Parrondo's Paradox-Based Enhanced Beacon Transmission in 6TiSCH Networks

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***Abstract*—The standardized 6TiSCH network offers high throughput, reliable, delay-bounded, and energy-efficient communication in Internet of Things networks. For 6TiSCH bootstrapping, 6TiSCH minimal configuration standard has been released, which uses a fixed transmission rate of Enhanced Beacon (EB) control frame throughout the network's lifetime. However, our theoretical analysis shows both high and low EB rates affect new joining nodes' synchronization time and energy consumption. To address this, we propose *Parrondo's Paradox-based EB Transmission* (PPET) scheme, which allows already joined nodes to transmit their EB frames probabilistically. Both theoretical and experimental results show the performance improvement by PPET compared to benchmark schemes.**

***Index Terms*—IoT, 6TiSCH, Parrondo's paradox, TSCH synchronization.**

I. Introduction

The IPV6 over IEEE 802.15.4e Time Slotted Channel Hopping (6TiSCH) is a wireless network protocol standard designed specifically for Internet of Things (IoT) to provides delay-bounded, energy-efficient, and reliable communication. Basically, 6TiSCH network is built on the top of TSCH mode of IEEE 802.15.4e to use IPv6 enabling end-to-end communication in IoT [1]. To provide minimal bandwidth to transmit control packets during the formation of 6TiSCH networks, IETF released *6TiSCH Minimal Configuration* (6TiSCH-MC) standard [2]. This standard allows the nodes to use only one *cell*, known as *shared* or *minimal* cell per slotframe for the transmission of all types of control packets. Note that combination of a timeslot and a physical channel is called cell, where time is divided into fixed duration *timeslots*, and the collection of fixed number timeslots is called *slotframe*, which repeats one after another. The *new nodes* (aka *pledges*) require different control packets such as *Enhanced Beacons* (EB), *DODAG (Destination Oriented Directed Acyclic Graph) Information Object* (DIO) to join 6TiSCH networks and become joined-node. Note that only 6TiSCH nodes can transmit control packets and pledges need to randomly scan all the physical channels one after another by keeping their radios active. A pledge gets synchronized with the network only after receiving a valid EB and after that, the pledge activates its radio only in shared cell to save energy. Hence, the synchronization time of the nodes is significant from the perspective of energy consumption of the nodes as well as reliability/criticality of the IoT networks. Nodes can transmit their sensory data only after joining networks, therefore, in mission critical IoT applications such as disaster management, Industrial IoT, and smart heath-care system, the initial (also re-joining) synchronization time would be significant. Furthermore, in a mobile IoT network, nodes may need to re-join in different networks several times.

Even though the work [3] reduces the synchronization time of the pledges by dynamically increasing the number of shared cells per slotframe, it increases the energy consumption of the nodes and also hampers the data transmission cells. The work in [4] varied the EB generation interval of the joined-nodes depending on the intensity of contention in the shared cell. However, this scheme may suffer from the herding problem where all the joined-nodes use either high or low beacon generation intervals at a time. Furthermore, during certain network conditions, the nodes transmit several DIO packets within short intervals, which increases the EB generation interval of the nodes leading to high synchronization time of the pledges. On the other hand, the work in [5] fixed the EB transmission probability per slotframe to 0.1, which is not suitable for sparse networks. The problems of EB highest priority and insufficient transmission of routing problems to reduce the formation time of 6TiSCH networks were studied in [6]. The work in [7] tried to reduce data packet transmission collision. However, it neither considered 6TiSCH network nor transmission of control packet in shared cell. So, none of the existing works can efficiently handle the transmission rate of EB frame in 6TiSCH networks, and so the initial pledges' synchronization time and energy consumption.

