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Game-theoretic approach for interference management in heterogeneous multimedia wireless personal area networks

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Abstract: Emergence of new wireless technologies has facilitated the way to higher data rates and more robust communication links. Ultra wideband (UWB) is one of these promising technologies that, despite its several outstanding benefits, can cause interference to other networks operating in the same frequency range because of its large bandwidth. In this study, the authors introduce a solution for interference management in heterogeneous UWB networks. The analysis can be generalised for other coexistence scenarios where we have wireless networks with different specifications. Game theory is used to study the joint power and rate control problem under mutual interference between two UWB standards, namely, multiband orthogonal frequency division multiplexing UWB and direct-sequence UWB. A non-cooperative joint rate and power control game with pricing (NRPGP) in which each node seeks to choose its possible transmit power and rate in order to maximise its own utility while satisfying its target signal-to-interference-and-noise ratio as quality-of-service requirement is introduced. Simulation results are provided to evaluate the performance of the proposed game, NRPGP.

1 Introduction

One of the newly emerged coexistence scenarios is between the two ultra wideband (UWB) standards. These standards, which have been proposed to the IEEE 802.15.3a task group, are multiband orthogonal frequency division multiplexing (MB-OFDM) UWB [1] and direct-sequence (DS) UWB [2]. The IEEE 802.15.3a task group could not finalise selection between these two standards. As a result, both standards will have to coexist together. Interference mitigation when these two technologies operate in the vicinity of each other is very challenging and appropriate solutions are yet to be developed. Efficient resource allocation such as power and rate adaptation can be useful to increase performance and reduce interference. In contrast, game-theoretic approaches have recently found their way to solve different resource allocation problems in wireless communications. Algorithms obtained using game theory are usually distributed (decentralised). In this context, we use a game-theoretic approach to study resource allocation in heterogeneous multimedia UWB wireless personal area networks (WPANs) [3–5]. As a result of their high transmission rates, UWB standards are the main candidates to be used in future multimedia WPANs.

Previous literature related to this work can be classified in two categories. First, research addressing the two UWB technologies' coexistence, for which works done so far are very limited. In [6], an approach based on multi-carrier waveform design is recommended to reduce the effect of MB-OFDM interference on a pulse-based UWB receiver; this work does not take into consideration the reverse case of interference on MB-OFDM. In contrast, in the work reported in [7], the authors simulated the MB-OFDM UWB and DS-UWB standards to study the effect of the mutual interference between both standards, and proposed to reduce the interference by means of power control. As will be discussed, power control by itself is not sufficient to improve the performance. In [8], an accurate bit error rate (BER) analysis for MB-OFDM UWB transmission in the presence of DS-UWB and time hopping UWB interference is proposed, considering the Nakagami-m fading channel model for both the interferers and the MB-OFDM transmitter. The latter work uses a waveforming technique for the purpose of interference mitigation between the two standards. The work in [9] treats the reverse case of the analysis considered in [8] and evaluates the performance of DS-UWB transmission when exposed to MB-OFDM interference, using a pulse collision model.

The second category concerns research related to parameter control for interference management. Several research works have used power control for interference mitigation [10–13]. In addition to power control, in order to support a variety of applications with diverse transmission rates, rate adaptation is also critical for wireless data networks. Thus, joint power and rate control are necessary. Relevant works in this regard, such as [14] and [15], mostly use mathematical optimisation tools to simultaneously optimise the transmit powers and rates. These global optimisation approaches imply that a centralised algorithm should be implemented. However, owing to several problems such as huge network signalling, centralised solutions are usually not practical. Game-theoretic-based rate and power control solutions in wireless networks have also been proposed, for example see [16–19]. In particular, the work in [19] presents a general game-theoretic approach for distributed asynchronous power and rate control for wireless *ad hoc* networks. This work allows nodes to freely choose their rate and power adaptation function without any special technological assumption.

Works in the two aforementioned categories are mostly developed for scenarios such as CDMA networks or cellular environments, which are different from distributed networks such as the distributed WPANs considered in this paper. Moreover, only few of the above-mentioned research works consider fading in their analysis.

In this study, we present a non-cooperative game solution for the coexistence of WPANs using two different UWB technologies, binary phase-shift keying direct sequence UWB and MB-OFDM. The game-theoretic approach is used as a resource management technique to jointly control the transmit power and rate for the UWB transceivers, while indirectly contributing to the mutual interference reduction. The problem is formulated by introducing a utility function for the proposed game, where each node seeks to determine its transmission power and rate so as to maximise its own utility while satisfying its target signal-to-interference-and-noise ratio (SINR) as quality-of-service requirement. A Rayleigh approximation of the IEEE 802.15.3 UWB standard channel model [20] is considered to derive the utility function based on a procedure similar to [21], for both cases of fast and quasi-static slow fading. A pricing of transmit power and rate is applied into the utility function to achieve Pareto improvement compared with the game with no pricing and enhance the overall system performance. Unlike conventional pricing schemes as in [10], which consider only a linear function of the transmit power, our scheme considers joint pricing for the transmit power and rate. The existence, uniqueness, best-response strategies and Pareto efficiency of Nash equilibrium (NE) for the proposed game are proved. To evaluate the performance, simulations are carried out within the framework of multimedia WPAN based on (i) a coexistence scenario with two transceiver pairs, a DS-UWB pair and a MB-OFDM one and (ii) a general network topology with arbitrary numbers of transceiver pairs. Our work also investigates the necessary compensations for the channel fading to be taken into consideration in the design. Game theoretic approaches for design of wireless systems are usually easier for practical system implementations because they are usually distributed in nature. In this work, we do not address directly the networking issues regarding practical system implementation for our algorithm, as this is out of the scope of this work. However, the huge growth of wireless networks' computational capacity as well as system designs based on game theoretic approaches in recent years [19, 22, 23], is a proof to feasibility of our algorithm for practical wireless scenarios.

