Cooperative Scheduling for Coexisting Body Area Networks

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***Abstract*—Body area networks (BANs), referring to embedded wireless systems in, on, and around bodies, are expected to take an important role for health, leisure, sports, and all the facets of our daily life. In many cases, several BANs coexist in a small area, resulting in very strong inter-BAN interference, which seriously disturbs intra-BAN communications. The goal of this paper is to decrease inter-BAN interference by cooperative scheduling, hence increasing packet reception rate (PRR) of intra-BAN communications. Cooperative scheduling here is divided into two sub-problems: single-BAN scheduling as an assignment problem and multi-BAN concurrent scheduling as a game. For the first sub-problem, a low complexity algorithm, horse racing scheduling, is proposed, which achieves near-optimal PRR for the BAN performing scheduling. For the second sub-problem, we prove the existence of a set of mixed strategy Nash equilibria (MSNE). Then, we propose a distributed cooperative scheduling scheme, which efficiently achieves higher PRR than the MSNE without degrading fairness.**

***Index Terms*—Body area network (BAN), cooperative scheduling, combinatorial optimization, Tian Ji horse racing, game theory**

I. INTRODUCTION

For some time past, wireless communication technologies have started filling the gap toward a pervasive world. After the very fast growing era of cellular networks, the time for Internet of Things is coming. Connecting things, machines, and humans in a spontaneous fashion becomes the key issue. Concerning the connections of humans, mobile phones will share their place with several embedded systems, spread over the human body to monitor, control, and help humans in different situations, such as healthcare to the elderly and body motion monitoring in sportive or leisure activities. To support this development, the research community recently increased its interest on body area network (BAN) technologies [1]–[3], focusing on various aspects, including physical (PHY) layer, medium access control (MAC) layer, network layer, channel modeling, security, etc.

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The design of BAN MAC could refer to IEEE 802.15.3/15.4 standards [8], [9] and the progresses of IEEE 802.15.6 working group [10]. As shown in Fig. 1, a BAN superframe contains four periods: control period, contention access period (CAP), contention free period (CFP), and inactive period. The CFP is composed of a number of time slots. In this period, transmission is based on time division multiple access (TDMA). Guaranteed time slot (GTS) requests in the control period are used to demand time slots in the CFP of the next superframe or a number of following superframes. Since TDMA-based protocols outperform contention-based ones for non-dynamic types of networks (e.g., BANs) [4], [11], data frames are mainly transmitted in the CFP. Therefore, it is of primary importance to improve the utilization of the CFP. When there is an isolated BAN, transmissions of sensors are scheduled by the coordinator into different time slots without causing any interference. However, it is common to have multiple BANs coexisting in a small environment, e.g., in a hospital room or during a marathon. If each BAN only considers its own sensors' transmissions for scheduling, there could be serious inter-BAN interference [12], [13]. Therefore, an appropriate scheduling approach to achieve harmonized coexistence of multiple BANs is required.

Scheduling has been extensively studied in various types of wireless networks in the past decades, but the BAN context offers new challenges for scheduling that have not been properly addressed yet. Traditional schemes, such as carrier-sense multiple access with collision avoidance (CSMA/CA) and listen-before-transmit (LBT), have been studied for the scheduling of an isolated BAN [5], [14], but they do not specifically work for an environment of multiple coexisting BANs. Former studies considering multiple coexisting BANs include time resource sharing [15], duty cycle adjustment [15], and the scheduling of a patient monitoring system [4]. All these schemes completely separate transmissions of different BANs into different time resources, so that collision could be avoided. They are called *non-concurrent transmission (NCCT)* in this paper. However, for BAN applications with relatively large traffic [3], [16], [17], NCCT is not efficient because its total time resource utilization can never exceed 1 (the utilization of an isolated BAN). Since the transmission range of BAN signals is very small, it is highly possible that sensors in different BANs with a certain inter-BAN distance can successfully perform *concurrent transmission (CCT)*, which should enable great performance enhancement in the case of multiple coexisting BANs.

The study of CCT scheduling schemes is limited in the literature. Patro et al. in [15] suggested a BAN scheduling

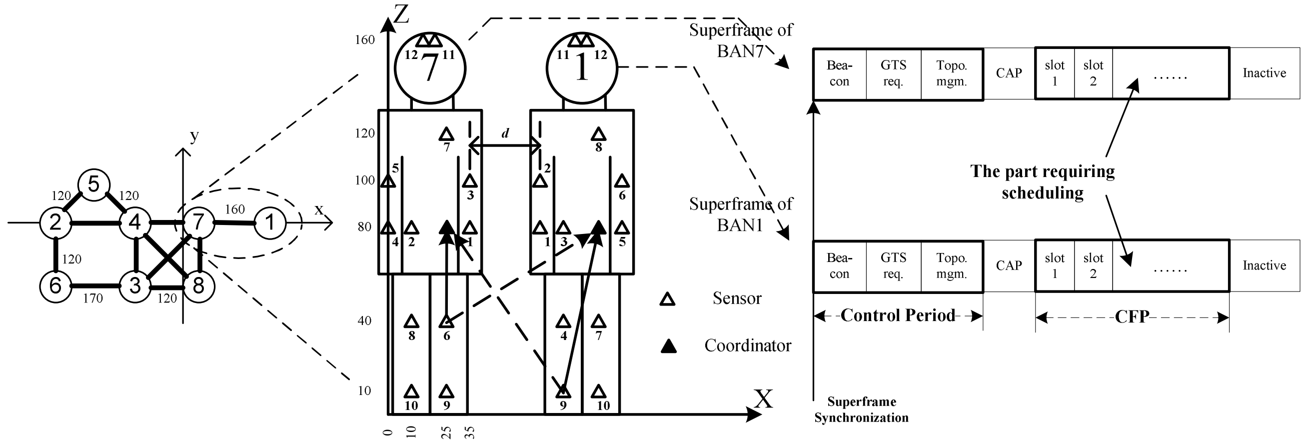


Fig. 1. Multi-BAN coexistence scenario.

approach based on multiple parameters, such as number of sensors, traffic, signal strength and application priority, to group BANs for CCT. This approach could be considered as a macro resource allocation scheme for multiple geometrically distributed BANs, but not a scheme for the scheduling of sensors in each BAN. Moreover, Naor et al. in [18] studied a random access scenario where multiple nodes transmit with certain probability in the same time slot. They showed that CCT might increase throughput. Son et al. in [19] presented an experimental study on CCT in wireless sensor networks. They offered a better understanding of CCT and showed the features of joint interference in the presence of multiple interferers. Liu et al. in [20] studied CCT scheduling for multi-hop multicast in wireless mesh networks and showed that CCT greatly increases throughput in mesh networks.

Actually, none of the above-mentioned studies considers how to schedule sensors in CCT to overcome inter-BAN interference, so as to achieve optimal transmissions for itself and/or all the coexisting BANs. Since such a scheduling procedure requires a certain level of information exchange or privity, we call it *cooperative scheduling*. In this paper, we consider a principal application of BAN technology, body monitoring, where all the sensors periodically send their data to the coordinator in real time [2]–[7]. Scheduling here is divided into two sub-problems: single-BAN scheduling as an assignment problem and multi-BAN concurrent scheduling as a game. For the first sub-problem, we assume that one BAN actively designs its strategy to maximize its own benefit, while the other BANs fix their strategies. We apply two well-known combinatorial optimization algorithms, Hungarian algorithm [21] and greedy algorithm [22], for the sake of comparison, but none of them could perfectly solve this practical issue as explained in Section III.A. Therefore, we propose a new scheme called horse racing scheduling, which is originated from an ancient Chinese horse racing story. This scheme is simple, fast, and let the BAN performing it achieve near-optimal packet reception rate (PRR). For the second sub-problem, we prove the existence of Nash equilibria (NE). Then, based on the knowledge that horse racing scheduling performs very well for single-BAN scheduling, we propose a distributed cooperative scheduling scheme, which efficiently achieves higher PRR than the mixed strategy NE without degrading fairness.

This article is organized as follows. The system model is described in Section II. In Section III and Section IV, we present our studies on the two sub-problems, respectively. We evaluate the performance of different schemes in Section V. Finally, the paper is concluded in Section VI.

