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Abstract

Industrial sensing, monitoring and automation offer a lucrative application domain for networking and communications. Wired sensor networks have traditionally been used for these applications because such networks adequately meet two vital requirements, i.e., low latency and high reliability, needed for an industrial deployment. Wired sensor networks, however, are not very cost effective due to higher components' cost. These networks also lack the flexibility needed for subsequent topological changes. Wireless sensor networks (WSN), on the other hand, are less expensive and offer high degree of flexibility. Wireless networks, therefore, can offer an attractive and viable solution for industrial sensing and automation. IEEE 802.15.4 standard defines a specification for MAC and PHY layers for short-range, low bit-rate, and low-cost wireless networks. However, the specified system is inefficient in terms of latency and reliability and fails to meet the stringent operational requirements for industrial applications. In this paper, we propose a set of new MAC superframes with an aim to enhance both performance metrics. We then use simulation to compare the performance of our proposed systems with that of the one specified in IEEE 802.15.4 standard.

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***Abstract*—Industrial sensing, monitoring and automation offer a lucrative application domain for networking and communications. Wired sensor networks have traditionally been used for these applications because such networks adequately meet two vital requirements, i.e., low latency and high reliability, needed for an industrial deployment. Wired sensor networks, however, are not very cost effective due to higher components' cost. These networks also lack the flexibility needed for subsequent topological changes. Wireless sensor networks (WSN), on the other hand, are less expensive and offer high degree of flexibility. Wireless networks, therefore, can offer an attractive and viable solution for industrial sensing and automation. IEEE 802.15.4 standard defines a specification for MAC and PHY layers for short-range, low bit-rate, and low-cost wireless networks. However, the specified system is inefficient in terms of latency and reliability and fails to meet the stringent operational requirements for industrial applications. In this paper, we propose a set of new MAC superframes with an aim to enhance both performance metrics. We then use simulation to compare the performance of our proposed systems with that of the one specified in IEEE 802.15.4 standard.**

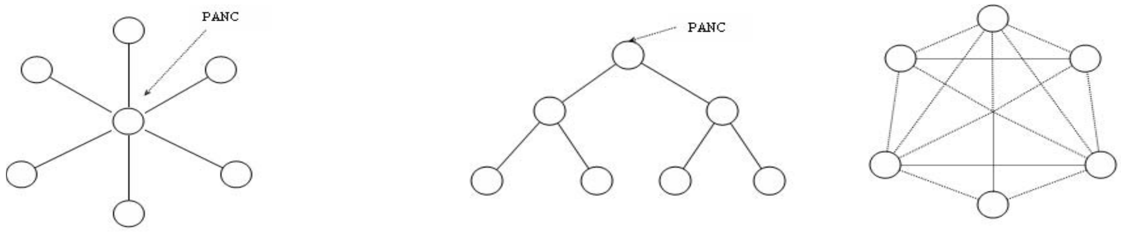
I. Introduction

In many industrial environments, monitoring the 'health' of industrial units is crucial for smooth functioning and responding to a malfunctioning in the system. A suddenly broken machine, for example, can incur much more damages as compared to the cost of a systematic shut down of a machine for service well before it breaks down, had we timely gotten its state information. Wired sensor networks are generally used for such applications due to the high degree of reliability and low latency that these networks offer. Such networks, however, are costly, complex, and inflexible. A change in topology of the network would mean reinstallation of the wired backbone that may not be cost effective and can force a prolonged down time. That leads to a need for a reconfigurable, low cost, and less installation intensive sensor networking technology that satisfies the requirements of industrial applications. The very possible solution may lie in the use of wireless sensor networks (WSN). These networks are both cheap to install and flexible to topological changes due to their relatively simple and fast setup procedures. The challenge, however, lies in providing a similar degree of performance for reliability and latency as offered by their counterpart wired networks. Limited resources that are generally available to sensor nodes effectively preclude the use of forward error correction codes or other computationally intensive approaches.