The remainder of this paper is organised as follows. In Section 2, the system model is presented. Section 3 derives the utility function for Rayleigh quasi-static slow and fast flat-fading channels. In Section 4, the non-cooperative rate and power control game with pricing (NRPGP) is introduced and the NE and Pareto optimality conditions are proven. Section 5 addresses the numerical results and performance in terms of transmission rate and power. Finally, concluding remarks are drawn in Section 6.

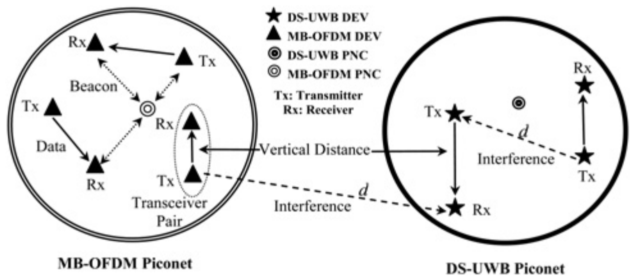

Fig. 1 *Typical heterogeneous WPAN topology*

2 System model and preliminaries

In this section we present the basic definitions for different aspects of the system, which comprise the network topology, utility function, channel model and BER.

2.1 Network topology

In the heterogeneous coexistence environment, a number of nodes with different UWB technologies share the UWB spectrum. We consider the WPAN as network topology. Fig. 1 shows a typical heterogeneous WPAN topology consisting of two piconets. In the WPAN standard terminology, a piconet is a collection of nodes which form a network with the same technology. We call the combination of neighbouring networks, whether of the same technology or different technology, a 'system'. Each 'node' is technically called a device (DEV). The piconet controller (PNC) is chosen by other DEVs and is responsible for coordinating and synchronising the DEVs within the piconet. For this purpose, PNC broadcasts beacons to the DEVs at regular superframe intervals. After coordination, the communication is performed directly between the transmitter and receiver, forming a 'transceiver pair'. The first piconet in Fig. 1 consists of N_{DS} number of DS-UWB transceiver pairs and the other piconet consists of N_{MB} number of MB-OFDM UWB transceiver pairs. Each receiver in a pair is subject to interference from other simultaneously transmitting nodes, whether located in the same piconet or in other piconets. The distance between the centre points of each transceiver pair with other interfering pairs is called 'vertical distance' and will be used in the simulation study as the measure of distance between different transceiver pairs. Each node desires to achieve a high quality of reception, that is, high SINR, while using the minimum possible amount of power in order to extend its battery life. The conflicting goal of each node to have a high SINR, which results in increasing the transmission power and, as a result, increases interference onto other nodes, is another reason to use game theory to find a tradeoff for these conflicting optimisation goals.

2.2 Utility function

Utility functions are a measure of the satisfaction level that a player attains by choosing an action from its strategy profile, given that other players' actions are known. A utility function maps the players' preferences into real numbers. In this paper, we consider a generally used form for the utility function of the transmitter node in the ith transceiver pair given by [10]

$$u_i(r_i, p_i) = \frac{Lr_i}{Mp_i} f(\gamma_i) \quad \forall i = 1, 2, \ldots, N \qquad (1)$$

where M is the transmitted packet length (bits) for transmitter node i, L is the number of information bits in a packet, r_i is the transmission rate (bits per second) for transmitter node i, p_i represents the average transmit power level for transmitter node i, $f(\gamma_i)$ is a function of SINR which approximates the average probability of correct reception of a packet (defined as P_c) at the receiver node i, and $N = N_{DS} + N_{MB}$ is the total number of transceiver pairs in the system. Hence, u_i provides the number of information bits that are successfully received, per joule of energy.

Assuming no error correction, the random packet's correct reception rate is given by $\prod_{l=1}^{M}(1-\tilde{P}_e(l))$, where $\tilde{P}_e(l)$ is the random BER of the lth bit at the given SINR.

2.3 UWB node's BER

In general, the SINR of the ith (DS-UWB or MB-OFDM) receiver node, γ_i, in the ith transceiver pair can be written as

$$\gamma_i = \frac{B_i}{r_i}\frac{p_i c_i \alpha_i^2}{\sum_{k\neq i}^{N} p_k c_k \alpha_k^2 + \sigma^2} = \gamma_i' \alpha_i^2 \tag{2}$$

where α_i is the path-fading coefficient between the transmitter node and its corresponding receiver node, which is constant for each bit in a fast flat-fading channel, and constant for each packet in a quasi-static slow flat-fading channel. p_i is the transmit power of the ith transmitter node, c_i is the path attenuation between the ith transmitter and its corresponding receiver. B_i is the two-sided bandwidth of the ith receiver node, p_k is the transmitted power of the kth interfering transmitter node, c_k is the path gain between the kth interfering transmitter node and the ith receiver node, and σ^2 is the variance of the additive white Gaussian noise (AWGN) which models the background thermal noise at the receiver. For simplicity, interference from all other transmitter nodes onto the ith receiver node is denoted by $I_i = \sum_{k\neq i}^{N} p_k c_k \alpha_k^2$ which comprises all the interferers, being nodes of the same or different technology.

We consider a conditional upper bound for the BER of the UWB received signal as [7]

$$\tilde{P}_{(\mathrm{MB,DS})}(e) = \frac{1}{2}\exp\left(-\frac{\theta_{(\mathrm{MB,DS})}\gamma_i^{\kappa}}{2}\right) \tag{3}$$

where $\kappa \simeq 2$ and $\theta_{(\mathrm{MB,DS})}$ is another constant defined based on the kind of UWB technology used (MB or DS).