II. System Model

A. Scheduling model for BANs

We consider a set of coexisting BANs $\{B_k|k=1,\ldots,M\}$, where M is the number of BANs and B_k stands for BAN k. Given B_k, we use B_{-k} to indicate the set consisting of the remaining BANs. Each BAN is composed of N sensors, denoted by $\{s_k^i|i=1,\ldots,N\}$, of equal importance and one coordinator, forming a star topology with the coordinator, as the receiver, in the center. BANs use identical superframe structure and inter-BAN superframe synchronization is achieved before transmission, so there is never collision between one BAN's data frame and another BAN's control information. However, between different BANs' data frames in the CFP there could be interference disturbing transmissions.

The coordinator of each BAN gathers channel state information for scheduling, including intra-BAN received signal strength (RSS) and inter-BAN joint received interference strength (JRIS). Intra-BAN RSS of B_k is denoted by $\{g_k^i|i=1,\ldots,N\}$, where g_k^i represents the RSS from s_k^i to its coordinator. Using s_{-k}^i to represent the set of $M-1$ sensors, one from each BAN except B_k, transmitting concurrently with s_k^i, the inter-BAN JRIS from B_{-k} can be denoted by $\{h_{-k}^i|i=1,\ldots,N\}$, where h_{-k}^i represents the vector of JRIS from s_{-k}^i to the coordinator of B_k. Thus, r_k^i, the PRR of s_k^i, can be written as a function of the signal-to-interference-plus-noise ratio (SINR) and it is given by $r_k^i=f(g_k^i/(h_{-k}^i+n_0))$, where n_0 denotes the variance of additive white Gaussian noise (AWGN). Finally, the utility of s_k^i is given by

$$u_k(s_k^i,s_{-k}^i)=\frac{(r_k^i)^{1-\alpha}}{1-\alpha}, \qquad (1)$$

TABLE I
MAIN NOTATIONS

B_k	BAN k
s_k^i	sensor i in B_k
$\mathcal{S}_{-k}^t$	$M-1$ sensors, one from each BAN of B_{-k}, in slot t
N	number of sensors in a BAN
n_0	variance of AWGN
g_k^i	RSS from s_k^i to its coordinator
$\mathcal{H}_{-k}^t$	JRIS from $\mathcal{S}_{-k}^t$ on the coordinator of B_k
r_k^i	PRR of s_k^i under JRIS of s_{-k}^i
$u_k(\cdot,\cdot)$	utility of a sensor in B_k
α	index of α-fairness
$\mathbf{U}_k$	$N\times N$ assignment matrix composed of $u_k(s_k^i,\mathcal{S}_{-k}^t)$
$\mathbf{P}_k$	set of pure strategies of B_k
p_k^ω	ωth pure strategy of B_k
$(\cdot)_t$	index of sensor in time slot t for certain pure strategy
$\mathscr{S}^\theta(p_k)$	θ cyclic right shifts of p_k
$\Pi_k^{\omega_1,\omega_2}$	permutation matrix mapping $p_k^{\omega_1}$ into $p_k^{\omega_2}$
$\mathbb{M}_k$	set of mixed strategies of B_k
$\mathbf{m}_k$	mixed strategy of B_k
m_k^ω	probability that B_k uses p_k^ω
$\mathscr{U}_k(\cdot,\cdot)$	utility of a strategy of B_k
$Supp(\mathbf{m}_k)$	support of $\mathbf{m}_k$

where α is the index for α-fairness [24].

For data transmission from sensors to the coordinator, we assume that the CFP is divided into N time slots, and each sensor gets one time slot in each superframe for transmitting packets with constant size from a backlogged buffer. Thus, a *pure strategy* of the scheduling of B_k is a permutation[1] of $\{s_k^i|i=1,\ldots,N\}$, given by $p_k^\omega\in\mathbf{P}_k$, where ω is the index in the set of pure strategies $\mathbf{P}_k$ and will be neglected if unnecessary. Here, p_{-k} is used to denote the opponents of p_k. Thus, the utility of B_k using p_k is given by

$$\mathscr{U}_k(p_k,p_{-k})=\sum_{t=1}^{N}u_k(s_k^{(p_k)_t},s_{-k}^{(p_k)_t}), \tag{2}$$

where $(\cdot)_t$ denotes the index of the sensor in time slot t for certain pure strategy. A *mixed strategy* of B_k is a probability distribution on $\mathbf{P}_k$, given by $\mathbf{m}_k=\{m_k^\omega|\omega=1,\ldots,N!\}\in\mathbb{M}_k$, where $\mathbb{M}_k$ is the set of mixed strategies of B_k, m_k^ω is the probability of using p_k^ω, and $\sum_\omega m_k^\omega=1$. The utility of B_k using mixed strategy $\mathbf{m}_k$ is given by

$$\mathscr{U}_k(\mathbf{m}_k,\mathbf{m}_{-k})=\sum_\omega m_k^\omega\mathscr{U}_k(p_k^\omega,\mathbf{m}_{-k}). \tag{3}$$

Throughout this work, scheduling is divided into two sub-problems: *single-BAN scheduling* and *multi-BAN concurrent scheduling*. For the first sub-problem, the BANs in B_{-k} fix their strategies and B_k searches for the strategy maximizing its own utility, which is a 2-dimensional assignment problem[2].

[1] In combinatorics, a permutation of a set of distinct objects is defined as an ordered arrangement of these objects [23].

[2] In combinatorial optimization, an assignment problem is a quest for an assignment of N persons to N jobs, each person on one and only one job, such that the sum of the N pair (<person, job>) utilities is maximized. The utilities of all the pairs <person, job> can be represented by an $N\times N$ matrix, called assignment matrix [21].

To simplify our discussion, the assignment matrix is written as $\mathbf{U}_k=\{u_k(s_k^i,\mathcal{S}_{-k}^t)|i,t=1,\ldots,N\}_{[N\times N]}$, where $\mathcal{S}_{-k}^t=s_{-k}^{(p_k)_t}$ denotes the sensors of B_{-k} transmitted in time slot t. In our study, s_k^i for $i=1,\ldots,N$, correspond to rows of the matrix $\mathbf{U}_k$ and are ranked from the strongest RSS to the weakest, while $\{\mathcal{S}_{-k}^t$ for $t=1,\ldots,N\}$ correspond to columns and are ranked by their JRIS $\{\mathcal{H}_{-k}^t=h_{-k}^{(p_k)_t}|t=1,\ldots,N\}$ from the strongest to the weakest. Taking an M-BAN case with 3 sensors per BAN as an example,

$$\mathbf{U}_k=\begin{pmatrix} u_k(s_k^1,\mathcal{S}_{-k}^1) & u_k(s_k^1,\mathcal{S}_{-k}^2) & u_k(s_k^1,\mathcal{S}_{-k}^3)\\ u_k(s_k^2,\mathcal{S}_{-k}^1) & u_k(s_k^2,\mathcal{S}_{-k}^2) & u_k(s_k^2,\mathcal{S}_{-k}^3)\\ u_k(s_k^3,\mathcal{S}_{-k}^1) & u_k(s_k^3,\mathcal{S}_{-k}^2) & u_k(s_k^3,\mathcal{S}_{-k}^3)\end{pmatrix}, \tag{4}$$

where $g_k^1>g_k^2>g_k^3$ and $\mathcal{H}_{-k}^1>\mathcal{H}_{-k}^2>\mathcal{H}_{-k}^3$.

In the second sub-problem, all the BANs decide their strategies, and originate a strategic game defined by a triple $\mathscr{G}=\big\{\{B_k|k=1,\ldots,M\},\mathbb{M}_1\times,\ldots,\times\mathbb{M}_M,\mathscr{U}_k(\mathbf{m}_k,\mathbf{m}_{-k})_{k=1,\ldots,M}\big\}$.

