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Novel MAC Layer Proposal for URLLC in Industrial Wireless Sensor Networks

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Abstract

Ultra-reliable and low-latency communications (URLLC) has become a fundamental focus of future industrial wireless sensor networks (IWSNs). With the evolution of automation and process control in industrial environments, the need for increased reliability and reduced latencies in wireless communications is even pronounced. Furthermore, the 5G systems specifically target the URLLC in selected areas and industrial automation might turn into a suitable venue for future IWSNs, running 5G as a high speed inter-process linking technology. In this paper, a hybrid multi-channel scheme for performance and throughput enhancement of IWSNs is proposed. The scheme utilizes the multiple frequency channels to increase the overall throughput of the system along with the increase in reliability. A special purpose frequency channel is defined, which facilitates the failed communications by retransmissions where the retransmission slots are allocated according to the priority level of failed communications of different nodes. A scheduler is used to formulate priority based scheduling for retransmission in TDMA based communication slots of this channel. Furthermore, in carrier-sense multiple access with collision avoidance (CSMA/CA) based slots, a frequency polling is introduced to limit the collisions. Mathematical modelling for performance metrics is also presented. The performance of the proposed scheme is compared with that of IEEE802.15.4e, where the performance is evaluated on the basis of throughput, reliability and the number of nodes accommodated in a cluster. The proposed scheme offers a notable increase in the reliability and throughput over the existing IEEE802.15.4e Low Latency Deterministic Networks (LLDN) standard.

Keywords

industrial wireless sensor network (IWSN); IEEE802.15.4e; Low Latency Deterministic Network (LLDN); low latency communications (LLC); ultra-reliable low latency communication (URLLC)

1 Introduction

The past couple of decades have witnessed a relatively perpetual rise in industrialization and automation of the processes [1]. In the competitive industrial world, automation is the key to cost reduction whether it is a production, nuclear power, oil refinement or chemical plant [2]. These industrial plants can greatly benefit from technological advancements and can implement successful process control with efficient and effective formation of a close loop control system. However, to introduce a suitable process control, a reliable communication infrastructure is needed which should also offer scalable architecture for future enhancements and permits infrastructural extension in the ever-changing industrial plants [3]-[6]. To cope with the first objective (reliability), wired networks offer suitable solutions but some intrinsic properties of these networks do not sit very well with the present-day industries. The lack of scalable architecture and flexibility of industrial wired networks poses serious limitations for dynamic industrial environments. On top of that, the high price tag in the wired networks also comes as a setback. As an alternate to the wired feedback systems in the industrial infrastructure, industrial wireless sensor networks (IWSNs) are also sometimes considered as a more cost-effective approach. However, the less predictable wireless communication links in IWSNs appear to be a major challenge [7]. Therefore, in order to establish a wireless feedback network, the reliability and real-time data delivery must be ensured in such networks.

The IWSNs offer a suitable reduction in the deployment cost as well as the maintenance cost of the feedback communication loop and in some cases these wireless networks offer a cost reduction by a factor of ten or even more [5], [8]. The IWSNs also offer other significant benefits over traditional wired networks. These benefits include scalability, cost efficiency, self-healing ability, reduced planning overload for network formation, and relatively less time for new installations of IWSNs [7]. All these benefits have encouraged the use of IWSNs in industries, eventually leading to an extensive increase in research and development activities to ensure suitable IWSN solutions for enabling it for wider variety of applications in the industries.

In the past couple of decades, the use of IWSNs has exponentially increased and can primarily be credited to the improvements in Micro Electro Mechanical Systems (MEMS) technology, which enabled the cost and size reduction of the sensor nodes and an increase in processing capabilities and memory capacity as well. The present IWSNs are capable of taking in account the channel conditions, sensor readings, network specifications and suitable responses to the sampled sensor data. These abilities if properly utilized can also serve as a tool to overcome uncertainty in wireless links and timely delivery of the information. All these improvements in IWSNs have encouraged their use in industrial environments. In past few years many industrial protocols and IEEE standards surfaced, which include Zigbee, WirelessHart, 6LoWPAN, WiaPA, ISA100.11a, IEEE802.15.4, and IEEE802.15.4e [9]–[16]. The time-division multiple access (TDMA) based channel access was introduced in IWSNs over traditional carrier-sense multiple access with collision avoidance (CSMA/CA) based access for guaranteed channel access and improved reliability. The research community also contributed in many research oriented solutions targeting improved reliability, network lifetime enhancement and real-time data delivery. A few priority based schemes were also defined to offer hierarchical access to the wireless channel resources. In some cases, the use of multiple channels for enhanced data rates was also considered as well.

Despite these benefits and the recent improvements, the researchers are still struggling to offer substantial solutions for the improved reliability and real-time data delivery in IWSNs to match the strict deadlines as needed for the close loop process control and ultra-reliable and low-latency communications (URLLC) [17], [18]. URLLC is mandatory for IWSNs, especially when dealing with emergency communications and regulatory and supervisory control feedback systems. To improve the overall acceptability of IWSNs, and to cope with fast paced improvements in industry and protocol stack developments, restructuring and procedural changes for URLLC in IWSNs are very important. Furthermore, the inclusion of Machine-to-Machine (M2M) communications in 5G offers potentially benefitting framework, targeting three main aspects of IWSNs: 1) supporting for large number of low-rate network devices, 2) sustaining a minimal data rate in all circumstances to satisfy the feedback control requirements, and 3) enabling very low-latency data transfer [19]. Further architectural improvements and procedure restructuring are necessary for 5G M2M infrastructure to address such requirements in IWSNs.

