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Abstract

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***Abstract*—Sub-1 GHz Wireless Communications of LPWAN (Low Power Wide Area Network) are attracting attention in IoT applications. In addition to battery-powered devices, the number of grid-powered and solar-powered sensor devices using LPWAN are also rapidly increasing for various IoT applications. We aim to improve reliability and efficiency of IEEE 802.15.4 CSMA/CA mechanism in the network consisting of devices without power constraint. We propose Suspendable Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithms for IEEE 802.15.4 to mitigate packet loss by channel access failure while maintaining compatibility with conventional IEEE 802.15.4 CSMA/CA. We have performed extensive simulations to valid the Suspendable CSMA/CA mechanism. Simulation results show that the proposed Suspendable CSMA/CA improves Packet Delivery Rate (PDR) by 9.7 points (89.9 % to 99.6 %) compared to the conventional IEEE 802.15.4g CSMA/CA and therefore, can lead higher spectrum efficiency for IoT applications operate in the limited Sub-1 GHz wireless bandwidth. The proposed Suspendable CSMA/CA mechanism has been also approved and adopted for the next IEEE 802.15.4 amendment by IEEE 802.15 Working Group.**

***Index Terms*—IEEE 802.15.4g, IoT, CSMA/CA, Spectrum Efficiency, Sensor Network**

I. Introduction

Sub-1 GHz Wireless Communications are attracting attention by industry IoT applications such as metering systems. Standardized communication technologies such as IEEE 802.15.4g [1] / Wi-SUN [2] and IEEE 802.11ah / Wi-Fi HaLow and proprietary communication technologies such as SigFox and LoRa WAN have been introduced to the LPWAN (Low Power Wide Area Network) market. These technologies have features of low data rate, long distance, flexible network topology and low power consumption for power constrained sensor networks. In recent years, the number of sensor devices without power constraint that apply these technologies are also rapidly increasing for various IoT applications, e.g., smart meters, smart grids, building management, lighting, remote operation of FA sensors and smart homes. In these use cases, a large number of sensor devices are deployed in the same area, and data must be efficiently collected from the sensor nodes. Furthermore, power consumption is not an issue for the devices that are connected to power grid compared to battery-powered devices.

IEEE 802.15.4 CSMA/CA is originally designed for battery-powered devices and has features for reducing power consumption. Therefore, IEEE 802.15.4 CSMA/CA does not perform carrier sense to minimize power consumption except in CCA (Clear Channel Assessment) period before transmission. This is a point where the IEEE 802.15.4 CSMA/CA differs significantly from IEEE 802.11 CSMA/CA and others. Figure 1 illustrates the operation of IEEE 802.15.4 CSMA/CA, where each device backoffs a random number of backoff periods and performs carrier sense at CCA period. When no other communication is detected during CCA period, the device transmits packet after *CCA to TX turnaround time*. Since IEEE 802.15.4 does not perform carrier sense during the backoff period, devices operate the hardware circuit only during transmission, which contributes to low power consumption. However, as the number of devices and communication frequency increase, packet loss becomes a serious problem caused by backoff failure. To be more specific, when an IEEE 802.15.4 device detects busy channel during CCA period, the device increments Number of Backoffs (NB) by 1. When the NB exceeds the specified threshold *macMaxCSMABackoffs*, the device concludes a backoff failure as shown in Figure 2.

Therefore, we propose Suspendable CSMA/CA with carrier sense during the backoff periods for IEEE 802.15.4g to improve packet delivery rate while maintaining compatibility with conventional IEEE 802.15.4 CSMA/CA. Authors are also leading IEEE 802.15.4 Sub-1 GHz Interest Group to standardize this feature in IEEE 802.15.4 standard.

The rest of this paper is organized as follows. Section II presents related work in the research and standardization communities. Section III describes the necessity of backoff suspension. Section IV introduces the proposed Suspended CSMA/CA for IEEE 802.15.4. Performance analysis and simulation results of our proposed scheme are demonstrated in Section V. Finally, we conclude our paper in Section VI.