B. Terminology

To help explain the following proposals and theorems, we define several new terms:

- *Shift*: for a given pure strategy p_k, a cyclic right shift, denoted by $\mathscr{S}^1(p_k)$, represents an operation that moves sensors $\{s_k^i|i=1,\ldots,N-1\}$ to the right by one place and the last sensor s_k^N to the first place on the left. We use $\mathscr{S}^\theta(p_k),\theta\in\{0,\ldots,N-1\}$ to denote θ cyclic right shifts of p_k.
- *Loop*: from an initial pure strategy p_k, $N-1$ other pure strategies could be obtained by $\mathscr{S}^\theta(p_k),\theta=1,\ldots,N-1$. These N pure strategies, including the initial one, form a loop. The initial pure strategy is called the *root* of the loop. If the sensors in the root of a given loop are ranked from the strongest RSS to the weakest, this loop is called a *horse racing loop*.
- *Transform*: an operation changing one pure strategy into another by interchanging the places of its sensors is called a transform. It can be represented by a permutation matrix $\Pi_k^{\omega_1,\omega_2}$ which performs a mapping from $p_k^{\omega_1}$ to $p_k^{\omega_2}$. Hence, a new pure strategy is obtained by multiplying pure strategy $p_k^{\omega_k}$ with the permutation matrix, i.e., $p_k^{\omega_k}\Pi_k^{\omega_1,\omega_2}$. Obviously, we have the following three basic properties for transform:

Property 1: $p_k^{\omega_1}\Pi_k^{\omega_1,\omega_2}=p_k^{\omega_2}$,
Property 2: $p_k^{\omega_k}\Pi_k^{\omega_1,\omega_2}\Pi_k^{\omega_2,\omega_1}=p_k^{\omega_k}$, *and*
Property 3: $\forall\Pi_k^{\omega_1,\omega_2}$, $u_k(s_k^{(p_k)_t},s_{-k}^{(p_k)_t})=u_k(s_k^{(p_k\Pi_k^{\omega_1,\omega_2})_\tau},s_{-k}^{(p_k\Pi_k^{\omega_1,\omega_2})_\tau})$, *where* $\Pi_k^{\omega_1,\omega_2}(t,\tau)=1$.

For multi-BAN concurrent scheduling, we consider two types of NE [25]:

Definition 1: *A set of pure strategies* $\{p_k^*\in\mathbf{P}_k|k=1,\ldots,M\}$ *is called a pure strategy NE (PSNE) if* $\forall k\in\{1,\ldots,M\}$ *and* $\forall p_k\in\mathbf{P}_k$, $\mathscr{U}_k(p_k^*,p_{-k}^*)\geq\mathscr{U}_k(p_k,p_{-k}^*)$.

Definition 2: *A set of mixed strategies* $\{\mathbf{m}_k^*\in\mathbb{M}_k|k=1,\ldots,M\}$ *is called a mixed strategy NE (MSNE) if* $\forall k\in\{1,\ldots,M\}$ *and* $\forall\mathbf{m}_k\in\mathbb{M}_k$, $\mathscr{U}_k(\mathbf{m}_k^*,\mathbf{m}_{-k}^*)\geq\mathscr{U}_k(\mathbf{m}_k,\mathbf{m}_{-k}^*)$.

III. Single-BAN Scheduling

In this section, we study the first sub-problem, in which B_{-k}, as *slaves*, fix their strategies and B_k, as a *master*, actively tries to maximize its own utility by scheduling. The issue is equivalent to the 2-dimensional assignment problem for finding the optimal combination of N entries in $\mathbf{U}_k$, such that one and only one entry in each row and each column is selected.

A. Common algorithms for 2-dimensional assignment problem

In combinatorial optimization theory, it is known that a 2-dimensional assignment problem can be precisely solved by Hungarian algorithm [21], with polynomial complexity of $O(N^3)$. However, the coherence time of the BAN channel is around 80 ms [17], so a BAN has at most tens of milliseconds to do the calculation based on the detected intra-BAN RSS and inter-BAN JRIS and make the final decision on the strategy to use. To the best of our knowledge, Hungarian algorithm is still too slow to be used for this issue in practice. Therefore, in this study, we use it only to find the maximum and minimum utilities of B_k as benchmarks.

Another widely used algorithm for combinatorial optimization is the greedy algorithm [22]. For this application, greedy algorithm consists of $N-1$ steps. In each step, it selects the entry satisfying $\max\limits_{i\notin I, t\notin T} u_k(s_k^i, \mathcal{S}_{-k}^t)$, where I and T represent the sets of indexes of rows and columns that have been selected in previous steps, respectively. The greedy algorithm has a time complexity of $O(N^2 \log N)$, but it does not guarantee to achieve the greatest utility.

B. Proposal 1: horse racing scheduling

In this subsection, we propose a new strategy for single-BAN scheduling. The idea is originated from an ancient Chinese horse racing story between a general called Tian Ji and his king, who both loved horse racing [26]. Once upon a time, they held a competition with the following rules. Each of them picked three horses (superior, medium and inferior) from their own. During the competition, the superior horses would race each other, then the medium horses and finally the inferior horses. As the king's horses were better in every category, Tian Ji had no chance to win. Then, Sun Bin, one of the most famous military strategist and counsellor in the ancient Chinese history, proposed him the following idea: to use his inferior horse to race the king's superior horse, then his superior horse to race the king's medium horse, finally his medium horse to race the king's inferior horse. In such a way, Tian Ji had chance to win the last two matches. This story is quite well-known as *Tian Ji horse racing* in China, and the mathematical principle behind this game was studied in [27]. However, to the best of our knowledge, this paper is the first one that uses this principle for a specific application scenario in communications.

Single-BAN scheduling is quite similar to the horse racing story: the master B_k maps to Tian Ji; B_{-k} map to the king; $\{s_k^i | i=1,\ldots,N\}$ and $\{\mathcal{S}_{-k}^t | t=1,\ldots,N\}$ map to Tian Ji's and the king's horses, respectively; $\{g_k^i | i=1,\ldots,N\}$ and $\{\mathcal{H}_{-k}^t | t=1,\ldots,N\}$ map to the strength of horses of Tian Ji and the king, respectively. Therefore, the strategy of horse racing scheduling for B_k corresponds to the best number of shifts from the root of the horse racing loop, given by

$$\theta^+ = \underset{\theta\in\{0,\ldots,N-1\}}{\operatorname{argmax}} \sum_{i=1}^{N} u_k(s_k^i, \mathcal{S}_{-k}^{i+\theta-1 \pmod N)+1}). \qquad (5)$$

Taking the M-BAN case with 3 sensors per BAN shown in (4) as an example, horse racing scheduling calculates the utility of B_k with 0, 1 and 2 shifts as $u_k(s_k^1, \mathcal{S}_{-k}^1) + u_k(s_k^2, \mathcal{S}_{-k}^2) + u_k(s_k^3, \mathcal{S}_{-k}^3)$, $u_k(s_k^1, \mathcal{S}_{-k}^2) + u_k(s_k^2, \mathcal{S}_{-k}^3) + u_k(s_k^3, \mathcal{S}_{-k}^1)$ and $u_k(s_k^1, \mathcal{S}_{-k}^3) + u_k(s_k^2, \mathcal{S}_{-k}^1) + u_k(s_k^3, \mathcal{S}_{-k}^2)$, respectively. The shift with the maximum utility is selected.

The computational cost of horse racing scheduling is quite low. The most relevant costs rise from three tasks: sorting of RSS and JRIS based on certain sort algorithms with complexity usually between $O(N \log N)$ and $O(N^2)$, summation of utilities with complexity $O(N^2)$, and selection of the maximum with complexity $O(N)$. Therefore, the computational complexity of horse racing scheduling is $O(N^2)$.

Horse racing scheduling achieves near-optimal PRR for the master, which can be intuitively explained as follows. The PRR curve as a function of SINR is similar to a sigmoidal function with very large slope at certain SINR [19]. Thus, the assignment matrix $\mathbf{U}_k$ with $\alpha = 0$ is a very special matrix, close to an upper triangular matrix with very small entries close to the main diagonal. Therefore, it becomes clear that a near-optimal solution to this assignment problem is obtained by taking the border of the upper triangle. This is exactly the strategy proposed by horse racing scheduling.

