Opportunistic Priority Alternation Scheme for Faster Formation of 6TiSCH Network

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Abstract

The 6TiSCH protocol layer in Industrial Internet of Things (IIoT) fills the gap between the IETF low-power IPv6 communication stack and TSCH. Along with reliability, timed data delivery, and interoperability in IIoT network, 6TiSCH also deals with network bootstrapping. In this paper, the formation method of 6TiSCH network is assessed. It is observed that because of highest priority of beacon frames and unawareness of the requirement of routing information by a new node, performance of 6TiSCH network formation degrades. Therefore, we propose an opportunistic priority alternation scheme for urgent requirement of other control packets to form the 6TiSCH network quickly. We also opportunistically increase the transmission rate of packets carrying routing information. The proposed scheme is implemented on Cooja simulator and compare the simulation results with the benchmark protocol - Minimal Configuration Standard. Simulation results show that the proposed scheme converges faster than the benchmark protocol in network formation.

CCS Concepts

• **Networks → Link-layer protocols**; **Network simulations**; **Network performance analysis**.

Keywords

Industrial IoT; 6TiSCH; Network formation

ACM Reference Format:
Alakesh Kalita and Manas Khatua. 2020. Opportunistic Priority Alternation Scheme for Faster Formation of 6TiSCH Network. In *21st International Conference on Distributed Computing and Networking (ICDCN 2020), January 4–7, 2020, Kolkata, India.* ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3369740.3369779

1 INTRODUCTION

Industrial Internet of Things (IIoT) is expected to deliver promising solutions in present industrial sector for cost-effective and sustainable production. With the deployment of sensors and actuators in industry, IIoT enables interconnection between physical things and high computing devices to offer industrial solutions with higher efficiency, finding counterproductive output, and do predictive maintenance in the current industrial system. Wireless technology is always being demanded as a communication technology for the things in IIoT. However, IIoT demands its communication to be reliable, low power consuming, scalable, and minimum delay communication. Hence, Internet Engineering Task Force (IETF) standardize 6TiSCH technology for IIoT, which provides interoperability between IEEE 802.15.4e Time Slotted Channel Hopping (TSCH) [1] and IPv6 protocols. Along with interoperability, 6TiSCH also deals with network bootstrapping. 6TiSCH Working Group (created by IETF) published 6TiSCH Minimal Configuration (6TiSCH-MC) [11] standard for efficient bootstrapping in 6TiSCH network. 6TiSCH-MC recommends to use only single shared slot in a slotframe or multi-slotframe for transferring all control packets in a 6TiSCH network.

In this paper, we try to address the problem of 6TiSCH-MC in which fixed priority assigned to different control packets and the sending rate of control packets is also predetermined. In 6TiSCH network, the rate of sending network information through Enhance Beacon (EB) frame is determined by the network administrator, and rate of sending the routing information through RPL-DIO packet is determined by the Trickle Algorithm [9]. Hence, the sending rates of above two information are independent. Again in a 6TiSCH network, EB is considered as the highest priority packet among all types of control packets as it advertises a network information and maintains global synchronization in a network. However, we observe that due to EB's highest priority, and incoherency between network and routing information sending intervals, network formation suffers from longer joining time. To deal with these problems, we propose an opportunistic priority alternation scheme (OPAS) for control packets during network formation. It also opportunistically increases the rate of sending routing information packet by resetting the Trickle Algorithm to form the 6TiSCH network more quickly.

State of the art approaches [3–6, 12] considered only EB frame transmission during network formation. However, during the formation of a multihop 6TiSCH network, both the EB frame and DAG Information Object (DIO) packet are necessary. In this work, we consider both the control packets during 6TiSCH network formation. In a recent work, Vallati *et al.* [10] used higher bandwidth for increasing number of network control packets, which approach is not 6TiSCH-MC compliant. In another work [13], authors considered same bandwidth as 6TiSCH-MC and tried to reduce the traffic in shared slot by sending the EB with a transmission probability equals .01 irrespective of the number of nodes present in the network. In brief, none of the existing approaches address the problem of EB's highest priority and effect of Trickle Algorithm for network

ICDCN 2020, January 4–7, 2020, Kolkata, India

ACM ISBN 978-1-4503-7751-5/20/01…$15.00
https://doi.org/10.1145/3369740.3369779

formation. Therefore, in this paper, we try to resolve these two issues.