2.4 Channel model

For the channels, we consider the UWB IEEE 802.15.3 standard channel model [20], which is common for both DS-UWB and MB-OFDM UWB. This model is based on a modified version of the Saleh–Valenzuela multipath model and is generally described by

$$h(t) = C\sum_{l=0}^{L_c}\sum_{k=0}^{K}\alpha_{k,l}\delta(t - T_l - \tau_{k,l}) \tag{4}$$

where $\alpha_{k,l} = \vartheta_{k,l}\psi_{k,l}$ is the gain coefficient of the kth ray in the lth cluster (channel measurements showed that signal rays arrive in clusters), $\vartheta_{k,l}$ takes the values $+1$ or -1 with equal probability (to consider signal inversion because of reflections), $\psi_{k,l}$ is a lognormal random variable, $\tau_{k,l}$ is the arrival time of the kth ray with respect to the lth cluster arrival time (T_l), L_c denotes the number of clusters, and K indicates the number of rays within each cluster. The term C in (4) models the path attenuation

$$C = \frac{G_T G_R \eta^2}{(4\pi)^2 d^{\nu} f^2} \tag{5}$$

where G_T is the UWB transmit antenna gain, G_R is the UWB receive antenna gain, d is the distance between the receiver and the considered transmitter node, f is the centre frequency for the UWB signal, η is the speed of light and ν is the path loss exponent.

It is known that if L_c and K in (4) are large enough, it is reasonable to approximate the standard channel model fading amplitude as Rayleigh fading [24]. Hence, the probability density function (PDF) of $|\alpha_i^2|$ can be approximated by the exponential distribution as

$$\Pr\{|\alpha_i^2|\} \simeq \frac{1}{\boldsymbol{E}\{|\alpha_i^2|\}}\mathrm{e}^{-((|\alpha_i^2|)/\boldsymbol{E}\{|\alpha_i^2|\})} \tag{6}$$

where $\boldsymbol{E}\{|\alpha_i^2|\} = 1.269$ for the four common channel realisations in the IEEE 802.15.3 standard (CM1, CM2, CM3 and CM4, defined in [24]) and $\boldsymbol{E}\{.\}$ denotes the expectation operator. With respect to (6) and (2), the PDF of γ_i for a given total interference, I_i, is expressed by [24]

$$f^{\gamma_i|I_i}(\omega) = \frac{0.78}{\gamma_i'}\mathrm{e}^{-0.78\omega/\gamma_i'} \tag{7}$$

3 Utility function under channel fading

In this section we derive the utility function for Rayleigh fast and quasi-static slow flat-fading channels. In impulse ratio (IR)-UWB channel models the fading is usually frequency selective. However, to simplify the analysis, we assume a flat-fading channel (in analytical approach we replace flat fading with a special case of frequency-selective multipath fading where the number of incoming paths equals one). This assumption is true for comparative purposes, as it has been used in several other research works on UWB [25–27]. Even in practical environments this assumption is not far from reality regarding that the two UWB standard use smaller portions of the UWB bandwidth instead of the whole bandwidth like in MB-OFDM where the entire available bandwidth is divided into 14 smaller sub-bands. In addition, in some special applications such as 4-G WLAN [28] or MIMO channels [29], the flat-faded assumption may be considered reasonably met. In our flat-faded Rayleigh channel model, we also investigate two specific cases of quasi-static slow fading and fast fading. In quasi-static slow fading, the fading is assumed to be static during the duration of one packet and independent between two packets. Quasi-static assumption is usually used in simulation to provide an averaged performance over many channel realisations. We have provided our analysis and the results for fast fading as well as the quasi-static slow fading. In general fast fading may not be a significant issue in UWB communications. However, this may be a matter of concern in some UWB applications which operate at large distances with low rates like radars. In highly dynamic environments, fast fading may be also considered for UWB propagation as investigated in [30].

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3.1 Rayleigh fast flat-fading channel

For the lth bit in a packet, the SINR and the interference term can be written as

$$\gamma_i = \frac{B_i}{r_i}\frac{p_i c_i \alpha_i^2(l)}{I_i(l) + \sigma^2} \quad (8)$$

$$I_i(l) = \sum_{k \neq i}^{N} p_k c_k \alpha_k^2(l) \quad (9)$$

Assuming that $\{\alpha_i(l)\}_{l=1}^{M}$ and $\{I_i(l)\}_{l=1}^{M}$ are independent and identically distributed (i.i.d.) random variables, the averaged probability of correct reception for all bits of a packet is given by $(1 - P_e)^M$, where P_e is the average BER and equals $P_e = \boldsymbol{E}\{\tilde{P}_e\}$. Hereafter, we omit the index (MB, DS) for θ and $\tilde{P}(e)$ in (3), for notation simplicity. The derived P_e is general for either of the two kinds of UWB techniques. However, to compute P_e for each UWB technology, θ should be replaced by its corresponding value. To find P_e, we start by finding $\tilde{P}(e|I_i)$ as follows

$$\begin{aligned}\tilde{P}(e|I_i) &= \boldsymbol{E}\{\tilde{P}(e|\gamma_i, I_i)\} = \int_0^\infty \tilde{P}(e|\omega, I_i)\, f^{\gamma_i|I_i}(\omega)\,\mathrm{d}\omega \\ &= \frac{0.78}{2\gamma_i'}\int_0^\infty \mathrm{e}^{-((1.56+\gamma_i'\theta\omega)/2\gamma_i')\omega}\,\mathrm{d}\omega \\ &= \frac{0.78\sqrt{2\pi}\mathrm{e}^{0.3042/\gamma_i'^2\theta}}{4\sqrt{\theta}\gamma_i'}\left(1 - \mathrm{err}\left(\frac{39\sqrt{2}}{100\gamma_i'\sqrt{\theta}}\right)\right) \end{aligned} \quad (10)$$

where $\mathrm{err}(x) = \left(2/\sqrt{\pi}\right)\int_0^x e^{-t^2}\,\mathrm{d}t$ is the error function. For large γ_i', we can approximate $\tilde{P}(e|I_i)$ by $0.195\sqrt{2\pi}/\left(\sqrt{\theta}\gamma_i'\right)$. Now we can find the averaged BER as

$$P_e = \boldsymbol{E}\{\tilde{P}(e|I_i)\} = \frac{0.195\sqrt{2\pi}}{\sqrt{\theta}}\frac{\boldsymbol{E}\{I_i\} + \sigma^2}{(B_i/r_i)p_i c_i} = \frac{0.195\sqrt{2\pi}}{\sqrt{\theta}\tilde{\gamma}_i} \quad (11)$$

where $\tilde{\gamma}_i$ is given by

$$\tilde{\gamma}_i = \frac{B_i}{r_i}\frac{p_i c_i}{1.269\sum_{k\neq i}^{N} p_k c_k + \sigma^2} \quad (12)$$

