A Novel Auction Based Scheduling Algorithm in Industrial Internet of Things Networks

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Abstract. Enabling low data losses and ensuring reliability are essential requirements to guarantee Quality of Service in Industrial Internet of Things (IIoT) applications. This can be achieved by the adoption of various architectures and standards, the most promising of which is IEEE 802.15.4 Time Slotted Channel Hopping mode. However, there are still several open issues, such as providing effective scheduling scheme in the standard. In this paper, we propose a novel auction based scheduling mechanism that uses a first-price sealed bids auction to solve the throughput maximizing scheduling problem. We considered a centralized IIoT network where the gateway makes frequency allocations and time slot assignment. Simulation results show that the proposed algorithm yields a very close throughput performance to the optimal one obtained through CPLEX with a much lower complexity.

Keywords: Industrial Internet of Things · TSCH · Auctions
IEEE 802.15.4-2015 · Centralized scheduling · Resource allocation

1 Introduction

The notion of the Industrial Internet of Things (IIoT) has moved beyond its hype of becoming the next wave of innovation, and today we are seeing a rapid increase in deployment of IIoT in many application areas, such as smart farming, smart grids, building automation. IIoT relies on low-cost, low power wireless sensor and actuator devices with constrained computational capabilities that are connected to the internet through wireless communication technologies [1,2]. The deployment of such devices has led to the convergence of operational technologies (i.e., industrial networks) and information technologies (i.e., internet). The principle of IIoT has also fostered the concept of Industry 4.0, where it is aimed to provide automation and information domain for services and people [3].

The increasing usage of wireless technologies in industrial environments has become appealing to many types of applications. This has introduced flexibility and a cost-effective solution in the network approach, but has also added

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numerous challenges, such as means to achieve wired-like reliability, security, performance guarantees, low power consumption, just to mention a few. The challenges of using wireless technologies in performing different industrial tasks is being addressed by standards such as IEEE 802.15.4.

IEEE 802.15.4 is one of the leading standard in IIoT and it defines the physical (PHY) and the Medium Access Control (MAC) layers for low power, low rate wireless personal area networks. The third revision of the standard called IEEE 802.15.4-2015 [4] was released to address the limitations of its previous releases. IEEE 802.15.4-2015 presents Time Slotted Channel Hopping (TSCH), which provides high reliability by mitigating the effects of interference and multipath fading through channel hopping, and ensures low power consumption through time synchronization to various industrial applications running in harsh environments. IEEE 802.15.4-2015 TSCH mechanism has been adopted into the industrial wireless standards such as ISA.100.11a [5] and WirelessHART [6]. Figure 1 shows the architecture of the proposed IEEE/IETF standardized IIoT.

The standard defines the mechanism of how TSCH executes a schedule, however, it does not mandate a specific scheduling mechanism, which is open to different implementations from the industry. In this paper, we propose an auction theory based scheduling method to address the throughput optimal scheduling problem formulated in [7]. The scheduling model in [7] was slightly modified by introducing multiple antennas, improving communication reliability. The proposed scheduling model is aimed at accomplishing many tasks at the same time such as frequency, time slot, data rate allocation in a heterogeneous multi-user and multi-channel environment. The scheduler, which is executed by the gateway, maximizes the total throughput of the nodes in the service area while ensuring that each node is assigned at least one time slot in any scheduling period, with no collisions occurring among the nodes.

The remainder of this paper is organized as follows: Sect. 2 discusses the basic concept about TSCH Mechanism and the related work. Section 3 introduces the system model and the problem formulation. Then, Sect. 4 proposes a novel scheduling approach based on auctioning. We discusses about the simulation results in Sect. 5 and finally in Sect. 6, we conclude the paper with some final remarks.

2 Background and Related Works

2.1 IEEE 802.15.4-2015 TSCH Concept

All nodes are synchronized in TSCH networks and communication occurs at well-defined times within a time slot. A typical time slot is sufficient to transmit a single frame and receive an acknowledgement. A slot frame is a group of time slots that repeats over time and can also be described as time-frequency offset channel distribution unit (CDU), where each cell represents a fixed time slot in a specific channel offset. Each node in the network only cares about the cell it participates in.