Wireless data networks have long been used in diverse environments. Wireless cellular networks, WiFi, Bluetooth, WiMax, and RF, for example, are all well suited to their respective application domains. A prime candidate technology for applications in industrial control and automation is the specification defined by IEEE 802.15.4 WG. It specifies both the MAC and physical layers for a multi-hop wireless network. However, IEEE 802.15.4 standard fails to satisfy the stringent requirements for latency and reliability performance necessary for industrial deployments. Recent research work has highlighted the limitations on its performance. For example, significant transmission delays in this MAC have been reported in [3] and a larger frame size has been suggested in [4] to relax throughput limitations. Analytical model in [5] targets ZigBee, which uses IEEE 802.15.4 Mac, to study the transmission delays and node lifetimes under single hop and multiple hop scenarios. Discrete Markov chains were used in [2] to model CSMA/CA algorithm used in IEEE 802.15.4 to study its throughput and energy consumption. However, to our best of knowledge, delay and reliability performance for time critical applications, operating under error-prone wireless channels, has not been specifically studied for IEEE 802.15.4 wireless networks.

In this paper, we propose three variants of the base IEEE 802.15.4 MAC with an aim to enhance the performance in order to support time-critical communications. These enhancements stem out of a provision for multiple and successive retransmission attempts for a failed transmission of a data frame. This is in contrast to the original specification, where a failed frame gets a delayed retransmission attempt and by that time the information may become obsolete. We simulate all three proposed schemes as well as the original MAC and compare their performance to show that significant performance gains are achievable by our proposed changes.

Rest of the paper is organized as follows. Section II describes 802.15.4 MAC and outlines its drawbacks. In Section III, we present our enhanced schemes for MAC. Section IV describes our simulation setup. A discussion on simulation results follows in Section V. Finally, in Section VI, we draw our conclusions.



(a) StarNetwork (b) Tree Network (c) Mesh Network

Fig. 1. Possible WPAN network topology

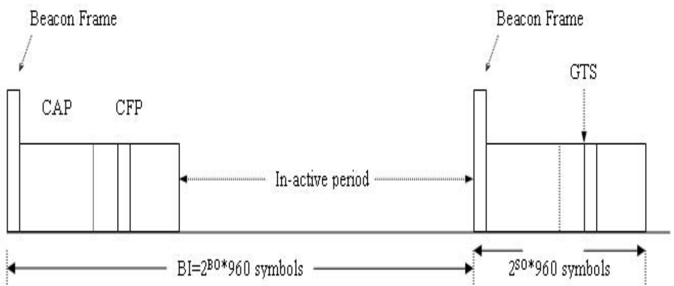


Fig. 2. Super-frame structure of IEEE 802.15.4 MAC

II. IEEE 802.15.4 MAC super-frame Structure

We now briefly describe the structure of 802.15.4 MAC layer. More details can be found in [1]. IEEE 802.15.4 standard allows a WSN to assume a topology of a mesh, tree, or a star network as depicted in Figure 1. The IEEE 802.15.4 MAC operates in two modes, i.e. beacon-enabled mode and nonbeacon-enabled mode[1]. In beacon-enabled networks, which can assume only a tree or star topology, all non-leaf nodes periodically transmit their beacon frames that provide a greater synchronization in the network. In this mode, PAN coordinator starts a superframe that consists of a beacon, an active period, and an inactive period as illustrated in Figure 2. While starting a PAN, coordinator sets PAN ID and the length of both active and inactive periods. The active period consists of sixteen equal sized time slots and contains (1) a contention access period (CAP), which uses CSMA/CA for channel access in a non-slotted Aloha fashion, and (2) a contention free period (CFP), which consists of guaranteed time slots (GTS) that are allocated on demand to nodes for a contention-free access to the channel. A joining node first listens for beacons in search for a desired PAN and then sends an association request to a potential parent. Member nodes can switch over to sleep mode during inactive period of the superframe to save battery power. For this work, we will study a beacon-enabled star network that consists of a central node, called PAN coordinator, which lies in the center of logical star topology and all other nodes, called end-devices or leaf nodes, are wirelessly linked with PAN coordinator. Contrary to a mesh or tree network, where nodes can directly communicate with peer nodes, the nodes in a star network can only communicate with the PAN coordinator. Notwithstanding the restrictions on peer-to-peer communications, star networks offer lower latency and higher reliability that enables them to be a good candidate for deployment under industrial environment.

In IEEE 802.15.4 standard, GTS traffic is considered independent from CSMA traffic at all nodes. That restricts the ability of a GTS frame that failed to transmit in its allocated slot to also use CAP for retransmission to better satisfy latency and reliability requirements. Such a scenario is increasingly more likely when a PAN is operating under a time varying channel and GTS frames are prone to channel errors.

