, higher densities occasion a most fair spreading of players over the neighboring BBNs, that will suffer from relatively fair interference environment. This explains why, for lower densities, the average SIR values by each BBN are spread out over a larger range of values.

Finally, it can be observed that the BR-SIM algorithm quickly converges to a stable operational point in few iterations, thus representing a practical solution for interference mitigation in realistic BBN scenarios. In particular, all BBNs converge to their best WiFi and ZigBee channel allocations in at most 3 and 5 iterations, respectively.

VI. Conclusion and perspectives

In this paper we studied the distributed interference mitigation problem in BBN scenarios from a game theoretic perspective. In particular, our work makes three main contributions. First, we formulate the problem as a game considering the SIR, which accurately models the channel capacity that can be achieved in the presence of mutual and cross-technology interference. Secondly, we study the properties of our game proving the existence of a Nash Equilibrium, which represents channel allocations that minimize the mutual and cross-technology interference. Third, we propose a two-stage algorithm (called BR-SIM) based on the best-response approach to compute the Nash Equilibria in a distributed fashion. Finally, we evaluate our approach in realistic BBN scenarios in order to show that the BR-SIM algorithm converges quickly and achieves feasible values for the utility functions.

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