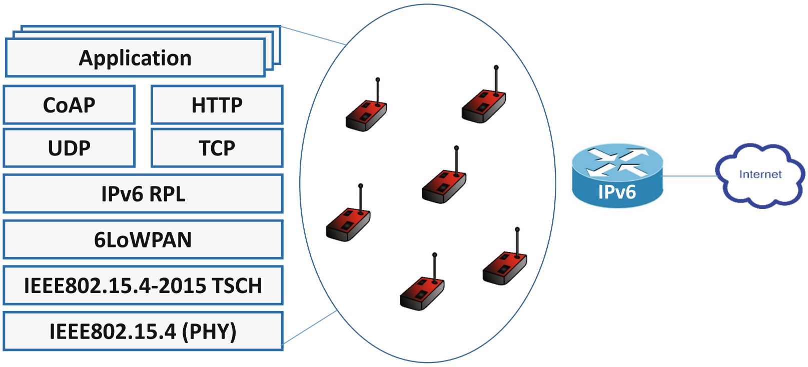


Fig. 1. IEEE/IETF standardised IIoT architecture

TSCH communication is orchestrated by a scheduler, where a schedule is defined by the time slot and channel on which a node should communicate with its neighbours. TSCH schedule can be represented by a 2-D slot frame-channel offset matrix as shown in Fig. 2. The two nodes at either end of the link communicate periodically once in every slot frame. To improve communication reliability, TSCH proposes to implement channel hopping, with frequency diversity to mitigate the effect of narrow-band interference and multipath fading. The channel offset is translated into a frequency f (i.e., a actual channel) using the following frequency translation function

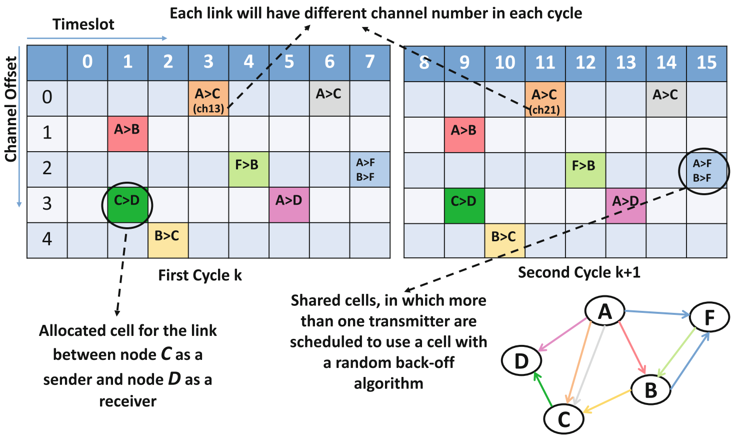
$$f = F_{MAP}(ASN + \text{channeloffset}) mod N_{ch} \tag{1}$$

where ASN (Absolute Slot Number) counts the number of time slots since the beginning of the network operation, F_{MAP} is the mapping function to find the frequency from a channel lookup table and N_{ch} indicates the number of available physical channels (e.g., 16 when using IEEE 802.15-4 compliant radios at 2.4 GHz).

2.2 Related Works

Several schedule-based MACs have been proposed in the wireless networking literature, but they can not be applied to the TSCH MAC. Nonetheless, TSCH paradigm brings this topic into the focus of research again due to the following reasons: (a) IEEE 802.15.4-2015 standard defines the mechanism for a TSCH node to communicate, but the standard does not specify how to build an optimized schedule and to construct a schedule is policy specific; and (b) TSCH brings new opportunities and challenges because of its time synchronization multiplexed in frequency to improve reliability.

