A Noncooperative Gaming Approach for Control Packet Transmission in 6TiSCH Network

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***Abstract*—The 6TiSCH communication architecture is widely used in Industrial Internet of Things (IIoT) to provide reliable, delay-bounded, and energy-efficient communication in multihop scenarios. However, the channel hopping feature and the resource allocation strategy of 6TiSCH minimal configuration (6TiSCH-MC) standard negatively impact the 6TiSCH network by increasing network formation time. 6TiSCH-MC allows only one cell (known as minimal cell) per slotframe to transmit control packets. When the number of joined nodes increases in the network, the formation time also increases because of the increasing congestion in the minimal cell. Furthermore, the existing works did not study the effect of transmission rates of all control packets together during 6TiSCH network formation. Therefore, in this work, a noncooperative game is formulated, for optimal transmission of control packets by the joined nodes. The obtained solution of the proposed game, using the Lagrange multiplier and Karush–Kuhn–Tucker (KKT) conditions, is used in the proposed congestion control scheme—game theory-based congestion control (GTCC). GTCC calculates the slotframe window (SW) size for every node to control the congestion in minimal cell without any signaling overhead. GTCC is validated using the analytical model as well as the FIT IoT-LAB testbed. The findings of both the analytical and testbed experiments show that GTCC significantly reduces the joining time and energy consumption of new nodes (i.e., pledges) as compared to previous benchmark schemes.**

***Index Terms*—6TiSCH, congestion control, game theory, Industrial Internet of Things (IIoT), network formation.**

I. Introduction

THE 6TISCH (IPv6 over the time slotted channel hopping (TSCH) mode of IEEE 802.15.4e [1]) wireless communication architecture is widely used in large scale multihop Industrial Internet of Things (IIoT) applications [2], [3] as it provides time bound, energy-efficient, and reliable communication. IETF formed 6TiSCH Working Group (6TiSCH-WG) to provide interoperability between TSCH medium access control (MAC) behavior and IETF's upper layer protocols [2], [4]. 6TiSCH-WG mainly deals with scheduling of communication cells for both the data and control packet transmissions between TSCH and upper layer 6TiSCH network protocol stack [2]. 6TiSCH-WG published 6TiSCH Minimal Configuration (6TiSCH-MC) standard [5] for effective joining of the new nodes. Note that IETF used the term *pledge* to designate a new joining node, which has not yet completed the join process in a given secure network, and is therefore not trusted by the network. So, a new node is referred to as pledge in this article. 6TiSCH-MC mentioned that only one minimal cell can be used per slotframe for control packet transmission during (or after) the formation of a network. Note that the minimal cell is shared by all the nodes and used only for control packet transmission, whereas the data packet is transmitted in dedicated cell. Note that the dedicated cells are managed by the transmitter and receiver pairs following the distributed cell management protocols such as [6] or any other scheduling algorithm (e.g., [7]).

In general, the 6TiSCH network uses RPL (Routing Protocol for Low-Power and Lossy Networks) protocol in the network layer. RPL organizes the nodes along a loop-free destination-oriented directed acyclic graph (DODAG) rooted at the sink node. Mainly, the basic network configuration carrying the enhanced beacon (EB) frame and routing information carrying DODAG information object (DIO) packet are necessary for a pledge to join in 6TiSCH networks. However, in addition to these two packets, few more control packets, such as DODAG information solicitation (DIS), destination advertisement object (DAO), DAO-ACK, keep-alive, join request (JRQ), and join response (JRS) are also transmitted in minimal cell.

Motivation: The works [8], [9] mentioned that 6TiSCH-MC does not provide enough resource, i.e., the number of minimal cell per slotframe to transmit all the generated control packets during network bootstrapping. The shared minimal cell severely gets congested when the number of nodes increases, which ultimately degrades the performance of the 6TiSCH network during its formation in terms of pledges' joining time and their energy consumption [8], [9]. Furthermore, increasing formation time also affects in throughput and end-to-end packet delivery latency as nodes are permitted to transmit their data packets only after joining the 6TiSCH network. To deal with this problem of 6TiSCH-MC, Vallati *et al.* [8] increased the number of minimal cells per slotframe. However, their proposed scheme consumes more energy, and also hinders the throughput and end-to-end latency. The work in [10] suggested to use beacon transmission probability 0.1 per slotframe irrespective of the number of nodes present in a network to reduce congestion in minimal cell. Similarly, the works in [9] varied the beacon generation interval of the joined nodes depending on the congestion in minimal cell. On the other hand, the work in [11] tried to provide sufficient routing information (i.e., DIO) during network bootstrapping, but did not consider the congestion issue in minimal cell. In brief, none of the existing

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works considered the impact of the transmission rates of EB and DIO packet together on the congestion in minimal cell, and so the 6TiSCH network formation. With the increasing number of nodes, on an average transmission of EB and DIO also increases, which creates congestion in minimal cell, and so increases the 6TiSCH network formation time. However, both of these control packets are required during network formation. Therefore, this article presents a new technique for providing optimal EB and DIO packet transmission probability per slotframe/minimal cell to reduce congestion in minimum cell, and so the network formation time.