We summarize the major contributions of this paper as follows,

- Analytically we show the demerits of having EB's highest priority and the effect of Trickle Algorithm during bootstrapping in 6TiSCH network.
- An opportunistic priority alternation scheme (OPAS) is proposed to deal with the demerits of having EB's highest priority.
- OPAS further opportunistically adjust the transmission rate of DIO control packet to deal with the disadvantages of Trickle Algorithm.
- Performance evaluation of the OPAS is performed using IoT network simulator.

The rest of the paper is organized as follows. Section 2 summaries the existing works related to network formation in 6TiSCH network. In section 3, we precisely describe few problems in 6TiSCH network formation and validate the problems using some analytical results. We also describe our proposed methodology in the same section. By presenting the performance evaluation of the proposed method and comparing its results with a benchmark scheme in Section 4, we conclude our paper in Section 5.

2 RELATED WORKS

At the very beginning, researchers considered only EB frame for TSCH network formation. A node is said to be a joined node if it successfully receives an EB frame from an already joined node. Therefore, Vogli *et al.* [12], [4] increased the rate of sending EB frame in a slotframe/multi-slotframe so that a new node gets an EB frame in less time. Guglielmo *et al.* [6] proposed a simple Random-based Advertisement (RA) algorithm for sending EBs. In this method, EB collision is reduced by varying the transmission probability of EB frames. Later, Guglielmo *et al.* [5] mentioned a Model-based Beacon Scheduling (MBS) algorithm. In this method, the PAN coordinator assigns a link to each joined node to transmit its EBs by solving an optimization problem. The authors also mentioned that equal spaced shared slots in a multi-slotframe schedule helps in faster network formation. Khoufi *et al.* [8] mentioned a Deterministic Beacon Advertising (DBA) algorithm for transmitting beacons in fixed advertising slots instead of selecting any slot as an advertising slot for faster formation of TSCH network.

There exist only a few works where both the EB frame and DIO packet are considered for network formation in 6TiSCH network. Vallati *et al.* [10] analytically proved that the 6TiSCH-MC does not provide enough resources to send control packets generated during network bootstrap. Hence, the authors allocate more number of shared slots to transmit more control packets in less time. However, the allocation of extra shared slots costs in higher energy consumption and also hamper in transmission of general data packet. Further, it does not follow the 6TiSCH-MC standard in terms of resource usage. Again the authors did not consider anything about resource usages by the non-deterministic unicast join request (JR) frames. Vucinic *et al.* [13] proposed that the beacon transmission probability should be 0.1 irrespective of the number of nodes present in the network for faster network formation. However, we observe that a new node suffers from longer joining time because of EB's highest priority and Trickle Algorithm. Therefore, we propose an opportunistic priority alternation scheme for control packets and modify the Trickle Algorithm for faster formation of 6TiSCH network.

3 PROBLEM STATEMENT AND PROPOSED SOLUTION

During network formation of 6TiSCH networks, we observe few shortcomings in the existing methods which motivate us to propose a better scheme for faster formation of 6TiSCH network. At first the observations are described and validated by numerical analysis. And then we proposed a solution method for those problem.