The mathematical ***Parrondo's Paradox*** model [8] states that two (or maybe more) *losing strategies* can be combined in a certain manner to get a *winning outcome*. This model is used in different domains such as thermodynamics, quantum theory, biology, and medicine [9]. In our theoretical analysis of 6TiSCH-MC standard, we observe that both low and high transmission rates of EB frames in 6TiSCH networks impact on pledges' initial synchronization time and energy consumption. In brief, both low and high transmission rates of EB frames turn out to be losing games. However, we theoretically find that by allowing some nodes to transmit EB frame at a high rate and some nodes at a low rate can improve the pledges' initial synchronization time and energy consumption. We propose a scheme called *Parrondo's Paradox based EB Transmission* (PPET), which probabilistically allows the nodes to transmit EB frame either at a high rate or low rate. Later, we

Manuscript received 19 February 2023; revised 10 April 2023; accepted 4 May 2023. Date of publication 9 May 2023; date of current version 2 January 2024. This work was supported by the National University of Singapore under MoE AcRF Tier-2 Grant through NUS WBS No. A00094520100 under Grant MoE T2EP50120-0021. The associate editor coordinating the review of this article and approving it for publication was R. Nejabati. *(Corresponding author: Alakesh Kalita.)*

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Digital Object Identifier 10.1109/LNET.2023.3274308

validate PPET using testbed experiments. In brief, the major contributions of this letter are as follows,

- We perform theoretical analysis of 6TiSCH-MC to show how both low and high EB transmission rates impact pledges' synchronization time and energy consumption.
- We propose PPET scheme to overcome the problem of fixed EB rate of 6TiSCH-MC.
- Along with the theoretical analysis, we also perform testbed experiments on FIT IoT-LAB [10] to validate the effectiveness of PPET.

The rest of this letter is organized as follows. Section II briefly describes Parrondo's Paradox model and Section III discusses the theoretical analysis of 6TiSCH-MC. In Sections IV and V, we describe our proposed approach, and theoretical and testbed experimental evaluation of the proposed scheme, respectively. Finally, Section VI concludes this letter.

II. Background

Parrondo's Paradox is a paradox in game theory that says "*there exist pairs of games, each with a higher probability of losing than winning, for which it is possible to construct a winning strategy by playing the games alternately*" [11], [12]. Parrondo's Paradox can be easily understood using the below coin-tossing example with two games where capital C_t is changed depending on the outcome of the game played at time *t*, *i.e.,* for winning $C_{t+1} = C_t + 1$ and for losing $C_{t+1} = C_t - 1$ [12]. The games are as follows,

- *Game A:* A bias-coin is used with winning probability $P_1 = \frac{1}{2} - \epsilon$, where $\epsilon > 0$. So, this game is a losing game.
- *Game B:* If the current capital C_t is a multiple of *M*, another bias-coin is used with winning probability $P_2 = \frac{1}{10} - \epsilon$, otherwise another bias-coin is used with winning probability $P_3 = \frac{3}{4} - \epsilon$. For any integer value such as $M = 3$ and $\epsilon = 0.003$, it can be seen that Game B also turns out to be a losing game if we model the game as a Markov Chain.

If we play these two losing games alternatively, (*e.g.,* $AABBAABB\ldots$ or $ABBABB\ldots$), paradoxically, gives a winning game. This coin-tossing example is a popular illustration of Parrondo's Paradox.

Recently, Parrondo's Paradox model is studied to restrict Covid-19 spreading and lower its impact on countries' economies in [9]. Using a Parrondo's paradox model, authors have shown that the alternation of imposing lockdown strategy and the strategy of keeping the community open in a specific way leads to a winning outcome. Apart from that, different researchers used Parrondo's Paradox in different application domains such as social dynamics, life science, ecology, evolutionary biology, and other interdisciplinary work.

III. Performance Evaluation of 6TiSCH-MC

A. System Model

We consider a single-hop 6TiSCH network with *n* joined-nodes, including the *JRC* (Join Registrar/Coordinator). All the joined-nodes are neighbor to each other and a pledge wants to join the network. We consider a dense network scenario so that we can study the performance of 6TiSCH-MC in highly congested network such as Cisco's CG-Mesh deployment. As mentioned before, in 6TiSCH networks, all the joined-nodes transmit their various control packets in a single shared cell per slotframe following the resource allocation made by 6TiSCH-MC standard. Let us assume joined-node *i* transmits its EB frame in each slotframe with the probability P^i_{eb} and other control frames/packets (such as DIO, keep-alive etc.) together with probability P^i_o. Now, the probability of successfully receiving an EB frame by the pledge, P^s_{eb} can be calculated as follows,

$$P^s_{eb} = \frac{1}{N_c} n P^i_{eb} \prod_{j=1, j\neq i}^{n-1} \{(1 - P^j_{eb})(1 - P^j_o)\}(1 - P_l). \quad (1)$$

