Game Theoretical Approach for Channel Allocation in Wireless Sensor and Actuator Networks

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***Abstract*—In this paper, multi-channel allocation in wireless sensor and actuator networks is formulated as an optimization problem which is NP-hard. In order to efficiently solve this problem, a distributed game based channel allocation (GBCA) Algorithm is proposed by taking into account both network topology and routing information. For both tree/forest routing and non-tree/forest routing scenarios, it is proved that there exists at least one Nash Equilibrium for the problem. Furthermore, the sub-optimality of Nash Equilibrium and the convergence of the Best Response dynamics are also analyzed. Simulation results demonstrate that GBCA significantly reduces the interference and dramatically improves the network performance in terms of delivery ratio, throughput, channel access delay, and energy consumption.**

***Index Terms*—Channel allocation, game theory, wireless sensor and actuator networks (WSANs), wireless sensor networks (WSNs).**

I. Introduction

WIRELESS sensor networks (WSNs) have been attracting a lot of attentions, in which low-cost, low-power, and multi-functionality wireless sensors can be densely deployed for various applications [1]–[3]. As a rapid development of embedded systems, wireless actuators are introduced to WSNs, which can facilitate wireless and automatic control of physical processes [4]. Sensors send their measurement packets to actuators which make decisions by mutual communications for the physical process. Actuators may also send packets to sensors for purpose of acknowledging or requiring sensed data. In Wireless Sensor and Actuator Networks (WSANs), communication and control are highly integrated [5], [6].

By using wireless technology to facilitate the control of dynamic systems, several features of the wireless communications, such as packet drop and delay, are inevitable issues in developing control policies [7]. Particularly, if the dynamic systems require swift and precise control/actuation, drop and delay of measurement packets from sensors may cause some actuators to perform undesired actuation to the dynamic processes and hence have critical impact on the overall control performances. To this end, the objective is to design sophisticated estimation and control mechanisms to tolerate a certain amount of packet loss and/or delay [8]. However, Sinopoli *et al.* have shown that there exists a critical value of the packet loss rate above which the estimation error covariance does not converge [9]. They have also proved the existences of critical values of packet loss rates for both the sensor-controller link and the controller-actuator link, such that the control system is stabilizable if the loss rates are lower than those critical values [10]. Although the distribution of packet delays does not affect the stability of the estimation error covariance [8], it is critical to the estimation performance in terms of the probability that the estimation error covariance is within a prescribed bound [11].

On the other hand, in the communication community, in order to reduce delay and loss, a number of self-proved protocols have been proposed for channel access control. However, most of them focus on single channel (single central frequency) [12]. Two representative protocols are described below. The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol uses an intended back-off strategy to reduce transmission collisions at the receiver sides and acknowledgements/retransmissions to increase successful transmission possibilities. A drawback is that packet delay may be increased due to back-offs. Another one is Time Division Multiple Access (TDMA) protocol that assigns distinct slots for sensors, so that transmissions will not collide. However, when the network becomes large in scale, ensuring distinct slots yields longer delay of the transmissions within the last slot. For fast changing physical processes, a large amount of timely information should be communicated in time. Thus, the protocols by using a single channel are not sufficient for such applications of WSANs, and using the available multiple channels in WSANs to effectively exploit parallel transmission within the same spatial range.

A. Related Work

There have been many multi-channel protocols proposed for wireless networks [13]–[18]. Most of them are under strong assumptions, e.g., the transceivers either use the frequency hopping spread spectrum wireless cards or operate on multiple channels simultaneously. Unfortunately, these protocols are not applicable to WSANs since each node is equipped with only one simple half-duplex radio transceiver. Moreover, the extra overhead caused by dynamic channel negotiations, poses even more challenges on the limited bandwidth in WSANs.

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Recently, several multi-channel protocols have been proposed for WSNs, where nodes are equipped with the same radio transceiver as most off-the-shelf sensors and actuators. These protocols can be divided into two categories: dynamic and static. The dynamic protocols allocate channels to links according to the immediate flows in the network [19]–[22]. Although these dynamic protocols can reduce interference to some degree, the requirements of frequent negotiations and highly accurate time synchronization incur extra large overhead. Alternatively, purely based on network topology [23]–[25], the static protocols can not efficiently reduce the interference due to the lack of the information of routing and transmitting flows. For example, MMSN in [23] balances the channel usage among two hop neighbors by exploiting the network topology information. Without considering routing information, they cannot track the instantaneous transmission flows when assigning channels, which will not guarantee load balance and result in wasting bandwidth. TMCP in [24] statically divides the whole network into mutually exclusive single channel subtrees, which takes advantage of the inter-tree routing information but does not exploit the intra-tree routing information. Different from the existing works, in this paper, we aim to design the channel allocation[1] by taking into account both Topology Information and Routing Information (TIRI) to reduce the interference more efficiently.

B. Contributions

Consider WSANs with following characteristics: 1) each node (a sensors, actuator or control unit) is only equipped with one simple half-duplex radio transceiver; and 2) the topology and routing of the network are static in a relative long time. The first characteristic makes the sophisticated multi-channel protocols not suitable for WSANs, while the simple multi-channel protocols in WSNs can not take advantage of the second one efficiently. To fully exploit TIRI, all nodes must be involved in the channel allocation and share information interactively. Moreover, Game Theory [26] is applied to study the interaction of autonomous agents, and thus makes it a promising approach to solve the competing problems in wireless networks, such as power control [27], coverage [28], sensor activation [29], etc. Accordingly, in order to fully exploit TIRI, we model the multi-channel usage problem in WSANs as a channel allocation game with the total interference of the whole network as the social objective.[2] In this channel allocation game, each node is considered as a player, whose payoff is defined as zero minus the sum of the interference it causes and suffers. The game evolves according to the Best Response (BR) dynamics, i.e., each player chooses the channel that maximizes its payoff. We first analyze the game in the tree/forest structure static routing with the help of constructing parent-children sets from the tree/forest structure. However, the routing in WSANs may not always be with tree/forest structure, since the flows among sensors, actuators and control units may intersect. Thus, we extend our approach to general static routing with non-tree/forest structure by introducing virtual nodes to facilitate the construction of parent-children sets in this routing. Finally, based on BR, we propose a Game Based Channel Allocation algorithm (GBCA) to handle the channel allocation problem in WSANs in a distributed way. The main contributions of this paper are summarized as follows:

- We analyze the relationship between the number of links heard by receiver and the interference suffered by sender, and define an interference metric. Based on this, we formulate the channel allocation in WSANs as an optimization problem and prove that it is NP-hard. We model it as a channel allocation game to fully exploit TIRI.
- For the tree/forest routing, we show that the game is an exact potential game and there exists at least one NE in the game. We analyze the price of anarchy of the game and bound it by $c - 1/c$ where c is the number of available channels, which means any Nash Equilibrium (NE) is suboptimal. We adopt BR as the evolution rule of the channel allocation game and prove that BR converges into an NE in at most $(|V|-1)^2$ iterations, where $|V|$ is the total number of nodes.
- We introduce several virtual nodes and add interfering links for each crossing node to facilitate the construction of parent-children sets in general routing with non-tree/forest structure, and verify that the conclusions in the tree/forest routing is also valid in general routing.
- In order to solve the channel allocation problem in a suboptimal way but in polynomial time, we propose a distributed algorithm, GBCA, which is compatible with both scheduling based and contention based medium access control schemes.
- Extensive simulations for both tree/forest routing and non-tree/forest routing scenarios are conducted to demonstrate that GBCA reduces interference significantly and achieves better network performance in terms of delivery ratio, throughput, channel access delay, and energy consumption than MMSN.

The remainder of the paper is organized as follows. Section II analyzes the interference and describes the channel allocation problem. In Section III, we formulate the problem and model it as a channel allocation game, analyze the convergence and suboptimality of the game, and extend the approach to the general routing case. Section IV demonstrates the game based channel allocation algorithm in detail. The performance of the algorithm is evaluated by simulations in Section V. Finally, we conclude this paper in Section VI.