3.1 Packet level starvation

As recommended by 6TiSCH standard, EB has the highest priority over all other network control packets such as DIO, keep-alive, etc. In a TSCH shared slot, initially, a sender node participates in contention for accessing the channel. The node sends its packet only if the channel is free. Otherwise, it goes to random backoff period. A node may generate EB frame during its backoff period if EB interval finishes inside the backoff period. Though the node gets a free shared slot for transmitting its control packet in the next coming shared slot, but, due to EB's highest priority, it ends up in sending newly generated EB frame instead of sending other network control packets. As a result, including DIO packet, other network control packets have to wait for more amount of time to get transmitted. This kind of control packet can be called as starving packet. When a new node waits for DIO packet from one of such starving packet containing joined node (i.e., new node's parent) then the new node has to wait for more amount of time to get admission in an existing 6TiSCH network. This results in a long joining time of the new node. Therefore, this issue needs to be solved in order to achieve a faster joining process of 6TiSCH network. Fig. 1 pictorially describes the packet level starvation problem. The figure shows that a DIO packet is replaced by a newly generated EB frame during backoff time of a node.

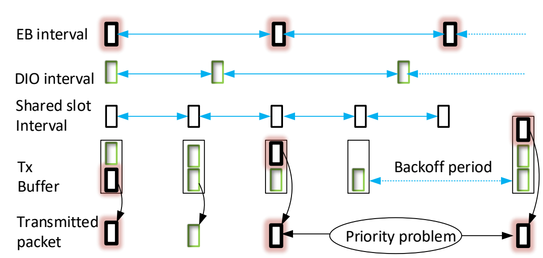


Figure 1: Starving DIO packets due to EB's highest priority

3.2 Effect of Trickle Algorithm

According to 6TiSCH-MC, the EB transmission rate is fixed while the DIO transmission rate varies with network condition. In Trickle Algorithm, DIO sending interval starts with a minimum duration (i.e., I_{min} = 8 ms). In a stable network, until the interval reaches its maximum value I_{max}, the interval duration becomes double at the end of each interval. If any inconsistency occurs, like, the parent of a node changes its rank, the node resets its trickle interval to minimum value I_{min}. During network formation, the parent node is completely unaware of the necessity of DIO packet by its new child node. As there is no change in Trickle Algorithm's interval when a new node sends its JR frame, so in a worst case, a new node needs to wait for at least maximum trickle interval value I_{max} to get DIO packet from its parent. Moreover, after generating a DIO packet, a joined node might encounter packet level starvation as explained in section 3.1. Hence, this will lead to higher joining time of a new node who is waiting for DIO packet from its parent node. Fig. 2 describes the effect of Trickle Algorithm. Here, a new node needs to wait for the completion of a trickle interval of its parent to receive a DIO packet.

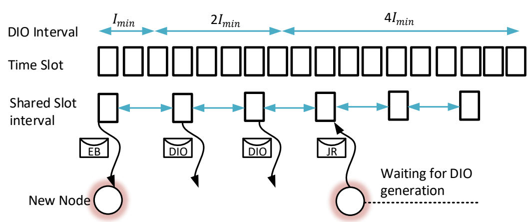


Figure 2: Negative effect of Trickle Algorithm

3.3 Objective of this paper

All the existing works do not consider the packet level starvation and the effect of Trickle Algorithm in 6TiSCH network formation. Therefore, the main objective of this paper is to eliminate both the problems. Packet level starvation occurs because of EB's highest priority. However, to eliminate packet level starvation, we can not assign same priority to all the control packets as EB is used for network advertisement and maintaining synchronization. Again, to deal with longer trickle interval, frequent transmission of routing information is not appreciative because it consumes more energy. Therefore, the main objective of this work is to assign priority to control packets opportunistically based on their requirements and maintain the rate of sending control packets as per the requirements of the network.

3.4 Validation of the Problems

In our earlier work [7], we designed an analytical model for network formation in 6TiSCH network using Markov Chain Model. For the validation of problem mentioned above, we use the same analytical model. The symbols, used in the analytical model, and their corresponding meaning are tabulated in Table 1.