where, N_c is total number of used channels in the network and P_l denotes the *channel loss* probability. The above equation can be described as follows: node *i* can successfully transmit its EB frame only when none of other joined-nodes does not transmit either EB frames or other control packets. As there are *n* joined-nodes in the network, so total probability is multiplied by *n* times, corresponding to each joined-node. On the other hand, as there are total N_c channels, and the pledge does not know in which channel control packets are being transmitted by the joined-nodes, so the total probability is divided by N_c. Finally, the time taken by the pledge to get synchronized with the network, T_s can be calculated as follows,

$$T_s = \frac{1}{P^s_{eb}}. \quad (2)$$

As the pledges keep their radios active all the time before getting synchronized the with network, i.e., before receiving valid EB frame, therefore, we can measure the charge consumption of the pledges, *C* (in `coulomb`) before their network synchronization as follows,

$$C = CC \times (T_s \times (SF_{size} \times TS)). \quad (3)$$

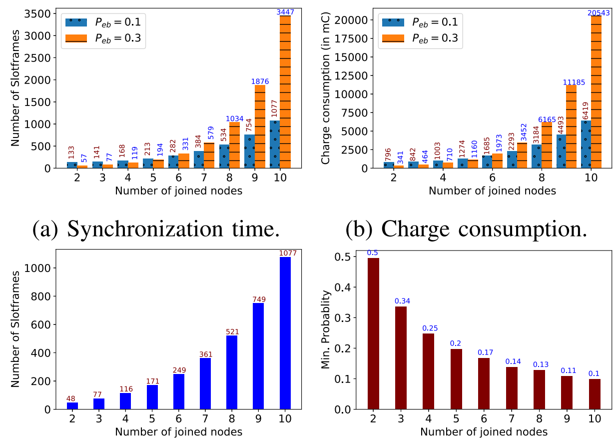
where *CC* denotes the *current consumption* in `ampere`, SF_{size} denotes the *slotframe* (SF) size in `timeslot`, and *TS* denotes the *timeslot* duration in `second`.

B. Theoretical Analysis

For theoretical analysis, we consider the values of different network parameters as follows: $P_{eb} = 0.1$ and 0.3, $P_o = 0.3$, $N_c = 16$, $P_l = .05$, and varied *n* from 2 to 10. As 6TiSCH-MC mentioned fixed (or static) EB rate for all the joined-nodes, therefore, we also consider fixed EB rate for all the nodes, i.e., $P^i_{eb} = P^j_{eb}$ and $P^i_o = P^j_o$; $\forall j$ in our analysis. We implement the above system model in Python language and open the code.[1] In Fig. 1, we provide the theoretical results obtained using the above network parameter values.

In Fig. 1(a), we provide the synchronization time of the pledge using low (i.e., $P_{eb} = 0.1$) and high ($P_{eb} = 0.3$) EB transmission probability per slotframe. It can be seen from the obtained results that low EB transmission probability helps when there are more number of joined-nodes in the network. Otherwise, when there are less number joined-nodes, low EB transmission probability increases the synchronization time of

[1] https://github.com/Alakesh1025/PPET



(a) Synchronization time. (b) Charge consumption.

(c) Minimum possible sync. time. (d) P_{eb} for minimum sync. time.

Fig. 1. Theoretical results.

the pledge significantly (i.e., $2\times$) compared to high EB frame transmission. It is because, the probability of receiving an EB frame by the pledge decreases and so the pledge needs to wait for more time to get an EB frame. On the other hand, high EB frame transmission probability significantly increases the synchronization time (i.e., $3\times$) of the pledge because of high contention in shared cell due to more joined-nodes in the network. We run our model by varying the EB transmission probabilities from 0.1 to 0.9 in step of $+0.05$ to determine the minimum number of required slotframe by the pledge to get synchronized with different network sizes. In Figs. 1(c) and 1(d), we provide the minimum number of required slotframes and the respective EB transmission probabilities to get minimum number of slotframes, respectively. These results signify that different network sizes require different EB transmission probabilities in order to reduce the synchronization of the pledges.