Contribution: In the 6TiSCH network, nodes selfishly transmit their control packets without considering the congestion in minimal cell. This selfish behavior increases the joining time of the pledges by increasing the congestion in minimal cell and, thus, reduces the lifetime and throughput of the network and increases end-to-end packet delivery latency. In fact, a joined node is not aware of the transmission rates of its neighboring nodes. So, a noncooperative game is formulated where all the joined nodes act as players. The optimal solution of the noncooperative gaming is to transmit control packets with maximum probability, so that congesting the minimal cell can be reduced, and so pledges' joining time and energy consumption. Furthermore, the optimal solution is obtained without any signaling overhead among the nodes. The obtained optimal solution is used in the proposed game theory-based congestion control (GTCC) scheme, which reduces the congestion in minimal cell, while allowing the players to maximize their pay-offs irrespective to the strategies of the neighboring players. In brief, the contributions of this article are as follows.

1) Design a noncooperative game to find out optimal control packet transmission probability to reduce congestion in minimal cell, which results in improving the joining time and energy consumption of the pledges.
2) It is proved that the proposed game has a unique Nash equilibrium point.
3) A GTCC scheme is proposed using the obtained optimal solution by which nodes can efficiently transmit their control packets.
4) At first, the proposed scheme is validated using an existing analytical model, then it is implemented on Contiki-NG and evaluated using the real FIT IoT-LAB testbed.

Paper Organization: The remainder of this article is organized as follows. Section II summarizes the existing works related to 6TiSCH network formation and congestion control in different networks using the game theory. Section III describes the modeling of the proposed game. Section IV describes the proposed GTCC schemes. Section V discusses the selection of different parameter values and analytical validation of the proposed scheme. Finally, in Section VI, testbed evaluation of the proposed schemes is done, and in Section VII, the conclusion of this work is drawn.

II. Related Works

The formation of the 6TiSCH network gains attention because of the channel hopping feature of TSCH. A node changes its packet transmitting channel after every timeslot to get rid of interference and multipath fading on channels. On the other hand, a pledge does not know in which channel the joined nodes transmit their control packets. Hence, a pledge needs to randomly scan on different channels one after another for EB in order to get synchronized with the network. Therefore, the works in [12]–[15] increased the number of transmitted EB per slotframe by proposing different schemes. However, these works have several disadvantages like—desynchronization happens between the parent–child pairs as both the parent and child nodes do not listen to each other's control packets. The energy consumption of the nodes is more as they transmit more EBs. Frequent transmission of EB also severely congests the channels when the number of nodes increases in the network, which increases collision.

The above-mentioned works are published just after the amendment IEEE 802.15.4e [1]. Later, IETF formed 6TiSCH-WG to manage communication cells for both data and control packets transmission. This 6TiSCH-WG published 6TiSCH-MC [5] which contains the details of minimum resource allocation, i.e., the number of minimal cells per slotframe for network bootstrapping. 6TiSCH-MC allowed only one minimal cell per slotframe for control packets transmission during or after the formation of the networks. A pledge comes to know about the position of the minimal cell (`[Slot Offset, Channel Offset]`) only after receiving one valid EB frame. So, after receiving one EB, the pledge listen only on the minimal cell for other control packets to completely join in the network. Furthermore, 6TiSCH-MC mentioned that a node can transmit its control packets for further expansion of the network and data packets to its destination only after completely joining the network.

However, Vallatti *et al.* [8] proved that the allocation made by 6TiSCH-MC is not sufficient for exchanging all the generated control packets during network bootstrapping. Therefore, the authors increased the number of minimal cells per slotframe dynamically, i.e., depending on the number of generated control packets. As a result, this scheme significantly improves the formation time. However, it consumes more energy as the nodes need to keep their radios active in all the allocated minimal cells. Furthermore, the existing underlying data transmission schedule needs to be modified as some of the data transmission cells are converted into minimal cells. Later, Vucinic *et al.* [10] proposed to keep the EB transmission probability 0.1 per slotframe to reduce the congestion in minimal cell. Simulation results show improvements over 6TiSCH-MC using this probabilistic beacon transmission. However, in a sparse network, a pledge might need to wait more time to get an EB, which results in a longer formation time. Later, Kalita and Khatua [9] dynamically varied the EB generation intervals of the nodes instead of using the fixed EB rate depending on the congestion in the minimal cell. However, the authors did not consider the impact of the DIO rate on channel congestion. The same authors mentioned in [11] that DIO packet starves to get transmitted due to EB's highest priority, and it results in longer formation of 6TiSCH networks. Furthermore, the authors showed the negative effect of the Trickle algorithm during 6TiSCH network formation. As a solution, the authors tried to transmit a sufficient number of DIO packets as well as dynamically changed the priority of a packet depending on its requirement in the network for faster formation. However, they did not consider the channel congestion problem in their solutions. Hence, all the existing works did not look into the channel congestion problem considering the transmission rate of EB and DIO packets together. However, the frequent transmission of both these control packets is very much important for forming a 6TiSCH network quickly. Although, the work in [16] decreases the joining time of the pledges significantly without increasing their duty cycle, and so energy consumption, but congestion is possible when the network usages only few channels.

Apart from these existing works, few research works [17]–[19] used the game theory-based solutions to solve the congestion problem in different networks, such as 6LoWPAN and VANET. The works [17], [18] tried to obtain the optimal data packet transmission rates of different priority-based applications in the 6LoWPAN network considering the remaining buffer capacities of the intermediate forwarding nodes and priority of an application as *price functions*. Both these works have the signaling overhead as the DIO packet is used for sharing the information related to buffer occupancy. The work [19] tried to find out the optimal beacon transmission rate for VANET, where congestion in the transmission channel is considered as the *price function*. However, in VANET, the beacon is transmitted in a dedicated physical channel. On the other hand, in the 6TiSCH network, including EB, other control packets are transmitted in the minimal cell. So, these existing game theory-based schemes will not be suitable to reduce congestion in the minimal cell.