Based on the analytical model [7], the probability of successfully sending an EB frame is,

$$P_{EB_S} = \frac{X}{1+KX} \tag{1}$$

where, $X = \frac{NP_{eb}(1-P_{eb})^{N-1}(1-P_{dio})^{N-1}(1-P_{loss})}{N_c}$

Similarly, the probabilities of sending a DIO packet and a JR frame successfully in a shared slot are,

$$P_{DIO_S} = NP_{dio}(1-P_{dio})^{N-1}(1-P_{eb})^{N}(1-P_{EB_S})^{K}(1-P_{loss}) \tag{2}$$

Table 1: List of frequently used symbols

Symbol	Meaning
N	Number of joined nodes
K	Number of new nodes
N_c	Number of available channels
L	Slotframe length
I_{eb}	Beacon generation interval
P_{eb}	Transmission probability of EB in a shared slot
P_{dio}	Transmission probability of DIO in a shared slot
P_{jr}	Transmission probability of JR in a shared slot
P_{loss}	Packet loss probability
P_{EB_S}	Successful transmission probability of an EB frame
P_{DIO_S}	Successful transmission probability of a DIO packet
P_{JR_S}	Successful transmission probability of a JR

$$P_{JR_S} = KP_{EB_S}(1-P_{EB_S})^{K-1}(1-P_{eb})^{N}(1-P_{dio})^{N}(1-P_{loss}) \tag{3}$$

Now, to compute Equations (1), (2), (3) we should know the transmission probabilities of EB (i.e., P_{eb}) and DIO (i.e., P_{dio}) in a shared slot. The probabilities P_{eb} and P_{dio} are computed as,

$$P_{eb} = \frac{L}{I_{eb}} \tag{4}$$

$$P_{dio} = (1-P_{eb})\frac{2^{N_D}(1-P_r)^{N_D} min(\frac{L}{2^{N_D} I_{min}},1)+ \sum_{i=0}^{N_D-1} P_r 2^i (1-P_r)^i min(\frac{L}{2^i I_{min}},1)}{P_r + 2^{N_D}(1-P_r)^{N_D} + \sum_{j=1}^{N_D-1} P_r 2^j (1-P_r)^j} \tag{5}$$

where, L is the slotframe length, I_{eb} is the beacon interval and I_{min} is the initial DIO interval, P_r is the Trickle algorithm reset probability and N_D represents total number of trickle algorithm states. Finally, we computed the average joining time (AJT) of a new node as follows,

$$AJT = ASF \times L \tag{6}$$

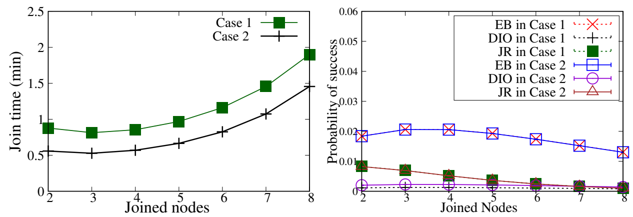
where, ASF (average slotframe) length is computed as follows,

$$ASF = \frac{1}{P_{EB_S}} + \frac{1}{P_{DIO_S}} + \frac{1}{P_{JR_S}} \tag{7}$$

Now, to validate packet level starvation, we consider that all the control packets have equal probability. So, the probability of sending a DIO packet does not depend on the existence of EB frame. Therefore, probability of sending a DIO packet in a slotframe can be derived from Equation (5) as follows,

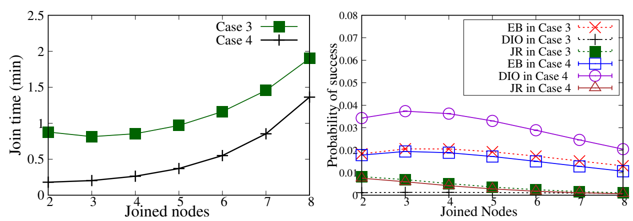
$$P_{dio} = \frac{2^{N_D}(1-P_r)^{N_D} min(\frac{L}{2^{N_D} I_{min}},1)+ \sum_{i=0}^{N_D-1} P_r 2^i (1-P_r)^i min(\frac{L}{2^i I_{min}},1)}{P_r + 2^{N_D}(1-P_r)^{N_D} + \sum_{j=1}^{N_D-1} P_r 2^j (1-P_r)^j} \tag{8}$$