II. Related Work

IEEE 802.15.4 is widely used in the market and has led to extensive performance studies in research community. The latest standard of IEEE 802.15.4-2020 includes amendments of IEEE 802.15.4e and IEEE 802.15.4g for IoT and industrial IoT applications.

J. Zhu et al. propose a stochastic analysis approach to evaluate the delay performance of IEEE 802.15.4 CSMA/CA scheme with heterogeneous buffered traffic [3]. S. Wijetunge et al. propose an improved wireless MAC protocol to provide an energy efficient, reliable and delay-limited data transmission

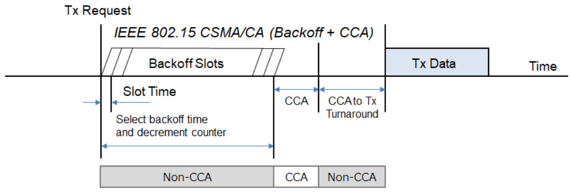

Fig. 1. IEEE 802.15.4 CSMA/CA Mechanism

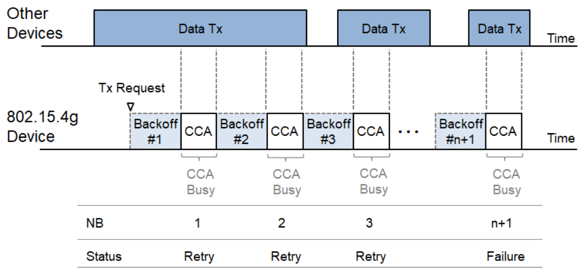

Fig. 2. Failure caused by NB exceeding *macMaxCSMABackoffs*

for hybrid monitoring applications. The proposed TDMA based protocol freezes the backoff counter during the time reserved for dedicated time slots (DTSs). Network Simulator (NS-2) is used for simulation [4]. L. Wang et al. propose a new backoff algorithm for IEEE 802.15.4 in high-density wireless sensor networks. According to the two-level periodical renewing information of channel busyness rate and packet collision rate, the proposed algorithm adjusts backoff window properly to maximize the channel utilization. Network Simulator (NS-2) is used for simulation [6]. IEEE 802.15.4g performance has been demonstrated in [9] and [10], which focus on the PHY and MAC protocol enhancement for higher-throughput, protocol efficiency and delay via simulation and measurement using prototypes. Japanese communication standard JJ-300.10 modifies IEEE 802.15.4 CSMA/CA to support ECHONET Lite which controls appliances in home area network [11]. NR (Number of Retries) and *macMaxFrameRetries* are proposed to control channel access in addition to conventional NB and *macMaxCSMABackoffs* defined in IEEE 802.15.4. Although this scheme contributes to reducing packet discard, the detrimental effect of scheme is the introduction of a LIFS delay before backoff. In terms of regulations, Sub-1 GHz frequency bandwidth is very constrained to support massive number of IoT devices. For example, ARIB STD-T108 [12] defines Japanese Sub-1 GHz frequency bands regulation which allows at most 2.9 MHz optimized for LPWAN including IEEE 802.15.4g / Wi-SUN, IEEE 802.11ah / Wi-Fi HaLow, SigFox, LoRa WAN and other technologies on Page 113. This limited band allocation leads to congestion and interference issues as more devices with different protocol exists in narrower bandwidth. To address Sub-1 GHz band coexistence, IEEE 802.19.3 provides guidance on the implementation, configuration and commissioning of systems based on IEEE 802.15.4g and IEEE 802.11ah operating in Sub-1 GHz frequency bands to achieve the best possible performance while sharing limited spectrum [13]. We led this IEEE 802.19.3 standardization as Task Group officers.

The papers and standardization mentioned above discuss the IEEE 802.15.4 evaluation and frequency tolerance issues in the Sub-1 GHz band, but they are not reflected in the IEEE 802.15.4 specification changes. Therefore, we have established Sub-1 GHz Interest Group (IG) within the IEEE 802.15 Working Group to improve IEEE 802.15.4g efficiency by proposing Suspendable CSMA/CA. This paper describes our standardization work and the proposed method in the following chapters.