III. Game Theoretical Modeling

A. 6TiSCH Network Formation

The 6TiSCH network formation process is initiated by the join registrar/coordinator (JRC) (or RPL root/sink node) by periodically broadcasting the EB frame. The pledges turn on their radios and start scanning on different random channels for EB to get synchronized with the network. Initially, a pledge does not know about the channel in which joined nodes transmit their EBs. Therefore, the pledge keeps its radio active in the listening state (i.e., performs channel scanning) on a random channel for receiving its first EB. The pledge moves to a different channel when it does not receive any EB for a particular period. In this manner, it keeps changing its physical channel one after another until it receives a valid EB. A pledge becomes a TSCH synchronized node when it receives a valid EB from any joined node. Now, the TSCH synchronized node knows the location of minimal cell, so, it activates its radio only in the minimal cell to receive or exchange other control packets such as DIO, JRQ, and JRS. Now, the TSCH synchronized node starts listening for the DIO packet after the completion of its secure joining process. When it receives a valid DIO packet, it becomes the RPL joined node or 6TiSCH joined node. Note that the formation of the 6TiSCH network and the construction of DODAG tree indicate the same event. In other words, both the events happen at the same time because a TSCH-synchronized node becomes a 6TiSCH joined node after receiving DIO while the same DIO is used to construct the DODAG. The formation process of the entire network gets completed, when all the pledges join the network one after another. In brief, the journey of a pledge can be depicted by the following states: new node/pledge → TSCH sync node → TSCH secured joined node → RPL/6TiSCH joined node. In this whole journey, the pledge receives EB, JRS, and DIO control packets, and it transmits the JRQ frame.

Before starting the network formation, the network administrator fixes the EB transmission period, and it remains unchanged in whole period [5]. On the other hand, the DIO rate is controlled by the Trickle Algorithm [20], who changes the DIO transmitting rate dynamically depending on the stability of the network. The works [8]–[10] have shown that the congestion in the minimal cell affects on the pledges' joining time and their energy consumption. Therefore, it is important to reduce the congestion in minimal cell by controlling the transmission rate of different control packets. However, one node does not know about the transmission rate of its neighbor(s). Therefore, a noncooperative gaming solution is proposed in the next section for obtaining the optimal control packet transmission probability of the nodes.

B. Noncooperative Game Formation

Let us consider a 6TiSCH network with one *JRC* and a set of joined nodes defined by the set $JN = \{J_1, J_2, \ldots, J_n\}$, where J_i denotes the ith joined node (i.e., $\forall J_i \in JN$, $i = \{1, 2, \ldots, n\}$). The joined nodes transmit their control packets selfishly, i.e., they do not bother about the control packet transmission rate of other nodes. Hence, high congestion in the minimal cell becomes an obvious outcome. The joined nodes do not have any information about the transmission rates of their neighboring nodes. Hence, a noncooperative game-theoretic approach is proposed to find the optimal control packet transmission probability in a slotframe of the joined nodes, so that congestion can be reduced in the minimal cell.

Let $G = \{JN, (\rho_i)_{J_i \in JN}, (\psi_i)_{J_i \in JN}\}$ be the proposed noncooperative game to find out the optimal control packet transmission probability in a slotframe of the nodes, in which all the three tuples are as follows.

1) *Players:* J_i; J_i is the member of set *JN*, i.e., $\forall J_i \in JN$, who wants to transmit its control packets in the minimal cell. Note that the JRC is also included in the set *JN*.
2) *Strategies:* S_i; S_i denotes the strategy for player J_i $\forall J_i \in JN$. Each strategy defines the transmission probability of the control packet in the minimal cell. The transmission rates of EB frame and DIO packets are different. Therefore, it is required to normalize them as follows. If the slotframe length is L *timeslot* with one *timeslot* duration T and the minimum EB generation interval is $I_{eb}^{\min}$, then the EB transmission probability per minimal cell is $p_{eb} = (L \times T)/I_{eb}^{\min}$. On the other hand, if the average DIO transmission probability per minimal cell is p_{dio} (p_{dio} can be calculated following the method described in [8]), then the probability of transmitting both these two control packets in a minimal cell by a joined node

is $\rho = p_{eb} + p_{\text{dio}}$. However, a node can transmit either an EB frame or a DIO packet in a slotframe. So, the minimum and maximum values of ρ_i can be in between 0 and 1, respectively. Thus, strategy space for player J_i is $S_i = [0, 1]$ and strategy space for all the players is $S = \prod_{i=1}^{n} \rho_i \quad \forall J_i \in JN$.

3) *Pay-Off Function:* $\psi_i : \rho \leftarrow \mathbb{R}$ denotes the pay-off function of player J_i $\forall J_i \in JN$. Player J_i tries to optimize its profit by maximizing its pay-off function ψ_i considering the best value of its ρ_i over [0, 1].