With respect to (1) and (11), the utility function of the ith transmitter node is given by

$$u_i(r_i, p_i) = \frac{Lr_i}{Mp_i}\left(1 - \frac{0.195\sqrt{2\pi}}{\sqrt{\theta}\tilde{\gamma}_i}\right)^M \quad (13)$$

3.2 Rayleigh quasi-static slow flat-fading channel

In a quasi-static slow-fading channel, the fading coefficient, α_i, changes independently for each packet so that $\alpha_i(1) = \alpha_i(2) = \ldots = \alpha_i(b)$, where $\alpha_i(b)$ is the fading affecting bit b in the packet. It is also assumed that α_i, the fading coefficient of the main signal, and α_k, the fading coefficient of the kth interfering signal, are independent. In this case, the conditional utility function is written as

$$u_{(i|\gamma_i, I_i)}(r_i, p_i) = \frac{Lr_i}{Mp_i}(1 - \mathrm{e}^{-\theta\gamma_i^2/2})^M \quad (14)$$

Similar to (10), we derive $u_{(i|I_i)}(r_i, p_i)$ by averaging over the conditional utility function in (14)

$$\begin{aligned} u_{(i|I_i)}(r_i, p_i) &= \int_0^\infty u_{(i|\omega, I_i)}(r_i, p_i) f^{\gamma_i|I_i}(\omega)\,\mathrm{d}\omega \\ &= \int_0^\infty \frac{0.78Lr_i}{Mp_i}(1 - \mathrm{e}^{-\theta\omega^2/2})^M \frac{1}{\gamma_i'}\mathrm{e}^{-0.78\omega/\gamma_i'}\,\mathrm{d}\omega \\ &= \frac{0.78Lr_i}{Mp_i\gamma_i'}\sum_{k=0}^{M}\binom{M}{k}(-1)^k \\ &\quad \times \int_0^\infty \mathrm{e}^{-((k\theta\omega/2)+(0.78/\gamma_i'))\omega}\,\mathrm{d}\omega \\ &= \frac{0.78Lr_i}{Mp_i\gamma_i'}\left(\gamma_i' + \sum_{k=1}^{M}\binom{M}{k}\frac{\sqrt{2\pi}(-1)^k}{2\sqrt{k\theta}} \right.\\ &\quad \left. \times\, \mathrm{e}^{0.304/k\theta\gamma_i'^2}\left(1 - \mathrm{err}\left(\frac{0.7}{\sqrt{2k\theta}\gamma_i'}\right)\right)\right) \end{aligned} \quad (15)$$

Considering $\gamma_i' \gg 1$ we can approximate (15) as

$$u_{(i|I_i)}(r_i, p_i) = \frac{0.78Lr_i}{Mp_i}\left(1 + \frac{1}{\gamma_i'}\sum_{k=1}^{M}\binom{M}{k}\frac{\sqrt{2\pi}(-1)^k}{2\sqrt{k\theta}}\right) \quad (16)$$

and finally u_i can be obtained as

$$\begin{aligned} u_i(r_i, p_i) &= \boldsymbol{E}\{u_{(i|I_i)}\} \\ &\simeq \frac{0.78Lr_i}{Mp_i}\left(1 + \frac{\boldsymbol{E}[I_i] + \sigma^2}{(B_i r_i)p_i c_i}\sum_{k=1}^{M}\binom{M}{k}\frac{\sqrt{2\pi}(-1)^k}{2\sqrt{k\theta}}\right) \\ &= \frac{0.78Lr_i}{Mp_i}\left(1 + \frac{1}{\tilde{\gamma}_i}\sum_{k=1}^{M}\binom{M}{k}\frac{\sqrt{2\pi}(-1)^k}{2\sqrt{k\theta}}\right) \\ &= \frac{0.78Lr_i}{Mp_i}\left(1 - \frac{\beta}{\tilde{\gamma}_i}\right) \end{aligned} \quad (17)$$

where

$$\beta = -\sum_{k=1}^{M}\binom{M}{k}\frac{\sqrt{2\pi}(-1)^k}{2\sqrt{k\theta}} > 0$$

4 Non-cooperative rate and power control game with pricing

In this section, the existence, uniqueness and Pareto efficiency, of NE for the proposed game are discussed.

4.1 Transmission rate nash equilibrium for NRPGP

In non-cooperative rate and power control, each transmitter node maximises its own utility by adjusting its rate and power, but ignores the harm it may cause to other receiver nodes by the interference it produces. Pricing is an effective tool in this condition. An efficient pricing mechanism makes the decentralised decisions compatible with the overall network efficiency by encouraging efficient sharing of the resources as opposed to the aggressive competition in pure non-cooperative games. In this section we define a non-cooperative game with pricing in which the price is proportional to the rate of the node. Let $G_p = [\mathcal{N}, \{\boldsymbol{r}, \boldsymbol{p}\}, \{u_i^c(\boldsymbol{r}, \boldsymbol{p})\}]$ denote the NRPGP, where $\mathcal{N} = \{1, 2, \ldots, N\}$ is the index set for the active transceiver pairs, $\boldsymbol{r} = \{r_i\}_{i=1}^N$ is the rate strategy set for all nodes, $\boldsymbol{p} = \{p_i\}_{i=1}^N$ is the power strategy set for all nodes and $u_i^c(\boldsymbol{r}, \boldsymbol{p})(.)$ is the complementary utility function of the ith transmitter node in the ith transceiver pair. The utility for the NRPGP is