Now, Let us consider a network with the following given values: $N_C = 16$, $P_{loss} = 0.2$, $I_{eb} = 2 * L$, $T_i = 10\ ms$, $I_{min} = 8\ ms$, $L = 5\ timeslots$, $N_D = 16$ and $P_r = 0.2$. We plot a graph in Fig. 3 considering two cases: first, EB has the highest priority among all network control packets, and second, EB has equal priority with other network control packets. The graph shows that the overall joining time of the network reduce when we consider EB has equal priority with other control packets. The reason is shown in Fig. 3b. It shows how the probability of successfully transmitting a control packet in a shared slot (mainly, here DIO packet) increases when EB has equal priority with other control packets. The increase in success probability of DIO packet decreases the average network joining time of the new nodes in the network.



(a) Node join time (b) Probability of success

Figure 3: Comparison on node joining time and the success probability of different control packet. Case 1: EB has highest probability, Case 2: EB has equal probability with others



(a) Node join time (b) Probability of success

Figure 4: Comparison on node joining time and the success probability of different control packet. Case 3: Trickle Algorithm based DIO interval, Case 4: fixed DIO interval

To validate the problem of Trickle Algorithm, instead of using Trickle Algorithm based DIO interval as in Equation (5), we use fixed DIO interval, i.e., p_{dio} = .03 and plot the results in Fig. 4. The figure shows that there is a significant improvement in new node joining time when we do not consider Trickle Algorithm for sending DIO packet. In Fig. 4b shows that the probability of successfully transmitted DIO control packet in a slotframe can be improved without using Trickle Algorithm. Trickle Algorithm decreases the number of transmitted DIO packet in a stable network. Hence, it lowers the transmission probability of sending DIO packet in a shared slot. This results in higher joining time of new nodes.

3.5 Proposed Solution

To overcome the problem of packet level starvation and the negative effect of Trickle Algorithm, we propose an opportunistic priority alternation scheme (OPAS). The OPAS also opportunistically increases the rate of transmission of routing information packet. Algorithm 1 describes our proposed scheme. As EB frame is mainly used for advertising the availability of a network and maintaining global synchronization among the nodes present in a network, so, in general network condition, the highest priority is given to EB frame. When the requirement of a DIO packet is more important (e.g; when a new node needs a DIO packet to completes its joining process) than an EB frame, we must give highest priority to DIO packet instead of EB frame. Again, variable DIO interval is used in a network to save energy consumption by transmitting minimum number of packets when the network is stable. Hence, if we use fixed DIO interval then it will affect the performance of a node in terms of energy consumption. Therefore, we propose to use the existing Trickle Algorithm with little modification such that it resets its interval during network inconsistency as well as when a joined node receives JR frame from a new node.

Algorithm 1: Opportunistic Priority Alternation Scheme

```
if the current Link_type is Shared then
    -Tx mode-
    if get the channel access to transmit then
        Transmit highest priority packet (EB/DIO)
        Set highest priority to EB (default value)
    end
    -Rx mode-
    if received a packet then
        if received packet is JR frame then
            Send Join Response (JRS) frame
            Set highest priority to DIO
            if no DIO packet is available in transmission buffer
             then
                Reset the Trickle Algorithm interval
            end
        end
        if received packet is DIS request for DIO then
            Set highest priority to DIO
        else
            Set highest priority to EB
        end
    end
end
```

4 PERFORMANCE EVALUATION

In this section, we inspect the proposed scheme using simulation. We implemented the proposed scheme on Contiki-OS [2]. The simulation parameters and their corresponding values are mentioned in Table 2. And we used Multipath Ray-tracer Medium (MRM) model for our simulation. We considered a Tree-like topology as shown in Fig. 5 for node placement. The PAN coordinator was placed at the top of the tree and lines denote communication between two nodes. The PAN coordinator initiates the network formation process by sending the EB frame and DIO packet with their configured interval.

