A Selective TSCH Autonomous Cell Scheduling Technique Depending on the Power Supply

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***Abstract*— IEEE 802.15.4 TSCH MAC uses time-sharing media access control and channel hopping technology to provide stable communication in an industrial environment. However, there is no scheduling technique defined by the standard. The Orchestra is an autonomous link-based cell scheduling technique in TSCH, but it has limitations such as link loss and delay time in high competition environments. ALICE addresses some of these limitations by creating links in both directions, but has the disadvantage of a high radio duty cycle proportional to the number of connected devices. When a device powered by a battery wants to connect, it generates a link using Orchestra, and a device that is supplied with constant power suggests using ALICE to generate a link. A TSCH SIM simulator was used to compare the performance of the Orchestra and ALICE networks, resulting in a 17.32% increase in PDR for the Orchestra network and a decrease in the duty cycle for battery-powered devices of up to 23.35% compared to ALICE.

***Keywords*—TSCH, IEEE 802.15.4, WSN, Orchestra, ALICE**

I. Introduction

With the increasing emergence of IoT devices, there is a push to apply IoT in industrial environments, particularly for data collection purposes. Unlike in general home environments, industrial environments require the use of different wireless network technologies due to the prevalence of multi-pass fading caused by numerous metal structures. Wireless network errors in industrial environments can result in significant harm to companies, necessitating a higher level of performance. To address these needs, IEEE 802.15.4 [1] Time-Slotted Channel Hopping (TSCH) MAC technology has been proposed.

TSCH MAC is one of the MAC modes specified in the IEEE 802.15.4 standard, but it only presents the operating mechanism of TSCH and does not define the link scheduling method. Autonomous link-based TSCH cell scheduling techniques are favorable for devices powered by batteries as they need to reduce radio duty cycles and there is little extra overhead to create links. One representative example is the Orchestra (Robust mesh networks through autonomously scheduled TSCH) [2].

However, in Orchestra, multiple devices compete for transmission, leading to radio collisions and packet retransmission. This not only increases the radio duty cycle but also reduces network performance, such as causing queue overflow. To address these issues, ALICE (Autonomous link-based cell scheduling for TSCH) [3] has been proposed as a solution.

ALICE, similar to orchestras, is an autonomous link-based cell scheduling technique for TSCH that aims to address the limitations of orchestras by assigning cells to links in both directions rather than based on nodes. The number of cells allocated to each link is proportional to the number of devices that established the link, resulting in an increase in radio duty cycle with the increasing number of allocated cells. If the energy consumption of all devices is not a concern, ALICE can be a suitable option. However, for many IoT devices powered by batteries, the power supply must be taken into consideration.

We present a method of selectively applying orchestra and ALICE based on the battery usage of the device, and compare the performance of these three autonomous link-based TSCH cell scheduling techniques by increasing the number of leaf nodes.

II. Background

A. TSCH

The TSCH MAC mode is part of the IEEE 802.15.4 standard. It employs a time division-based link scheduling and channel hopping mechanism to avoid external interference. All devices are synchronized using an Enhanced Beacon (EB) and are based on the Absolute Slot Number (ASN), which represents the number of time slots elapsed since the start of the network. The slotframe, consisting of a fixed number of time slots, is repeated continuously, and communication between devices takes place within a single time slot. The slot offset determines the order of the time slots in the slotframe. TSCH assigns a cell, which is a bundle of slot offsets and channel offsets shared between a pair of devices, and cell scheduling allocates these cells among devices.