Note that a difference between the horse racing story and single-BAN scheduling is the utility function of the two players. The former can be modeled as a zero-sum game, where the total utility of two competing horses is always 1. While the latter actually extends the game into a more general case, where the total PRR of M concurrently transmitting sensors can be any value within $(0, M)$. Hence, horse racing scheduling can bring us benefits. Another difference is in the way to sort sensors versus sorting horses by Tian Ji and the king, respectively. In the horse racing story, the king's horses are sorted by their own strength; while in our case, $\{\mathcal{S}_{-k}^t | t=1,\ldots,N\}$ are sorted by their total JRIS on the coordinator of B_k. This is equivalent to the fact that Tian Ji sorts the king's horses by his own observation.

IV. Multi-BAN Concurrent Scheduling

In this section, we study the second sub-problem, in which all the BANs decide their strategies with the purpose of maximizing their own utilities. We first study the NE in the game. Then, we propose an efficient scheme to achieve high utilities for all the BANs in a distributed and autonomous manner.

A. Study on NE

For the proof of the following theorems, we first present two lemmas: Lemma 1 states that the utility of p_k, when the opponents apply strategy p_{-k}, does not change if the same transform is applied to both strategies. Lemma 2 states that the utilities of different pure strategies of B_k are identical, given a mixed strategy of B_{-k} with equal probabilities on the N strategies of a loop.

Lemma 1. *For* $\forall k \in \{1,\ldots,M\}$ *and* $\forall p_k \in \mathbf{P}_k$, $\mathscr{U}_k(p_k,p_{-k}) = \mathscr{U}_k(p_k\Pi_k^{\omega_1,\omega_2}, p_{-k}\Pi_k^{\omega_1,\omega_2})$.

Proof: Based on Property 3, we have

$$\begin{aligned} & \mathscr{U}_k(p_k\Pi_k^{\omega_1,\omega_2}, p_{-k}\Pi_k^{\omega_1,\omega_2}) \\ = \;& \textstyle\sum_\tau u_k(s_k^{(p_k\Pi_k^{\omega_1,\omega_2})_\tau}, s_k^{(p_k\Pi_k^{\omega_1,\omega_2})_\tau}) \\ = \;& \textstyle\sum_t u_k(s_k^{(p_k)_t}, s_{-k}^{(p_k)_t}) \\ = \;& \mathscr{U}_k(p_k,p_{-k}).\blacksquare \end{aligned} \tag{6}$$

Lemma 2. *Let* $(\mathbf{m}_{-k})_\omega$*, the* ω*th component of* $\mathbf{m}_{-k}$*, be equal to* $\frac{1}{N}$ *for* $p_{-k}^\omega \in \{\mathscr{S}^\theta(\cdot)|\theta=0,\ldots,N-1\}$ *and* 0 *elsewhere, then* $\forall\omega_1,\omega_2 \in \{1,\ldots,N!\}$, $\mathscr{U}_k(p_k^{\omega_1},\mathbf{m}_{-k}) = \mathscr{U}_k(p_k^{\omega_2},\mathbf{m}_{-k})$.

Proof: For $\forall\omega \in \{1,\ldots,N!\}$,

$$\begin{aligned} \mathscr{U}_k(p_k^\omega,\mathbf{m}_{-k}) = \;& \textstyle\sum_{\theta=0}^{N-1}\frac{1}{N}\mathscr{U}_k(p_k^\omega,\mathscr{S}^\theta(p_{-k})) \\ = \;& \textstyle\frac{1}{N}\sum_{\theta=0}^{N-1}\sum_{t=1}^{N} u_k(s_k^{(p_k^\omega)_t},\mathcal{S}_{-k}^t), \end{aligned} \tag{7}$$

where $\mathcal{S}_{-k}^t = \{s_l^{(\mathscr{S}^\theta(p_l))_t}|l=1,\ldots,N, l\neq k\}$.

The above expression represents the sum of utilities of every sensor in B_k under the JRIS from $\mathcal{S}_{-k}^t$ in every time slot, which is independent of ω. Therefore, we have $\mathscr{U}_k(p_k^{\omega_1},\mathbf{m}_{-k}) = \mathscr{U}_k(p_k^{\omega_2},\mathbf{m}_{-k})$. $\blacksquare$

The mathematical principle behind Tian Ji horse racing story was studied in [27] which derived, with the help of LINDO (a linear programming solver), the optimal mixed strategies of both the king and Tian Ji in the case where each of them has 3 horses. Referring to their work, we prove two theorems (for PSNE and MSNE, respectively) for the multi-BAN concurrent scheduling game where each BAN has N sensors.

Theorem 1. *If one PSNE* $\{p_k^*|k=1,\ldots,M\}$ *with utility* $\{\mathscr{U}_k(p_k^*,p_{-k}^*)|k=1,\ldots,M\}$ *exists, there should be at least* $N!$ *PSNE with the same utility.*

Proof: Given a PSNE $\{p_k^*|k=1,\ldots,M\}$, $\forall k\in\{1,\ldots,M\}$ and for a given $\omega \in \{1,\ldots,N!\}$, based on Lemma 1 and Property 1,

$$\begin{aligned} \mathscr{U}_k(p_k^*,p_{-k}^*) = \;& \mathscr{U}_k(p_k^*\Pi_k^{*,\omega}, p_{-k}^*\Pi_k^{*,\omega}) \\ = \;& \mathscr{U}_k(p_k^\omega, p_{-k}^*\Pi_k^{*,\omega}). \end{aligned} \tag{8}$$

Meanwhile, $\forall\omega' \in \{1,\ldots,N!\}$, based on Definition 1, Property 2, and Lemma 1,

$$\begin{aligned} \mathscr{U}_k(p_k^*,p_{-k}^*) \geq \;& \mathscr{U}_k(p_k^{\omega'}\Pi_k^{\omega,*}, p_{-k}^*) \\ = \;& \mathscr{U}_k(p_k^{\omega'}\Pi_k^{\omega,*}, p_{-k}^*\Pi_k^{*,\omega}\Pi_k^{\omega,*}) \\ = \;& \mathscr{U}_k(p_k^{\omega'}, p_{-k}^*\Pi_k^{*,\omega}). \end{aligned} \tag{9}$$

Combining (8) and (9), we get

$$\mathscr{U}_k(p_k^\omega, p_{-k}^*\Pi_k^{*,\omega}) \geq \mathscr{U}_k(p_k^{\omega'}, p_{-k}^*\Pi_k^{*,\omega}). \tag{10}$$

Therefore, if $\{p_k^*|k=1,\ldots,M\}$ is a PSNE, there should be at least $N!$ PSNE $\{p_k^\omega|k=1,\ldots,M\}$ corresponding to $\omega=1,\ldots,N!$. $p_{-k}^*\Pi_k^{*,\omega}$ represents the pure strategies of B_{-k}, which forms a PSNE with p_k^ω. Moreover, according to (8), these PSNE have the same utility $\{\mathscr{U}_k(p_k^*,p_{-k}^*)|k=1,\ldots,M\}$. $\blacksquare$

Theorem 2. *The game has infinite MSNE, denoted by* $\{\mathbf{m}_k^* = \sum_{\alpha_k=1}^{(N-1)!}\lambda_k^{\alpha_k}\mathbf{m}_k^{\alpha_k}|k=1,\ldots,M\}$*, where* $\mathbf{m}_k^{\alpha_k}$ *represents a mixed strategy with equal probability (i.e.,* $\frac{1}{N}$*) on support* $Supp(\mathbf{m}_k^{\alpha_k}) = \{\mathscr{S}^\theta(p_k^{\alpha_k})|\theta=0,\ldots,N-1\}$*, where* $\{p_k^{\alpha_k}|\alpha_k=1,\ldots,(N-1)!\}$ *represent the* $(N-1)!$ *pure strategies with the same fixed sensor at the first place.* $0\leq\lambda_k^{\alpha_k}\leq 1$*, and* $\sum_{\alpha_k=1}^{(N-1)!}\lambda_k^{\alpha_k}=1$.