$$u_i^c(\boldsymbol{r}, \boldsymbol{p}) = u_i(\boldsymbol{r}, \boldsymbol{p}) - c_i(\boldsymbol{r}, \boldsymbol{p}) \tag{18}$$

where $c_i: \Re \times \Re \to \Re_+$ is the pricing function of $i \in \mathcal{N}$ and

$$u_i(\boldsymbol{r}, \boldsymbol{p}) = u_i(r_i, p_i | R_{-i}, P_{-i}) \tag{19}$$

where p_i and r_i are the transmit power and rate of the ith transmitter node and P_{-i} and R_{-i} are the transmit power and rate vector of all other other nodes. We propose a pricing scheme in which the price increases monotonically with the rate and power of the transmitter node i

$$c_i(\boldsymbol{r}, \boldsymbol{p}) = \lambda_i r_i p_i \tag{20}$$

The pricing factor λ_i is set based on the type of the node (DS-UWB or MB-OFDM), such that each node's self-interest leads to overall improvement of the system performance. In our distributed environment, these pricing factors are broadcasted to DEVs through PNCs. The NRPGP with linear pricing is defined by

$$\text{NRPGP} \max_{r_i \in \boldsymbol{r}, p_i \in \boldsymbol{p}} u_i^c(\boldsymbol{r}, \boldsymbol{p}) \quad \forall i \in \mathcal{N} \tag{21}$$

Theorem 1: (a) Existence: For the Rayleigh fast flat-fading case, NE in the transmission rates exists in the NRPGP game (called G_{p1} hereafter) if, for all $i = 1, 2, \ldots, N$, first, $\boldsymbol{r}$ is a nonempty, convex and compact subset of the Euclidean space $\Re^N$, and second, $u_i^c(\boldsymbol{r}, \boldsymbol{p})$ is continuous in $\boldsymbol{r}$ and quasi-concave. *(b) Uniqueness*: The NE point of G_{p1} is unique.

Proof 1a: We assume that each transmitter node has a strategy space that is defined by the maximum and minimum rates, and all rates in between. So the first condition on the strategy space, $\boldsymbol{r}$, is satisfied. To check whether the function is quasi-concave, we first derive the second derivative (see (22))

Then (see (23))

To show that the utility function is a quasi-concave function of r_i we should have $((\partial^2 u_i^c(\boldsymbol{r}, \boldsymbol{p}))/\partial r_i^2) < 0 \quad \forall i \in \mathcal{N}$. This condition is fulfilled if

$$\frac{\partial^2 u_i^c(\boldsymbol{r}, \boldsymbol{p})}{\partial r_i^2} < 0 \quad \forall \quad \tilde{\gamma}_i > \left(\frac{39\sqrt{2}\pi(M+1)}{400\sqrt{\theta}} = \tilde{\gamma}_{i-\min} \right) \tag{24}$$

where $\tilde{\gamma}_{i-\min}$ is defined as the minimum required SINR, in order for the NE to exist.

Proof 1b: The NE point is unique if the best response vector of all transmitter nodes is a standard vector function. The best response vector of a transmitter node i is the best strategy that the node i can take to attain the maximum utility. The best response vector of all transmitter nodes is defined as $\rho(r) = (\rho_1(r), \rho_2(r), \ldots, \rho_N(r))$ and the best response vector of transmitter node i is given by

$$\rho_i(r) = \min(r_i^{\max}, r_{i-\max}) \tag{25}$$

where $r_{i-\max}$ is the maximum allowed transmission rate of the transmitter node i in the strategy space $\boldsymbol{r}$ and $r_i^{\max}$ is the the maximising transmission rate of transmitter node i based on the utility function concavity constraint and can be derived by setting (22) to zero and solving it numerically. In the case of the game with no pricing we have

$$r_i^{\max} = \frac{200\sqrt{\theta}B_i}{39\sqrt{2}\pi(M+1)} \frac{p_i c_i}{\sum_{k \neq i}^N p_k c_k + \sigma^2} \tag{26}$$

A function is said to be standard if it satisfies the following properties [10]: (i) positive: $\rho(r) > 0$; (ii) monotone: if $r \geq r'$ then $\rho(r) > \rho(r')$; and (iii) scalable: for all $\mu > 1$, $\mu\rho(r) > \rho(\mu r)$. These properties can be easily verified for fixed point $r_i^{\max} = \rho_i(r_i)$. Therefore the NE is unique.

Theorem 2: Existence: For the Rayleigh quasi-static slow flat-fading channel, NE in the transmission rates exists in the NRPGP game (called G_{p2} hereafter) and is unique.

Proof 2: To show the concavity of the utility function we find the first and second order derivatives based on (17) as

$$\frac{\partial u_i^c(\boldsymbol{r}, \boldsymbol{p})}{\partial r_i} = \frac{0.78L}{Mp_i}\left(1 - \frac{2\beta}{\tilde{\gamma}_i}\right) - \lambda_i p_i \tag{27}$$

and

$$\frac{\partial^2 u_i^c(\boldsymbol{r}, \boldsymbol{p})}{\partial r_i^2} = -\frac{1.56L\beta}{Mr_i p_i \tilde{\gamma}_i} \tag{28}$$

Considering $\beta > 0$ we get $((\partial^2 u_i^c(\boldsymbol{r}, \boldsymbol{p}))/\partial r_i^2) < 0$ and the utility function is concave. Therefore NE exists for the

$$g_i = \frac{\partial u_i^c(\boldsymbol{r}, \boldsymbol{p})}{\partial r_i} = \frac{2^{-5M/2}L\left(100\sqrt{2\theta} - (39\pi(M+1)/\tilde{\gamma}_i)\right)\left(4\sqrt{2} - (39\pi)/\left(25\sqrt{\theta}\tilde{\gamma}_i\right)\right)^M}{Mp_i\left(100\sqrt{2\theta} - (39\pi/\tilde{\gamma}_i)\right)} - \lambda_i p_i \tag{22}$$

$$\frac{\partial^2 u_i^c(\boldsymbol{r}, \boldsymbol{p})}{\partial r_i^2} = \frac{39.2^{-5M/2}\pi L\left(39\pi(M+1) - 200\sqrt{2\theta}\tilde{\gamma}_i\right)\left(4\sqrt{2} - (39\pi/25\sqrt{\theta}\tilde{\gamma}_i)\right)^M}{p_i r_i\left(100\sqrt{2\theta}\tilde{\gamma}_i - 39\pi\right)^2} \tag{23}$$

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game G_{p2}. The uniqueness can be easily verified similarly to proof 1.