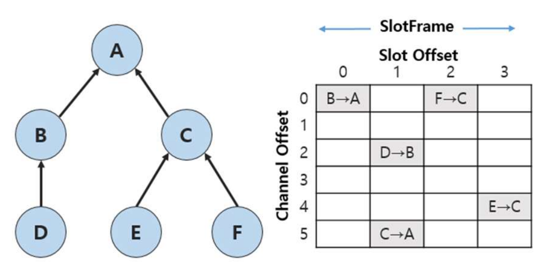

Fig 1. Example of TSCH Link Scheduling by Network Topology

TSCH scheduling can be classified into three categories: centralized, distributed, and autonomous. The centralized approach involves a central device that collects and manages the scheduling of all devices in the network, but this can lead to excessive overhead in dynamic networks or large-scale networks. The distributed approach involves negotiation between nodes to allocate cells, but this leads to increased network overhead. The autonomous approach scheduling cells without negotiation, resulting in lower overhead, but can result in decreased performance in highly competitive situations due to limited cell allocation.

(1) is a method for determining the channel used by a device in a TSCH network for communication. The $macHopSeq$ is an array of channel hopping sequences, Ch_{offset} is the assigned channel offset, and $macHopSeqLen$ is the length of the channel hopping sequence array. The ASN, which changes over time, is also included in the calculation, allowing for the use of different channels for each communication. As shown in Fig. 1, TSCH cell scheduling is demonstrated. For instance, device D communicates with B using slot offset 1 and channel offset 2. Meanwhile, device C tries to communicate with A in the same slot offset, but because it is using a different channel offset, it does not interfere with the communication between D and B.

$$CH = macHopSeq\big[(ASN + Ch_{offset})\%macHopSeqLen\big] \quad (1)$$

B. Orchestra

Orchestra is an autonomous link-based TSCH cell scheduling technique that allocates cells based on the MAC address of the device. It contains three slotframes - EB slotframes, broadcast slotframes, and unicast slotframes - which operate simultaneously using different fixed channel offsets for communication. As a result, there may be overlapping time slots, and scheduling is done based on the priority of the slotframes.

In Orchestra's unicast slotframes, there are two types of scheduling - receiver-based and sender-based. Receiver-based scheduling allocates one receive slot per device using its MAC address, resulting in low radio duty cycle, but increased competition and link loss as more nodes try to transmit. This type of scheduling is shown in "Fig 3". On the other hand, sender-based scheduling has high energy consumption as transmission slots are assigned using the device's MAC address. This type of scheduling is demonstrated in "Fig 4". The paper focuses on receiver-based scheduling for its low radio duty cycle.

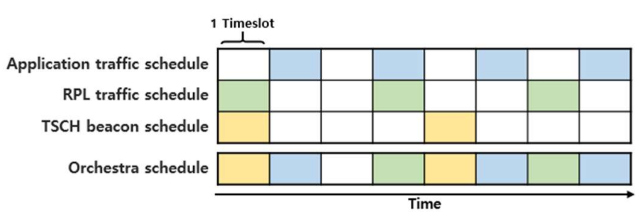

Fig 2. Example of orchestral scheduling

C. ALICE

ALICE is a link-based Time Slotted Channel Hopping (TSCH) cell scheduling technique that allocates cells based on links rather than nodes. It assigns cells for each link in both directions, using both node addresses when assigning links from node k to l. Equation (2) calculates the slot offset for communication from node k to l, where t_0^{UC} is the slot offset and L_{SF}^{UC} is the length of the slotframe. Equation (3) calculates the channel offset, where c_0^{UC} is the channel offset and L_{CH} is the number of channel offsets used. ALICE also has three slotframes, similar to Orchestra.

$$t_0^{UC}(k,l) = mod\big(Hash\big(\alpha ID(k) + ID(l)\big), L_{SF}^{UC}\big) \quad (2)$$

$$c_0^{UC}(k,l) = mod\big(Hash\big(\alpha ID(k) + ID(l)\big), L_{CH} - 1\big) + 1 \quad (3)$$

In ALICE, each slotframe uses the ASFN (Absolute Slot-Frame Number) to avoid overlapping links. Equation A calculates the slot offset by applying ASFN, while Equation B calculates the channel offset with ASFN. ALICE scheduling is efficient, with no additional overhead, and improves PDR (Packet Delivery Ratio) and latency compared to Orchestra as it allocates cells based on links rather than nodes. However, it does not address the issue of high traffic load.