III. Improved Low Latency super-frame Structure

In this section, we describe the proposed modifications to the superframe structure of IEEE 802.15.4 specification in order to improve latency and reliability performance. First, we note, in IEEE 802.15.4 spec, that CFP is placed near the end of active period of the superframe just after the CAP. That, in fact, is a major factor in introducing a large latency because a failed GTS frame will have to wait for the next superframe to get a retransmission attempt. It must wait at least for the duration of inactive period and a beacon frame. Please note that the size of inactive period is generally much larger than that of the active period in these networks. A quick and simple resolution for that problem is to swap the position of CAP and CFP in the superframe. That is our first proposed scheme, which makes a basis for further changes. Since a GTS is always allocated in the following superframe after a request is received, the swapping will not affect the way it gets allocated. To get a full potential of available bandwidth and further reduce latency, we need to provide additional opportunities for retransmission of a failed GTS frame in the following CAP of same superframe as explained in the following section.

A. Retransmission Mechanism

As mentioned in the previous section, the delay encountered by a failed GTS frame, which needs a retransmission, can be significantly high in IEEE 802.15.4 MAC because that frame can possibly get a chance of retransmission only in a GTS of next superframe. That delay can be reduced by allowing a retransmission of this GTS frame during a CAP while competing with non-GTS frames. We study that possibility for IEEE 802.15.4 MAC, where the failed GTS frame can only be tried in CAP of the next superframe, and for our flipped

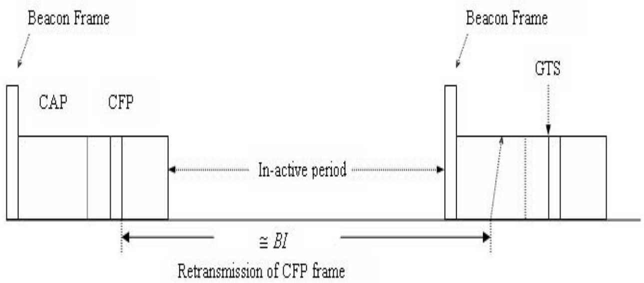


Fig. 3. Proposed retransmissions of CFP frames in CAP

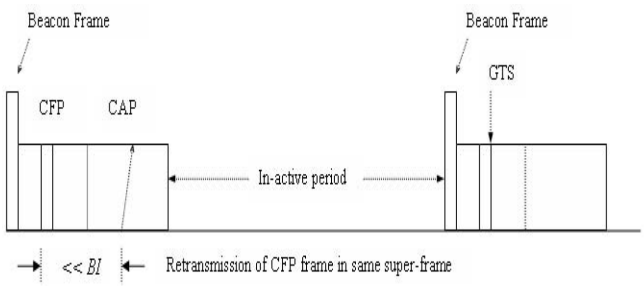


Fig. 4. Swap of CFP and CAP and retransmissions of GTS frames in CAP

version, where a retransmission of the failed GTS frame can be attempted in CAP of the same superframe. The concept is illustrated in Figure 3 and Figure 4. As expected, significant performance gains for latency were observed in our simulations. Our final proposed MAC scheme uses a superframe with swapped CFP and CAP and allows retransmission of failed GTS frames in CAP.

We assume that sensor nodes check for new GTS frame arrivals right before the start of their allocated GTS only. In addition, when a new GTS frame arrives, the current GTS frame, if still lingering in the buffer, is dropped. Under such a mechanism, allowing a re-transmission in CAP of failed GTS frames also results in enhanced reliability performance of IEEE 802.15.4 MAC. That is true because of the fact that more retransmission attempts can be made before the frame is eventually dropped.

IV. Simulation Settings

We use OPNET simulation software for performance evaluation of (1) IEEE 802.15.4 standard MAC, (2) our proposed MAC with swapped CAP and CFP, (3) IEEE 802.15.4 MAC with retransmission of GTS frames in CAP (of the following superframe), and (4) our swapped MAC with retransmission of GTS frames in CAP (of the same superframe). We assume a network having a star topology and consisting of a PAN coordinator and 27 sensor nodes. Only 7 sensor nodes are statically allocated a GTS that is the maximum number of allocations in IEEE 802.15.4 specification. All data frames, GTS or otherwise, are transmitted by sensor nodes to PAN coordinator and the receiver must acknowledge the received frames. We assume an error-free transmission for ACK frames. The data frames, however, encounter an error-prone channel having a pre-defined probability of error. We also assume error free transmission for control frames including GTS request frames. When a frame is received in error, PAN coordinator does not process its acknowledgment, thus, forcing the sender node to time out and schedule a retransmission.