II. System Model

The estimation and control performance of networked control system depend on the loss and delay of packets transmitted through the wireless medium in WSANs. Therefore, it is important to scrutinize the sources of packet loss and delay. In addition to the reasons such as environmental noises which are not manipulatable, transmission interferences directly causing packet

[1]Due to the limited bandwidth in WSANs, dynamic allocation is usually avoided, and thus we focus on static allocation in this paper.

[2]The preliminary results were presented at the IEEE INFOCOM'10, San Diego, CA [30].

loss and delay[3] can be moderated by designing better communication strategies. In this paper, we utilize multiple channels for communication since transmissions through different channels do not interfere with each other. Note that for channel allocation in WSANs,

- the channel allocation problem can be solely designed for packet transmission, since the control design and communication design can be separately considered;
- the wireless devices in the off-the-shelf sensors, actuators and control units are equipped with actually the same half-duplex radio transceivers.

Therefore, sensors, actuators and control units are the same insofar as we allocate channels to them, and thus, in the remaining parts of this paper, we treat all sensors, actuators and control units as nodes without intentionally differentiating them.

A. Interference Model

In wireless networks, whether a message gets corrupted or not is closely related to whether other links, which are heard by the receiver, are transmitting message at the same time or not. In general, as long as there is another message transmitted simultaneously through some of these links, there is a collision at the receiver and the message may be corrupted. We study the relationship between the number of links heard by the receiver and the interference suffered by a message delivered to the receiver in a simple case [31], [32] as follows.

Assume that there are I links heard by the receiver and the probability that a message is being transmitted through a link at a given time is q. Therefore, the probability of a successful transmission with one try is

$$p = (1-q)^{I-1}. \tag{1}$$

If there is no maximum number of retries constraint, the average number of retries before a successful transmission is

$$R = \sum_{k=1}^{+\infty} kp(1-p)^{k-1} - 1 = \frac{1}{p} - 1. \tag{2}$$

Apparently, (2) holds because the MAC layer allows relatively large number of retries. Substituting (1) into (2), we have

$$R = \left(1 + \frac{q}{1-q}\right)^{I-1} - 1. \tag{3}$$

Since q is very small for the light communication load in WSNs (WSANs) [33], an approximate R can be obtained as follows:

$$R \doteq \frac{q}{1-q}(I-1). \tag{4}$$

Equation (4) reveals that the more links the receiver hears, the more retries a message needs to be successfully received. Furthermore, it is undoubted that more retries will consume more energy and increase the transmission delay, which in turn results in the decrease of both throughout and delivery ratio. Thus, the average number of retries, R, is a key metric to characterize the interference suffered by the sender. Furthermore, according to (4), I is approximately linear with R, so we choose I as the interference metric in this paper.

[3]Due to retransmissions of packets previously collided with others.

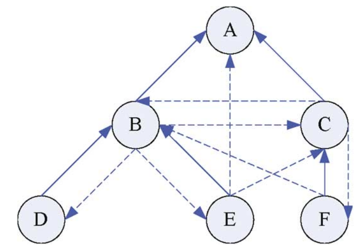

Fig. 1. Example of channel allocation in tree/forest routing, where A and B use channel $c1$ to receive message, and C uses channel $c2$ to receive message. The solid arrows represent intersecting links, while the dashed arrows represent interfering links.

B. Motivation

The links toward a receiver can be divided into two categories: intersecting links and interfering links [25]. The transmissions in intersecting links aim at the receiver, while the transmissions in interfering links do not aim at the receiver but can be overheard by the receiver. If only a single channel is used, then both intersecting links and interfering links may interfere with the transmission aiming at the receiver. Note that we can not reduce the interference caused by intersecting links since there is only one half-duplex radio transceiver in a node and thus the receiver can not receive multiple messages simultaneously, however we can reduce the interference caused by the interfering links by using multiple channels. In this paper, we allocate channels in a receiver-centric way, i.e., each node is allocated a fixed channel to receive message, the neighbors which have messages to deliver to it should use this channel to send, and obviously all links always use the channels that their senders use to send. For example, in Fig. 1, intersecting link $\overrightarrow{EB}$ uses channel $c1$, and interfering link $\overrightarrow{FB}$ uses channel $c2$. If there are enough non-overlapping channels, we can guarantee that all interfering links use different channels from the ones their receivers use. In this case, the receivers can not overhear the transmissions in interfering links and the interference in the network can be remarkably reduced. However, the number of non-overlapping channels is usually fixed and limited in practice [24]. Hence, the problem becomes to optimally allocate the limited channels to minimize interference.

III. Game Based Channel Allocation

In this section, we first formulate the channel allocation in the tree/forest routing as an optimization problem and analyze the hardness of the optimization problem, then model it as a channel allocation game, and finally extend our game based approach to accommodate the general routing with non-tree/forest structure.

A. Problem Formulation

We first define some notations in Table I and make some assumptions as follows: 1) The network routing is with tree/forest structure, i.e., children always deliver their messages to their parents in the network; 2) Channels are all non-overlapping and do not interfere with each other; and 3) Communication between

TABLE I
NOTATION DEFINITIONS

Symbol	Definition
$\|\cdot\|$	$\|\cdot\|$ represents the cardinality of a set.
C	the set of non-overlapping channels, i.e., C={1,2,...,c}.
V	the set of nodes including both normal nodes which know their parents and sink nodes which only collect messages and have no parent.
E	the set of links including both intersecting links and interfering links. Any pair of connected normal nodes are connected by two links with different directions, while any pair of connected normal and sink nodes are only connected by one link. And there is no link between sink nodes.
$G(V, E)$	the topology graph of the network. It is a directed graph and composed of V and E.
$s(e)$,$r(e)$	the sender and receiver of link e.
$parent(i)$	the parent of node i.
$Child(i)$	the set of children of node i.
P	the set of all non-leaf nodes which have children in the tree/forest structure, i.e., P={1,2,...,m}.
f	the channel allocation that allocates each non-leaf node one channel to receive message, i.e., $f : P \to C$.
E_s	the set of intersecting links, i.e., E_s=$\{e : e \in E$ and $s(e) \in Child(r(e))\}$.
E_f	the set of interfering links, i.e., E_f=$\{e : e \in E$ and $s(e) \notin Child(r(e))\}$.
$ch(e)$	the channel of link e, i.e., $ch(e)$=$f(parent(s(e)))$.
$J(e)$	the potential interference that link e may yield to the network, i.e., $J(e)$=$\|Child(r(e))\|$.
$I(i, f)$	the interference suffered by node i in allocation f, i.e., $I(i, f)$=$\|\{e : e \in E, r(e) = parent(i)$ and $ch(e) = f(parent(i))\}\|$. Since the sink nodes just collect messages in the network, they suffer no interference.
$L_r(f)$, $L_u(f)$	for a given f, L_r is the set of all the interfering links that can not be heard by its receiver, and L_u is the set of all the interfering links that still can be heard by its receiver, i.e., $L_r(f)$=$\{e : ch(e) \neq f(r(e)), e \in E_f\}$ and $L_u(f)$=$\{e : ch(e) = f(r(e)), e \in E_f\}$.

two nodes is symmetric, i.e., given that nodes i and j are connected, if i uses j's channel to transmit, then i can be heard by j, and vice versa. We then use the total interference suffered by all nodes as the optimization objective, since it is corresponding to the average number of retries over the network and in turn reflects the network performance.

Definition 1: The primal optimization problem ($\mathbf{PP}$): Given $G(V, E)$ and C, the primal optimization problem is to find a channel allocation f to minimize the total interference $\sum_{i \in V} I(i, f)$.