In this paper, a multi-channel TDMA based hybrid scheme is proposed, which benefits from the use of multiple-channels and short frame communication for the communication of time critical data. The proposed scheme targets real-time data delivery with improved data reliability. The effectiveness of the scheme is demonstrated with a test case with two frequency channels: one is used for the slotted access of the medium of communication for low latency networks, and the other channel used for the communication of the urgently required or critically needed information to be delivered to the control center within a specified time deadline. The second channel is also used for the retransmission of the failed communications to improve reliability of the communication taking place in the network. The time deadline enforced by the control society is taken into consideration to offer a reliable solution for close loop control systems in industrial plants.

The performance of the proposed work is also presented in this paper in comparison with the IEEE802.15.4e LLDN, specifically defined for industrial automation. Since the proposed scheme considers typical IWSNs, the work can further be extended to certain specific 5G network application areas. Communications for ubiquitous machine type devices, Moving Networks (MNs) and Ultra Reliable Communication (URC) [20] are some of the examples. Besides, as demonstrated in the results, the proposed protocol is able to use multi-channel diversity to incorporate a large number of nodes. This ability enables it to be considered for applications in 5G ultra dense networks (UDNs) [21].

The rest of the paper is organized as follows. Section 2 presents literature review. The proposed system model is presented in Section 3. Section 4 discusses the results and presents performance analysis. Finally, Section 5 gives conclusions and future directions.

2 Literature Review

The IWSNs are now widely used in various industrial processes. Different industrial wireless protocols are also defined to facilitate certain industrial applications and to encourage the use of IWSNs in these applications. Most of the industrial protocols presently used in the industry are CSMA/CA based and the core functionalities of physical and media access control (MAC) layers are inherited from IEEE802.15.4. Zigbee and 6LoWPAN are examples of such protocols. Although the specified protocols offer flexibility of operation and can be used to establish ad-hoc on-demand networks with the ability of active network formation and handling runtime changes, these protocols are more suitable for monitoring traditional wireless sensor networks (WSNs) applications. Since the suitability of WSNs in time insensitive applications is widely accepted, this paper is focused on time sensitive and reliable IWSNs.

In 2012, the IEEE 802.15.4e standard was launched, which mainly targets the critical applications of WSNs and primarily focuses on industrial environments where time-sensitive and information-critical data are to be routed [15]. It uses TDMA based channel access to ensure collision free access to the wireless resources on pre-specified and dedicated time slots. This standard also takes into consideration the low latency demands of the industrial processes and so a special framework, Low Latency Deterministic Network (LLDN) is introduced to meet the critical time deadlines for the emergency and close loop control applications. Some widely used industrial protocols (ISA100.11a, WirelessHART, etc.) also use TDMA based channel access.

Some recent researches have also targeted the priority based communications in IWSNs. In [22], the authors established priority levels based on the critical nature of information. The entire traffic in the network is divided in four levels where the highest priority nodes get instant channel access and its communication is facilitated by allocating the channel bandwidth of low priority nodes to it. In other words, based on the assigned priority level, a high priority node can hijack the low priority traffic bandwidth. The protocol offers an improved QoS for high priority nodes at the price of the low priority node's communication sacrifice. In [23], the authors present an arbitration based protocol where each node is assigned with a unique frequency. The frequency assignment is linked to the priority of the node and hence, on the basis of these preassigned frequencies a priority-wise schedule of transmission is created. The protocol executes in two phases, an arbitration decision period and an arbitration execution period. In the arbitration decision period, each node that wants to communicate broadcasts its preassigned frequency to determine a deterministic channel access order. This allows each node participated in the arbitration decision period to know how many time slots it has to wait before its transmission can take place, thus, the node assigned with arbitration frequency of the highest priority communicates instantly, while the node with the lowest priority arbitration frequency waits until all the other nodes have communicated. The scheme allows multilevel priority system, however, it requires a special coordinator to identify the received arbitration frequencies and respond to them accordingly. The frequencies are also preassigned on the basis of the pre-specified priority system which implements static priority system. Furthermore, with the increase in number of nodes, the problem in defining orthogonal frequencies also surfaces.

The multi-channel schemes in IWSNs for MAC optimization offer improved medium utilization. Many schemes are presented in literature which use multi-channels to offer improvements in the existing scenarios. In [24], the authors demonstrated the effectiveness of the multi-channel schemes in improving throughput over other schemes. In [25], the authors took into account the benefit of the availability of multiple channels, defined a scalable media access and considered the limitation of the presently available sensor nodes. However, this scheme requires frequent channel hopping and has relatively high scheduling overhead. In [26], the authors used TDMA based channel access in a multi-channel scenario. The scheme is relatively static and does not exploit the available resources. In [27], a pseudo random scheduling was introduced where each node randomly decides two factors, the wakeup time and the channel sequence. The primary aim of the protocol is to distribute the traffic in the available communication resources. However, the scheme fails to offer an efficient traffic scheduling and resource sharing mechanism. In [28], the authors used multiple channels to increase the network throughput. The proposed algorithm eliminates collisions by establishing coordinated transmissions. The scheme schedules both periodic and event based traffic using reinforcement learning to establish collision free transmissions on parallel data streams using multiple channels. However, the scheme fails to offer a differentiated treatment for different datasets of different priorities. It also fails to suggest a suitable alternate in case of communication failure. In [29], the authors proposed a multi-channel scheme where the network is divided into sub-trees. Once divided, each subtree is allocated a unique channel. In [30], the authors present a multi-channel scheme for the static networks. The scheme benefits from the TDMA based source aware scheduling. However, the scheme fails to give satisfactory assurance on reliability of the scheme. In [31], the multichannel overhead reduction was achieved using the regret matching based algorithm. For the evaluation of the proposed scheme, both software and hardware based analyses were presented. In [32], the authors proposed a hybrid scheme that uses both TDMA and CSMA/CA for communication purposes. The proposed work offers a mechanism to switch between the two access schemes based on the traffic density. The proposed protocol also considers multi-channel scenario. However, in this proposed scheme suitable reliability and QoS can only be achieved using much higher delays acceptable in critical industrial processes, making the scheme unsuitable for time critical and information sensitive industrial processes.