Proof: With $\{\mathbf{m}_k^* = \sum_{\alpha_k=1}^{(N-1)!}\lambda_k^{\alpha_k}\mathbf{m}_k^{\alpha_k}|k=1,\ldots,M\}$, for $\forall k\in\{1,\ldots,M\}$,

$$\begin{aligned} & \mathscr{U}_k(\mathbf{m}_k^*,\mathbf{m}_{-k}^*) \\ = \;& \textstyle\sum_{\alpha_k=1}^{(N-1)!}[\lambda_k^{\alpha_k}\mathscr{U}_k(\mathbf{m}_k^{\alpha_k},\mathbf{m}_{-k}^*)] \\ = \;& \textstyle\sum_{\alpha_1=1}^{(N-1)!}\Big\{\lambda_1^{\alpha_1}\sum_{\alpha_2=1}^{(N-1)!}\big[\lambda_2^{\alpha_2}\sum_{\alpha_3=1}^{(N-1)!}\ldots \\ & \textstyle\sum_{\alpha_M=1}^{(N-1)!}\big(\lambda_M^{\alpha_M}\mathscr{U}_k(\mathbf{m}_k^{\alpha_k},\mathbf{m}_{-k}^{\alpha_{-k}})\big)\big]\Big\} \\ = \;& \textstyle\sum_{\alpha_1=1}^{(N-1)!}\Big\{\lambda_1^{\alpha_1}\sum_{\alpha_2=1}^{(N-1)!}\big[\lambda_2^{\alpha_2}\sum_{\alpha_3=1}^{(N-1)!}\ldots \\ & \textstyle\sum_{\alpha_M=1}^{(N-1)!}\big(\lambda_M^{\alpha_M}\sum_{\theta=0}^{N-1}\frac{1}{N}\mathscr{U}_k(\mathscr{S}^\theta(p_k^{\alpha_k}),\mathbf{m}_{-k}^{\alpha_{-k}})\big)\big]\Big\}. \end{aligned} \tag{11}$$

For $\forall\omega\in\{1,\ldots,N!\}$, based on Lemma 2,

$$\mathscr{U}_k(\mathscr{S}^\theta(p_k^{\alpha_k}),\mathbf{m}_{-k}^{\alpha_{-k}}) = \mathscr{U}_k(p_k^\omega,\mathbf{m}_{-k}^{\alpha_{-k}}), \theta=0,\ldots,N-1. \tag{12}$$

Taking (12) into (11), we get

$$\begin{aligned} \mathscr{U}_k(\mathbf{m}_k^*,\mathbf{m}_{-k}^*) = \;& \textstyle\sum_{\alpha_k=1}^{(N-1)!}[\lambda_k^{\alpha_k}\mathscr{U}_k(p_k^\omega,\mathbf{m}_{-k}^*)] \\ = \;& \mathscr{U}_k(p_k^\omega,\mathbf{m}_{-k}^*). \end{aligned} \tag{13}$$

For $\forall\mathbf{m}_k\in\mathbb{M}_k$, based on (13),

$$\begin{aligned} \mathscr{U}_k(\mathbf{m}_k,\mathbf{m}_{-k}^*) = \;& \textstyle\sum_{\omega=1}^{N!}m_k^\omega\mathscr{U}_k(p_k^\omega,\mathbf{m}_{-k}^*) \\ = \;& \mathscr{U}_k(\mathbf{m}_k^*,\mathbf{m}_{-k}^*). \end{aligned} \tag{14}$$

Therefore, based on Definition 2, $\{\mathbf{m}_k^*|k=1,\ldots,M\}$ is MSNE. $\blacksquare$

Taking the 2-BAN case with 3 sensors per BAN as an example, B_k has totally 3! pure strategies $\mathbf{P}_k=\{p_k^\omega|\omega=1,\ldots,6\}$, given by (s_k^1,s_k^2,s_k^3), (s_k^3,s_k^1,s_k^2), (s_k^2,s_k^3,s_k^1), (s_k^1,s_k^3,s_k^2), (s_k^2,s_k^1,s_k^3) and (s_k^3,s_k^2,s_k^1). Here, $p_k^i, i=1,2,3$ form a horse racing loop, obtained from the root p_k^1; while $p_k^i, i=4,5,6$ also form a loop, obtained from the root p_k^4. The utility matrix of B_k can be represented by

$$\mathbf{V}_k = \left(\begin{array}{ccc:ccc} v_k^1 & v_k^2 & v_k^3 & v_k^4 & v_k^5 & v_k^6 \\ v_k^3 & v_k^1 & v_k^2 & v_k^6 & v_k^4 & v_k^5 \\ v_k^2 & v_k^3 & v_k^1 & v_k^5 & v_k^6 & v_k^4 \\ \hdashline v_k^4 & v_k^6 & v_k^5 & v_k^1 & v_k^3 & v_k^2 \\ v_k^5 & v_k^4 & v_k^6 & v_k^2 & v_k^1 & v_k^3 \\ v_k^6 & v_k^5 & v_k^4 & v_k^3 & v_k^2 & v_k^1 \end{array}\right), \tag{15}$$

where the rows correspond to $\mathbf{P}_k$, while columns correspond to $\mathbf{P}_{-k}$ with the same order for its 6 pure strategies. For example, $v_k^2 = \mathscr{U}_k(p_k^1,p_{-k}^2) = \mathscr{U}_k(p_k^2,p_{-k}^3) = \mathscr{U}_k(p_k^3,p_{-k}^1) = \mathscr{U}_k(p_k^4,p_{-k}^6) = \mathscr{U}_k(p_k^5,p_{-k}^4) = \mathscr{U}_k(p_k^6,p_{-k}^5) = u_k(s_k^1,\mathcal{S}_{-k}^3) + u_k(s_k^2,\mathcal{S}_{-k}^1) + u_k(s_k^3,\mathcal{S}_{-k}^2)$. Note that, for B_{-k}, the matrix

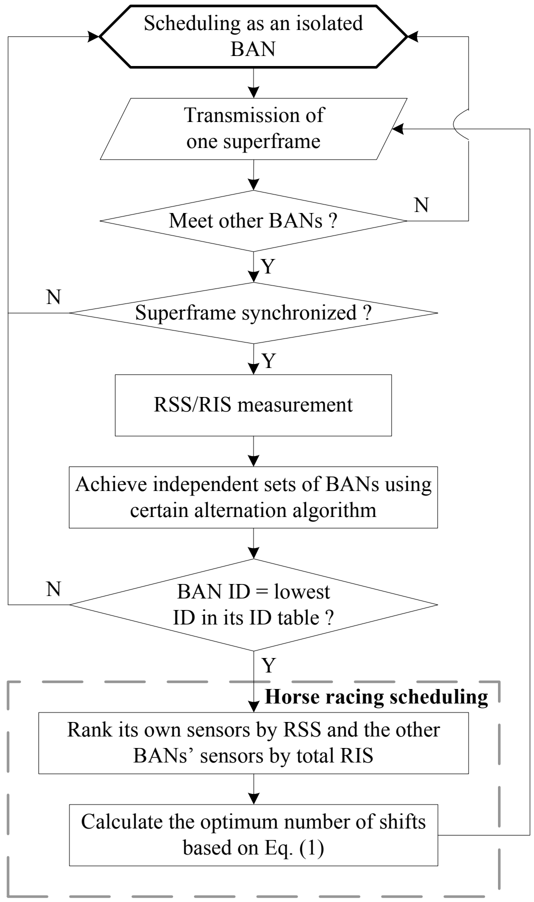


Fig. 2. DCS algorithm performed autonomously and distributedly by each BAN.

$\mathbf{V}_{-k}^T$ is in a similar form, where T denotes the transpose. By looking at $\mathbf{V}_k$ and $\mathbf{V}_{-k}^T$, Theorem 1 is apparent. We find the maximum entry in row 1 of $\mathbf{V}_k$ and the maximum entry in row 1 of $\mathbf{V}_{-k}^T$, if the two entries appear in the same column, e.g., v_k^2 and v_{-k}^3 both in column 2, one PSNE is found. Meanwhile, we can see that 5 other such entry pairs correspondingly appear in other rows, so we totally have 6 PSNE. Theorem 2 tells us that, two mixed strategies with equal probabilities on the 3 pure strategies in any of the 4 sub-matrices in (15) form a MSNE, e.g., $\mathbf{m}_k = \{\frac{1}{10}, \frac{1}{10}, \frac{1}{10}, \frac{7}{30}, \frac{7}{30}, \frac{7}{30}\}$ and $\mathbf{m}_{-k} = \{\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{12}, \frac{1}{12}, \frac{1}{12}\}$.