4.2 Transmission rate Pareto optimality for NRPGP

The NE is usually the solution to the power and rate control problems where no transmitter node can increase its utility any further unilaterally. Therefore such a distributed scenario is supposed to be less efficient than a possible power and rate allocation obtained through cooperation between transceiver pairs as a result of centralised optimisation. Indeed, it is well known that in general NEs are inefficient. A resource (power or rate) allocation is said to be more efficient (or Pareto dominant) if it is possible to increase the utility of some of the transmitter nodes without hurting any other receiver nodes. Mathematically speaking, a transmission rate vector $\boldsymbol{r}^0 = (r_1^0, r_2^0, \ldots, r_N^0)$ in game G_p, is said to be Pareto optimal if there exists no other vector $\hat{\boldsymbol{r}}$ in the strategy space such that $u_i(\boldsymbol{r}^0, \boldsymbol{p}) > u_i(\hat{\boldsymbol{r}}, \boldsymbol{p})$, $\forall i \in \mathcal{N}$.

Theorem 3: A NE point for the game G_p is Pareto rate optimal for the fast flat-Rayleigh fading case.

Proof 3: Let us consider $r_i^0 = \varphi_i \hat{r}_i$, $i \in \mathcal{N}$ where $\varphi_i > 1$, $\forall i \in \mathcal{N}$. Then based on (13) and (21) we have

$$u_i^c(\boldsymbol{r}^0, \boldsymbol{p}) = \frac{L r_i^0}{M p_i}\left(1 - \frac{0.195\sqrt{2\pi}}{(\sqrt{\theta}B_i/r_i^0)\left(p_i c_i/\left(\sum_{k\neq i}^N p_k c_k + \sigma^2\right)\right)}\right)^M - \lambda_i r_i p_i \tag{29}$$

To analyse the behaviour of $u_i^c(\boldsymbol{r}^0, \boldsymbol{p})$ with φ_i, we find the first derivative as follows (see (30))

It is easy to see that $g_i(\hat{r}_i/\varphi_i) < g_i(\hat{r}_i) = 0$, $\forall i \in \mathcal{N}$. Hence $((\partial u_i^c(\boldsymbol{r}^0, \boldsymbol{p}))/\partial \varphi_i) < 0$, $\forall i \in \mathcal{N}$ which means that $u_i^c(\boldsymbol{r}^0, \boldsymbol{p})$ is a decreasing function of $\varphi_i > 1$. Thus the NE point of game G_{p1} is Pareto rate optimal.

Theorem 4: A NE point of the game G_{p2} is Pareto rate optimal for the quasi-static slow flat-Rayleigh fading case.

Proof 4: Can be easily proven similar to Theorem 3.

Similarly, the same theorems can be proven for transmit power equilibrium point.

5 Numerical results

An asynchronous rate and power control algorithm similar to [10] is considered, which converges to the unique NE point. In this algorithm, the nodes update their transmission rate and power in the same step. In the beginning, an initial power and rate vector is assigned to the system, then at each step the NE is calculated using (13) for both, the rates and powers, and the new values are chosen as the minimum between the value for NE and the maximum defined values.

To get the most out of the system performance, the pricing factor is considered adaptive and for each iteration an optimum value, λ_i^{opt} is calculated [10]. Once the NE with no pricing is obtained, the NPRGP is played again after incrementing the pricing factor, λ_i, by a positive value, $\Delta\lambda_i$. If the utilities improve with this new equilibrium, that is, $u_i^c(\lambda_i) < u_i^c(\lambda_i + \Delta\lambda_i)\forall i \in \mathcal{N}$, the pricing factor is incremented and the procedure is repeated. We let this process continue until an increase of the pricing factor results in utility levels worse than the previous equilibrium values for at least one node. This last value is taken as the optimum pricing factor. For the DS-UWB standard (channel 4) [2] the maximum data rate is considered as 220 Mbps, the two-sided bandwidth, B_i, is considered to be 1352 MHz, the centre frequency is 4056 MHz and the coefficient θ is 0.74. For the MB-OFDM (band group 1) standard [1], theses values are taken as 200 Mbps, 1584 MHz, 3960 MHz and 1.05, respectively. The noise power is −174 dBm/Hz and the maximum allowed transmit power of both networks in the system is −9.9 dBm. Two scenarios are simulated for the purpose of performance evaluation.

In the first scenario, we consider two transceiver pairs in two heterogeneous piconets. One DS-UWB transceiver pair with a transmit–receive distance of 1.2 m in the DS-UWB piconet and another transceiver pair of MB-OFDM with a distance of transmit–receive 4 m in the MB-OFDM piconet. These two transceiver pairs are positioned parallel to each other, whereas their parallel distance varies. Fig. 2 shows the transmission rate performance of each transceiver pair. As observed, in the case of NPRGP parameter control, both pairs achieve their maximum transmission rate even at much nearer interfering distances. The plots are drawn starting from 7-m distance because below this value the system is supposed to be shut off because of enormous performance degradation. The other noticeable result in the plot is the effect of fading. We can observe that the quasi-static slow flat-fading case has a slightly better performance. Fig. 3 shows the power consumption of each transceiver pair. We observe that the power consumption is reduced more than half in the case of NPRGP. This performance can be interesting in scenarios like sensor networks where power consumption is a critical issue.