$$t_0^{UC}(k,l,ASFN) = mod(Hash(\alpha ID(k) + ID(l) + ASFN), L_{SF}^{UC}) \quad (4)$$

$$c_0^{UC}(a,b,ASFN) = mod(Hash(\alpha ID(k) + ID(l) + ASFN), L_{CH} - 1) + 1 \quad (5)$$

As illustrated in "Fig. 5", the star topology is connected to check the performance difference according to cell scheduling by increasing the number of leaf devices connected to one root device. The experiment in "Fig 6" shows the result of increasing the number of nodes connected to a single root device from one to ten, with each node generating one packet every 30 seconds. The comparison of PDR performance between Orchestra and ALICE in a star topology is shown and the difference in cell scheduling, resulting in a PDR difference of up to 24.37%.

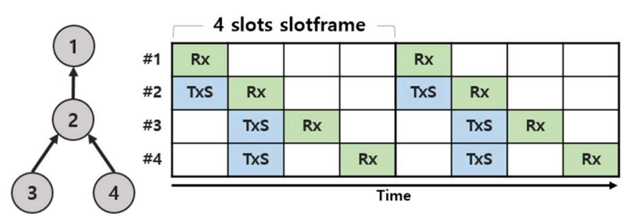

Fig 3. Receiver-based Orchestral Unicast Slotframe

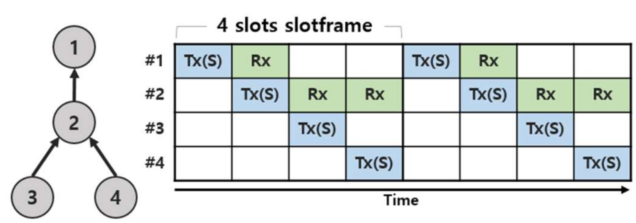

Fig 4. Sender-Based Orchestra Unicast Slotframe

D. RPL

The Internet Engineering Task Force (IETF) ROLL Working Group has proposed RPL[4] as a standard routing protocol for IPv6-based low-power wireless networks in IoT devices, allowing for the forwarding of data between nodes through DODAG (Destination-Oriented DAG) generation. Nodes in the network build the DODAG using control messages DIO (DODAG Information Object), DAO (Destination Advertising Object), and DIS (DODAG Information Solicitation).

The network participation process of nodes in RPL is as follows. Nodes broadcast DIS messages when they want to join the network. When other devices in the network receive a DIS, they respond with a DIO to induce node participation in the network. The node receiving the DIO calculates the rank of the sender based on the objective function and selects the device with the lowest rank value as the parent. Both Orchestra and ALICE build networks based on RPL.

III. CELL SCHEDULING ACCORDING TO THE POWER SUPPLY METHOD OF THE DEVICE

When using ALICE to allocate cells to links in each direction, high PDR is achieved, but in network topologies with a tree structure such as WSN, parent nodes that need to generate links with all child nodes can experience high radio duty cycles. This can result in uneven energy consumption among nodes and shorten the lifespan of the entire network. The network equipment utilizes ALICE to establish a link only when the device attempting to create the link has a constant power source. In this case, information on the power source (battery or not) of the other device is shared using the Information Element (IE) field. By using this method of link creation, the device using a battery has a low radio duty cycle as it only has one receive cell assigned to its address. And if the parent device has a constant power source, it can decrease the radio duty cycle by reducing radio collisions among its child nodes that use batteries, as links are established in both directions.