According to our simulations with Lemke-Howson algorithm [28] and Dickhaut-Kaplan [29] algorithm for various scenarios, the existence of NE is highly related to the positions of sensors in the BANs. PSNE usually achieves high utilities for all the BANs, but it usually does not exist, except for some very special scenarios. For example, PSNE sometimes exists on the diagonals of some sub-matrices in the utility matrix of the game, such as (15). For MSNE, we care about those with small supports, i.e., those having small number of pure strategies with non-zero probabilities. That is because it usually takes much more time to find an MSNE with large supports than with small ones, which is especially important for this game due to the size of the utility matrix (i.e., $N! \times N!$). MSNE with small supports usually does not exist. Infinite MSNE with supports equal to N indicated by theorem 2 always exist, but they lead to low utilities for all the BANs. To sum up, the above studies on PSNE and MSNE provide the following important insights. First, once one PSNE exists, there are at least $N!$ PSNE with the same utility, and our later proposed scheme approaches it. Second, since MSNE with small supports usually does not exist, the MSNE in theorem 2 should be used for comparison with our schemes and to compare with the optimal strategy to assess the Price of Anarchy.

B. *Proposal 2: distributed cooperative scheduling (DCS)*

For this task, the $N! \times N!$ utility matrix and the $N!$ strategy set are too large to be processed by even a very powerful computer, not to mention by the coordinator of a BAN, so it is impossible to use certain algorithms to search for a good NE in practice. Instead, we design an efficient scheme, called DCS, which achieves high utilities for all the BANs. Note that when one BAN uses horse racing scheduling to maximize its own utility, the other BANs' utilities may be not as much degraded due to the fact that different BANs' utilities depend on RSS and JRIS to their own coordinators. Therefore, a simple idea is to let the M BANs alternatively be a master (using horse racing scheduling to achieve near-optimal PRR for itself) superframe by superframe. Hence, each BAN has $1/M$ opportunity to be a master. However, let us consider a 4-BAN square system where each BAN is only interfered by the 2 neighbouring BANs, such as the 4 BANs indexed by 2, 3, 4 and 6 in Fig. 1. In this case, it is possible to let B_2 and B_3 be masters at the same time and let B_4 and B_6 be masters at the same time due to the fact that they do not interfere each other. Therefore, it is possible to find a way to arrange the BANs into groups of masters depending on the topology of the graph, so that each BAN has more than $1/M$ opportunity to be a master. By abstracting each BAN as a node, this issue can be treated as an extended clustering issue in wireless sensor networks. Therefore, classical clustering algorithms for finding an independent set of clusterheads might be quickly extended for usage. We emphasize that finding the optimum way to group nodes in a graph is out of the scope of this paper, so we use one of the simplest clustering algorithm, i.e., the lowest-ID algorithm [30], to explain the extension of clustering algorithms to this problem. Note that we choose this algorithm as an example due to its simplicity. If some other clustering algorithm, e.g., the modified lowest-ID algorithm in [31], is used, it is still possible to further improve the performance.

The lowest-ID algorithm in [30] requires each BAN to broadcast an update message (e.g., in topology management of a control period) indicating its BAN ID to its neighbours in each superframe. Each BAN should keep an ID table including IDs of all the neighbours and itself, as indicated by the first step in Fig. 3. The BAN whose ID equals the lowest ID in the table becomes the master for the next superframe, such as $\{B_1, B_2, B_3\}$ in the first step 1 in Fig. 3. If the ID table does not change, the masters in a static graph never changes. Our extension to this algorithm is to insert an indictor in the update message indicating whether the BAN is a master

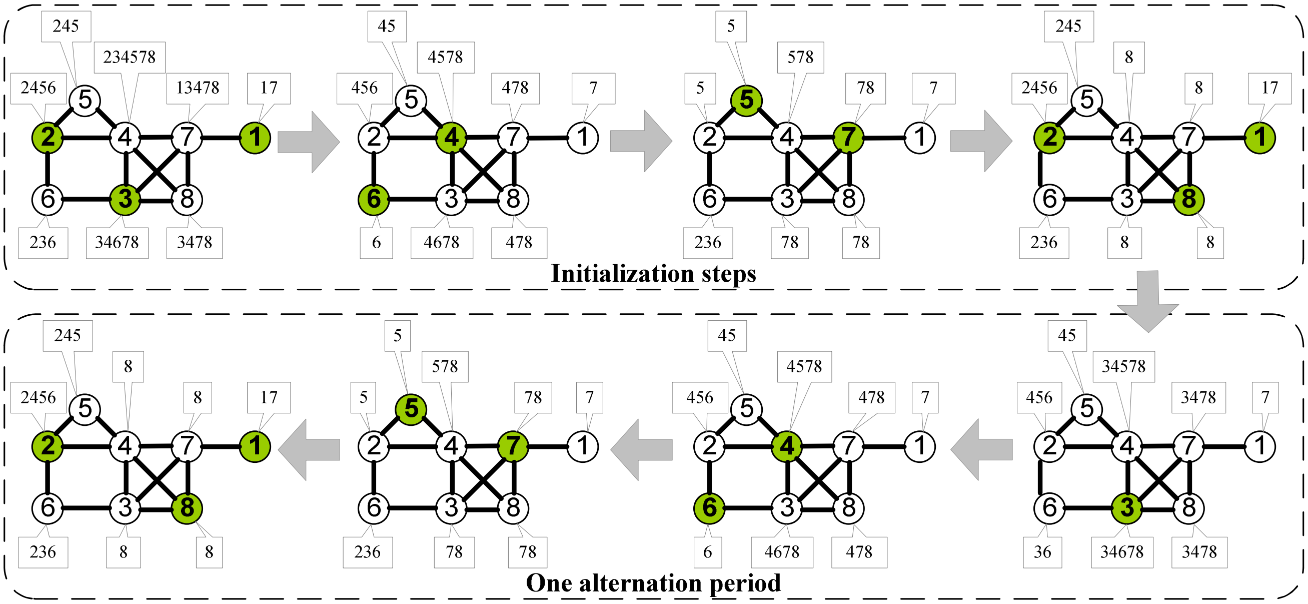


Fig. 3. Using lowest-ID algorithm as an example of alternation in DCS.

in the current superframe. Upon receiving this indicator, all its neighbours remove the master's ID from their own ID tables. Meanwhile, the master also removes itself from its own ID table. For example, $\{B_1, B_2, B_3\}$ are all removed from the lists in the second step in Fig. 3. Thus, when a BAN compares its own ID with its new ID table, a new group of masters come out. In the end, once a BAN's ID table becomes empty, it refills its ID table and starts from the beginning. Note that when a BAN receives an update message from a neighbour which is not in its ID table (e.g., B_7 receives the update message from B_1 before the one from B_8), it puts a negative entry in its ID table for this neighbour so that this negative entry can delete the corresponding entry when its ID table is refilled. After an initialization procedure during a few superframes, several groups of masters are gradually stabilized and appear alternatively. Taking the 8-BAN system in Fig. 3 as an example, the groups of masters are $\{B_1, B_2, B_8\}$, $\{B_3\}$, $\{B_4, B_6\}$ and $\{B_5, B_7\}$.

The relationship between the alternation algorithm and horse racing scheduling is shown in Fig. 2. When the alternation algorithm decides that the BAN is a master, it uses horse racing scheduling, otherwise it schedules as an isolated BAN. Similar to the reason explained in Section III for horse racing scheduling achieving near-optimal PRR for the master, DCS achieves PSNE when PSNE appears on a set of strategies in horse racing loop, such as the main diagonal of $\mathbf{U}_k$.