To calculate the energy consumption of the pledge in terms of charge, we consider the `TI CC2650` device which consumes, *CC* $= 5.9$ *mA* in active `Rx` state. We consider *SF* $= 101$ *timeslots* and *TS* $= 10$ *ms*. In Fig. 1(b), we show the charge consumption of the pledge when the joined-nodes transmitted their EB frames in a slotframe with 0.1 and 0.3 probability values. It can be seen that the charge consumption of the pledge increases with its synchronization time. This is because the pledge needs to keep its radio active all the time for scanning on all the physical channels to get an EB frame.

Therefore, from these results, it can be seen that it is necessary for different networks to use different EB transmission rates in order to reduce synchronization time and energy consumption of the pledges. In brief, neither low nor high EB transmission probabilities are suitable for all types of 6TiSCH networks. So, both low and high transmission probabilities impact on the synchronization time of the pledges as well as their energy consumption, and so are *losing games*.

IV. Proposed Approach

It is observed in Section III-B that both high and low EB transmission probabilities are not good for all types of networks, and so, can be considered as *losing games*. To address this issue, in our proposed approach, we probabilistically allow some of the joined-nodes to use high transmission probability, and other nodes to use low transmission in every slotframe like the Parrondo's Paradox model to improve the performance of the network in terms of pledges' synchronization time and energy consumption, i.e., to get a *winning* outcome. We decide the EB transmission probability of nodes in each slotframe so that some nodes do not consume more energy by transmitting more EB frames, while other nodes preserve their energy by transmitting less EB frames.

Algorithm 1 Parrondo's Paradox Based EB Transmission

1: **INPUT**: Number of neighbors, N_{nbr}
2: **OUTPUT**: EB transmission probability/slotframe, P_{eb}
3: Calculate $\alpha = \frac{1}{N_{nbr}}$
4: β=[0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9]
5: Generate a random decimal number, $D < 1$
6: **if** $D < \beta$ (**or** $D < (1-\alpha)$) **then**
7: $\quad P_{eb} = 0.1$
8: **else**
9: $\quad P_{eb} = 0.3$ (**or** $P_{eb} = \alpha$ for improved result)
10: **end if**

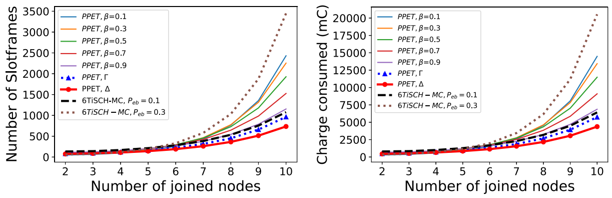
Algorithm 1 describes the steps of our proposed *Parrondo's Paradox based EB Transmission* (PPET) scheme. Note that, as EBs are transmitted by the already joined-nodes, so only the joined-nodes use the PPET scheme for their EB transmission. In **Step: 4**, a joined-node decides the probability, β (which is in between 0.1 to 0.9) to transmit its next EB with the probability either $P_{eb} = 0.1$ or $P_{eb} = 0.3$ (**Steps: 5-9**). For example, if the joined-node chooses $\beta = 0.3$, then there is 30% chance that the joined-node transmits its next EB with probability $P_{eb} = 0.1$ and 70% chance to transmit its next EB frame with probability $P_{eb} = 0.3$. The term α is calculated based on the number of neighbor nodes of a joined-node and its purpose is explained in the next section.

V. Evaluation

A. Theoretical Results

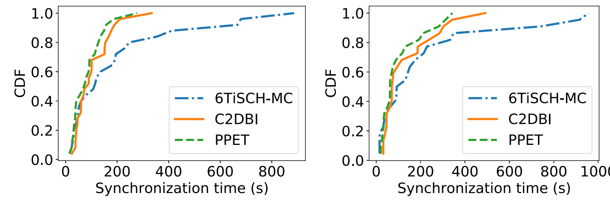
In Fig. 2, we show how the proposed scheme PPET behaves for varied β. We also provide results for 6TiSCH-MC with $P_{eb} = 0.1$ and 0.3 using our system model. Results show that PPET improves the pledges' synchronization time and energy consumption in all cases (i.e., β) compared to the fixed value of $P_{eb} = 0.3$. PPET even slightly improves the performance of the pledge compared to the fixed value of $P_{eb} = 0.1$ when $\beta = 0.95$. So, Parrondo's Paradox exists during the formation of 6TiSCH networks. In brief, theoretically, our proposed scheme PPET improves the performance of the pledge by probabilistically allowing the joined-nodes to transmit EB frames with either high or low transmission probabilities.