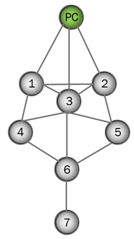
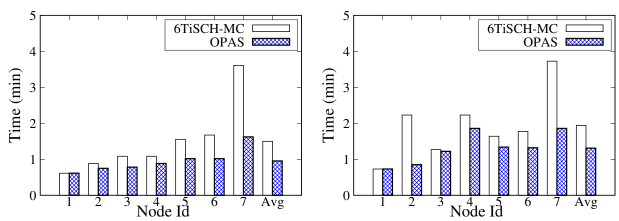


Figure 5: Considered Network Topology

Parameter	Value
Number of channels	16
Timeslot length	10 ms
Slotframe size	101 timeslots
EB interval	4 sec
RPL version	RPL Lite
RPL DIO interval	Trickle Algo.
Propagation Model	MRM
Simulation duration	1 hour

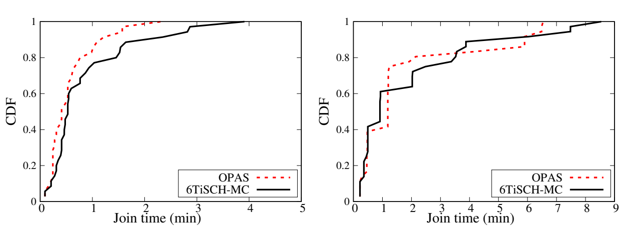
Table 2: Simulation parameters

We ran the simulation for 60 minutes, and the received results are plotted in Fig. 6. The Fig. 6a shows the average time a node waited to receive its first EB frame. And the Fig. 6b shows the time needed by a node to receive both EB frame and DIO packet from its co-ordinator. A node is eligible to send its beacon frame for network expansion only after the time mentioned in the Fig. 6b. It is observed that, in both the plots, the proposed scheme outperforms the existing 6TiSCH-MC scheme. The 6TiSCH-MC is taking more amount of time because of EB's priority over the other control packets. Moreover, in a best case, a new node needs to wait for its parent's trickle interval to receive a DIO packet. Both the demerits are eliminated in the proposed scheme, and hence it performs better than 6TiSCH-MC.



(a) TSCH formation time **(b) 6TiSCH formation time**

Figure 6: Node wise joining time and their average joining time in Tree-like topology



(a) TSCH formation time **(b) 6TiSCH formation time**

Figure 7: Network formation time in grid topology

Apart from the Tree-like topology, we also experimented square Grid topology with 36 nodes. The PAN coordinator is always placed at the left top corner of a grid. We plotted the received results in Fig. 7 which depicts the cumulative distribution function (CDF) of the joining time of node. Fig. 7a shows the TSCH synchronization time and the Fig. 7b shows the 6TiSCH synchronization time. In both the graphs, the proposed scheme outperforms 6TiSCH-MC because of the elimination of EB priority over other control packets during network formation and resetting trickle algorithm when a joined node receives a JR frame from its new child node.

5 CONCLUSION

In this paper, an opportunistic priority alternation scheme (OPAS) is proposed for faster association of nodes in 6TiSCH networks. In 6TiSCH network, it is considered that EB frame has the highest priority over all other network control packets and there is no relation between new node joining request and DIO sending rate of already joined node. Therefore, at the beginning, analytically we show that the performance of 6TiSCH network formation degrades because of having EB's priority and no change in DIO sending rate during network formation. To overcome these two problems, we propose an opportunistic priority alternation scheme with resetting the DIO transmission rate in Trickle Algorithm. In the proposed scheme, a joined node gives highest priority to a DIO packet over an EB frame whenever it is required, and resets its Trickle Algorithm when it receives a JR frame from a new node. The validation of the proposed scheme is done by simulation, and the received results are compared with the benchmark protocol 6TiSCH-MC. The obtained results show significant improvement with respect to network joining time if the network follows the proposed scheme.

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