Only few works have focused on scheduling in TSCH networks. The pioneering work [8] proposed by Palattella et al. focused on a centralized approach based on matching and colouring of graph theory to plan the distribution of time slot



	0	1	2	3	4	5	6	7
0				A>C (ch13)			A>C	
1		A>B						
2					F>B			A>F B>F
3		C>D				A>D		
4			B>C					

	8	9	10	11	12	13	14	15
0				A>C (ch21)			A>C	
1		A>B						
2					F>B			A>F B>F
3		C>D				A>D		
4			B>C					

Fig. 2. Time Slotted Channel Hopping (TSCH) slot-channel matrix with a simple topology

and channel offset. A distributed scheduling approach [9] was also proposed to construct optimum multi-hop schedules based on neighbour-to-neighbour signalling. Another non-graph approach for scheduling is Orchestra [10], a solution for autonomous scheduling of TSCH in IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL). Orchestra runs without any central entity, nor any negotiation, but allocates the slots in such a way that it can be automatically installed or removed as the RPL topology evolves. In [11], the authors proposed a scheduling scheme to maximize the energy efficiency, while [12] addresses latency issues.

In this paper, we focus on a centralized scheduling method based on auctioning to maximize the total throughput in an interference-aware system, since a centralized approach have been proven to be more effective in practice [13]. The major novelty of our work is that we provide a much more general and complete scheduling model that achieves frequency, time slot, data rate allocation in a heterogeneous multi-user and multi-channel environment. Our auction procedure uses a first-price sealed-bid mechanism [14] to address the throughput scheduling problem in IEEE 802.15.4-2015 TSCH networks. In first-price sealed-bid auctions, all bidders simultaneously submit sealed bids (hidden from other bidders) to the auctioneer. The bidder with the highest bid wins the auction.

Auction based mechanism have been applied to other networks such as cognitive radio networks [15] cellular networks device to device communication systems [16] peer to peer networks [17], but to the best of our knowledge, this is the first work that addresses scheduling in IEEE 802.15.4-2015 TSCH networks using auction based mechanism.

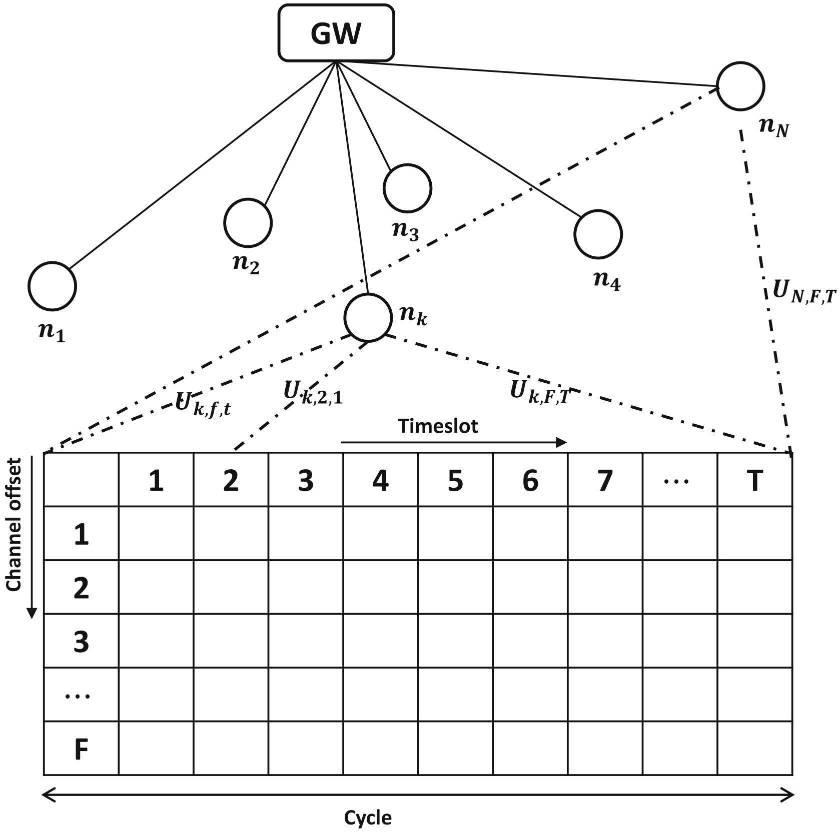


Fig. 3. Time Slotted Channel Hopping (TSCH) slot-channel matrix where each n_k maintains a link with the gateway (GW) for both frequency f and time slot t, where $k \in \{1, ...N\}$; $f \in \{1, ..., F\}$, $t \in \{1, ..., T\}$