The discussed schemes though offer suitable improvements in the existing scenarios, almost all of the encountered schemes fail to offer suitable plans for retransmission of failed communications. In most of the cases, the importance of retransmission is ignored, which results in extended delay and failure in deterministic behavior of the network. The proposed scheme in this paper focuses on how to ensure the retransmission of failed communications up to certain desirable extent within the superframe and time deadline, which helps in improving both the overall delay and communication reliability.

3 Proposed System Model

Feedback control systems play a very important role in automation and process control. In such applications, the IWSNs serve as the feedback path for the sensory information. For better control of the processes, the reliability of the feedback link is very important and can be termed as an integral ingredient for smooth running of control processes. The deadline in the discrete feedback systems also alters the performance of the

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implemented process control, hence, making the processes more time sensitive.

The proposed scheme uses TDMA based channel access to minimize interference and to ensure URLLC. Apart from this, the scheme also considers a multi-channel scenario where channels are effectively used to offer improved throughput, reliability and timely delivery. The proposed scheme focuses on short burst communications where a dedicated channel is used to facilitate the retransmissions and urgently required data. A detailed description of the network topology, superframe structure, channel specifications and system modelling is presented as follows. Before this, the frequently used parameters in the discussion are first listed in **Table 1**.

3.1 Superframe Structure

The proposed scheme targets improvement in MAC layer architecture by taking in account the availability of multiple channels. More specifically, the frequency and time division multiple access is utilized so as to improve the QoS and meet the time and reliability requirements of critical industrial processes. From the available frequency channels, a Special Purpose (SP) channel is specified which is dedicated for the short frame communications for highly time sensitive or erroneous packet communications. Any failures in transmissions from Regular Communication (RC) channels which require urgent retransmission due to sensitive nature of the data are facilitated by the SP channel. Superframe structure for the proposed system is presented in **Fig. 1**, where the superframe structure for RC and SP channels are presented. Except for the SP channel, all the channels use TDMA based access scheme for collision free communications. The SP channel, however, is implemented using CSMA/CA based as well as TDMA based access.

3.2 Network Architecture and Multi-Channel Scenario

In the proposed scenario, a star topology is considered, where the coordinator (cluster-head) considers the nodes' suitability for association and disassociation with a cluster (**Fig. 2**). Each node affiliated to a cluster is assigned a local id starting from 1 to w, where W is the maximum number of nodes in the cluster. All the TDMA based channels maintain a uniform superframe duration (T) in which the synchronization takes place at the start of every frame with a synchronization beacon transmitted by the cluster-head. In each superframe, the communication takes place in n time slots, each of duration t. These time slots are preassigned to the nodes in the cluster in sequence of the highest priority node to lowest priority node. Each time slot is further divided into data transmission and acknowledgement section. Note that in Fig. 2, the cluster represented is only with respect to a single frequency channel and there can exist more than n nodes in a cluster. The incorporation of multiple channels can be used to either improve the data rate of the individual nodes in a cluster or increase the number of affiliated nodes to the cluster head. Time slotted channel hopping (TSCH) is also considered for low latency and lossy networks by imposing a maximum limit on number of channels to C_u^s, where u is the total number of channels available and s is the number of channels selected for communications at certain time.

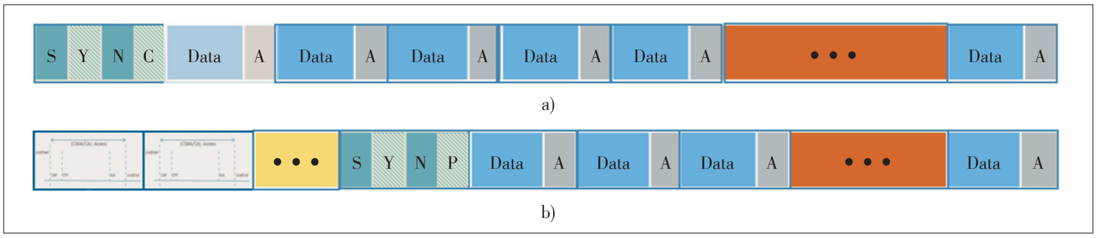
▼**Table 1. Description of frequently used variables in the paper**

Parameters	Variables
Total nodes	W
High priority nodes	K
Time slots in a superframe	N
Total RC channels	H
Total high priority nodes communicating in a single superframe	w
Frequency bands for RC channels	$f_1, f_2, \ldots, f_H$
TDMA based time slots in SP channel	n-k
Probability of successful communication of a node	P