In the second scenario, we study the impact of increasing the number of active transceiver pairs on the average throughput and power performance, without considering any specific WPAN piconet structure. An initial topology is considered similar to the first scenario but with a fixed vertical distance of 10 m. Later different transceiver pairs,

$$\frac{\partial u_i^c(\boldsymbol{r}^0, \boldsymbol{p})}{\partial \varphi_i} = \frac{\hat{r}_i 2^{-5M/2} L\left(100\sqrt{2\theta} - \left(39\pi(M+1)/(B_i/\varphi_i\hat{r}_i)\left(p_i c_i/\left(\sum_{k\neq i}^N p_k c_k + \sigma^2\right)\right)\right)\right)\left(4\sqrt{2} - \left(39\pi/\left(25\sqrt{\theta}B_i/\varphi_i\hat{r}_i\right)\cdot\left(p_i c_i/\left(\sum_{k\neq i}^N p_k c_k + \sigma^2\right)\right)\right)\right)^M}{M p_i\left(100\sqrt{2\theta} - (39\pi/B_i/\varphi_i\hat{r}_i)\left(p_i c_i/\left(\sum_{k\neq i}^N p_k c_k + \sigma^2\right)\right)\right)} - \lambda_i p_i$$
$$= \hat{r}_i g_i\left(\frac{\hat{r}_i}{\varphi_i}\right), \quad \forall i \in \mathcal{N} \tag{30}$$

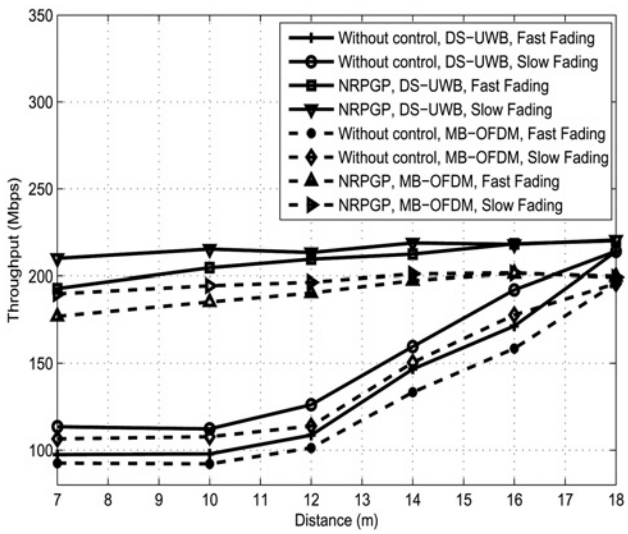

Fig. 2 *Throughput against vertical distance between two transceiver pairs ($N_{MB} = N_{DS} = 1$)*

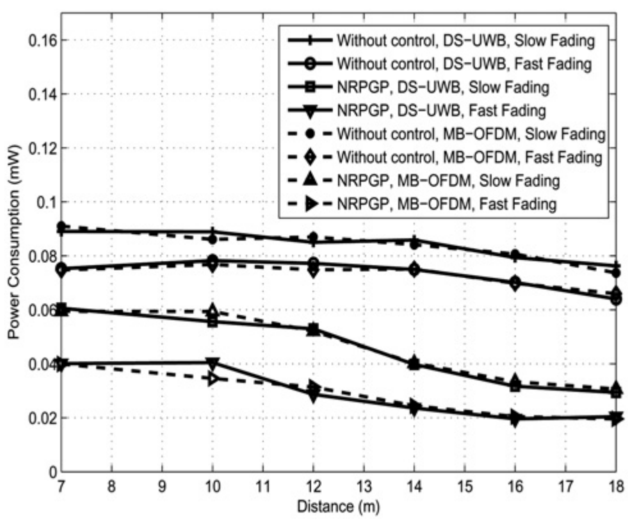

Fig. 3 *Power consumption against vertical distance between two transceiver pairs ($N_{MB} = N_{DS} = 1$)*

that is, either DS-UWB or MB-OFDM, are placed around the initial DS-UWB transceiver pair, whereas the same 10-m vertical distance is kept constant between the newly placed transceiver pair and the initial transceiver pair. At each iteration, we have $N_{\rm MB} = N_{\rm DS}$, that is 50% DS-UWB and 50% MB-OFDM pairs. Fig. 4 plots the average network throughput for different number of active transceiver pairs around the initial DS-UWB transceiver pair. It is observed that our proposed game, NPRGP, has the best performance. The results are also compared with the algorithm in [10] based on power control only. It is seen that the joint power and rate control algorithm outperforms the algorithm based on power control only. Fig. 4 also demonstrates that the average system throughput decreases as the number of active pairs increases. Fig. 5 shows the average system power consumption against the number of active transceiver pairs. As expected the performance is better than the case without any control. However, the algorithm based on

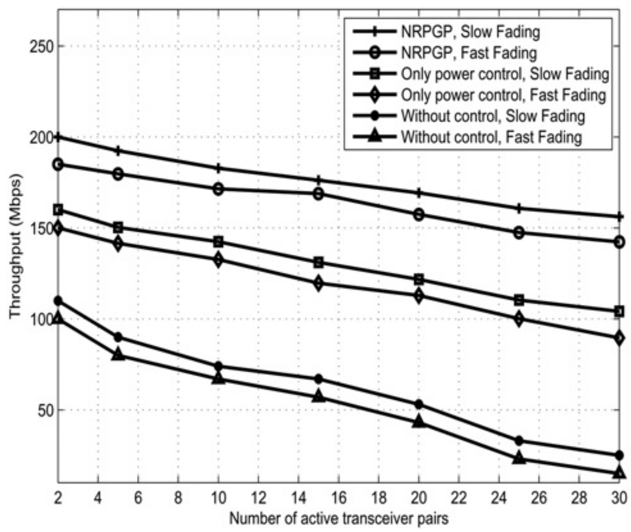

Fig. 4 *Average system throughput against number of active transceiver pairs ($N_{MB} = N_{DS}$ at each iteration)*