3 System Model and Problem Formulation

We consider a time-slotted IEEE 802.15.4-2015 network, where the nodes are managed by the gateway in a centralized manner as shown in Fig. 3. The network consists of static nodes, and their locations are assumed to be known. Each node is equipped with a radio with a communication range R_f and the radio is assumed to transmit at a fixed transmission power. In addition, different channels can support different link capacities and transmission ranges. We are given a set of nodes n_k where $k \in \{1, ..., N\}$, characterized by its frequency $f \in \{1, ..., F\}$ and its time slot $t \in \{1, ..., T\}$. A communication graph $G(V, E)$ is used to model the network, where every node $k \in V$ corresponds to a device in the network, and there is a link $e = (u, v) \in E$ if there exists a common channel available for between u and v. Transmission is successful if the distance between them $\|u - v\| \leq R_f$ condition is satisfied.

At the beginning of the slot frame, each node n_k calculates the transmission capacity of the channel for each available frequency, and transmits this information to the gateway in addition to the number of packets in its buffer (Q_k). In this way, the gateway constructs a matrix $U = [U_{k,f,t}]$, where $U_{k,f,t}$ is the number of packets that can be transmitted by node k using frequency f. Upon collection of all state information such as topology information, traffic generated by each node etc., the scheduler decides on the frequency assignment with the goal of maximizing the throughput.

Let $C_{k,f,t}$ denote the Shannon's capacity of the link between n_k and the gateway GW at frequency f. $C_{k,f,t}$ is a function of the signal-to-noise ratio $SNR_{k,f,t}$ and represents the theoretical upper bound. In the calculation of $C_{k,f,t}$, only the background noise is considered as we focus on an orthogonal frequency assignment. The number of packets that can be sent during a slot frame duration, $M_{k,f,t}$, equals $C_{k,f,t}T$ where T is the slot frame duration. Accordingly, $U_{k,f,t}$ becomes $min(M_{k,f,t}, Q_k)$.

Considering the binary variable $X_{k,f,t}$ defined as:

$$X_{k,f,t} = \begin{cases} 1 \text{ if node } n_k \text{ transmits using frequency } f \text{ in time slot } t; \\ \\ 0 \quad \text{otherwise;} \end{cases}$$

$\boldsymbol{x} = [X_{k,f,t}, k \in \{1, ...N\}; f \in \{1, ...F\}; t \in \{1, ...T\}]$ is the scheduling decision vector with elements $X_{k,f,t}$. Note that $X_{k,f,t}$ is a function of the information available to n_k. We calculate the total throughput in TSCH network as

$$\mathrm{C} = \sum_{k=1}^{N} \sum_{f=1}^{F} \sum_{t=1}^{T} U_{k,f,t} X_{k,f,t} \tag{2}$$

Interference and spectrum availabilities are constrained in the derivation of the formula for $U_{k,f,t}$. For instance, if a node k is very close to a node i that uses frequency f in time slot t, then node k cannot use frequency f in the same time slot, i.e., $U_{k,f,t} = 0$. $U_{k,f,t}$ value quantifies the slot availabilities (i.e., the higher the $U_{k,f,t}$ value is, the higher the data rate node k can have if it uses frequency f in time slot t). $U_{k,f,t}$ values are input variables for the optimization problem in this paper. In the following, $U_{k,f}$ is used instead of $U_{k,f,t}$ because we assume that all parameters are to remain constant for each time-slot t of the slot frame period. The slot frame period is a time duration in which the network conditions remain fairly stable. For instance, in voice applications, the value of T tends to be fairly large.