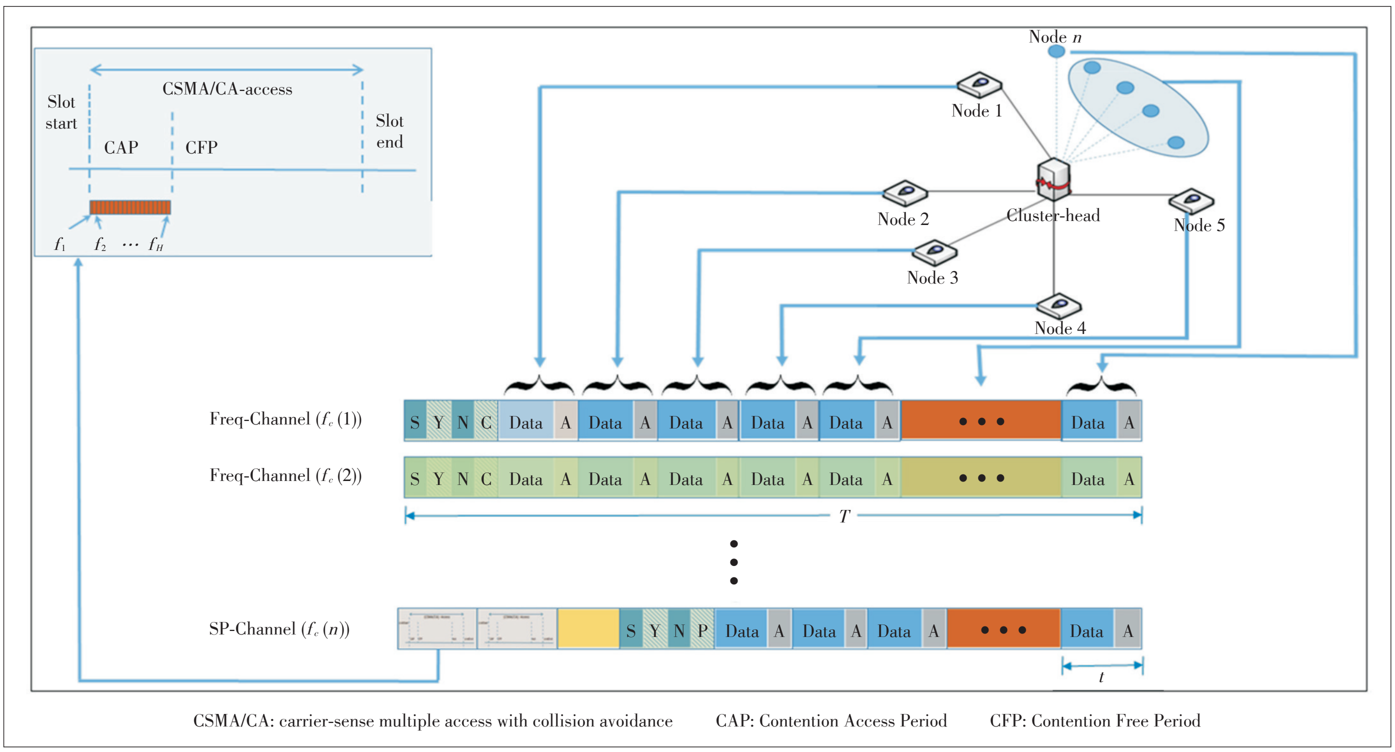
RC: Regular Communication SP: Special Purpose TDMA: time-division multiple access

The SP channel is used to offer both contention based and TDMA based channel access, where the initially first k-slots are used for contention based access and the remaining (n-k) slots are used for TDMA based communications. In the contention based time slots, the nodes in the cluster get the flexibility to transmit time sensitive information by using CSMA/CA. Since the communication failures from the same time frame (with possibly different channels) are used so at the start, the number of contenders trying to access the channel in first couple of time slots, using a CSMA/CA based channel access mechanism, is relatively low and hence most of the nodes get access to one of the first k-slots. The scheme also allows retransmission of failed communications in RC channels using the SP channel by implementing instant retransmission. The delayed synchronization beacon in SP channel serves to synchronize the upcoming TDMA based communications in this channel. Along with synchronization the transmission schedule of urgently required or failed communications in last k time slots is also broadcasted. In other words, the TDMA based time slots of SP channel are used for rescheduling failed communications in the other RC channels. In **Fig. 3**, a broadcasted schedule for retransmission of selected nodes' information is presented. The schedule is part of SYNP as represented in Fig. 2. The schedule consists of a sequence of 0's and 1's, where one bit is specified for each node. The position of the bit from left to right is assigned as per the nodes' id. In this sequence, the left most bit is for node 1, next for node 2, and so on until the rightmost bit specified for node w. The total 1's in the sequence cannot exceed n-k, the total number of TDMA based slots in the current superframe of SP channel.