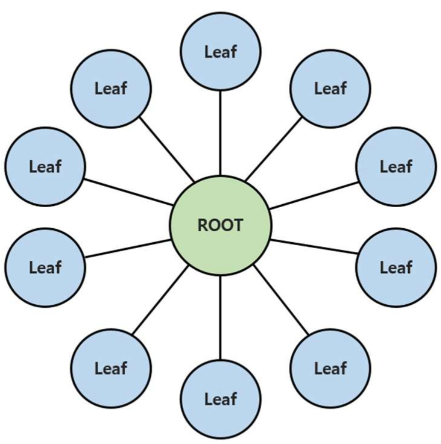

Fig 5. Simulation Network Topology

IV. SIMULATION ENVIRONMENT

This experiment is evaluating the performance of a wireless network with TSCH SIM. The network consists of one root node, two router nodes, and a varying number of leaf nodes. The leaf nodes send packets to the router nodes, which then forward the packets to the root node. The unicast slotframe size is set to 31 and the number of MAC retransmissions is set to 3. The experiment was conducted 10 times for each increase in the number of leaf nodes and the mean results were measured.

V. PERFORMANCE

A. PDR

"Fig .6" shows the results of the packet delivery ratio (PDR) as the number of leaf nodes connected to each router increases. The results were presented based on the number of devices connected to each router. The PDR decreases as the number of leaf nodes increases and the decrease becomes more rapid as the number of nodes increases. When there are 10 leaf nodes connected to each router, the PDR decreases to 83.18% in the networks using only orchestras.

However, in networks using ALICE, the PDR is consistently at 100% even when there are 10 leaf nodes connected to each router. The performance decreases due to competition between the router and the leaf nodes and between the root and the router. The battery-operated routers in the proposed technique show improved performance over the networks with only orchestras, with a PDR of 97.59% when there are 10 leaf nodes connected to each router.

TABLE I. SIMULATION ENVIRONMENT

Features	Description
Number of slots	108000
Number of nodes	Root:1 Router: 2 Leaf: 2, 4, 6, 8, 10, 12, 14, 16, 18, 20
Slotframe length	31 timeslot
Timeslot Length	10 ms
Packet Period	30 s
Number of Mac retransmissions	3
Link Quality	100%
RPL OF	MRHOF [5]
Scheduling Function	Orchestra, Proposal, ALICE
Number of simulations per experiment	10

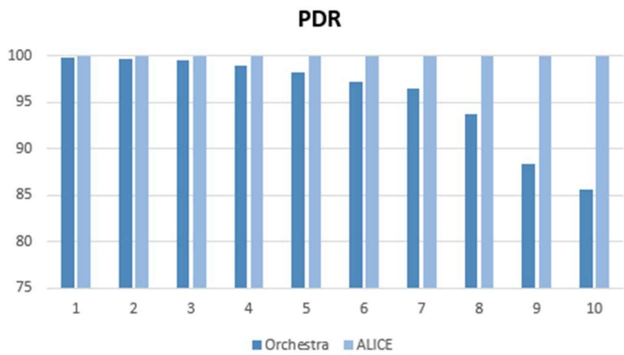

Fig 6. PDR in Star Topology

B. PAR

"Fig. 7" shows the relationship between the number of Leaf nodes connected to each router and the Packet ack ratio (PAR). The losses shown are only due to competition between nodes, not link issues. This is because the link loss was excluded from the simulation setting. The difference in PAR was greater than that of PDR. In the case of orchestras, the PAR fell to 64.88% with 10 nodes due to increased collisions caused by having only one receiving cell. The lower the PAR, the higher the radio duty cycle resulting from packet retransmission. The proposed technique showed a PAR of 83.02%, while Alice had results over 94% in all experiments.

When a packet transmission fails, the device will attempt to retransmit the packet. If the experiment has limited the number of MAC layer retransmissions to three, then the device will retransmit the packet up to three times, and drop the packet if all transmissions fail. The more retransmissions that occur, the lower PAR becomes.