For superframe structure, we set $BO = 5$ and $SO = 2$, which gives a duty cycle of 12.5%. The PHY data rate is assumed to be 250 Kbps. Also, we use a 2.4 GHz channel with Quadrature Phase Shift Keying modulation for the PHY with symbol size equal to 4. That gives a superframe duration of 61.44 ms. The duration for CAP is 33.94 ms and that for CFP is 26.8 ms. Besides, the duration for beacon frame is 0.7 ms. In addition, each GTS time slot has a duration of 3.84 ms. All other CSMA/CA parameters are assumed to be the default values as defined in IEEE 802.15.4 standard. Besides, each data frame has a fixed size of 304 bits including the MAC and PHY headers. The wireless channel is assumed to be static in our simulations.

The data frames (for both of GTS as well as CSMA traffic) are assumed to have Poisson arrivals. We assume that the buffering capacity, for GTS traffic, at MAC level is one and for CSMA traffic is 35 frames. Each simulation run runs 5 hours of simulated time.

V. Results and Discussion

In our simulations, we focused on studying two important performance metrics, that is, transmission latency and frame drop rate. The GTS frame arrival rate for each node was fixed at 0.5 frames per second. System performance at different arrival rates for CSMA traffic and using different levels of channel quality (by varying channel error probability) is studied in these simulations. Let us first consider the frame drop rate (for GTS data frames) for the four schemes. In Figure 5, we plot GTS frame drop rate against CSMA offered load. For this plot, we fixed a relatively low value for channel error probability, i.e. $P_e = 0.1$, implying that about 10% of all data frames will fail to transmit due to a channel error. That means about one-tenth of GTS frames will not transmit successfully in their allocated slots. As the plot in Figure 5 shows, if these failed frames are allowed to compete for channel access in the following CAP, GTS frame drop rate decreases. However, that benefit is available only at lower CSMA traffic load (i.e. less than 30 CSMA frames per second). At higher traffic load, the contention for channel access becomes high and overall probability of a successful transmission in CAP becomes low, thus, rendering retransmission attempts useless.

Figure 6 examines the effect of link quality on the GTS frame drop rate. For this plot, CSMA traffic load is fixed at 0.125 frames/second for each node. Here the two schemes with retransmissions show much better reliability performance than those without retransmissions. The gain is significant at low values of P_e and more so at high values of channel error probability. At a relatively low CSMA load (i.e. 0.125 frames/second), GTS frames get more opportunities for re-transmission and better channel access that results in lower GTS frame drop rate.