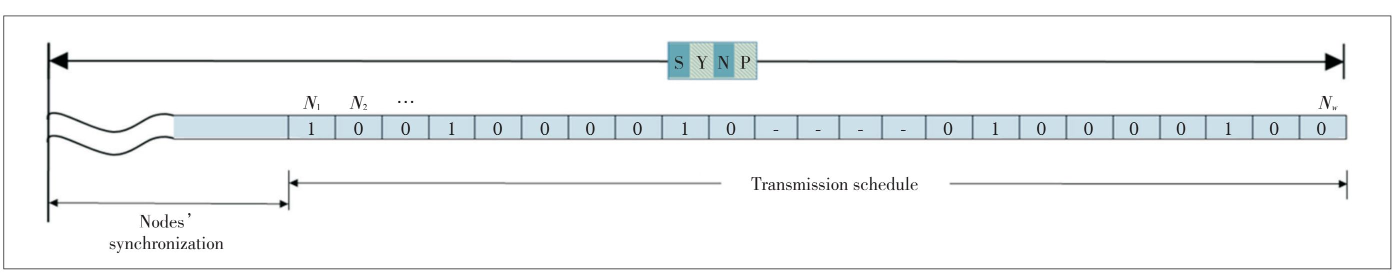
In the proposed scheme a hierarchical architecture is used to offer suitable scalability features. The number of RC channels (H) are also limited to a maximum of 10 with one SP chan-



▲Figure 1. Superframe structure: a) TDMA based (RC) channels and b) SP channel .



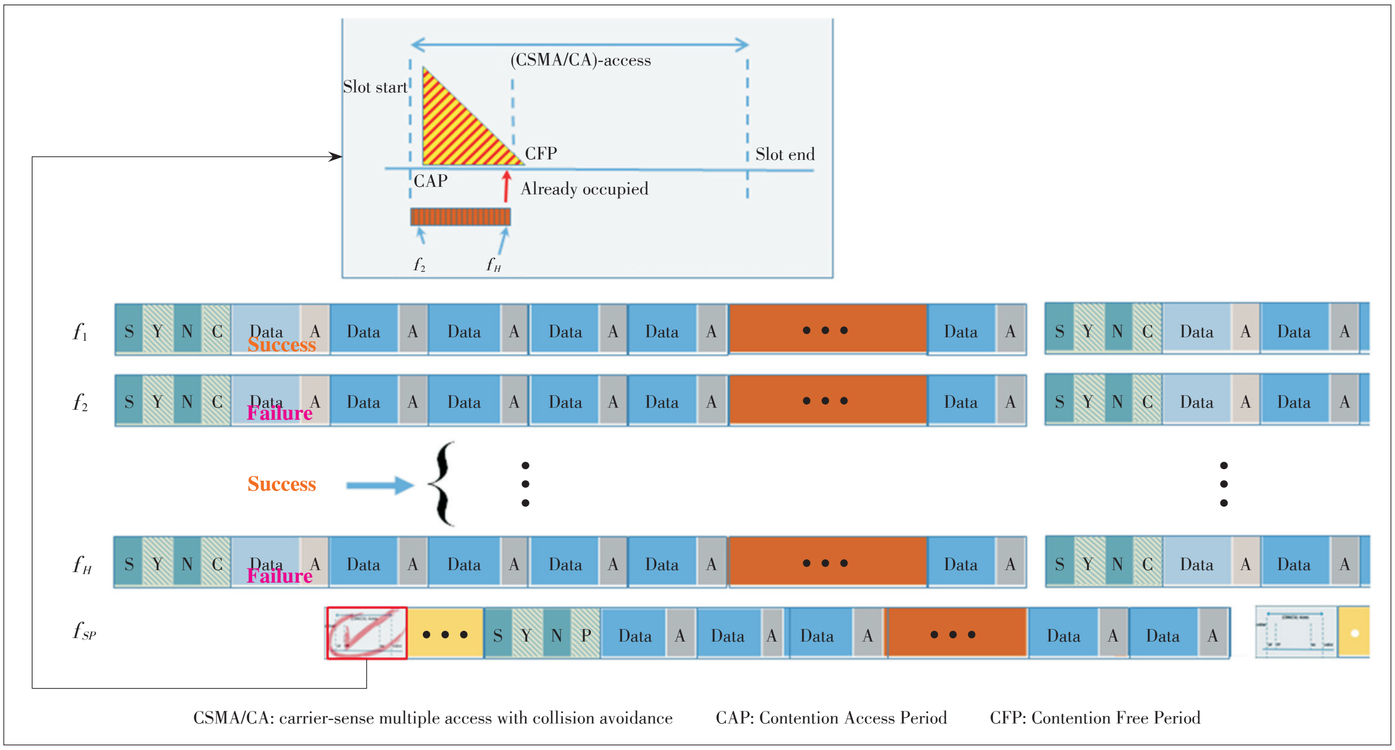
▲Figure 2. Superframe Structure, channel distribution and cluster representation.



▲Figure 3. Schedule of the nodes transmitting in TDMA slots of SP channel.

nel. Each superframe in RC channels is divided in 20 time slots and the time duration of the superframe is limited to 10 milliseconds (ms) to establish low latency and deterministic networks. Apart from this, the communication from all the RC channels and the SP channel are aligned as represented in **Fig. 4** and all superframes are of the same duration. Note that the start of the superframe in case of SP channel is shifted by exactly one time slot (t duration) after the beacon of all the RC channels. In this way every node in the cluster is synchronized with SP channel. For the evaluation purposes, the scope of this paper is limited to the cases where multiple channels are used for the increase in the number of nodes affiliated to single cluster head. Other multi - channel diversity improvement techniques including throughput enhancement, data replication, etc. and relevant investigations are not presented in this paper.