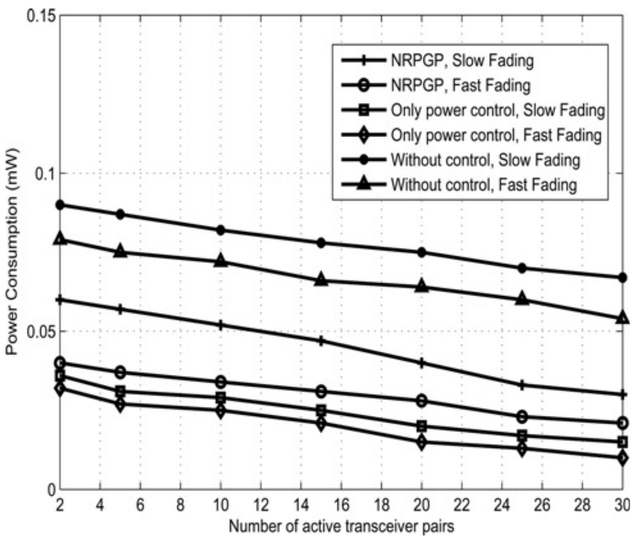

Fig. 5 *Average system power consumption against number of active transceiver pairs ($N_{MB} = N_{DS}$ at each iteration)*

power control only, has a slightly better performance. Owing to not having the transmission rate constraint, this can be interpreted as having more freedom in choosing transmission power values in the power strategy space.

Fig. 6 shows the throughput of one DS-UWB transceiver pair while the number of active interfering MB-OFDM transceiver pairs varies. Fig. 7 show similar results as in Fig. 6 but for a MB-OFDM transceiver pair while the number of active DS-UWB interfering transceiver pairs varies. It is observed that although the maximum achievable throughput for the MB-OFDM pair is a bit lower than for a DS-UWB pair, the rate of performance deterioration, as the number of interfering pairs increases, is better than DS-UWB, which implies better robustness of MB-OFDM to external interference. In Figs. 4–7, we have fixed a minimum rate of 30 Mbps for all the nodes to obtain the results based on only power control algorithm. Therefore the curves are comparable with the best case scenario of the algorithm only based on power control.

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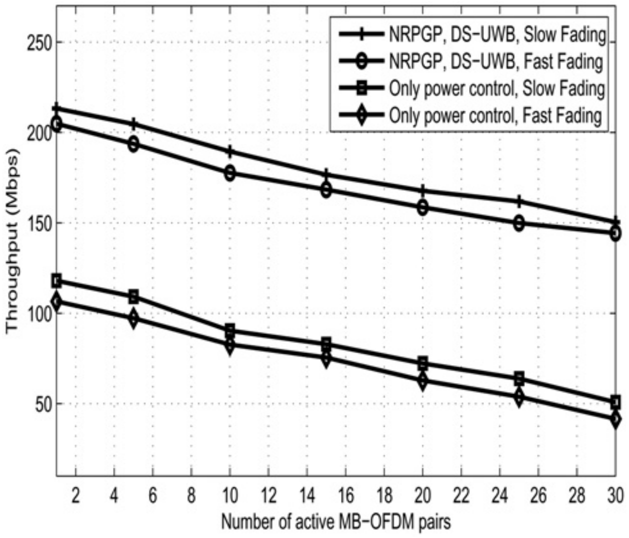

Fig. 6 *Throughput of a DS-UWB transceiver pair ($N_{DS} = 1$) against number of active MB-OFDM interfering pairs, N_{MB}*

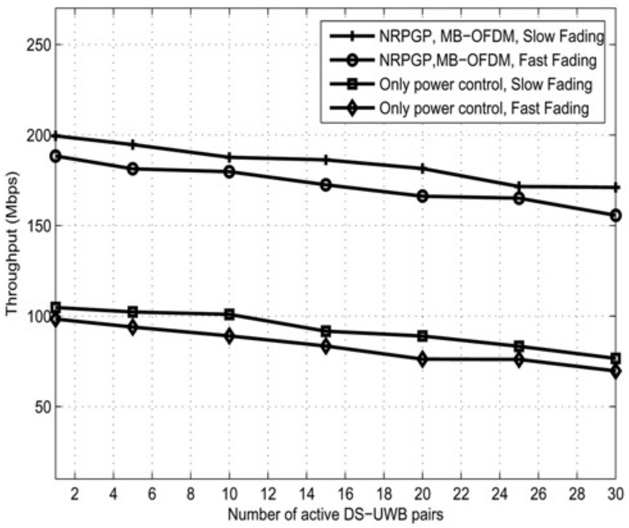

Fig. 7 *Throughput of a MB-OFDM transceiver pair ($N_{MB} = 1$) against number of active DS-UWB interfering pairs, N_{DS}*

6 Conclusion

In this paper, the coexistence issue between MB-OFDM and UWB standards has been addressed, considering a WPAN topology. Specifically, a game-theoretic approach has been proposed for interference mitigation between WPANs using the two UWB technologies. A non-cooperative game model was used for joint rate and power control in these heterogeneous networks, which can lead to overall network interference reduction. To derive the expression for the utility function, Rayleigh fading model was considered. A pricing mechanism has been integrated into the defined game to compensate for the effect of interference. Later, the existence, uniqueness and Pareto efficiency of the NE for the proposed game were discussed. It has been observed that in the case of NPRGP parameter control, both kinds of networks achieve their maximum transmission rate even at much closer distances and the power consumption is reduced. The latter specification is notable, specifically for applications like sensor networks where power consumption is a critical issue. The effect of the number of transceiver pairs on performance was also investigated.

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