III. Necessity of Backoff Suspension

This section validates the necessity of backoff suspension in IEEE 802.15.4 standard from protocol perspective. As more and more communication technologies have been developed, IoT network environment has changed dramatically in terms of the device resource and capability, the number of devices in a network and the number of homogeneous and/or heterogeneous coexisting networks. For example, the sensor devices are conventionally battery-powered. However, the grid-powered and solar-powered sensor devices have been emerging in recent years. Therefore, IoT communication technologies need to take advantages of more capable sensor devices to make network more reliable and efficient. Backoff suspension is one of functions that needs to be supported by IEEE 802.15.4 standard to benefit sensor devices without power constraint. Backoff suspension can bring benefits including: (1) improving IEEE 802.15.4 network reliability and (2) allowing IEEE 802.15.4 networks to better coexist with more channel access aggressive networks such as IEEE 802.11 networks.

Figure 3 demonstrates that backoff suspension can reduce backoff failure of IEEE 802.15.4 devices, in which device A represents one of other IEEE 802.15.4 device, device B is a standard IEEE 802.15.4 backoff device and device C is a Suspendable IEEE 802.15.4 backoff device. These devices contend for channel access for transmission. At time T_1, device A receives data transmission request and starts backoff. Both device B and device C receive data transmission request at time T_2 and start backoff. Assume they also draw the same number of the unit backoff periods and therefore, need to backoff for the same amount of time. At time T_3, device A finishes backoff and starts CCA operation, which detects idle channel. Thus, device A performs CCA to transmission turnaround. At time T_4, device A starts data transmission. Since device C senses channel in each unit backoff period, it detects transmission of device A and therefore, suspends its backoff process. On the other hand, device B does not suspend its backoff and completes backoff at time T_5 and performs CCA. However, at time T_5, device A still transmits. As a result, device B detects busy channel and returns backoff failure at time T_7. Meanwhile, device C detects the end of device A transmission at time T_6 and resumes remaining backoff. At time T_8, device C completes backoff and starts CCA operation, which detects idle channel as well. Accordingly, device C performs CCA to transmission turnaround. At time T_9, device C successfully transmits its data. It is possible that device C may also detect busy channel, but device B detects busy channel for sure, i.e., 100% of backoff failure. If the transmission of device A completes before time T_5, both device B and device C will succeed backoff. However, device C will backoff more time due to suspension. If transmission of device A starts after time T_7, both device B and device C will succeed backoff with same amount of backoff time. As for coexistence benefit, Y. Nagai et al. demonstrate in paper [5] that performing active carrier sense can improve IEEE 802.15.4 network packet delivery rate. The active carrier sense is performed in Suspendable CSMA/CA.

IV. Suspendable CSMA/CA Algorithm

This section presents the proposed Suspendable CSMA/CA algorithm for IEEE 802.15.4 standard to improve packet delivery rate with densely deployed devices operating in the narrow Sub-1 GHz bands.

A. Suspendable CSMA/CA Algorithm

The right part of Figure 4 shows the proposed Suspendable CSMA/CA algorithm for non-slotted IEEE 802.15.4 mode. The left part illustrates standard CSMA/CA for non-slotted and slotted IEEE 802.15.4 modes, respectively. The Suspendable CSMA/CA algorithm sets NB = 0 and BE = macMinBE. A backoff time (BT) parameter is introduced to avoid unexpected long backoff. The BT is set to 0 initially. The algorithm then uniformly draws a random number of unit backoff periods within [0, 2^{BE-1}] and sets number of unit backoff periods (NUBP) to the random number drawn. It then performs active CCA in each unit backoff period. If channel is busy, the Suspendable CSMA/CA algorithm waits until to next unit backoff period and updates BT parameter. If BT exceeds the IEEE 802.15.4 standard defined threshold *macSuspendedCsmaMaxTime*, backoff fails. Otherwise, the algorithm performs active CCA again. In this case, NUBP is not decreased, in other words, the backoff is suspended because all backoff parameters including NB are not updated. If channel is idle, the Suspendable CSMA/CA algorithm decreases NUBP by 1. If the NUBP is not 0, then backoff has not completed. Therefore, the Suspendable CSMA/CA algorithm waits until to next unit backoff period and updates BT parameter. If BT exceeds the threshold *macSuspendedCsmaMaxTime*, backoff fails. Otherwise, the algorithm performs active CCA again. Otherwise, if the NUBP is 0, then backoff has been completed. Then Suspendable CSMA/CA algorithm performs standard CCA. If channel is idle, backoff successes. Otherwise, if channel is busy, Suspendable CSMA/CA algorithm increases NB by 1. If NB exceeds the predefined threshold macMaxCSMABackoffs, backoff fails. Otherwise, Suspendable CSMA/CA algorithm performs another round of backoff.