The binary integer linear programming is as follows:

$$\sum_{k=1}^{N} \sum_{f=1}^{F} \sum_{t=1}^{T} U_{k,f} X_{k,f,t} \quad \text{s.t} \tag{3}$$

$$\sum_{f=1}^{F} \sum_{t=1}^{T} X_{k,f,t} \geq 1; \quad \forall k \in \{1, ..., N\} \tag{4}$$

$$X_{k,f,t} + X_{k',f,t} \leq 1; \quad \forall k, k' \in N, k \neq k', \forall f, \forall t \tag{5}$$

$$\sum_{f} X_{k,f,t} \leq a_k \quad \forall k; \forall t \tag{6}$$

$$X_{k,f,t} \in \{0, 1\}; \quad \forall k \in N; \forall f \in F; \forall t \in T \tag{7}$$

In the problem formulation, the objective function in (3) maximizes the total throughput of all the nodes in TSCH network governed by the gateway. The constraint in (4) ensures that each node is assigned at least one time slot and hence provides temporal notion of fairness. The constraint in (5) is used to avoid collision, by guaranteeing that at most one user can transmit in a certain slot and frequency offset. Constraint in (6) indicates that node k cannot transmit at the same time using more frequencies than the number of its transceivers (antennas) a_k because each transceiver can tune to at most one frequency at a time, and finally (7) indicates a binary decision variable.

We assume in the simulations part of this work that the buffers of the nodes are continuously backlogged; i.e., there are always enough packets to be transmitted with the data rate determined by the scheduling algorithm. This is necessary in order to effectively evaluate the scheduling process performance by avoiding the possible influence of the traffic arrival process. The above formulation does not assert a minimum throughput guarantee for a node's transmission, however it can be extended by simply adding the following constraint for each node and frequency pair: $U_{min} X_{k,f,t} \leq U_{k,f}$, where U_{min} is the minimum throughput.

4 Auction Based Mechanism Scheduler

In this section, we propose an auction based scheduling algorithm to address the optimization problem formulated in (3)–(7). Our motivation for using a first-price sealed-bid auction in designing suboptimal scheduler for the throughput maximizing scheduler is manifold. First, $U_{k,f}$ values of any node k are independent from other nodes' values, and each node knows only its own $U_{k,f}$, namely its bid value. Since the bid values do not affect each other, the auctions are held in a sealed bid fashion. Secondly, in order to maximize the network throughput, first price auctions are used in our algorithm and an auctioned frequency time resource pair ($FTRP$) is assigned to a node whose bid is greater than all other bids. The result of an auction related to an $FTRP$ does not impact another auction which is held simultaneously.

In our TSCH model, we assume that all nodes managed by the same gateway have the same number of transceivers. The auctioning procedure requires three main identifiers which are (1) The auctioned resources (r) (2) The bidders (3) The auctioneer. We indicate the auctioned resources as $FTRP$; the bidders as the nodes in the network; and lastly the auctioneer as the gateway (where the scheduler resides).

If we ignore constraint (4), (6) and (7), the optimal solution is achieved when a $FTRP$ is assigned to the node k that has the maximum $U_{k,f}$ value for the frequency f (of this resource r). The aim is to assign at least one $FTRP$ to each node, and to avoid any starving node at the end of the algorithm. A starving node is indicated as the node that has not been assigned any time slot during any stage of the algorithm. Our proposed scheduling algorithm is explained through steps 1 to 6 below.

STEP 1: For each frequency f, find the node who transmits the maximum number of packets using that frequency. Assign the frequency to that node for all time slots of the slot frame period. In other words, assign f to node k where $k = argmax_k U_{k,f}$. We denote w_k the number of frequencies assigned to node k at the end of step 1.

STEP 2: If every node is assigned at least one $FTRP$ and $w_k \leq a_k, \forall k$, end. Otherwise, each node that is assigned more than one frequency sorts its frequencies according to their $U_{k,f}$ values. If any node k has w_k greater than a_k, go to step 4 and 5, else go to step 6.

STEP 3: Do we have a starving node? if yes, go to step 4, otherwise go to step 5.

STEP 4: Any node k whose $w_k \geq a_k$ auctions all time slots of $w_k - a_k$ of its frequencies which have the smallest $U_{k,f}$ values. The $FTRPs$ are auctioned simultaneously. The starving node bids to the $FTRP$, whose corresponding $U_{k,f}$ value is the greatest one. When the starving node gets a $FTRP$, it is removed from the auction procedure. The auctions continue until all the starving node gets a $FTRP$ or when no $FTRP$ remains. At the end of the auctioning procedure, if we still have $FTRP$ that are not assigned to any node, they are auctioned out to the nodes that have available transceivers. Otherwise, if there still exists a starving node and all resources are assigned, then go to step 6.