V. Performance Evaluation

A. Simulation configuration

We use two methods for performance evaluation: numerical analysis using Matlab and system simulation using WSNet[3]. PRR is related to not only scheduling but also body area propagation, modulation, channel coding, etc. We should emphasize that the study on propagation is not within the scope of this paper. Therefore, instead of using a sophisticated channel model, we use free-space propagation in our simulation due to the fact that its trend of increment of pathloss with regard to distance is the same as channel model for BAN [33]. The received power is given by

$$P_r = P_t \lambda^2 / (4\pi d)^2, \tag{16}$$

where P_t is the transmission power, d is the distance between transmitter and receiver, and λ is the wave-length [34]. Then, we use OQPSK modulation [34], so the bit error rate (BER) of s_k^i interfered by s_{-k}^i is given by

$$\gamma_k^i = 1 - \left[1 - 0.5erfc\left(\sqrt{2g_k^i/(h_{-k}^i + n_0)}\right)\right]^2. \tag{17}$$

TABLE II
MAIN PARAMETERS IN THE SIMULATIONS

Number of BANs	2 / 8
Number of sensors per BAN	12
Number of coordinators per BAN	1
Number of frequency channels	1
Simulation time	100 s
MAC protocol	IEEE 802.15.3
Superframe length	30 ms
Control period length	4 ms
CAP length	1 ms
CFP length	24 ms
Packet size	60 Bytes
Transmission power	-25 dBm
Sensitivity of receiver	-92 dBm
Transmission frequency	2450 MHz
Pathloss	2.0
AWGN variance	-92.2 dBm

[3]WSNet is a simulation platform developed by INRIA and INSA for simulations of wireless sensor networks [32].

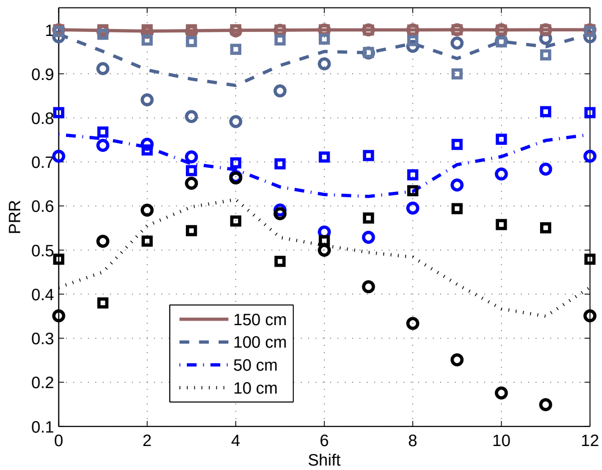


Fig. 4. The effect of shifts with horse racing scheduling in a 2-BAN scenario (circles: master, squares: slave, curves: average).

Since we do not consider any channel coding, the PRR is obtained as

$$r_k^i = (1 - \gamma_k^i)^{N_b}, \tag{18}$$

where N_b is the number of bits in a packet. The parameter setting is listed in Table II.

B. Simulation results of a 2-BAN scenario

In this simulation, we consider a 2-BAN case where the two BANs are standing side-by-side and motionless with a certain distance in between, i.e., B_7 and B_1 in Fig. 1. Each BAN contains 1 coordinator on the left waist and 12 sensors placed on the head, chest, waist, arms and legs. B_7 is considered as the master for single-BAN scheduling. Note that the indexes of sensors in B_1 are sorted by JRIS for an inter-BAN distance of 10 cm, and the sensors may be sorted in a different way for other inter-BAN distances.

1) Shift in horse racing scheduling: In order to help understanding horse racing scheduling and the effect of shifts, we first show in Fig. 4 the PRR of each BAN and the average PRR of the two BANs with different inter-BAN distances and different number of shifts. We can see that, for a given inter-BAN distance, the PRR of each BAN could be totally different for different number of shifts. For example, the best numbers of shifts θ^+ are 4, 0 and 0 for inter-BAN distances 10, 50 and 100 cm, respectively.

2) PRR vs. inter-BAN distance:

The PRRs of different scheduling schemes with regard to inter-BAN distance are shown in Fig. 5(a) and 5(b). In these figures, curves represent numerical results, while symbols represent the results of system simulation using WSNet. The upperbound and lowerbound are obtained by Hungarian algorithm. From these figures, we can observe the following key features:

- When the two BANs are close, PRR of any CCT strategy is far from 1 (corresponding to the total transmission rate of two isolated BANs), which indicates serious inter-BAN interference.
- The upperbound is much higher than 0.5 (corresponding to the maximum transmission rate of NCCT in a 2-BAN case), indicating that CCT can provide significant improvements.
- The upperbound is much higher than the PRR corresponding to the MSNE indicated by Theorem 2, so it is quite necessary to find an efficient scheme approaching the upperbound.
- Horse racing scheduling always achieves a PRR for the master as high as the upperbound.
- Greedy algorithm usually does not lead to high PRR, except for an inter-BAN distance around 40 cm, where this algorithm is occasionally as good as horse racing scheduling.
- MSNE indicated by Theorem 2 lead to low PRR in most cases, hence the Price of Anarchy is large.
- DCS achieves higher PRR than the MSNE in most cases. The only exception happens when the inter-BAN distance is between 20 and 40 cm. Typically, horse racing scheduling is very beneficial for a small inter-BAN distance. B_7 is affected by very strong interference due to the position of its coordinator, and this leads to serious PRR degradation when B_1 uses horse racing scheduling.

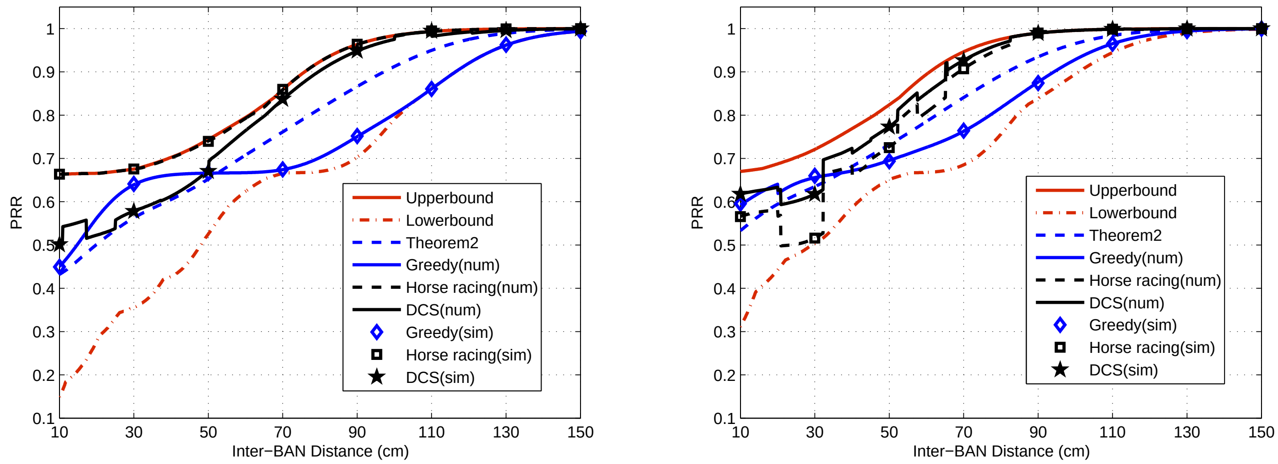
Note that the jumps of curves of DCS correspond to the changes of the best number of shifts or the changes of the order of JRIS of interfering sensors. While the jumps of curves of greedy algorithm correspond to the changes of the best strategy.

C. Simulation results of a 8-BAN scenario

In this simulation, we consider a 8-BAN case as shown in Fig. 1, where each BAN is represented by a node in the graph. The topology is carefully designed so that it includes nodes with different degrees, such as 1 (B_1), 2 (B_5 and B_6), 3 (B_2 and B_8), 4 (B_3 and B_7) and 5 (B_4), and various shapes, such as line (B_1 and B_7), triangle (B_2, B_4 and B_5), complete rectangle (B_3, B_4, B_7 and B_8) and incomplete rectangle (B_2, B_3, B_4 and B_6). For single-BAN scheduling, B_3 is considered as the master as step 5 in Fig. 3. For multi-BAN scheduling, we consider the 4 groups of masters, shown in Fig. 3.

The combination of the scheduling strategies of the slave BANs has impact on the results because the global optimization of an M-BAN system is an M-dimensional assignment problem. However, according to our experience, the impact of changing the slave BANs' strategies is small because the main interference is usually from the nearest slave BAN due to the small transmission range of BAN technology. Since the scheduling based on intra-BAN information is out of the scope of this paper, we use the order of B_7 in Fig. 1 as the default scheduling of each slave BAN in the following simulations.