For a given $G(V, E)$ and an allocation f, we have

$$\sum_{i \in V} I(i, f) = \sum_{e \in E_s} J(e) + \sum_{e \in L_u(f)} J(e). \quad (5)$$

Since both the total potential interference that all the intersecting links may generate and the one that all the interfering links may generate are constants in a given $G(V, E)$, we have

$$\sum_{e \in E_s} J(e) = A, \sum_{e \in L_u(f)} J(e) + \sum_{e \in L_r(f)} J(e) = B \quad (6)$$

where A and B are constant independent of f. Substituting (6) into (5), we have

$$\sum_{i \in V} I(i, f) = A + B - \sum_{e \in L_r(f)} J(e). \quad (7)$$

Hence, $\mathbf{PP}$ can be equivalently transformed into a dual optimization problem.

Definition 2: The dual optimization problem ($\mathbf{DP}$): Given $G(V, E)$ and C, the interference reduction problem is to find a channel allocation f to maximize the total removed interference $U(f) = \sum_{e \in L_r(f)} J(e)$.

Definition 3: The minimum same-color edges coloring problem (MSCP): Given undirected graph $\mathbb{G}(\mathbb{V}, \mathbb{E})$ and integers $0 < K \leq |\mathbb{V}|$, $0 \leq M < |\mathbb{E}|$, to find a coloring (i.e., assign each vertex one of the K colors) such that the number of same-color edges (i.e., the colors of its two vertexes are the same) is not more than M.

Lemma 1: MSCP is NP-complete.

Proof: We set $M = 0$ in MSCP, thus MSCP is restricted to GRAPH K-COLORABILITY problem [34] which is a typical NP-complete problem. Hence, MSCP is NP-complete. ■

Definition 4: The relative decision problem (RP): Given $G(V, E)$, C and a non-negative integer W, determine whether there exists a channel allocation f such that $\sum_{i \in V} I(i, f) \leq W$.

Theorem 1: $\mathbf{PP}$ is NP-hard.

Proof: To prove this theorem, it is sufficient to prove RP to be NP-complete. It is easy to see that RP is in NP. Then, we transform MSCP into RP. For an arbitrary $\mathbb{G}$, we create a G in the following way. For each node i in $\mathbb{G}$, we create two normal nodes in G, i.e., p_i and s_i, and p_i is the parent of s_i. Two directed edges are added: one is from s_i to p_i and the other is from p_i to s_i. For each edge e_{ij} in $\mathbb{G}$, we create two directed edges in G: one is from s_i to p_j and the other is from p_j to s_i. Finally, we create a sink node r and $|\mathbb{V}|$ edges each of which is from p_i to r. Thus, we get a new graph $G(V, E)$ where $|V| = 2|\mathbb{V}| + 1$ and $|E| = 3|\mathbb{V}| + 2|\mathbb{E}|$. Apparently, this transformation is in polynomial time. Let the channel assigned to p_i in G correspond to the color assigned to i in $\mathbb{G}$ and the interfering links heard by the non-leaf nodes to the same-color edges. Thus, MSCP with K, M and $\mathbb{G}$ is transformed, in polynomial time, into RP with $|C| = K$, $W = |\mathbb{V}|^2 + |\mathbb{V}| + M$ and G. According to Lemma 1, MSCP is NP-complete, and hence RP is also NP-complete. Therefore, $\mathbf{PP}$ is NP-hard. ■

Obviously, since $\mathbf{DP}$ is completely equivalent to $\mathbf{PP}$, we have a corollary as follows.

Corollary 1: $\mathbf{DP}$ is also NP-hard.

B. Channel Allocation Game

Since $\mathbf{DP}$ is NP-hard, it is difficult to find a solution with both polynomial execution time and optimal result. Instead, we model a channel allocation game to construct a distributed algorithm to solve $\mathbf{DP}$ with polynomial execution time and suboptimal result in this subsection.

Recalling the assumption of tree/forest structure, we construct parent-children sets from the network to exploit its TIRI, i.e., each non-leaf node in the network and its children constitute a Parent-Children Set (PCS). We define interfering PCSs as a pair of PCSs such that the message sent by a child in one PCS may be heard by the parent in the other, e.g., $PCS - A$ and $PCS - B$, and $PCS - B$ and $PCS - C$ in Fig. 2. Correspondingly, the parents in the pair of PCSs are called interfering parents, e.g., A and B in Fig. 2. All the interfering parents of parent i are denoted by a set $\Theta(i)$. In fact, the interference

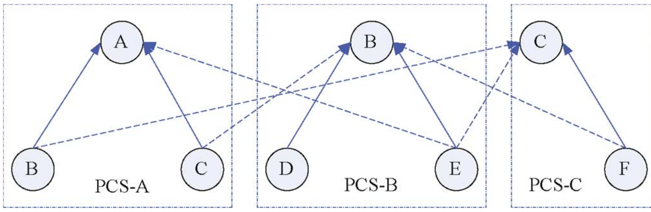

Fig. 2. Example of channel allocation among interfering PCSs, which is constructed from Fig. 1.

suffered by any child in a PCS is determined by the channel usage among the PCS and its interfering PCSs. In other words, the more parents in $\Theta(i)$ use the same channel as parent i uses, the more interference the children of parent i suffer. Thus, to minimize the interference suffered by their children, the PCSs should autonomously compete and interact with each other for the channel usage. In this case, the channel allocation among the PCSs can be naturally modeled as a channel allocation game.

In the channel allocation game, the players are all parents of the PCSs, i.e., P. Each player i chooses a channel $s_i \in C$ as its strategy. The strategies of all players make a channel allocation $s = (s_1, s_2, \ldots, s_m)$, and we denote the strategies of all players except player i by s_{-i}. The payoff of player i is a function of s and denoted by $u_i(s)$. To minimize the total interference of the network, we consider both the interference suffered by the children of player i and that caused by its children when constructing $u_i(s)$. Upon choosing a channel, player i must try to choose a channel different from its interfering players to minimize the interference suffered by its children; On the other hand, it should bring as less interference as possible to the children of its interfering players because excessive selfishness may result in extra interference to each other's children. Therefore, we define $u_i(s)$ in two parts as follows:

$$\begin{aligned} u_i(s) &= -\sum_{e \in X(i,s)} J(e) - \sum_{e \in Y(i,s)} J(e), \\ X(i,s) &= \{e : e \in L_u(s), s(e) \in Child(i)\}, \\ Y(i,s) &= \{e : e \in L_u(s), r(e) = i\}. \end{aligned} \tag{8}$$

For example, in Fig. 2, the payoffs of players A, B and C are -4, -4 and 0, respectively.

The channel allocation game is designed to be a repeated game, and players negotiate the channel usage according to the Best Response (BR) dynamics. Specifically, in each iteration of the game, each player chooses the channel to maximize its payoff based on the channel allocation in the last iteration, and the channel chosen in the last iteration is preferred if it is among those channels that maximize the payoff, but the interfering players can not change their channels simultaneously. However, BR does not guarantee convergence in all cases and the stable state is not always with the optimal social utility. Hence, we study the characteristics of our channel allocation game in terms of convergence and sub-optimality in the following. We begin with the definition of the famous stable state in Game Theory—Nash Equilibrium (NE), and then discuss the convergence of BR to NE and the sub-optimality of NE.

Definition 5: Nash Equilibrium (NE): In a game, a strategy profile s^* is called NE if and only if, for each player i and an arbitrary strategy s_i in its strategy space, the following inequality is always satisfied:

$$u_i(s^*) \geq u_i\left(s_i, s^*_{-i}\right). \tag{9}$$

To demonstrate the convergence of BR, we have the following theorem.

Theorem 2: The channel allocation game is an exact potential game [35].