Frequent transmission of control packets helps the pledges to join the network quickly when the congestion in the minimal cell is minimum. However, it consumes more energy of the transmitting node, and also increases congestion in the minimal cell. Therefore, the proposed pay-off function is designed to keep balance among the control packet transmission probability, channel congestion, and energy consumption of the transmitting nodes. Thus, the proposed pay-off function for a player J_i is described as follows:

$$\psi_i(\rho_i, \rho_{-i}) = U_i(\rho_i) - 1/(1 - MBR_i(\rho_i, \rho_{-i})) - E_{TX_i}(\rho_i) \quad (1)$$

where $\psi_i(\rho_i, \rho_{-i})$ denotes the pay-off function of player J_i; ρ_i denotes the control packet transmission probability by J_i; and ρ_{-i} denotes the control packet transmission probabilities of other players except J_i. The term $U_i(\rho_i)$ in (1) denotes the *utility function*, and the other two terms, i.e., $1/(1 - MBR_i(\rho_i, \rho_{-i}))$ and $E_{TX_i}(\rho_i)$ denote the *price functions* correspond to *minimal cell busy ratio* and *energy consumption*, respectively. $MBR_i(\rho_i, \rho_{-i})$ is the observed minimal cell busy ratio by player J_i, and E_{TX_i} is the required amount of energy to transmit a control packet with respect to its current residual energy. The values of $U_i(\rho_i)$, $MBR_i(\rho_i, \rho_{-i})$ and E_{TX_i} are calculated as follows:

$$U_i(\rho_i) = \log\ \rho_i + 1 \quad (2)$$

$$\begin{aligned} \text{MBR}_i(\rho_i, \rho_{-i}) &= \frac{\text{Busy minimal cell}}{\text{Busy minimal cell} + \text{Idle minimal cell}} \\ &= \frac{\sum_{t=0}^{W} 1 - (1 - \rho_i)^n}{\sum_{t=0}^{W} 1 - (1 - \rho_i)^n + (1 - \rho_i)^n} \\ &= 1 - (1 - \rho_i)^n \end{aligned} \quad (3)$$

$$E_{TX_i} = (\rho_i \times E_{tx})/RE_i. \quad (4)$$

The logarithmic *utility function* is used [in (2)] because it has strict concave property and its second derivative is always negative. The value of *MBR* is calculated using the packet transmission probabilities of the joined nodes and number of occurred minimal cells W in an interval as shown in (3). A player considers a minimal cell busy if it receives any control packet transmitted by other joined nodes or the player transmits itself; otherwise, the minimal cell is considered as idle. Similarly, in (4), E_{tx} is the required energy to transmit a packet and RE_i is the residual energy of player J_i. The overall pay-off function of player J_i can be derived from (1) as follows:

$$\psi_i(\rho_i, \rho_{-i}) = \alpha_i(\log\ \rho_i + 1) - \frac{\beta_i}{(1 - \rho_i)^n} - \frac{\gamma_i \rho_i E_{tx}}{RE_i} \quad (5)$$

where α_i, β_i, and γ_i are the preference parameters for player J_i with positive values for the *utility function* and *price functions*, respectively.

C. Solution of the Game to Find ρ_i^*

The procedure for calculating the optimal solution (ρ_i^*) for the proposed game $G = \{JN, (\rho_i)_{J_i \in JN}, (\psi_i)_{J_i \in JN}\}$ is described in this section. First, it is important to check the existence of the Nash equilibrium point in the proposed game G because G can have a solution only when there exists a Nash equilibrium point. Further, the solution of the proposed game should be unique and it is possible when there exists only one unique Nash equilibrium point. This two conditions are mentioned in Lemmas 1 and 2 with their corresponding proofs.

Lemma 1: The proposed pay-off function $\psi_i(\rho_i, \rho_{-i})$; $\forall J_i \in JN$ is strictly concave in its strategy space $S_i \quad \forall J_i \in JN$ and the game G has at least one Nash equilibrium point.

Proof: The Nash equilibrium of the proposed game G exists when a player cannot improve its pay-off function by changing its strategy while the other players do not change their strategies. To prove that the pay-off function $\psi_i(\rho_i, \rho_{-i}) \quad \forall J_i \in JN$, is a concave function, the Hessian matrix H of ψ_i can be defined as follows:

$$H = [H_{rs}]_{r \times s} \quad (6)$$

where $H_{rs} = (\delta^2 \psi_r / \delta\rho_r \delta\rho_s) \quad \forall H_{rs} \in JN$. Now, using (5), we can calculate H_{rs} as follows:

$$H_{rs} = \begin{cases} -\frac{\alpha_r}{(\rho_r+1)^2} < 0, & \text{if } r = s \quad \forall H_{rs} \in JN \\ 0, & \text{if } r \neq s \quad \forall H_{rs} \in JN. \end{cases} \quad (7)$$

From (7), it can be seen that the leading principal minor of H is negative definite for all $\rho_i \quad \forall J_i \in JN$. Thus, from the work in [21], we can say that the function $\psi_i(\rho_i, \rho_{-i}) \quad \forall J_i \in JN$ is a strictly concave function. It can be further concluded that the proposed game G has at least one Nash equilibrium point. ■

Lemma 2: The solution of the proposed game G is unique as it has a unique Nash equilibrium point.