Figure 5 shows the proposed Suspendable CSMA/CA algorithm for slotted IEEE 802.15.4 mode, in which each operation starts at the boundary of backoff period.

Key differences between standard CSMA/CA algorithm and Suspendable CSMA/CA algorithm:

1) Suspendable CSMA/CA algorithm performs CCA in each unit backoff period, standard CSMA/CA algorithm does not perform CCA during entire backoff process.

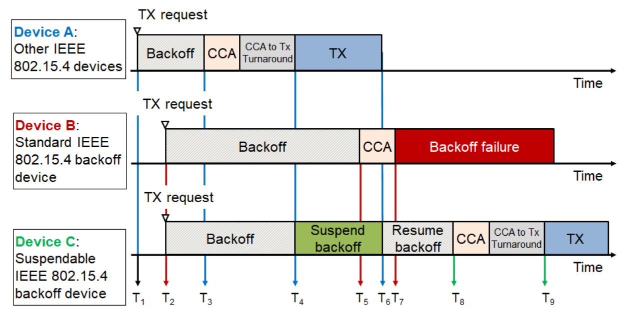

Fig. 3. Backoff Failure Reduction by Backoff Suspension

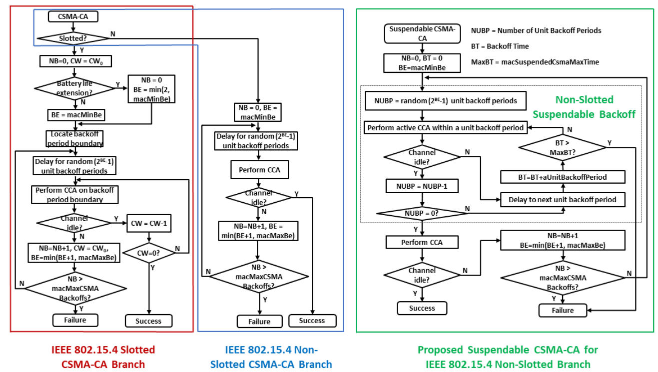

Fig. 4. Suspendable CSMA/CA Algorithm for Non-Slotted IEEE 802.15.4 Mode

2) Suspendable CSMA/CA algorithm performs CCA only if channel in the last unit backoff period is detected to be idle. On the other hand, standard CSMA/CA algorithm performs CCA no matter channel in the last unit backoff period is busy or idle.
3) Suspendable CSMA/CA algorithm increases NB only if other transmission starts within CCA period. On the other hand, standard CSMA/CA algorithm increases NB no matter other transmission starts before CCA period or within CCA period. Accordingly, standard CSMA/CA algorithm has greater probability to increase NB, which in turn causes more chance of backoff failure.
4) By performing active CCA, Suspendable CSMA/CA algorithm has capability to avoid packet discard caused by interference from non-IEEE 802.15.4 devices such as IEEE 802.11 devices.