Proof: We construct the potential function as follows:

$$\varphi(s) = \frac{1}{2}\sum_{i \in P} u_i(s). \tag{10}$$

Consider player i unilaterally changes its strategy from s_i^1 to s_i^2, we have

$$\begin{aligned} &\varphi\left(s_i^2, s_{-i}\right) - \varphi\left(s_i^1, s_{-i}\right) \\ &= \frac{1}{2}\sum_{j \in P}\left[u_j\left(s_i^2, s_{-i}\right) - u_j\left(s_i^1, s_{-i}\right)\right] \\ &= \frac{1}{2}\Bigg\{\sum_{j \in \{s_j = s_i^2\} \bigcap \Theta(i)}\left[u_j\left(s_i^2, s_{-i}\right) - u_j\left(s_i^1, s_{-i}\right)\right] \\ &\quad - \sum_{j \in \{s_j = s_i^1\} \bigcap \Theta(i)}\left[u_j\left(s_i^1, s_{-i}\right) - u_j\left(s_i^2, s_{-i}\right)\right] \\ &\quad + u_i\left(s_i^2, s_{-i}\right) - u_i\left(s_i^1, s_{-i}\right)\Bigg\}. \end{aligned} \tag{11}$$

Let $Z(a,b) = \{e : s(e) \in Child(b), r(e) = a\}$, we have

$$\begin{aligned} &\sum_{j \in \{s_j = s_i^2\} \bigcap \Theta(i)}\left[u_j\left(s_i^2, s_{-i}\right) - u_j\left(s_i^1, s_{-i}\right)\right] \\ &= -\sum_{j \in \{s_j = s_i^2\} \bigcap \Theta(i)}\left\{\sum_{e \in Z(j,i)} J(e) + \sum_{e \in Z(i,j)} J(e)\right\} \\ &= -\sum_{e \in X\left(i,\left(s_i^2, s_{-i}\right)\right)} J(e) - \sum_{e \in Y\left(i,\left(s_i^2, s_{-i}\right)\right)} J(e) \\ &= u_i\left(s_i^2, s_{-i}\right). \end{aligned} \tag{12}$$

Similarly, the second sum in (11) is equal to $u_i(s_i^1, s_{-i})$. Hence, (11) becomes

$$\varphi\left(s_i^2, s_{-i}\right) - \varphi\left(s_i^1, s_{-i}\right) = u_i\left(s_i^2, s_{-i}\right) - u_i\left(s_i^1, s_{-i}\right). \tag{13}$$

Accordingly, we prove that the channel allocation game is an exact potential game and one of its potential functions is $\varphi(s)$. ■

Since $\varphi(s)$ is bounded and of integral value, (13) indicates that $\varphi(s)$ will continue increasing in BR until it reaches a local maximum point. Hence, the number of iterations to converge is finite. From this finite improvement property [35], we have the following corollary.

Corollary 2: The existence of NE in the channel allocation game is guaranteed, and the channel allocation maximizing $\varphi(s)$ must be an NE.

Theorem 3: In the channel allocation game, BR always converges to an NE, and the number of iterations to converge is less than $(|V|-1)^2$.

Proof: The potential function

$$\begin{aligned}\varphi(s) &= \frac{1}{2}\sum_{i\in P}\left\{-\sum_{e\in X(i,s)} J(e) - \sum_{e\in Y(i,s)} J(e)\right\}\\ &= -\sum_{e\in L_u(s)} J(e) = -\sum_{i\in P}\sum_{e\in Y(i,s)} J(e). \end{aligned} \tag{14}$$

For each $i \in P$, $|Y(i,s)| \leq |V|-1-|Child(i)|$ and $\sum_{i\in P} Child(i)| \leq |V|-1$. Thus

$$\varphi(s) \geq -\sum_{i\in P} |Child(i)|\,(|V|-1-|Child(i)|) \tag{15}$$

$$\begin{aligned} &= -(|V|-1)\sum_{i\in P}|Child(i)| + \sum_{i\in P}|Child(i)|^2\\ &> -(|V|-1)^2. \end{aligned} \tag{16}$$

Hence, we have $0 \geq \varphi(s) > -(|V|-1)^2$.

According to BR, each player tries to choose the channel that maximizes its own payoff in each iteration. Thus, in iteration k, the situation is always one of the following two cases:

Case 1) none of the players changes channel, i.e., for each player i and an arbitrary s_i, $u_i(s^k) \geq u_i(s_i, s^k_{-i})$. According to the definition of NE, s^k is an NE.

Case 2) at least one player changes channel. Suppose that there are $m \geq 1$ such players and denoted by a set $\Omega(k)$. According to BR, these players must not be interfering players, and hence

$$\varphi(s^k) - \varphi(s^{k-1}) = \sum_{i\in\Omega(k)} \left[u_i(s^k) - u_i(s^{k-1})\right]. \tag{17}$$

Moreover, each term in the sum of (17) is no less than 1. Thus

$$\varphi(s^k) - \varphi(s^{k-1}) \geq m \geq 1. \tag{18}$$

Therefore, before satisfying Case 1, each iteration will make φ increase at least one. Since $0 \geq \varphi > -(|V|-1)^2$, BR will take at most $(|V|-1)^2$ iterations to converge to an NE. ■

Remark 1: According to Theorem 3, the number of iterations to converge to an NE is $\mathcal{O}(|V|^2)$. In Section IV, it will be shown that each iteration can be executed in polynomial time. Thus, the channel allocation problem can be handled in polynomial time.

Remark 2: In Inequalities (15) and (16), the lower bound of $\varphi(s)$ is very relaxed. The number of links towards a node is usually bounded by a constant K, which is related to the node density. The children of a non-leaf node are usually comparable to the number of its interfering links. Let $0 < \delta < 1$ be the upper bound of the ratio of interfering links to all links towards a non-leaf node. Then $\varphi(s) \geq -K\delta(|V|-1)$. Moreover, $\varphi(s)$ usually increases more than one in one iteration because many players could change their channels simultaneously if they are not interfering players. Hence, the number of iterations to converge is usually much less than $(|V|-1)^2$.

From (14), $-\varphi(s)$ is equal to the total interference caused by the unremoved interfering links. Thus, from (6), $\varphi(s)$ also reflects the social objective in $\mathbf{DP}$. According to Corollary 1, the optimal allocation must be an NE. Based on these observations, we further study the social efficiency of NE as follows.

Corollary 3: Any NE of the channel allocation game is locally optimal, i.e., in an NE, all non-leaf nodes can not reduce interference unilaterally and thus $\mathbf{DP}$ reaches a local maximum point.

Theorem 4: The Price of Anarchy [36]: let s^o be the optimal solution of $\mathbf{DP}$ and s^* be an arbitrary NE, then we have $(c-1/c) \leq (U(s^*)/U(s^o)) \leq 1$.

Proof: According to the definition of NE, under channel allocation s^*, the payoff of any player in the chosen channel is no less than the potential payoffs in the other channels in C, and obviously no less than the average potential payoff over all the channels in C. Thus, we have the following inequality:

$$\begin{aligned} u_i(s^*) &= -\left\{\sum_{e\in X(i,s^*)} J(e) + \sum_{e\in Y(i,s^*)} J(e)\right\}\\ &\geq -\frac{1}{c}\left\{\sum_{e\in\{s(e)\in Child(i)\}\bigcap E_f} J(e) + \sum_{e\in\{r(e)=i\}\bigcap E_f} J(e)\right\}. \end{aligned} \tag{19}$$

Therefore, the potential function can be bounded as

$$\varphi(s^*) \geq -\frac{1}{2c}\left\{\sum_{i\in P}\sum_{e\in\{s(e)\in Child(i)\}\bigcap E_f} J(e) + \sum_{i\in P}\sum_{e\in\{r(e)=i\}\bigcap E_f} J(e)\right\} \tag{20}$$

$$= -\frac{1}{2c}\times 2\sum_{e\in E_f} J(e) = -\frac{B}{c}. \tag{21}$$

Thus, according to (6) and (14), we have

$$U(s^*) = B - \sum_{e\in L_u(s^*)} J(e) = B + \varphi(s^*) \tag{22}$$

$$\geq B - \frac{B}{c} \geq \frac{c-1}{c}U(s^o). \tag{23}$$

Apparently, $U(s^*) \leq U(s^o)$, and thus

$$\frac{c-1}{c} \leq \frac{U(s^*)}{U(s^o)} \leq 1. \tag{24}$$

■

Remark 3: According to Theorem 4, any NE is a suboptimal solution of $\mathbf{DP}$. Taking Micaz—a typical node—as an example, there are 8 non-overlapping channels available, which is verified in [24]. According to Inequality (23), in an NE, at least 87.5% of the interference caused by interfering links is reduced. According to Inequality (24), the NE is at most 12.5% worse than the optimal allocation.