STEP 5: Any node k whose $w_k \geq a_k$ takes a_k of its frequencies with the largest $U_{k,f}$ values. The $FTRPs$ which belong to the remaining $w_k - a_k$ frequencies are assigned greedily to the nodes who have available transceivers.

STEP 6: Any node k that is assigned more than one frequency auctions $w_k - 1$ number of its frequencies which have the smallest $U_{k,f}$ values until either no starving node remains or the auctioned $FTRP$ run out. When all nodes have at most a single frequency, if any starving node exists they auction out their remaining frequencies.

5 Performance Evaluation

A simulation based study was carried out in order to evaluate the performance of the proposed algorithm. We consider a TSCH network consisting of sensor nodes randomly placed over a square area of 100 m × 100 m and a gateway located in the center. The x and y coordinates of each node follow a uniform distribution. Every node is equipped with a radio that has a transmission range of 30 m. $U_{k,f}$ values are different owing to the changing network conditions and are obtained for 3000 slot frame periods in each set of simulations where the average is considered. Each slot frame period consists of 30 time slot, where each time slot has a duration of $t = 10$ ms. We then solve for the throughput maximizing scheduling problem in (3)–(7). using ILOG-CPLEX [18]. We compare the proposed auction heuristic scheduler with the optimal result obtained through ILOG-CPLEX.

Figure 4 highlights how the average network throughput is affected by varying the number of nodes and frequencies. F_{opt} indicate the number of frequencies used in the ILOG-CPLEX simulations, whereas F_{auc} indicates the number of frequencies used in our proposed auction based heuristic algorithm. It can be seen that the performance of our heuristic is very close to the optimum value in all cases. Moreover, it can also be seen that the average network throughput is almost invariant for varying the number of nodes when F is small (i.e. $F = 3$) in both cases. This is because the number of frequencies available for the nodes is small, which makes no much difference to have increasing number of nodes in the system because almost all of the resources are already occupied by all nodes even when the number of nodes is small. As the number of frequencies increases, the average network throughput grows with the number of nodes. This behaviour does not change up to a threshold where network throughput saturates.

We also point out in Fig. 5 how the number of frequencies and antennas affects the performance of the throughput maximization scheduler as shown. We can notice that increasing the number of antennas of each node in the network only makes sense when there is a certain number of frequencies in the system. For instance, having only one antenna i.e., $a = 1$ has the performance as having multiple antennas i.e., $a > 1$ when the number of frequencies is small (when $F < 8$). On the other hand, there is a significant difference in the throughput when we increase the number of antennas from 1 to 2 if the frequencies are between 8 and 16. The reason for this behaviour is highlighted by constraint (4), where each node is assigned at least one $FTRP$. In order to comply with this constraint, the scheduler which resides at the gateway tends to assign some frequency to the first antenna of each node, and then continue to assign frequencies to other antennas. For instance, in Fig. 5, we assume that $N = 8$, and until the point where $N = F$, the scheduler assigns the frequencies to the first antennas of each node. Increasing the number of antennas has similar effect on the total throughput as increasing the number of nodes. Moreover, between $F = N$ and $F = 2N$, the scheduler assigns the frequencies to the second antenna of each node.