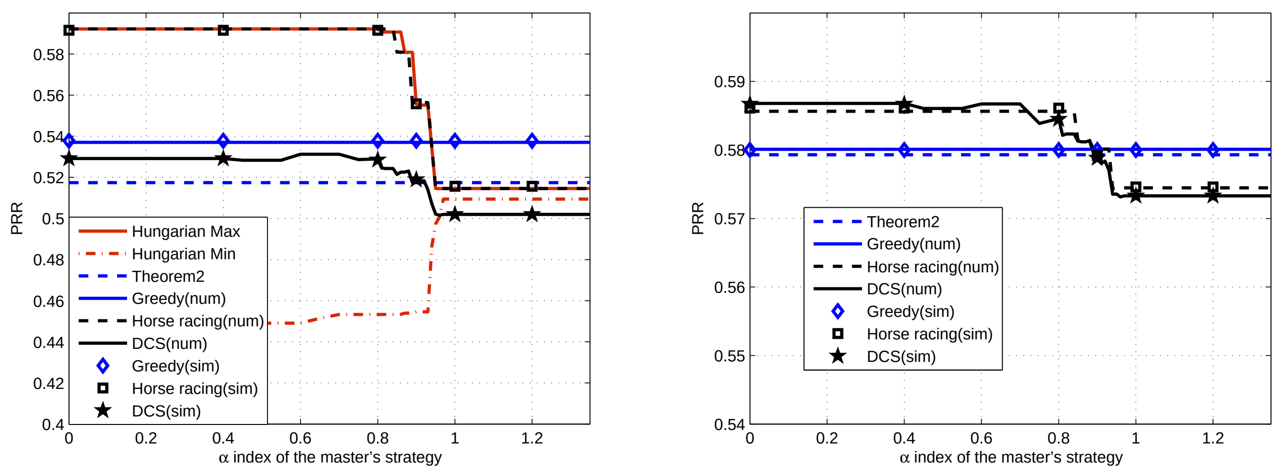
1) PRR vs. α: The index α indicates the tradeoff between fairness and PRR for the design of a cooperative scheduling scheme. Since α is used to obtain the assignment matrix of B_3 for selecting its strategy, this tradeoff is decided by B_3. $\alpha = 0$ indicates the maximization of the total PRR of B_3, $\alpha = 1$ indicates the proportional fair strategy for the sensors in B_3, while $\alpha = \infty$ indicates the max-min fair strategy for the sensors in B_3. Note that Hungarian Max and Hungarian Min in Fig. 6 indicate the results of Hungarian algorithm with given α, which do not provide upperbound or lowerbound. The



(a) BAN7 as the master

(b) BAN1

Fig. 5. PRR of different schemes in a 2-BAN scenario.



(a) BAN3 as the master

(b) Average of the 8 BANs

Fig. 6. PRR of different schemes in a 8-BAN scenario.

upperbound and lowerbound of the total PRR of B_3 in the 8-BAN case are indicated by the points with $\alpha = 0$ on these two curves. Seen from these figures, horse racing scheduling and DCS performs well not only for maximizing the PRR (i.e., $\alpha = 0$) but also with a certain level of fairness (i.e., $0 < \alpha < 0.9$). For the master B_3, as shown in Fig. 6(a), it is clear that horse racing scheduling and DCS generally achieve higher PRR than other schemes. For the 8 BANs, horse racing scheduling and DCS could both guarantee the average PRR higher than using other schemes, as shown in Fig. 6(b).

2) Fairness: The fairness of sensors is highly related to the scheduling strategy. For example, a sensor relatively far from its coordinator may have more difficulty to transmit successfully, but a fair scheme should still try to guarantee its transmission. A sensor is considered to be unfairly treated if it is always scheduled with strong interfering sensors of other BANs to increase global PRR by sacrificing it. Since the transmission rates of different sensors are assumed identical in this study, PRRs of sensors can be used to calculate the Jain's fairness index [35] to represent how they are treated by the scheduling strategy, i.e., the fairness of sensors. Moreover, we also evaluate the fairness of BANs to make sure the BANs in the central part of the graph (e.g., B_4) is not sacrificed by our schemes due to its poor position.

As shown in Fig. 7, the fairness of BANs is always high, no matter which scheme is used. Schemes may change the PRR of each BAN, but they do not sacrifice any BAN's transmission to improve the others. For example, when B_3 uses horse racing scheduling as shown in Fig. 6, most BANs achieve a PRR close to the average PRR of the 8 BANs, including B_3. The only exception is B_4 due to its poor position, but its total PRR (around 0.44) is not much worse than the others.

The fairness of sensors is not largely affected by the schemes, either. Schemes mainly change the fairness of sensors inside the master BAN as shown in Fig. 8, but the fairness of all the sensors does not change much. Meanwhile, fairness

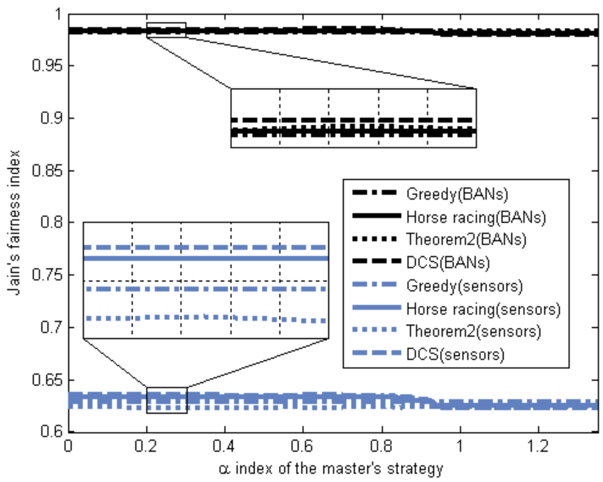


Fig. 7. Fairness of BANs and fairness of sensors in a 8-BAN scenario.

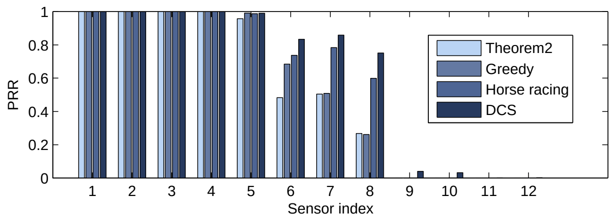


Fig. 8. Average per-sensor PRR of the masters in a 8-BAN scenario.

of sensors is always low because sensors on the head and the feet always have difficulty to transmit due to the large distance to their coordinator and the large JRIS from other BANs. To improve their transmission, we might consider a threshold between CCT and NCCT or a threshold for using relay technology, but those studies are out of the scope of this paper.

As shown in Fig. 7, horse racing scheduling has better fairness than greedy algorithm. That is because the latter sacrifices half of the sensors but the former only sacrificies a few sensors, which is further demonstrated by Fig. 8. DCS let each BAN be the master once during an alternation period with the lowest-ID algorithm in Fig. 3, so it achieves better fairness than other schemes.

VI. Conclusions

This paper studied cooperative scheduling of multiple coexisting BANs. Our first conclusion is that CCT schemes could achieve much higher PRR than NCCT schemes, so concurrent transmission is quite promising for BAN communications. Second, our results showed that inter-BAN interference is critical, so scheduling for coexisting BANs is a key issue for the current development of BAN technology. Third, when BANs are close, the difference between the upperbound and the MSNE indicated by Theorem 2 is large, so it is important to compare different CCT schemes to find an efficient one approaching the upperbound for practical usage.

We studied two sub-problems: single-BAN scheduling as an assignement problem and multi-BAN concurrent scheduling as a game. For single-BAN scheduling, we studied Hungarian algorithm and greedy algorithm. Then, we proposed a new algorithm, horse racing scheduling, which achieved near-optimal PRR for the BAN performing it. Based on horse racing scheduling, we proposed DCS for multi-BAN concurrent scheduling, which was quite efficient to achieve high PRR for the whole multi-BAN system. Meanwhile, our studies showed that DCS did not degrade the fairness of sensors or the fairness of BANs compared with other schemes.

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