Remark 4: Since $\varphi(s)$ is an integer, and it is not always that all the interfering players of a player use different channels and

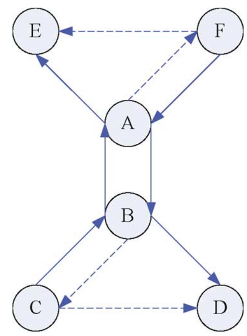

Fig. 3. Example of static general routing, where there exist two transmission flows: $C \to B \to A \to E$ and $F \to A \to B \to D$, and two crossing nodes: A and B. The solid arrows represent intersecting links, while the dashed arrows represent interfering links.

have the same potential interference to it, then the relaxations in Inequalities (19) and (20) are usually a little excessive. Thus, NE is usually much closer to the optimal allocation than the given bound implies.

Since the sub-optimality of NE is closely related to c, we have an encouraging corollary as follows when c is large enough.

Corollary 4: When $c > \max_{i \in V} |\Theta(i)|$, any NE is optimal and removes all the interference caused by interfering links.

Proof: Since $c > \max_{i \in V} |\Theta(i)|$, in an arbitrary NE, any player i can and have to choose a channel s_i^* which is different from all its interfering players's. Hence, $u_i(s_i^*, s_{-i}^*) = 0$. Furthermore, $\varphi(s_i^*, s_{-i}^*) = 0$. According to (22), we have $U(s^*) = B$. In addition, $U(s^*) \le U(s^o) \le B$. Therefore, $U(s^*) = U(s^o) = B$. ■

In summary, in the channel allocation game, BR will converge to an NE after at most $(|V|-1)^2$ iterations, and the sub-optimality of NE is guaranteed by $(c-1/c) \le (U(s^*)/U(s^o)) \le 1$.

C. Extension to General Routing

In the previous sections, the static routing of the network has been considered to be with tree/forest structure. In WSN for environment monitoring, sensed data are usually destined to one (multiple) sink node. Thus a tree/forest structure is formed and the mechanism discussed in the previous section can be applied. We may also find that the mechanism is suitable for WSANs where all sensed data are gathered and all actuators are controlled by a single centralized controller. However, large-scale WSANs may require distributed estimation and control, and thus sensor-actuator and actuator-actuator communications are necessary [37]. Therefore, the non-tree/forest routing structure has to be taken into account. To this end, we extend our approach to general static routing with non-tree/forest structure in this subsection. The main difference between tree/forest routing and general routing is that a node delivers packets to a sole node in tree/forest routing while a node may deliver packets to several nodes in general routing. These nodes which have to deliver packets to multiple nodes in general routing are called crossing nodes, e.g. nodes A and B in Fig. 3. Since our game based approach solely depends on the PCSs constructed from the tree/forest structure, it is necessary to equivalently construct these PCSs from general routing, i.e., we should handle these crossing nodes properly. In fact, for the crossing node, we can create a virtual "child" for each of its multiple "parents" to take the responsibility of the crossing node, e.g. virtual nodes $A1$ and $A2$ are corresponding to node A in Fig. 4. Each virtual node has the same interfering relationship with other nodes except these "parents" as its corresponding crossing node. Since the transmission of a crossing node to one "parent" may interfere with the transmission aiming at another "parent", the intersecting link between the crossing node and one of its "parents" actually implies an interfering link between each virtual node and "parent" pair except this "parent" and its corresponding virtual node. Thus, by adding these virtual nodes, we have a structure in which each node has a sole node to deliver message, and the equivalent PCSs can be constructed conveniently from this structure. For example, the PCSs in Fig. 4 are constructed from the non-tree/forest routing in Fig. 3, and obviously the intersecting link $\overrightarrow{AB}$ implies the interfering link $\overrightarrow{A1B}$.

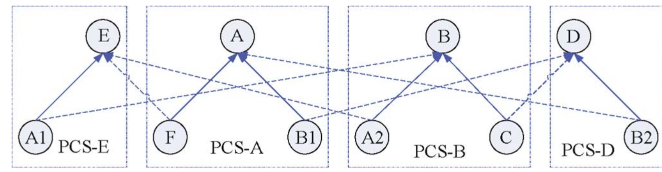

Fig. 4. Example of constructing PCSs from non-tree routing, where these PCSs are constructed from Fig. 3, $A1$ and $A2$ are virtual nodes for A, and $B1$ and $B2$ are virtual nodes for B.

In addition, since the static general routing includes the static tree/forest routing case, channel allocation problem in general routing is obviously NP-hard. Consider that the analysis in Section III-B only depends on the constructed PCSs, we can easily conclude that the conclusions in Section III-B are also valid in general routing since we can properly construct these PCSs with the help of virtual nodes. Therefore, we have the following theorems for general routing.

Theorem 5: In general routing, BR always converges to an NE, and the number of iterations to converge is less than $(\mathcal{N}-1)^2$, where $\mathcal{N}$ is the number of real nodes in the network.

Theorem 6: In general routing, the ratio of the interference reduced by the NE allocation to that by the optimal allocation is between$c - 1/c$ and 1.

We skip the proofs of these theorems, since they are similar to the proofs in Section III-B.

IV. Game Based Channel Allocation Algorithm

The payoff of a player depends only upon the channels chosen by its interfering players, so players only need to exchange information with their interfering players to implement BR. Based on BR, we propose a distributed Game Based Channel Allocation algorithm (GBCA) to cope with $\mathbf{DP}$. For the channel allocation game, the most important elements are the payoff functions of players, which reflect the benefit of players and further determine the NE of the game and its performance, and the BR dynamics of players, which determines the dynamic evolution of the game. The payoff functions and BR also constitute GBCA. Thus, according to Section III, the existence of stable state, the convergence of BR to stable state and the sub-optimality of stable state are guaranteed in GBCA. The details of GBCA are stated as follows.

Suppose each node knows its "parents", its "children" and the nodes which have interfering links towards it. Each node keeps a structure $(rcv\_ch, snd\_ch[], id)$ (i.e., the channel it uses to receive packets, the channel it uses to send packets to its "parents", and its ID number, respectively) and a Related Non-leaf Nodes Table (RNNT) which is used to record information about its interfering parents: their channels, their number of children and the corresponding intermediate nodes. GBCA is conducted in two phases: the interfering parent discovery phase and the channel negotiation phase.

In the first phase, each node broadcasts twice. For the first broadcast, each node broadcasts a message with its id and its number of children; For the second broadcast, each node rebroadcasts the messages which are received in the first broadcast, with its id added. After that, each non-leaf node knows its interfering "parents", their number of "children" and the intermediate nodes. All the information can be used to calculate payoff in the next phase.

In the second phase, BR is implemented and the channel negotiation is conducted iteratively. Each iteration occupies a time slot and is divided into four time windows: the RTC window, the PTC window, the STC window and the RCC window. This phase is the core of GBCA, and we present its pseudo-code in Algorithm 1. Apparently, each iteration in the second phase could be completed in polynomial time. Additionally, $(|V|-1)^2$ iterations are sufficient to converge to an NE. Therefore, this algorithm converges in polynomial time.