5.1 Computational Complexity

In this section, we compute the computational complexity of our algorithm. At the end of step 1, assigning a $FTRP$ to each node has a complexity of $\mathcal{O}(NF)$ because for each frequency, we determine the maximum number of packets $U_{k,f}$. This is the best case scenario, when every node is assigned at least one frequency. In the worst case scenario, when all the frequencies are assigned to only one node which in practice is very unlikely. We need to take into account the additional complexity of steps 2–6. In step 2, the frequencies are sorted out and the complexity is $\mathcal{O}(F \log F)$. Since we have $N - 1$ starving nodes to bid for the frequencies, it will require $\mathcal{O}((N-1)\log(N-1))$ time to sort out their bids

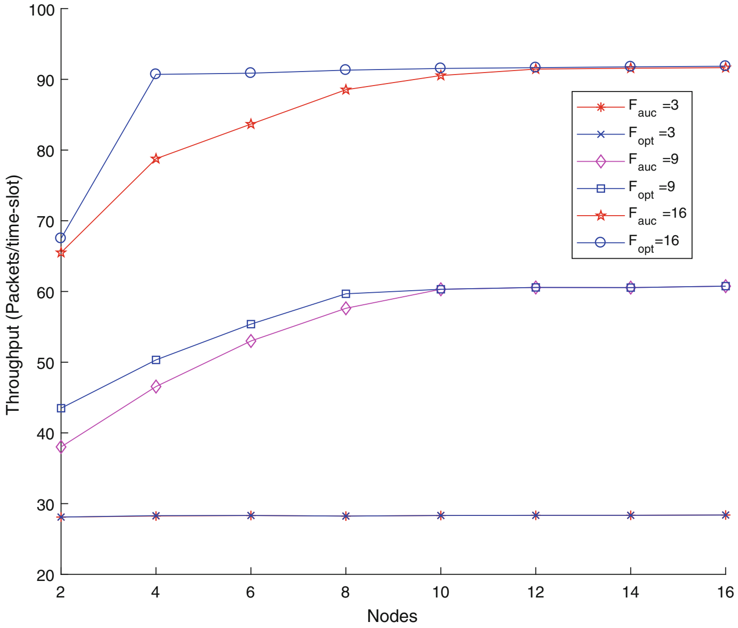


Fig. 4. Comparison of the proposed scheduling algorithm with the optimum results obtained through CPLEX simulations

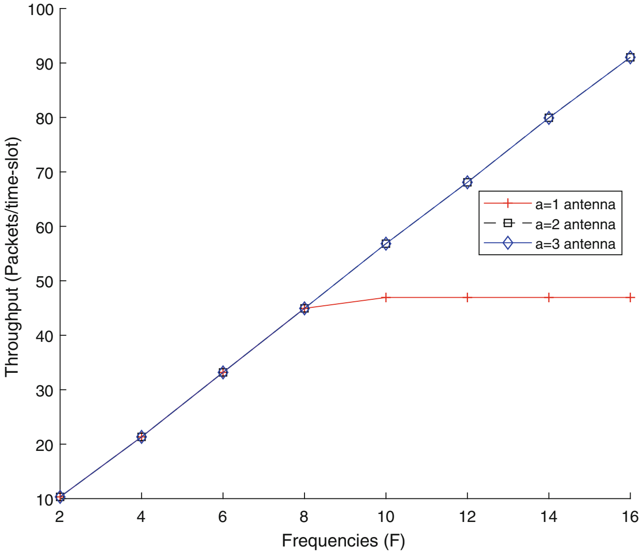


Fig. 5. Average total network throughput for the throughput maximization scheduling problem by varying the number of antennas and frequencies

according to $N-1$ starving node. Therefore the total computational complexity of the algorithm is $\mathcal{O}(NF) + \mathcal{O}(F \log F) + (N-1) \times \mathcal{O}((N-1) \log (N-1))$, that simplifies it to $\mathcal{O}((NF) + N^2 logN)$.

6 Conclusions

In this paper, we formulated the throughput maximization scheduling problem for IIoT-TSCH based networks in a centralized way. In more detail, we proposed a novel heuristic scheduling algorithm based on first-price sealed bid auction mechanism to solve the problem. The performance of our sub-optimal scheduler is close to the optimal one obtained through ILOG-CPLEX. We observed that having many antennas, (i.e., $a > 2$) does not increase the average throughput. Moreover, the computational complexity for the best case scenario is $\mathcal{O}(NF)$ while for the worst case scenario is $\mathcal{O}((NF) + N^2 logN)$.

In our future work, we plan to design approximation algorithms, which have theoretically provide performance guarantee for the throughput maximization scheduling problem.

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