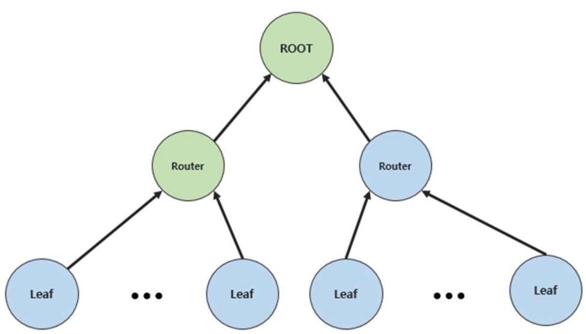

Fig 7. Simulation Network Topology

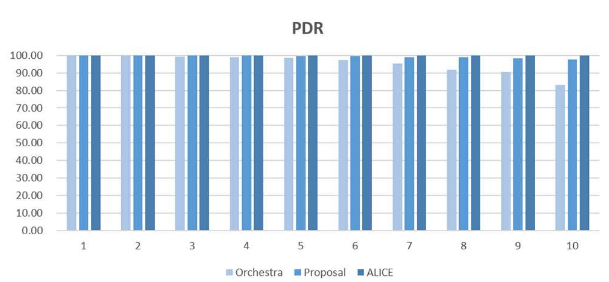

Fig 8. PDR

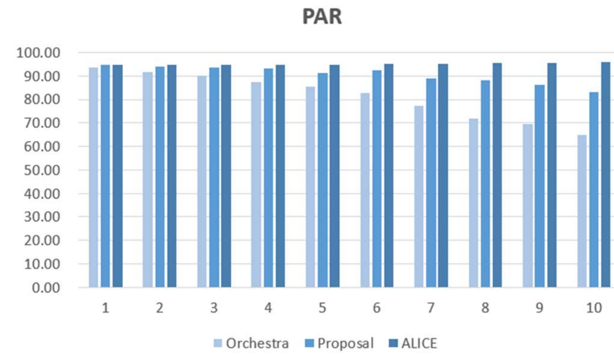

Fig 9. PAR

C. Sum of the radio duty cycles for devices using batteries.

"Fig. 8" illustrates the sum of the radio duty cycles for battery-operated devices according to the number of Leaf nodes connected to each router. As the number of devices increases, the sum of the radio duty cycles also increases. The orchestra has the lowest radio duty cycle among all experiments, due to the fact that only one cell is used for reception, leading to a lower ratio of the total radio duty cycle for reception compared to the increase in radio duty cycle caused by unicast transmission. The orchestra and the proposed technique have similar results in the radio duty cycle of battery-operated devices, but ALICE has the highest battery consumption.

D. Sum of the radio duty cycles for all devices

"Fig. 9" displays the sum of the radio duty cycles for all devices in relation to the number of Leaf nodes connected to each router. As the experiment progresses and the number of devices increases, the sum of the radio duty cycles also increases. The network using orchestras has the lowest sum of radio duty cycles among all experiments, while the proposed technique has the second highest. The network using only ALICE has the highest sum of radio duty cycles. The difference in radio duty cycle occurs depending on how the receiving cell is allocated rather than the increase in radio duty cycle due to packet retransmission due to the decrease in PAR.