Algorithm 1 GBCA: Game Based Channel Allocation algorithm for node i

Input: the initial channel s_i^0
Output: the final channel s_i^*
for each iteration $k = 1, 2, \ldots, (|V|-1)^2$ **do**
  //window RTC:
  compute the channel to maximize the non-leaf node i's payoff: $ch = \arg\max_{s_i \in C} u_i(s_i, s_{-i}^{k-1})$;
  if ch is not equal to s_i^{k-1} **then**
    broadcast a REQ message with i's id;
  else
    $s_i^k = ch$;
  end if
  collect messages in window RTC;
  //window PTC:
  if node i has received REQs in window RTC **then**
    find the max id in REQs and reply a PER message to it;
  end if
  collect messages in window PTC;
  //window STC:
  if node i has broadcasted REQ in window RTC **then**
    if node i has received PERs from all its neighbors in window PTC **then**
      set both its rcv_ch and s_i^k to ch;
      broadcast a CHA message with ch and its id;
    else
      set both its rcv_ch and s_i^k to s_i^{k-1};
    end if
  end if
  collect messages in window STC;
  //window RCC:
  if node i has received CHAs in window STC **then**
    if the id of one CHA is its parent **then**
      set its snd_ch to the ch in this CHA;
    end if
    rebroadcast the CHAs with i's id added;
  end if
  collect messages in window RCC;
  if node i receives CHAs in window RCC and the CHAs are not from itself **then**
    update channel information in its RNNT according to the ch and id of the CHAs;
  end if
end for
//the final allocation s^* must be an NE.

In addition, the communications in these two phases use a designated channel. After the two phases, a fixed channel is allocated to each non-leaf node, and then the network starts to use this channel allocation to communicate for the future data transmissions. And time synchronization is needed only in the second phase but not required in transmitting data. Besides, conducting data transmission task, GBCA is compatible with different MAC protocols, including both scheduling based ones and contention based ones. So we do not intend to design a medium access control scheme specially for GBCA. Currently, IEEE 802.15.4 standard is very popular in WSNs, so we use its medium access control scheme (i.e., CSMA/CA) in the simulations of this paper.

V. Performance Evaluation

A. Convergence and Sub-Optimality Evaluation

In Section III-B, we analyze the convergence and sub-optimality of GBCA theoretically. In this subsection, we evaluate these characteristics of GBCA numerically. We set the field to 200 m $\times$ 200 m, and communication radius to 30 m. The number of non-overlapping channels is 2 $\sim$ 8 and the number

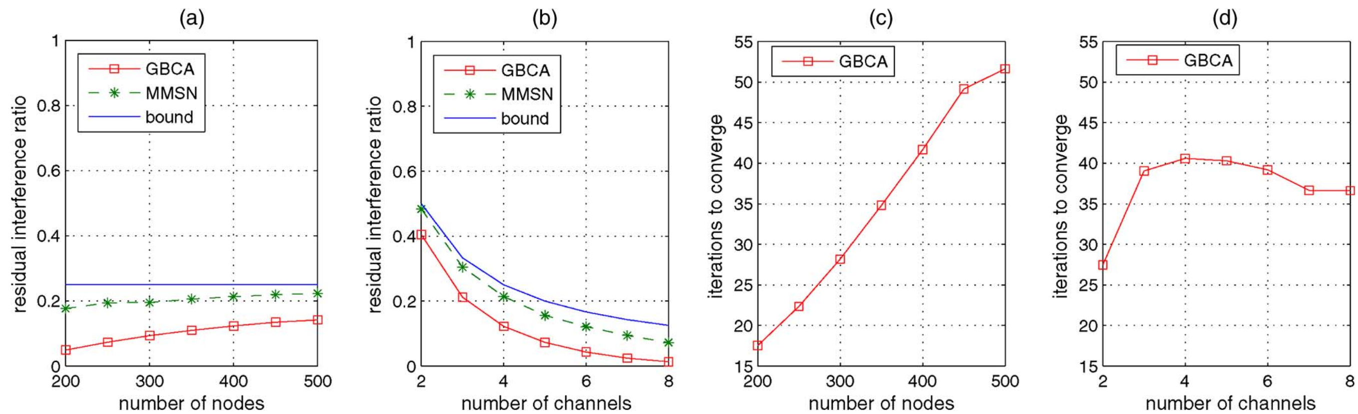

Fig. 5. Numerical results of GBCA in terms of convergence and sub-optimality.

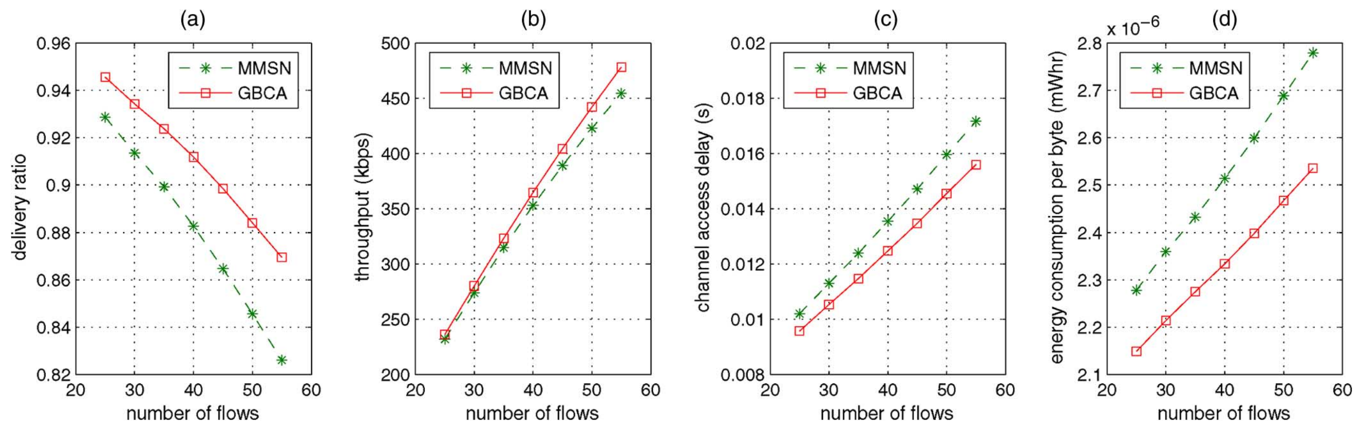

Fig. 6. Performance comparison between GBCA and MMSN with number of flows increasing in tree/forest routing scenario.

of nodes is 200 $\sim$ 500. According to Inequality (23), we use $1/c$ as the upper bound of residual interference ratio, i.e., $[\sum_{e\in L_u(f)} J(e)]/B$. For comparison purpose, MMSN is also used as a baseline, and this paper implements the even-selection version of MMSN, which can be used when non-overlapping channels are not sufficient and lead to less interference [23]. We depict the numerical results in Fig. 5, where each point is the average result of 50 independent computations.

From Fig. 5(a) and (b), we can see: 1) GBCA always reduces more interference than MMSN, and its residual interference is far less than the upper bound, which means NE is usually much better than its lower bound and closer to the optimal solution in Inequality (24); 2) With the number of nodes increasing, the residual interference ratio of GBCA increases. This is because the increasing number of nodes in the same area exacerbates interference; and 3) With the number of channels increasing, the residual interference ratio of GBCA decreases quickly to zero, since increasing number of channels gives more choices to each non-leaf node and removes more interference. From Fig. 5(c) and (d), we can see: 1) GBCA converges very fast and usually less than 50 iterations, which is far less than the bound $(|V|-1)^2$; 2) Approximately, the number of iterations required for convergence increases linearly with the number of nodes, since more nodes in networks cause more channel changes; and 3) With the number of channels increasing, the number of iterations first increases and then decreases, since the number of nodes to change channel increases with the increase of the number of channels, when it is relatively small, and the probability that nodes become stable at early iteration increases with the increase of the number of channels, when it is relatively large.