B. Realization of Suspendable CSMA/CA in IEEE 802.15.4

The proposed Suspendable CSMA/CA is realized through association request and response message exchange, where nodes can indicate their intentions to perform backoff suspension based on their observations and network coordinators can decide if backoff suspension is permitted. Accordingly, the compatibility with conventional IEEE 802.15.4 CSMA/CA is maintained. Figure 6 shows the proposed ”Table 8-121 MAC PIB attributes” for IEEE 802.15.4me Task Group that incorporates accumulated approved amendments and corrigenda into the standard. The Suspendable CSMA/CA bit shall be set to one to indicate that the device will perform backoff suspension in Capability Information field format of Association Request command. Thus, each node can detect whether an associating

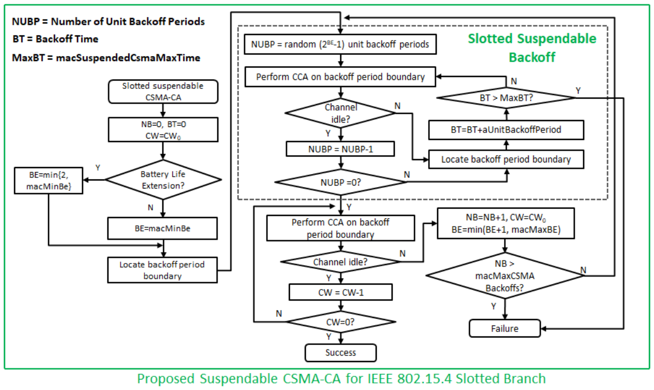

Fig. 5. Suspendable CSMA/CA Algorithm for Slotted IEEE 802.15.4 Mode

Attribute	Type	Range	Description	Default
macSuspendedCsma	Boolean	TRUE, FALSE	Indication that that suspended	FALSE
macSuspendedCsmaMaxTime	Integer	Implementation dependent	Timeout value for suspending backoff timer	Implementation dependent

Fig. 6. MAC PIB attributes on IEEE 802.15.4me Draft

Bits:0	1	2	3	4	5	6	7
Reserved	Device Type	Power Source	Receiver On When Idle	Association Type	**Suspendable CSMA/CA**	Security Capability	Allocate Address

Fig. 7. Capability Information field format on IEEE 802.15.4me Draft

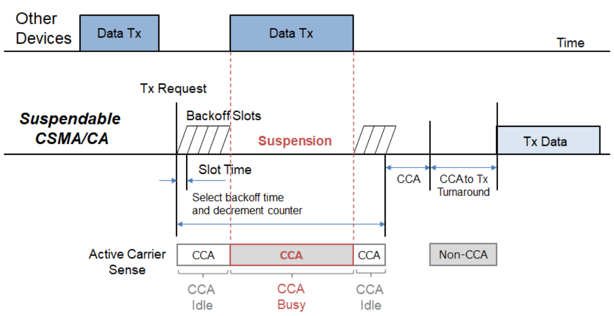

Fig. 8. Illustration of Proposed Suspendable CSMA/CA Mechanism

node supports Suspendable CSMA/CA or not. Figure 7 shows the proposed "Figure 10-140 Capability Information field format" for IEEE 802.15.4me TG as well. The proposed method has been approved at IEEE 802.15 Working Group Interim Meeting May 2023 for the next official IEEE 802.15.4 standard [17].

C. Illustration of Suspendable CSMA/CA Operation

Since the conventional IEEE 802.15.4g CSMA/CA tends to increase NB parameter faster when the network is congested and/or the network coexists with aggressive interfering networks as shown in Figure 2, the proposed Suspendable CSMA/CA suppresses the NB increase by active carrier sense during backoff process at the expense of increased delay and power consumption.

Figure 8 shows the operation of Suspendable CSMA/CA transmission when other devices transmit data during backoff period. In details, if CCA is busy during the backoff delay period, the backoff timer shall be suspended until sensing the channel indicates that the channel is clear or *macSuspendedCsmaMaxTime* is exceeded. Upon CCA detecting clear, the backoff time shall resume. if *macSuspendedCsmaMaxTime* is exceed, backoff ends in "Failure" and CSMA/CA algorithm terminates with a channel access failure [16].