Proof: To prove the existence of a unique solution in game G, the weighted nonnegative sum $\delta(\rho_i, \rho_{-i}; m)$ of ψ_i must be diagonally strictly concave. For that, using (5), we can write $\forall J_i \in JN$

$$\frac{\delta\psi_i}{\delta\rho_i} = \triangledown\psi_i = \frac{\alpha_i}{\rho_i + 1} - \frac{n\beta_i}{(1 - \rho_i)^{n+1}} - \frac{\gamma_i E_{tx}}{RE_i}. \quad (8)$$

Based on Rosen's Theorem [22], the weighted nonnegative sum of the proposed pay-off function can be calculated as follows:

$$\delta(\rho_i, \rho_{-i}; m) = \sum_{i=1}^{n} m_i \psi_i(\rho_i, \rho_{-i}), m_i \geq 0. \quad (9)$$

The pseudogradient of $\delta(\rho_i, \rho_{-i}; m)$ can be written as

$$g(\rho_i, \rho_{-i}; m) = [m_i \triangledown \psi_i]_{n \times 1}. \quad (10)$$

Similarly, the Jacobian matrix $M(\rho_i, \rho_{-i}; m)$ of $g(\rho_i, \rho_{-i}; m)$ can be written as follows:

$$M(\rho_i, \rho_{-i}; m) = [m_i H_{is}]_{n \times n};\ \ M_{is} \in JN;\ \ m_i > 0 \quad (11)$$

where $m_i H_{is}$ is calculated as follows:

$$m_i H_{is} = \begin{cases} -\frac{\alpha_i m_i}{(\rho_i+1)^2} < 0, & \text{if } i = s; \forall H_{is} \in JN \\ 0, & \text{if } i \neq s; \forall H_{is} \in JN. \end{cases} \quad (12)$$

From (11) and (12), it can be written that $[M(\rho_i, \rho_{-i}; m) + M^T(\rho_i, \rho_{-i}; m)]$ is again negative definite in the entire strategy space. Hence, Rosen's theorem [22] confirms that the function $\delta(\rho_i, \rho_{-i}; m)$ is diagonally strictly concave, and so the proposed game G has a unique Nash equilibrium point and it has a unique solution. ■

It is already proven that the game G has a unique Nash equilibrium point and a solution. Each player choose a strategy to maximizing its control packet transmission probability (ρ_i) per slotframe, i.e., its pay-off function. Therefore, the following *constrained nonlinear optimization* problem is constructed to solve the proposed game G:

$$\begin{aligned} &\underset{\rho_i \in S_i}{\text{maximize}} \quad \psi_i(\rho_i, \rho_{-i}) \\ &\text{subjectto } 0 \leq \rho_i \leq \rho_i^{\max}; \forall J_i \in JN. \end{aligned} \quad (13)$$

To solve this optimization problem, the *Lagrange function* $L_i(\rho_i, a_i, b_i)$ is used for player J_i $\forall J_i \in JN$, as follows:

$$L_i(\rho_i, a_i, b_i) = \psi_i(\rho_i, \rho_{-i}) + a_i \rho_i + b_i\left(\rho_i^{\max} - \rho_i\right) \quad (14)$$

where a_i and b_i are the Lagrange multipliers. The Karush–Kuhn–Tucker (KKT) conditions for player J_i are as follows:

$$\begin{aligned} &a_i, b_i \geq 0 \\ &\rho_i \geq 0 \\ &\rho_i^{\max} - \rho_i \geq 0 \\ &\nabla_{\rho_i} \psi_i(\rho_i, \rho_{-i}) + a_i \nabla_{\rho_i}(\rho_i) + b_i \nabla_{\rho_i}\left(\rho_i^{\max} - \rho_i\right) = 0 \\ &a_i \rho_i, b_i\left(\rho_i^{\max} - \rho_i\right) = 0. \end{aligned}$$

Using these conditions, the optimal control packet transmission probability (ρ_i^*) of player J_i can be calculated as follows:

$$\rho_i^* = \begin{cases} 0; & \text{if condtion 1} \\ \rho_i^{\max}; & \text{if condtion 2} \\ \frac{\alpha_i}{\frac{n\beta_i}{\chi_i} + \frac{\gamma_i E_{tx}}{RE_i}} - 1; & \text{otherwise} \end{cases} \quad (15)$$

where condition 1 is

$$\frac{n\beta_i}{\alpha_i - \frac{\gamma_i E_{tx}}{RE_i}} \geq \chi_i \quad (16)$$

where the term $\chi_i = (1-\rho_i)^{n+1}$ denotes the *minimal cell idle ratio* observed by the player J_i; $\forall J_i \in JN$ and condition 1 is obtained considering $a_i = 0$ and $b_i = 0$ and $(0 < \rho_i < 1)$. Similarly, condition 2 is

$$\frac{n\beta_i}{\frac{\alpha_i}{\rho_i^{\max}+1} - \frac{\gamma_i E_{tx}}{RE_i}} \leq \chi_i. \quad (17)$$

Condition 2 is obtained considering $\rho_i = \rho_i{}^{\max}$ and $a_i = 0$. The "*otherwise*" condition denotes all the conditions which do not satisfy conditions 1 and 2 and is obtained considering the Lagrange multiplier constants equals 0, i.e., $a_i = 0$ and $b_i = 0$.

Proposition 1: The value of ρ_i^* lies between 0 and 1 in the "*otherwise*" condition of (15) always.