B. Network Performance Evaluation

GBCA uses game theory as a tool to exploit TIRI as much as possible to reduce the interference suffered by the network. In this subsection, we evaluate GBCA and compare it with MMSN by simulations with OMNeT++. We conduct six groups of simulations in two scenarios: tree/forest routing and non-tree/forest routing. In all these simulations, the energy and time parameters of nodes are in accordance with CC2430 [38].

1) Tree/Forest Routing Scenario: In the first three groups of simulations, the field is set to 200 m $\times$ 200 m, in which 320 nodes are uniformly distributed. They form a forest with 16 sink nodes, and the CSMA/CA is used to control medium access with one modification: when performing the CCA, the node should check both its channel to send and its parent's channel to send to avoid colliding with its siblings and parent.

In the first group of simulations, let the number of non-overlapping channels be 6 and communication radius be 30 m, and vary the number of flows from 25 to 55. The rate of each flow is 25 packets per second. These flows are randomly generated in space but the number of flows transmitting simultaneously is fixed according to the setting. The simulation results are shown in Fig. 6, where each point is the average result of 45 independent simulations, and the trial times are the same for the re-

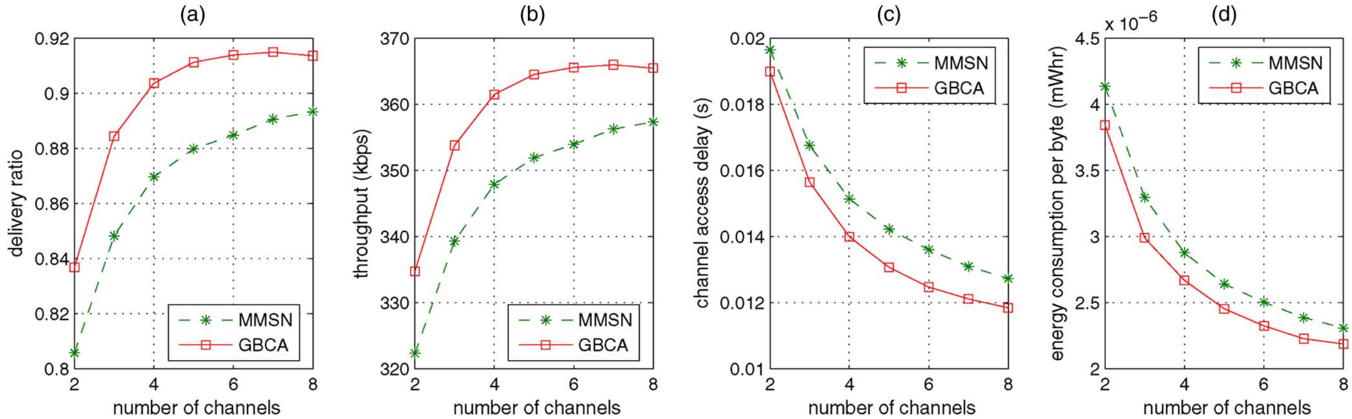

Fig. 7. Performance comparison between GBCA and MMSN with number of channels increasing in tree/forest routing scenario.

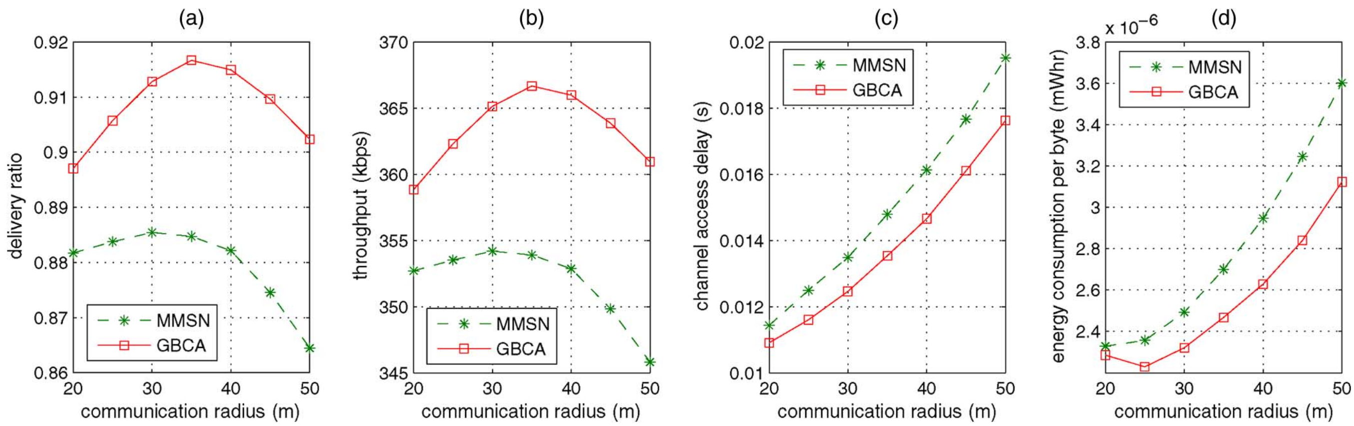

Fig. 8. Performance comparison between GBCA and MMSN with communication radius increasing in tree/forest routing scenario.

maining groups. From Fig. 6, we can see: 1) GBCA outperforms MMSN in all these metrics, i.e., it has larger delivery ratio and higher throughput but yields smaller channel access delay (i.e., the time a node spends competing for medium access and transmitting a packet) and lower energy consumption; 2) These advantages get more remarkable with the increase of the number of flows since GBCA takes full advantage of TIRI but MMSN just tries to balance the channel usage in two-hop neighborhood. And when the load of networks gets heavier, the effect of TIRI becomes more obvious.

In the second group of simulations, let the number of flows be 40 and communication radius be 30 m, and vary the number ofnon-overlapping channels from 2 to 8. The way to generate flows is the same as the first group and so is for the third group. The simulations results are shown in Fig. 7. We can see: 1) GBCA outperforms MMSN in all these metrics. 2) GBCA achieves the near-best performance with fewer non-overlapping channels than MMSN does, e.g., it almost yields the largest delivery ratio and highest throughput when the number of channels is 5, while MMSN may achieve this when the number of channels is 7 or more. This is because GBCA can combine TIRI with the limited channels rationally to reduce interference in the network. This characteristic of GBCA makes it more practical than MMSN, as the non-overlapping channels are still imited in practice [24].

In the third group of simulations, let the number of non-overlapping channels be 6 and the number of flows be 40, and vary the communication radius of nodes from 20 m to 50 m, which means the number of neighbors of node increases and generates more interference. We depict the simulation results in Fig. 8, and it can be seen that: 1) GBCA outperforms MMSN in all these metrics; 2) These advantages become more significant with the communication radius increasing; 3) When the communication radius is small, the delivery ratio and throughput of GBCA increase faster than those of MMSN, and when the radius is large, the delivery ratio and throughput of GBCA decrease slower than those of MMSN. The increment in delivery ratio and throughput with the increase of radius when the radius is relatively small results from the following reason: the nodes get shorter path to transmit message when the simulation builds the forest.

2) Non-Tree/Forest Routing Scenario: In the next three groups of simulations, the field is set to 200 m $\times$ 200 m, in which 200 nodes are uniformly distributed. The transmission flows are generated randomly, and the CSMA/CA is used to control medium access with one modification: when performing the CCA, the node should check the channel it intends to use. Hereby, we do not use the same MAC protocol as the first three groups, because the channels that one node's multiple "parents" use may be different. So the node may be unnecessarily forced to check most of the available non-overlapping channels, exacerbating the exposed terminal problem.