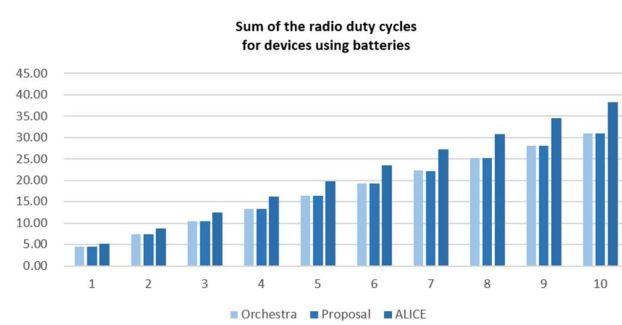

Fig 10. Sum of the radio duty cycles for devices using batteries

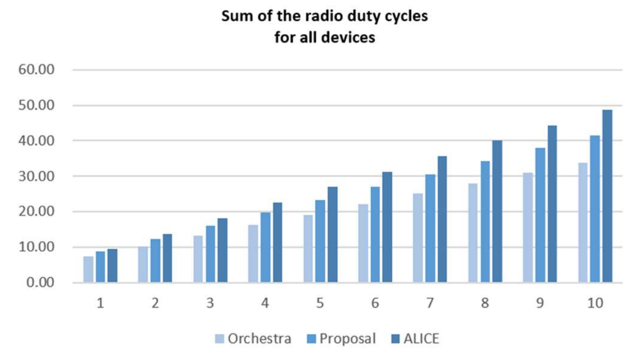

Fig 11. Sum of the radio duty cycles for all devices

VI. CONCLUSION

We have applied different scheduling techniques depending on the power supply method of the network device. We compared orchestras, ALICE, and suggestion techniques, increased the number of Leaf nodes, and identified performance changes with competition. In the case of PDR, there was a maximum performance improvement of 17.32% compared to orchestra, and 2.47% lower performance than ALICE. Likewise, PAR showed 27.96% performance improvement compared to orchestras and 15.42 performance decline compared to ALICE. In the case of the radio duty cycle of devices using batteries, the result was almost similar to that of the orchestra, but the performance was improved by 23.35% compared to ALICE. The radio duty cycle for the entire network increased by 22.57% compared to the orchestra and decreased by 17.7% compared to the ALICE.

Our proposed technology is significant because it showed similar radio duty cycle results for battery-operated devices compared to orchestras, despite a slight reduction in PDR. Our technique utilizes information about the power type of devices in the network with minimal overhead and selects the most appropriate scheduling method and cell allocation to improve performance. This results in improved radio duty cycle results compared to ALICE, by 23.35%, while also being efficient in terms of energy consumption.

We expected to gain two advantages by choosing a scheduling method depending on whether the device uses a battery or not.

The first is to reduce the radio duty cycle by not using ALICE in devices that use batteries, thereby maintaining the long life of the device. The first advantage was confirmed through "Fig. 10". Some devices that use batteries showed lower duty cycles than networks that only use ALICE by scheduling using orchestras.

The second advantage is that when ALICE is used to create a link with child nodes that use a battery in a powered device, wireless packet collision due to competition decreases and the number of retransmissions decreases, lowering the radio duty cycle of the battery-using device. As can be seen in "Fig. 9", it was found that PAR fell as the number of competing nodes increased. In other words, the number of retransmissions increased due to wireless packet collisions.

However, as "Fig. 10" shows, the radio duty cycle of battery-powered devices showed almost similar results between orchestral-only networks and proposed networks. That is, the radio duty cycle that increases due to packet retransmission has a low percentage of the total radio duty cycle. Reducing the packet generation period or increasing the number of MAC retransmissions can increase the duty cycle due to retransmission, but queue overflow occurs due to the presence of many packets in the queue. Accurate experiments for radio duty cycle measurement have not been performed because packets are dropped without transmission when queue overflow occurs. In conclusion, when the radio duty cycle increases due to packet retransmission, other side effects such as queue overflow already occur.

We selected only two simple autonomous cell scheduling techniques and a link generation method according to whether or not the battery is used. Since both scheduling techniques do not provide solutions for excessive traffic, there was a limitation that excessive traffic load could not be imposed.

However, various studies are currently being conducted in autonomous cell scheduling, such as [6], [7], [8], [9], [10] and [11]. We plan to conduct a study that can compare various autonomous cell scheduling in future studies and extend the life of devices that use batteries in consideration of link quality, traffic, PDR, etc. in a network including battery devices. The QoS(Quality of Service) required by each application is different, but an autonomous cell scheduling technique is required in which a device using a battery consumes the minimum energy and satisfies the QoS according to the application.

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