Proof: The value of $\rho_i^{\max} = 1$, because it denotes the maximum control packet transmission probability in the minimal cell of player J_i. Now, let us assume the value of ρ_i^* in the "*otherwise*" condition as follows:

$$\begin{aligned} \rho_i^* &\geq 1 \\ &\Rightarrow \frac{\alpha_i}{\frac{n\beta_i}{\chi_i} + \frac{\gamma_i E_{tx}}{RE_i}} - 1 \geq 1 \\ &\Rightarrow \alpha_i \geq 2 \times \left(\frac{n\beta_i}{\chi_i} + \frac{\gamma_i E_{tx}}{RE_i}\right) \\ &\Rightarrow \chi_i \geq \frac{n\beta_i}{\frac{\alpha_i}{\rho_i^{\max}+1} - \frac{\gamma_i E_{tx}}{RE_i}}. \end{aligned}$$

But, after simplification, it can be seen that the value of ρ_i^* in "*otherwise*" condition is contradicting with the condition 2 of (15). Therefore, ρ_i^* in the "*otherwise*" condition cannot be more than one. Similarly, ρ_i^* in the "*otherwise*" condition is not less than 0 and it can be proved assuming $\rho_i^* \leq 0$, which contradicts condition 1. ■

IV. Game Theory-Based Congestion Control

In this section, the solution of the proposed game G [i.e., (15)] is used to propose a novel GTCC. As all the nodes keep active their radios in the minimal cell either for transmission or reception, a joined node can calculate the *minimal cell busy ratio* (*MBR*) for a time interval by itself. It can be done by dividing the total number of minimal cells in which the joined node has received control packets or the node transmits itself by the total number of minimal cells present in the interval. It does not require any implicit signal to/from other neighbors. Now, by subtracting this *MBR* value from 1, it gives the minimal cell idle ratio, i.e., χ_i, which is used in (15). Now, using the value of χ_i and (15), the joined node calculates its optimal control packet transmission probability (ρ_i^*) in a minimal cell.

As ρ_i^* is the control packet transmission probability in a minimal cell, therefore, the value of ρ_i^* is converted into the number of minimal cells (referring as, *slotframe window*) SW_i as follows:

$$SW_i = \begin{cases} SW_{\max}; & \text{if } \rho_i^* = 0 \\ \min\left(\left\lceil \frac{1}{\rho_i^*} \right\rceil, SW_{\max}\right); & \text{otherwise} \end{cases} \quad (18)$$

where SW_i denotes the number of slotframes that node J_i has to wait to transmit its next control packet and $SW_{\max}$ denotes the maximum slotframe window (SW) length for all the nodes. Therefore, a node cannot transmit its control packets in every consecutive minimal cell when there is high congestion, which ultimately reduces congestion. Even though GTCC does not modify the control packets generation rate of the joined nodes, it restrains their transmissions by forcing them to wait for their respective SW periods, which results in less congestion in the minimal cell. Note that GTCC is run by the joined node(s) only to reduce congestion in the minimal cell. Algorithm 1 describes the steps of the proposed GTCC.

V. Parameters Selection and Analytical Results

The analytical model described in [9, Sec. 4.1] is used to evaluate how the used preference parameters (i.e., α, β, γ) of

Algorithm 1 GTCC Scheme

Set χ_i calculation interval I
if I ends **then**
  Calculate the value of $\chi_i = (1-\rho_i)^{n+1}$
  Calculate the value of ρ_i^* using Equation (15)
  Calculate the value of SW_i using Equation (18)
  Wait SW_i amount of time
  if SW_i number of slotframe ends **then**
    Attempt to transmit next buffered control packet
  end if
  Wait I amount of time
end if

the proposed game G affect the joining time and energy consumption of nodes in 6TiSCH networks. The same Markov Chain-based analytical model is used to compare GTCC with the existing state-of-the-art schemes 6TiSCH-MC [5], and C2DBI [9]. For evaluation, the slotframe length (L) is taken as 101 *timeslots*, with each *timeslot* duration of 10 ms. The minimum value of SW is taken same as minimum EB generation interval, i.e., $4 \times$ *slotframe length*, and the maximum value of SW is taken as $10 \times$ *slotframe length*. The values of other variables are as follows: number of channels $N_c = 16$, packet loss probability $P_{\text{loss}} = 0.2$, number of Trickle states $N_D = 8$.

At the beginning, a single-hop network topology with 20 nodes is considered, where all the nodes are neighbor to each other. The results are obtained by varying any of the preference parameters while keeping other two parameters constant. Observed results are tabulated in Table I. When the *price function* for the minimal cell congestion, i.e., β is less, all the nodes transmit their control packets more frequently. Hence, it congests the minimal cell, and so the joining time of the pledges increases. On the other hand, when the value of β is equal to 1, nodes do not transmit their control packets frequently because of the high price. Though, it reduces congestion but increases the waiting time of the pledges to get the control packets, which again results in longer network formation. On the other hand, when the value of α is 1, again the nodes transmit less frequently, and results in longer formation time. However, when $\alpha = 10$, nodes transmit their control packets more frequently. This results in higher congestion in the minimal cell, and so the joining time of nodes increases. Note that the varied values of γ with the constant values of α and β have a similar effect like β on the formation time of network. The best values of α, β, and γ are taken as 5.0, 0.5, and 0.1, respectively, to analytically compare GTCC with 6TiSCH-MC [5] and C2DBI [9]. Fig. 1(a) shows the 6TiSCH formation time, and Fig. 1(b) and (c) shows the EB and DIO reception probabilities per slotframe of a pledge. In all the three schemes, the EB and DIO reception probabilities of the pledges are very less in small networks as only few nodes transmit them. This results in longer formation of the networks. However, by increasing the number of nodes (up to seven nodes), the joined nodes transmit a sufficient number of control packets without congesting the minimal cell, and so helps in faster formation. But, further increment of the nodes congests the