In the fourth group of simulations, the number of non-overlapping channels is 4, communication radius is 40 m, and the number of flows varies from 20 to 50. The rate of each flow

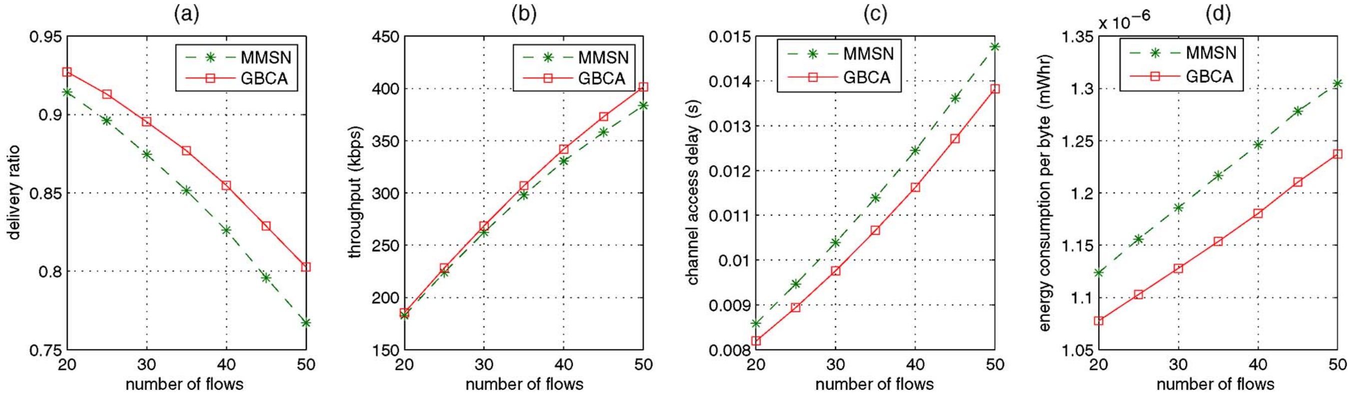

Fig. 9. Performance comparison between GBCA and MMSN with number of flows increasing in non-tree/forest routing scenario.

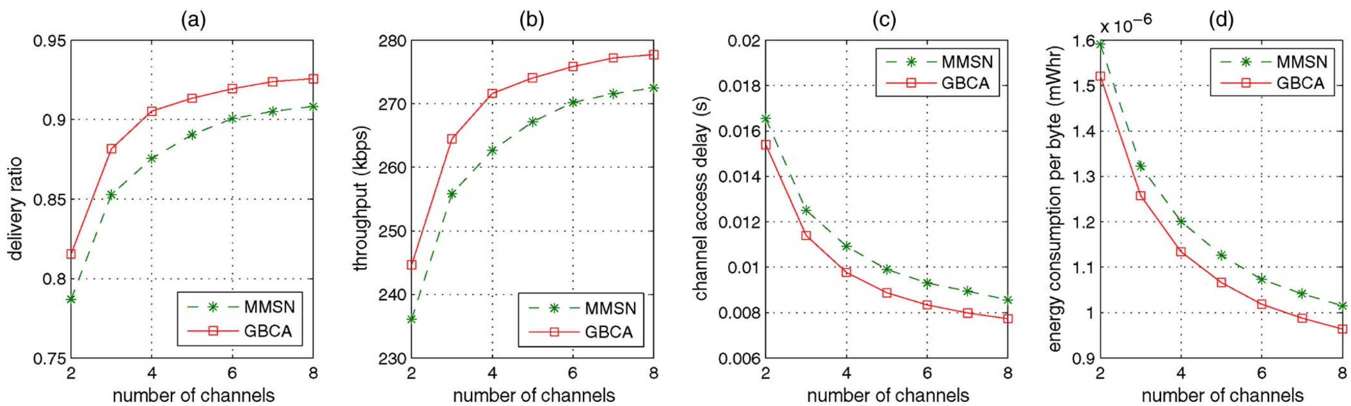

Fig. 10. Performance comparison between GBCA and MMSN with number of channels increasing in non-tree/forest routing scenario.

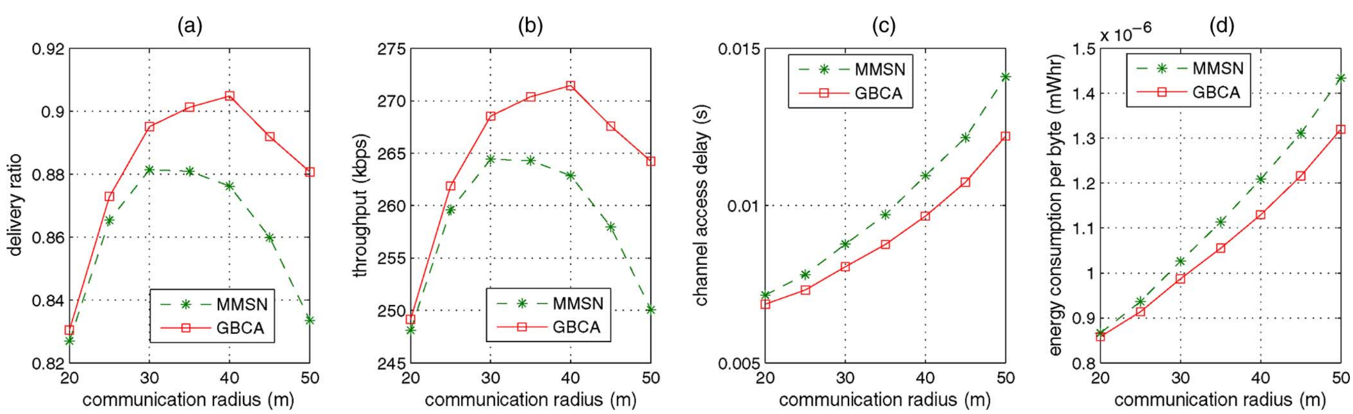

Fig. 11. Performance comparison between GBCA and MMSN with communication radius increasing in non-tree/forest routing scenario.

is 25 packets per second. The simulation results are shown in Fig. 9. We have almost the same observations as those in the first group of simulations: 1) GBCA outperforms MMSN in all these metrics; and 2) These advantages get remarkable with the increase of the number of flows.

In the fifth group of simulations, the number of flows is 30 and communication radius is 40 m, the number of non-overlapping channels varies from 2 to 8. The simulation results are shown in Fig. 10. We have the same observations as those in the second group: 1) GBCA outperforms MMSN in all these metrics; and 2) GBCA achieves the near-best performance with fewer non-overlapping channels than MMSN does, e.g., it almost yields the largest delivery ratio and highest throughput when the number of channels is 6, while MMSN may achieve this when the number of channels is 8 or more.

In the sixth group of simulations, the number of non-overlapping channels is 4, the number of flows is 30, and the communication radius of nodes varies from 20 m to 50 m. We depict the simulation results in Fig. 11, and it can be seen that: 1) GBCA outperforms MMSN in all these metrics; 2) These advantages become more significant with the increase of communication radius; and 3) When the communication radius is small, the delivery ratio and throughput of GBCA increase faster than MMSN as the radius increases, and when the radius is large, the delivery ratio and throughput of GBCA decrease slower than MMSN as the radius increases.

In summary, GBCA achieves almost the same advantages in non-tree/forest routing as that in tree/forest routing. This is because we construct PCSs properly in the non-tree/forest routing, by introducing virtual nodes, to exploit the TIRI efficiently. In addition, both GBCA and MMSN seemingly achieve lower delivery ratio, smaller channel access delay, and less energy consumption in non-tree/forest routing than that in tree/forest routing. This is mainly because different medium access schemes are used in the two scenarios. Double CCA checks in tree/forest routing scenario will yield higher delivery ratio but larger access delay and more energy consumption than single CCA check does in non-tree/forest routing scenario.

VI. Conclusion

In this paper, we have studied channel allocation issue in WSANs to reduce interference and improve network performance. Different from previous static allocation schemes, we take full advantage of both network topology and routing information to allocate channels in WSANs. Although the original optimization problem is NP-hard, a distributed game based algorithm (GBCA) has been proposed to efficiently solve this problem sub-optimally. Furthermore, we prove that GBCA can converge to an NE in finite iterations, and provide bounds on the sub-optimality of NE theoretically. Extensive simulations demonstrate that GBCA does achieve better network performance than MMSN.

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