We also observe that the performance of the pledges can be further improved by choosing the β value depending on the number of neighbor nodes, N_{nbr} of the joined-nodes, i.e., based on $\alpha = \frac{1}{N_{nbr}}$. For this, we calculate the



(a) Synchronization time. (b) Charge consumption.

Fig. 2. Theoretical results for the proposed scheme, PPET.



(a) Synchronization time. (b) Synchronization time.

Fig. 3. Testbed results for (a) 5 × 5, (b) 12 × 2 Topologies.

value α as in **Step: 3** and applied it on **Step: 6**'s '**or**' statement, i.e., $D < (1 - \alpha)$ in Algorithm 1. The corresponding results to this step are shown in Figs. 2(a) and 2(b) using '$PPET, \Gamma$' notation. Furthermore, if we also set the high and low EB transmission probabilities as per α, i.e., $[min(0.1,\ \alpha),\ max(0.1,\ \alpha)]$ as mentioned in '**or**' statement of **Step: 9**, the results can be further improved as shown in Figs. 2(a) and 2(b) using '$PPET, \Delta$' notation. From the figures we note that, '$PPET, \Delta$' improves the synchronization time and charge consumption by ≈82% and 77%, respectively, compared to 6TiSCH-MC with $P_{eb} = 0.3$, when $n = 10$. So, '$PPET, \Delta$' takes 3900*mC* out of 36000*mC* of a 10*mAh* battery, i.e., (1/10)*th* of total lifetime, whereas 6TiSCH-MC takes (6/10)*th*, *i.e.,* 20000/36000.

B. Testbed Experimental Analysis

We implement the proposed scheme PPET on Contiki-NG OS and flash the created binary files on FIT IoT-LAB's `M3` nodes [10]. For experiments, we consider two multi-hop topologies, i.e., (5 × 5) Grid topology in Lille and 12 × 2 linear topology in Grenoble and slotframe length equals to 101 *timeslots* with each timeslot duration 10*ms*. We consider EB intervals as follows: 4 *slotframes* for 6TiSCH-MC [2], which gives $P_{eb} = 0.25$; $P_{eb}^{min} = 0.25$ and $P_{eb}^{max} = 0.1$ for C2DBI [4]; $P_{eb}^{min} = 0.25$ and $P_{eb}^{max} = 0.1$ for PPET, where P_{eb}^{min} and P_{eb}^{max} denote the minimum and maximum EB transmission probability per slotframe. C2DBI [4] varies the EB generation interval depending on channel busy ratio, *i.e.,* contention level for a period of time to reduce contention in shared cell. So, PPET is computationally simpler than C2DBI. Note that we choose β and EB transmission probability of the nodes based on their neighbor node count, i.e., α for PPET.

From the testbed experimental results shown in Fig. 3, it can be seen that the PPET improves the performance of 6TiSCH networks in terms of pledges' synchronization time compared to the 6TiSCH-MC standard and existing scheme C2DBI. The reason for this improvement is that PPET helps the pledges to get EB frame quickly by allowing some of the joined-nodes to transmit EB frames frequently. On the other hand, by restricting some of the joined-nodes from frequent transmission of EB frames, PPET reduces contention in the shared cell, and so reduces collision. However, due to fixed EB transmission rate in 6TiSCH-MC, collision increases in the shared cell with the increasing number of joined-nodes in the network. Hence, 6TiSCH-MC gives poor performance. Because of the nodes' distance from the root node, we receive different results for both the network topologies for all the schemes. As the charge consumption of the pledges is directly proportional to their network synchronization time [3] and [4], from the testbed results on synchronization times, we can conclude that PPET decreases the pledges' energy consumption.

VI. Conclusion and Future Work

In this letter, we showed that both fixed high and low EB transmission rates impact pledges' synchronization time and energy consumption in 6TiSCH networks. To deal with this problem, we proposed *Parrondo's Paradox based EB Transmission* (PPET) scheme, which probabilistically allows the joined-nodes to transmit EB frames at either high or low rates. Using both theoretical and testbed experiments, we showed that PPET improves the performance of pledges during their network-joining compared to existing benchmark schemes including 6TiSCH-MC.

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