TABLE I
SIMULATION PARAMETERS OF IEEE 802.15.4G

Parameter	**Value**
PANC	1
Node	20, 50, 100
Offered load (Network) [kbps]	10 - 100
Packet size [byte]	100
PHY parameters	
Frequency [MHz]	920
Modulation - Data Rate	2-FSK - 100 kbps OFDM Option 3 MCS 4 - 300 kbps OFDM Option 3 MCS 5 - 400 kbps
Channel spacing [kHz]	400
MAC parameters (JJ-300. 10 v2.2, Table 5-28, 5-29)	
LIFS [us]	1000 (for JJ-300.10)
phyCCADuration [us]	130
aTurnaroundTime [us]	1000
aUnitBackoffPeriod [us]	300
Rx-to-Tx Turnaround time [us]	300 (300 us or more, 1000 us or less)
Tx-to-Rx Turnaround time [us]	300 (Less than 300 us)
macMaxBE [us]	8
macMinBE [us]	8
macMaxCsmaBackoffs [us]	4
macMaxFrameRetries [us]	3

V. EVALUATION

IEEE 802.15.4 standard includes multiple physical layer (PHY) and medium access control (MAC) sublayer specifications for low-data-rate wireless connectivity [1]. In the simulation, we focus on IEEE 802.15.4g-FSK/OFDM PHY and IEEE 802.15.4/4e MAC for IoT applications operating in the Sub-1 GHz band.

Performance of the proposed Suspendable CSMA/CA was evaluated using Network Simulator 3 (NS-3). Table I describes the simulation parameters for IEEE 802.15.4g in the Sub-1 GHz band. In addition to 2-FSK PHY mode, OFDM PHY modes for higher throughput required IoT application are listed. In consideration of the narrower Sub-1 GHz band in Japan, Japanese communication standard JJ-300.10 MAC parameters are used. These parameters set has been discussed as typical IoT use case scenario at Sub-1 GHz Japan Interest Group of IEEE 802.15 Working Group for evaluation [18] [19]. Packet delivery rate (PDR) and data packet latency (DPL) are used as performance metrics for evaluation. Figure 9 shows the node deployment of 20 Nodes. The PANC (Personal Area Network Coordinator) is placed at the center of a 100 m circle. Data nodes are placed using the Sunflower algorithms used in IEEE 802.15 Working Group and IEEE 802.19.3 Task Group. The offered network load is uniformly distributed to data nodes. The data packet at each data node is generated using Poisson distribution. Each data node sends packets to PANC.

a) Packet Delivery Rate

Figure 10, 11 and 12 show the variation of the conventional IEEE 802.15.4 CSMA/CA and the proposed Suspendable CSMA/CA PDR with respect to different modulations, where Y-axis represents the ratio of the packet successfully delivered and X-axis represents the offered network load.

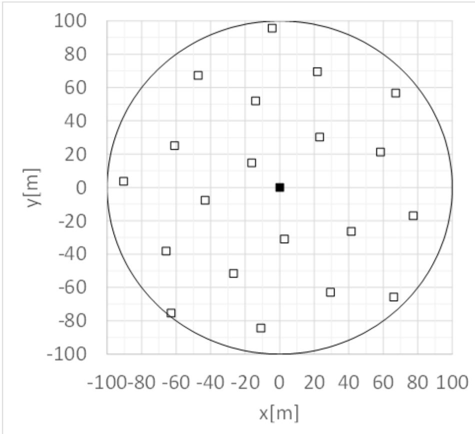

Fig. 9. Node deployment for 20 Nodes

20 Nodes: Figure 10 shows PDR curve for 20 nodes. PDR of 2-FSK was improved from 94.2 % to 98.8 % when the offered load was 50 kbps by applying the proposed Suspendable CSMA/CA. For OFDM MCS 4 and MCS 5, PDRs of the conventional IEEE 802.15.4 CSMA/CA and the proposed Suspendable CSMA/CA were almost same.

50 Nodes: Figure 11 shows packet PDR curve for 50 nodes. PDR of 2-FSK was improved from 89.9 % to 98.1 % when offered load was 50 kbps by applying the proposed Suspendable CSMA/CA. PDR of OFDM MCS 4 was improved from 94.3 % to 99.5 % when offered load was 70 kbps. PDR of OFDM MCS 5 was improved from 94.7 % to 99.6 % when offered load was 80 kbps.