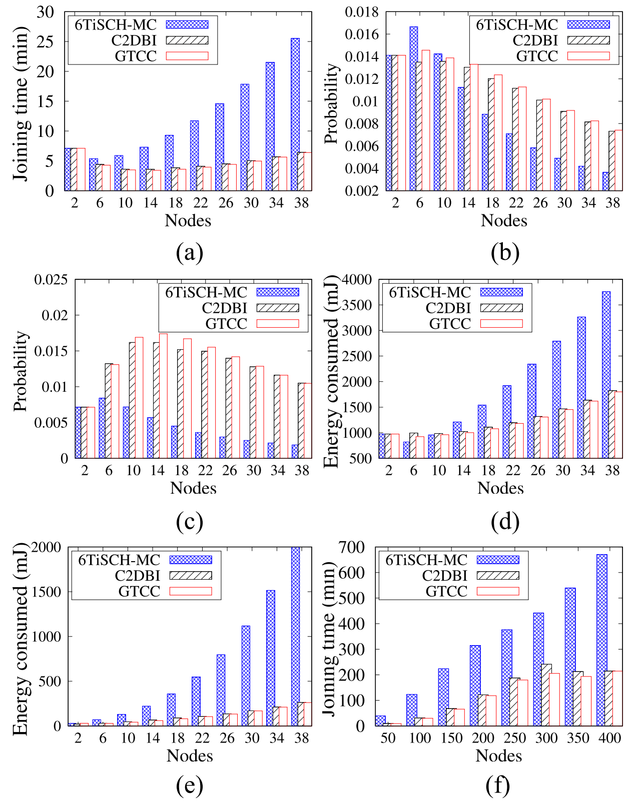

Fig. 1. Analytical results on 6TiSCH joining time, EB, and DIO reception probabilities and energy consumption of a pledge. (a) 6TiSCH formation time. (b) EB reception probability. (c) DIO reception probability. (d) Pledge energy consumption. (e) Joined node energy usage. (f) Scalability experiment.

minimal cell (the worst in 6TiSCH-MC), which again results in low EB and DIO reception probabilities of the pledges, and so delays the formation of the networks. Both the C2DBI and GTCC reduced the congestion in the minimal cell by limiting the control packet transmission, and so achieve better results than 6TiSCH-MC. Although, GTCC improves the joining time compared to C2DBI, it is not significant. This is because the complete behavior of the DIO packet generation Trickle algorithm is not considered in the analytical model of [9], and so the congestion due to DIO transmission is not so significant. Therefore, using the analytical model, GTCC only controls the EB transmission probability like C2DBI but does not control the DIO transmission probability. Hence, both C2DBI and GTCC show almost similar results.

As longer joining time of the pledges also increases the energy consumption of the nodes; therefore, from Fig. 1(d) and (e), it can be seen that the proposed scheme GTCC reduces the energy consumption of both the joined nodes and the pledges compared to that in the existing benchmark schemes. Furthermore, Fig. 1(f) shows the 6TiSCH formation time of few bigger networks to prove the scalability of GTCC, where GTCC outperforms the existing schemes.

VI. Performance Evaluation

A. Experimental Setup

The proposed GTCC is implemented on Contiki-NG OS [23]. Two benchmark schemes, i.e., 6TiSCH-MC [5]

TABLE I
JOINING TIME UNDER VARIED PREFERENCE PARAMETERS

Constant	$\alpha = 5, \gamma = 0.1$				$\beta = 0.5, \gamma = 0.1$		
Varied	β				α		
	0.05	0.1	0.5	1	1	5	10
Joining time (min)	3.91	3.77	3.75	3.86	3.78	3.758	3.82

TABLE II
EXPERIMENTAL SETTINGS

Parameter	Value
Operating System	Contiki-NG
Network Topologies	5×5 and 2×12
Testbed	FIT IoT-LAB, Grenoble
Testbed `mote` type	M3
Number of channels	16
Timeslot and Slotframe length	10 ms, 101
RPL version, DIO interval	RPL Lite, Trickle
RPL Objective Function	MRHOF-ETX
Experiment duration	60 minutes

and C2DBI [9] are considered for showing comparative performance study. The values of different parameters of all the schemes are taken same as the values mentioned in Section V. The open and real FIT IoT-LAB [24] is used for running testbed experiments. The various testbed experimental settings are mentioned in Table II, and two different topologies are used for the testbed experiments. The first topology is a 5×5 grid topology and the other one is a 2×12 linear topology.

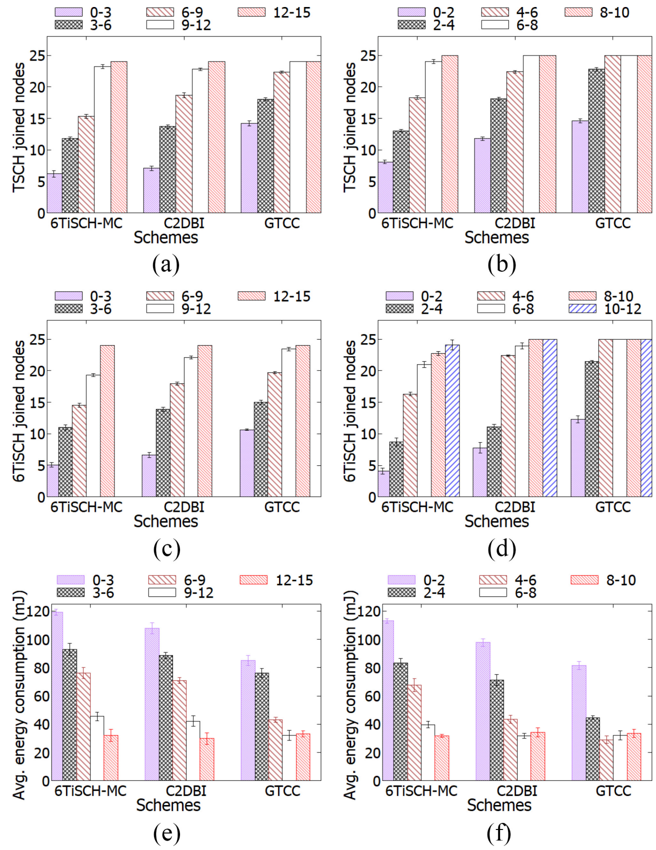

Fig. 2. Testbed results on joining time and energy consumption. Each bar in (a) and (b) shows the number of TSCH synchronized nodes, in 2(c) and (d) number of 6TiSCH joined nodes, and in (e) and (f) average energy consumption under various time intervals (e.g., 0–2, 2–4, 4–6). The measuring units of time intervals are minutes.