The superframes at different frequency channels are synchronized in a manner represented in Fig. 4, which allows the allocation of first three time slots in superframes of all RC channels to highest priority nodes in the cluster. Furthermore, the priority of these nodes is also distinguished by affiliating a



▲**Figure 4. Synchronized superframe structure for NC and SP channel and priority based access.**

priority factor based on frequency of the channels. To further elaborate, please consider the scenario where, after the beacon synchronization, the communication of first time slot in superframe of all RC channels takes place. In this time slot, all the nodes to whom this time slot is allocated try to communicate. Out of these communications, one or more communications can fail. As represented in Fig. 4, the nodes with unsuccessful communications (communicating at f_2 and f_H) will try to access the CSMA/CA based time slot of the SP channel (marked with √) and try to get hold of it during Contention Access Period (CAP). A magnified view of this slot is also presented in the figure, where based on frequency, the access to the slot is divided. Each node based on its channel frequency will sense the channel first and if vacant will initiate its access beacon giving a signal for the rest of the nodes that the Contention Free Period (CFP) of this slot is reserved for its communication. In the presented case, the node operating at frequency channel f_2 will sense the channel and finds no other access beacons, so its beacon is broadcasted. The node communicating at frequency f_H, due to higher frequency is allowed to access the channel later in CAP and finds beacon of node operating at f_2 and hence withdraws its access till the next time slot. Any node, which fails to access CSMA/CA based communication slots for retransmission of its information, is scheduled for transmission by the coordinator and its transmission schedule is included in the SYNP for retransmission on TDMA based time slots in SP channel. Doing so improves the communication reliability and timely delivery of information to the coordinator. Since this scheme tries to improve the reliability and real time data delivery of high priority nodes, the total number of nodes benefitting from this scheme are limited to w, where $w = k \times H$.

3.3 Mathematical Formulation

The proposed scheme considers the impact of multiple channels compared to single channel schemes and evaluates improvements in number of nodes per cluster, communication reliability and overall throughput. To evaluate the performance of the proposed scheme, a mathematical formulation of the possible scenarios for typical IWSNs as well as for the proposed scheme in IWSNs is presented as follows.

The communication from all the affiliated nodes in a cluster periodically originates in a specified time slot of every superframe. The success of each individual communication is dependent on the channel conditions and probability of success of an individual communication, which is represented with p whereas the total successes in every time slot are modelled as binomial (p, w) distribution.

In a typical IEEE802.15.4e system, using a single frequency channel, the frame error rate depends on several factors including the number of high priority nodes, multipath fading, dispersion, reflection, refraction, jitter, interference, distance, congestion, transmission power restrictions, and receiver sensitivity. To demonstrate the frame error rate for various number of high priority nodes, a mathematical formulation is presented in (1), where k is the number of high priority nodes and changes from 1 to 10. The total communications in a single frame are limited to n.

$$P(frame\_error\_rate|H=1)=\sum_{x=1}^{k}\binom{k}{x}(1-p)^{x}p^{k-x}. \quad (1)$$

The use of multiple channels introduces a significant improvement in the throughput of the system but the reliability in such cases is dependent on the number of RC channels and ratio of RC and SP channels. A mathematical expression for the frame error rate in case of multiple channel scenarios is given in (2) to (4). The maximum number of high priority nodes are limited to k per RC channel whose maximum numbers are limited to H. Based on the total number of the high priority nodes permitted (k) and total communications in a single frame (n), limits can be generalized to w_1 and w_2 for (2) to (4), where $w=k\times H$, $w_1=n/2$ and $w_2=n$.

$$P\left(frame\_error\_rate\ |(H>1)\&(w\leqslant w_1)\right)=$$
$$\frac{\left[\left(\sum_{x=1}^{w}\left(\binom{w}{x}(1-p)^{x}p^{w-x}\times\left(\sum_{y=1}^{x}\binom{x}{y}(1-p)^{y}p^{x-y}\right)^{2}\right)\right)\right]}{H}, \quad (2)$$

$$P\left(frame\_error\_rate\ |(H>1)\&(w_1<w\leqslant w_2)\right)=$$
$$\left[\left(\sum_{x=1}^{w_1}\left(\binom{w}{x}(1-p)^{x}p^{w-x}\times\left(\sum_{y=1}^{x}\binom{x}{y}(1-p)^{y}p^{x-y}\right)^{2}\right)\right)+\right.$$
$$\left\{\sum_{x=w_1+1}^{w}\left(\binom{w}{x}(1-p)^{x}p^{w-x}\times\left\{\left(\sum_{y=1}^{z=n-x}\binom{x}{y}(1-p)^{y}p^{x-y}\right)^{2}+\right.\right.\right.$$
$$\left.\left.\left.\left.\left(\sum_{v=z+1}^{x}\binom{x}{v}(1-p)^{v}p^{x-v}\right)\right\}\right)\right\}\right]\Big/H, \quad (3)$$