100 Nodes: Figure 12 shows PDR curve for 100 nodes. PDR of 2-FSK was improved from 89.9 % to 99.6 % when offered load was 50 kbps by applying the proposed Suspendable CSMA/CA. PDR of OFDM MCS 4 was improved from 90.0 % to 99.1 % when offered load was 80 kbps. PDR of OFDM MCS 5 was improved from 89.8 % to 99.1 % when offered load was 90 kbps. The trend of PDR was similar to 50 node case.

From Figure 10, 11 and 12, the proposed Suspendable CSMA/CA improves packet delivery rate by 9.7 points (89.9 % to 99.6 %) in 100 Nodes, 50 kbps offered load case.

b) Data Packet Latency

Data Packet Latency is defined as time difference from the time a packet transmission process starts to the time packet is successfully confirmed. Therefore, the latency is $T_{Backoff}+T_{DataTx}+T_{WaitingACK}+T_{ACKRx}$. Figure 13, 14 and 15 show the variation of the conventional IEEE 802.15.4 and the proposed Suspendable CSMA/CA latency with respect to different modulations, where Y-axis represents latency in ms and X-axis represents the offered network load.

20 Nodes: For 2-FSK, latency was increased by about 30ms by the proposed Suspendable CSMA/CA. For OFDM MCS 4 and 5, latency was increased by about 10 ms and 5ms, respectively.

50 Nodes: For 2-FSK, latency was increased by about twofold when offered load was 50 kbps. For OFDM MCS 4, latency was increased by about 120 ms when offered load was 70 kbps. For OFDM MCS 5, latency was increased by about 80 ms when offered load was 80 kbps.

100 Nodes: For 2-FSK, latency was increased by about twofold when offered load was 50 kbps. For OFDM MCS 4, latency was increased by about twofold when offered load was 80 kbps. For OFDM MCS 5, latency was increased by about twofold when offered load was 90 kbps.

Since the proposed Suspendable CSMA/CA is designed to mitigate packet loss by channel access failure, the latency tends to increase in exchange for improved packet delivery rate and less packet discard.

VI. Conclusion

Sub-1 GHz Wireless Communications of LPWAN are attracting attention for IoT applications. In addition to battery-powered devices, the number of grid-powered and solar-powered sensor devices using LPWAN are also rapidly increasing for various IoT applications. We focus on improving the efficiency of IEEE 802.15.4 CSMA/CA when a large number of the non-power supply constrained devices are deployed. Suspendable CSMA/CA proposed for IEEE 802.15.4 can mitigate packet loss by channel access failure while maintaining compatibility with conventional IEEE 802.15.4 CSMA/CA. The proposed algorithms have been validated using NS-3 (3.23). Using simulation parameters discussed in IEEE 802.15.4 Working Group, simulation results show that the proposed schemes achieve 9.7 points (89.9 % to 99.6 %) improvement in Packet Delivery Rate (PDR) compared to the conventional IEEE 802.15.4 CSMA/CA. Although the delay time will increase, we believe that the impact on IoT applications with low real-time performance, such as sensor readings, will be minimal by applying the proposed *macSuspendedCsmaMaxTime* threshold. Suspendable CSMA/CA has been also approved for the next IEEE 802.15.4 amendment by our leading activities in IEEE 802.15 Working Group. This leads higher spectrum efficiency in the limited Sub-1 GHz wireless bandwidth for IoT applications. The results of the evaluation on actual equipment will be reported in the future.