B. Performance Metrics

We consider three metrics for the evaluation of the proposed scheme. The first metric is *TSCH synchronization time*. It is the time when a pledge receives its first valid EB frame. It is already mentioned in Section III-A that, before receiving an EB, a pledge needs to keep its radio active all the time, which consume significant amount of energy. A pledge knows the location of the minimal cell after receiving a valid EB. So, it keeps radio active only in the minimal cell to save energy. So, the TSCH synchronization time is an important metric to consider during network formation.

6TiSCH joining time is considered as second metric, which denotes the time when the TSCH synchronized node receives the DIO packet from its parent. Note that the 6TiSCH joining time is the same time for the node to join the DODAG. A node is allowed to transmit its control packet for further expansion of the network after joining the 6TiSCH network. Hence, this 6TiSCH or DODAG joining time of the nodes is important to consider during the network formation.

As it is already mentioned that a pledge consumes more energy before it gets synchronized with the TSCH network, therefore, *energy consumption* is taken into consideration as the third metric. Although the radio duty cycle (RDC) of a node reduces from 100% to 1% after getting an EB frame, its child node(s) still have the RDC of 100%. It is because neither the node has started transmitting its control packets nor the children receive EB frame. Therefore, quick and sufficient transmission of both these EB and DIO packet is necessary to increase the lifetime of a network.

C. Results and Discussion

The received results from the testbed experiments are shown using a 95% confidence interval. Fig. 2(a) and (b) shows the number of TSCH synchronized nodes in different time intervals, such as 0–2, 2–4, 0–3, 3–6 min, etc., for both the 2×12 linear and 5×5 grid topologies, respectively. Similarly, Fig. 2(c) and (d) shows the number of 6TiSCH joined nodes in different time intervals. It can be seen from the results that GTCC outperforms both 6TiSCH-MC and C2DBI in terms of number of joined TSCH synchronized nodes and 6TiSCH joined nodes in different time intervals. It is because GTCC is used to maintain balance between the congestion in the minimal cell and sufficient transmission of the EB and DIO packet in the networks during their formation. Although C2DBI reduces the congestion in the minimal cell by dynamically changing the EB generation rate, that is not sufficient to fully reduce the congestion in minimal cell. It is because C2DBI does not control the DIO transmission rate, which is necessary. When a node transmits the DIS request for a DIO packet, nearby joined node(s) reset their Trickle algorithm, which turns out burst transmission of DIOs and congests the minimal cell. Therefore, to deal with this kind of scenarios, GTCC restrains the transmission of joined nodes by forcing them to wait for their respective SW periods so that congestion gets reduced. Hence, it significantly achieves better performance compared to C2DBI. 6TiSCH-MC suffers the most because it does not provide any mechanism to deal with the congestion in minimal cell.

The average energy consumption by a pledge in different time intervals is shown in Fig. 2(e) and (f) for the 2×12 and 5×5 topologies, respectively. At the beginning of the formation process, all the schemes consume more energy. It is because, initially, most of the nodes do not get synchronized with the TSCH networks. They randomly scan on different channels by keeping their radios active for EBs, which causes more energy consumption. Therefore, in 6TiSCH-MC, average energy consumption of the nodes is more because only few nodes immediately get synchronized with the TSCH networks due to congestion in the minimal cell. On the other hand, in GTCC, nodes do not need to wait for longer time to receive their first EBs because of the less congestion in the minimal cell, which significantly saves nodes' energy. All the three schemes consume almost same energy when their formation process is over as nodes keep their radios active only in the minimal cell.

VII. Conclusion

This work proposed a game-theoretic approach to reduce congestion in the minimal cell so that the performance of the 6TiSCH network can be improved during its formation. For this, we design a noncooperative game, where a joined node acts as player who wants to maximize its profit irrespective of the strategies of other neighboring nodes. In the pay-off function, control packet transmission probability is considered as a *utility function*, and the minimal cell busy ratio and energy of a node are considered as *price functions*. The obtained solution of the proposed game using the Lagrange multiplier and KKT conditions is further used in a newly proposed GTCC. GTCC calculates the SW size of the nodes to restrain them in transmitting control packets frequently so that congestion in the minimal cell can be reduced without any signaling overhead. An existing analytical model given in [9, Sec. 4.1] is used to find out the best combination of preference parameters used in the proposed game. We used the same analytical model to compare the proposed GTCC with the benchmark schemes, such as 6TiSCH-MC [5] and C2DBI [9]. Furthermore, the GTCC is implemented on Contiki-NG and evaluated using the FIT IoT-LAB testbed. The received results from both the analytical analysis and the testbed experiments showed that GTCC significantly improves the joining time and energy consumption of the pledges compared to the benchmark schemes.

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