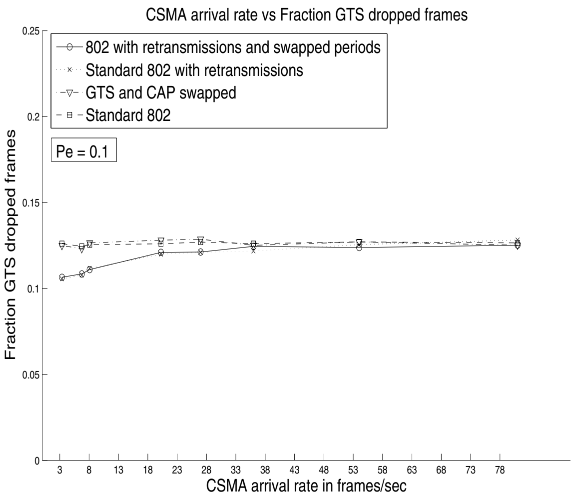


Fig. 5. GTS frame drop rate vs CSMA load for various schemes

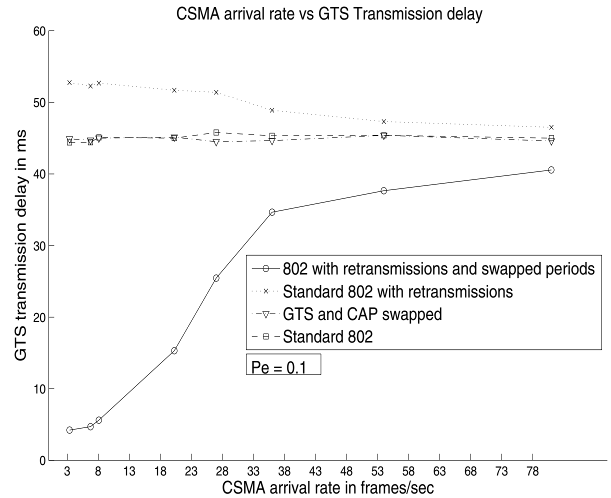


Fig. 7. GTS frame transmission delay vs CSMA load for various schemes

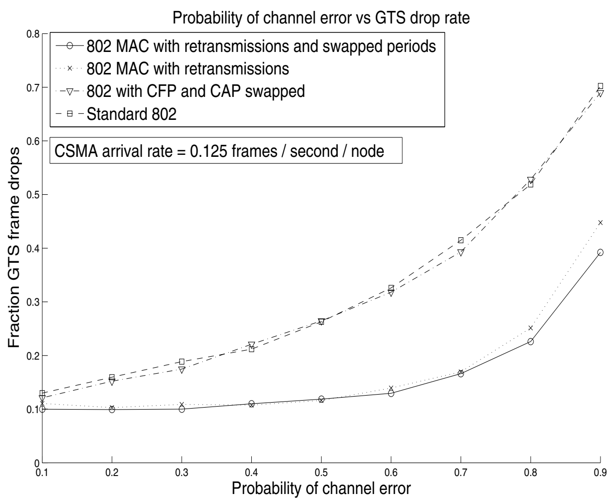


Fig. 6. GTS frame drop rate vs Probability of frame error for various schemes

The simulation experiments for Figure 7 and Figure 8 aim at latency performance evaluation of the four schemes when the CSMA load or channel error probability is changed. Figure 7 shows the core results of this paper. The plot in that figure shows huge gains, especially at lower and middle values for load, which are achieved by our proposed scheme. These results are indicative of the fact that retransmission attempts for failed GTS frames are available soon after the failed transmission of that frame. Even at higher degree of CSMA loads, our scheme performs significantly better than the other schemes. On the other hand, IEEE 802.15.4 with retransmissions performs worse (than even schemes without retransmissions) because failed GTS frames may be successfully retransmitted in CAP. However, that happens only in the next superframe, thus, registering large delays. For the schemes without retransmissions, significant portion of the failed GTS frames end up being dropped resulting in lower overall delay since delay is counted only for successfully transmitted frames.

The plot in Figure 8 shows transmission delay as a function of P_e. As we can see, the schemes with CAP retransmissions perform relatively better than other two schemes. Our proposed MAC, however, performs superior to all schemes even at higher values of P_e. An interesting case emerges for IEEE 802.15.4 with retransmissions. As opposed to the case in Figure 7, it now performs better than the two schemes without retransmissions. Because of the higher values of P_e, most of the GTS frames need more retransmission attempts to get successfully transmitted. Given the lower CSMA arrival rate, failed GTS frames get better chance to succeed in a CAP. This is in contrast to the schemes with no retransmissions, where these GTS frames can only be retransmitted in GTS and hence the number of frames seeing longer delays is significant in spite of the inherent drop rate. This is in contrast to the case when $P_e = 0.1$ hence IEEE 802.15.4 with retransmissions outperforms the two schemes that do not allow retransmissions in CAP.

In Figure 9 and Figure 10, we study the impact of CSMA traffic load on queue size and CSMA frame transmission delay, respectively. The goal is to see the effect of GTS frame retransmissions in CAP on overall performance of CAP mechanism. As we can see in Figure 9, allowing failed GTS frames to contest for channel access in CAP have no noticeable impact on the queuing capacity. On the other hand, CSMA traffic mildly suffers, especially so for higher CSMA arrival rates, by extra transmission delay in schemes with CAP retransmissions. That is so because some of the GTS frames get retransmissions in CAP resulting in not only a higher contention for channel but also less transmission opportunity since GTS frames get preferential treatment in CAP.