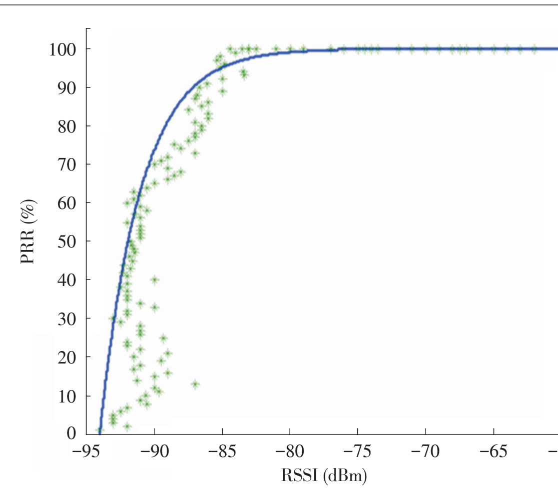
$$P\left(frame\_error\_rate\ |(H>1)\&(w>w_2)\right)=$$
$$\left[\left(\sum_{x=1}^{w_1}\left(\binom{w}{x}(1-p)^{x}p^{w-x}\times\left(\sum_{y=1}^{x}\binom{x}{y}(1-p)^{y}p^{x-y}\right)^{2}\right)\right)+\right.$$
$$\left\{\sum_{x=w_1+1}^{w_2}\left(\binom{w}{x}(1-p)^{x}p^{w-x}\times\left\{\left(\sum_{y=1}^{z=n-x}\binom{x}{y}(1-p)^{y}p^{x-y}\right)^{2}+\right.\right.\right.$$
$$\left.\left.\left.\left.\left(\sum_{v=z+1}^{x}\binom{x}{v}(1-p)^{v}p^{x-v}\right)\right\}\right)\right\}+\left\{\sum_{x=w_2+1}^{w}\left(\binom{w}{x}(1-p)^{x}p^{w-x}\right)\right\}\right]\Big/H. \quad (4)$$

4 Results and Discussion

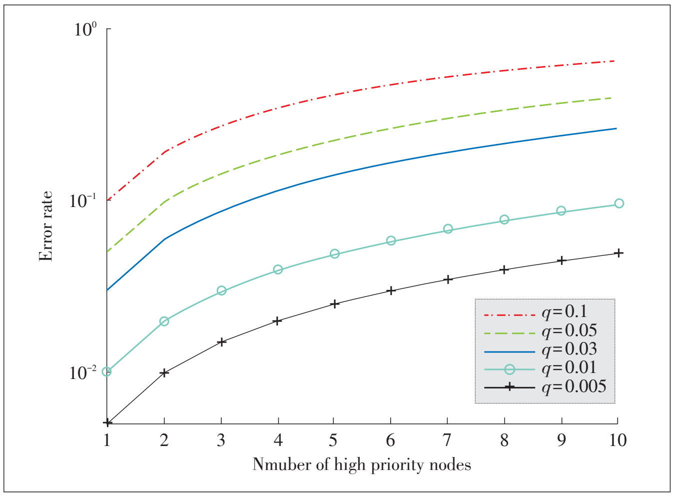
The performance of the proposed multiple channel scheme with a dedicated retransmission channel (SP channel) is evaluated as a function of probability of successful communication of an individual node, total number of parallel data streams, i.e. the number of communication channels (RC channels) and the number of high priority nodes (k) trying to communicate in a single superframe duration. For the evaluation purposes, the maximum number of RC channels (H) and k are limited to 10. Twenty transmissions in a single superframe are used (n = 20), so w_1 and w_2 are set to 10 and 20 respectively.

In **Fig. 5**, the probability of successful communication of a node is presented as a function of received signal strength indicator (RSSI), and the packet reception rate (PRR) is plotted against the RSSI. The plot is acquired using a communication established between the SunSPOT sensor node and SunSPOT base-station. The nodes use CC2420 radio, which operates at 2.4 GHz and uses offset quadrature phase-shift keying (OQPSK) modulation with a chip rate of 2 Mchips/s. The plot in Fig. 5 represents the percentage of successfully received packets for different values of RSSI, with blue line representing polynomial curve fitting of scatter plot. As can be seen in the figure, if the received RSSI is maintained above −87 dBm, 90% or more successful transmissions are expected. To counter the effect of uncertainty of the wireless channel, 10 dBm margin is suggested when establishing a link between the coordinator/cluster-head and sensor nodes. For communication, a superframe duration of 10 ms is used. The maximum number of parallel data streams is limited to 10 and synchronized in time domain. To evaluate the performance of the proposed scheme, the performance of typical IEEE802.15.4e system with single a channel is presented as a reference in **Fig. 6**. The performance is evaluated, based on the number of high priority nodes (k) communicating within the superframe where the total number of nodes trying to attempt a communication in a single superframe is limited to 20. The frame error rate is evaluated for different channel conditions under which the probability of communication failure (1-p) is represented by q.

By introducing a SP channel in the typical IEEE 802.15.4e system as expressed in the proposed scheme, a significant error rate reduction can be seen in the communication of high priority nodes. Since the rest of the n-k nodes communicating



▲Figure 5. Packet reception rate as a function of RSSI using CC2420 [33].

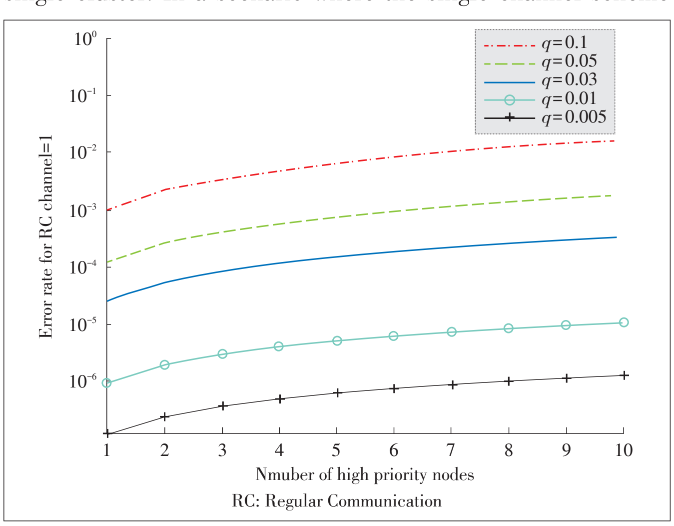


▲Figure 6. Frame error rate for typical IEEE802.15.4e (LLDN) with one RC channel and no SP channel.