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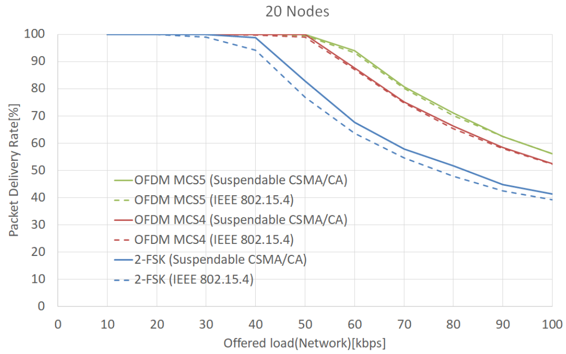

Fig. 10. Packet Delivery Rate of 20 Nodes

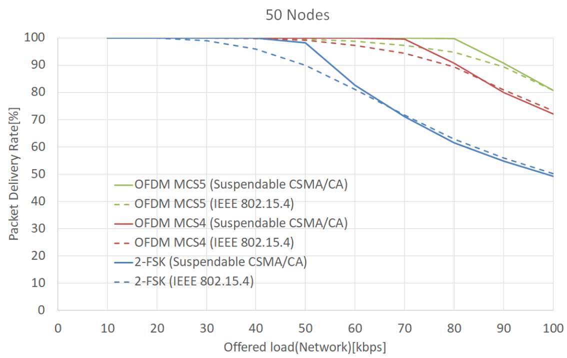

Fig. 11. Packet Delivery Rate of 50 Nodes

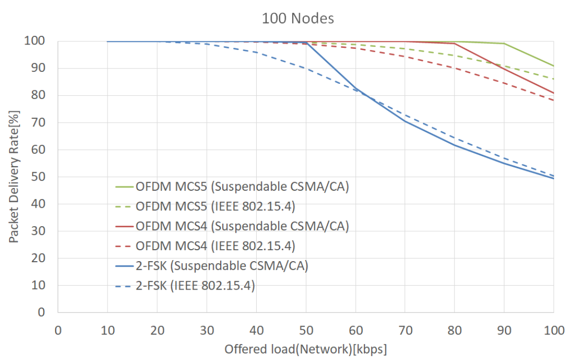

Fig. 12. Packet Delivery Rate of 100 Nodes

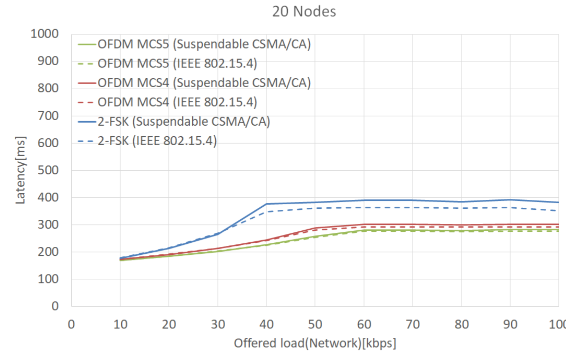

Fig. 13. Data Packet Latency of 20 Nodes

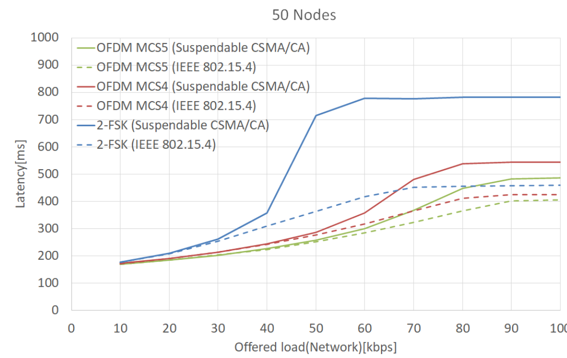

Fig. 14. Data Packet Latency of 50 Nodes

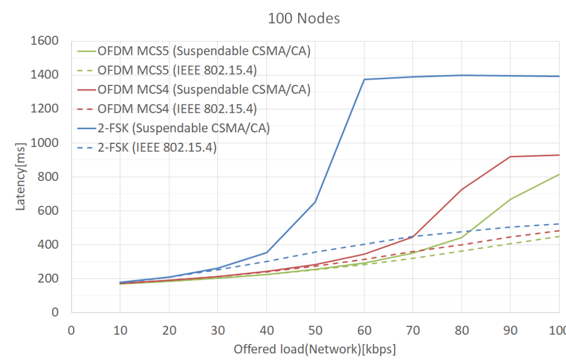

Fig. 15. Data Packet Latency of 100 Nodes

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