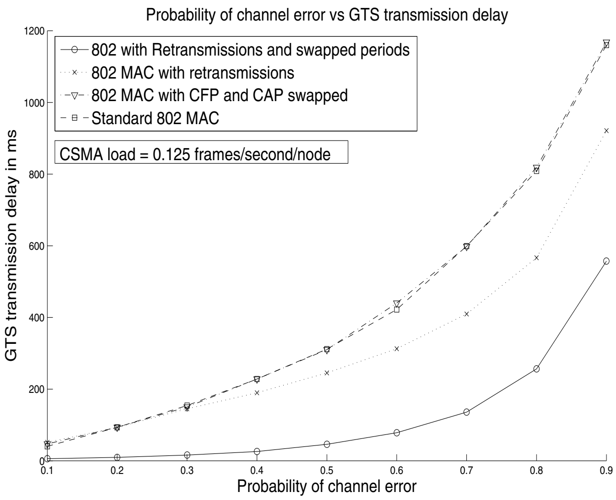


Fig. 8. GTS frame transmission delay vs Probability of frame error for various schemes

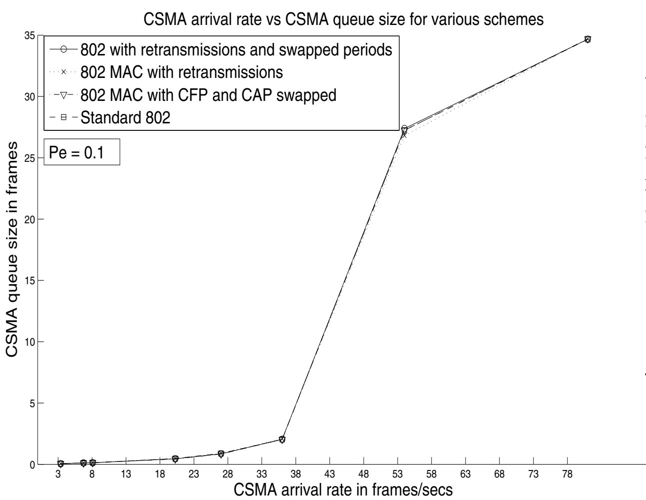


Fig. 9. CSMA queue size vs CSMA load

VI. Conclusion

In this paper, we proposed three variants of IEEE 802.15.4 MAC for enhancing vital performance metrics, namely, transmission latency and packet drop rate, to target deployments of wireless sensor networks in industrial environments. We used simulation to compare the performance of all four schemes. We showed that the performance of IEEE 802.15.4 MAC is not adequate for such applications. Our proposed scheme with both modifications achieves significant gains, especially in reducing the transmission delays, by incorporating relatively minor changes in the structure of superframe. We observed that, under low CSMA load at nodes and low P_e, there was an improvement of more than 95% in latency performance. Reliability increased by almost 50% at low CSMA load moderate P_e.

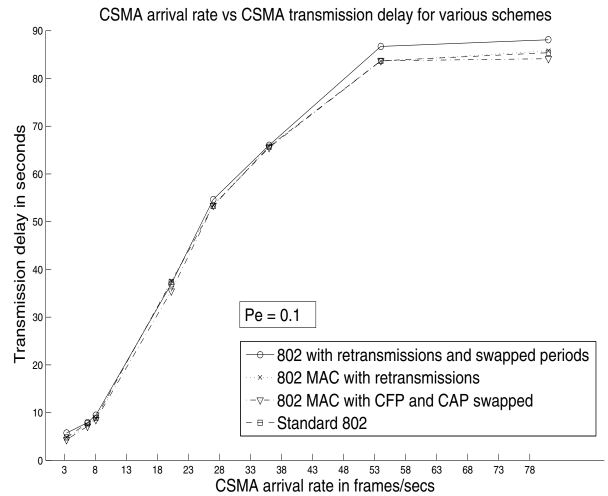


Fig. 10. CSMA frame transmission delay vs CSMA load

VII. Future Work

The simulation results shown in this paper can be verified by defining an analytical model of the system. In addition, it will be nice if a failed GTS frame can get another GTS for retransmission in the same superframe rather than getting retransmission attempt in the CAP. That will help the sending node to get uncontested channel access and a better chance of successful transmission.

Acknowledgment

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