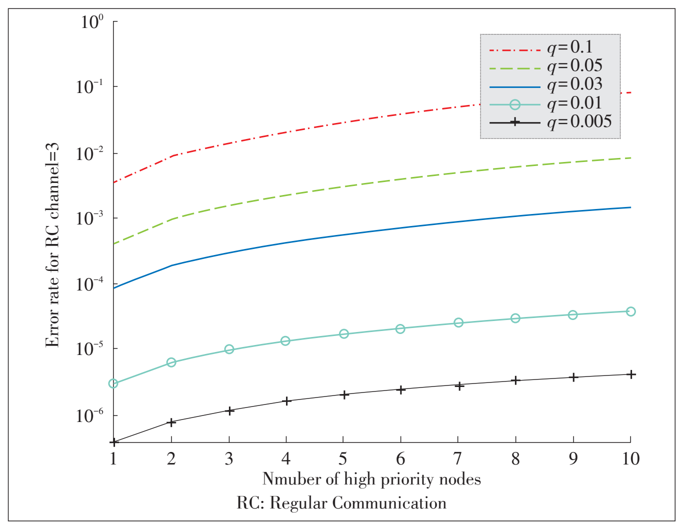
in the network are considered as low priority nodes, so the failure in communication of these nodes is not critical and will not affect the performance of feedback control systems. With the retransmission of failed communication in RC channel through SP channel, a significant improvement in the reliability of communication can be seen. Similar conclusion can be deducted by comparing the error-rate of IEEE802.15.4e presented in Fig. 6, and proposed multi-channel scheme with one RC channel and one SP channel, presented in **Fig. 7**. To further evaluate the effect of using multi-channel scheme for a higher number of parallel data streams, the error rate is evaluated for the cases with one SP channel and 3, 5 and 10 RC channels, as presented in **Figs 8**, **9** and **10** respectively.

Due to the introduction of multi-channel scheme, the overall throughput of the network greatly increases along with the potential rise in the total number of nodes which can affiliate to a single cluster. In a scenario where the single channel scheme is compared with the two-channel scheme (one SP and one RC channel), the throughput is relatively the same as in the case the single channel scheme because only one channel is used for communication. However, a notable improvement in the communication reliability can be seen. The use of more than one RC channels, however, strongly influences the overall throughput and with the increase in these communication channels the throughput is increased several times. The overall throughput for different number of frequency channels is represented in **Fig. 11**. As represented in this figure the overall throughput of the network can increase up to 900 percent with additional ten frequency channels in use. Apart from the throughput, as discussed earlier the reliability of the communication also improves along with the throughput.

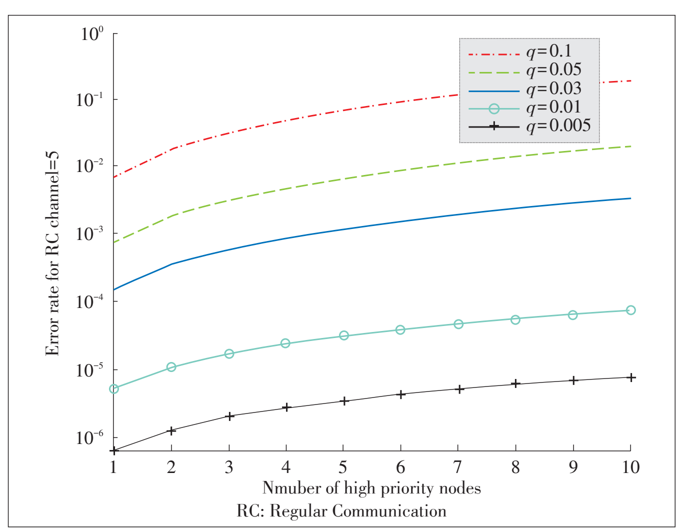
The total number of nodes that can communicate to the cluster-head in time T with different number of frequency channels



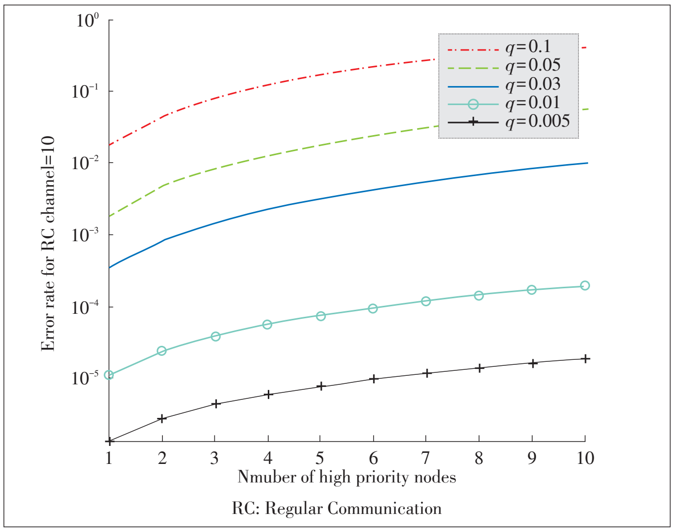
▲Figure 7. Frame error rate for proposed scheme with one RC channel and one SP channel.



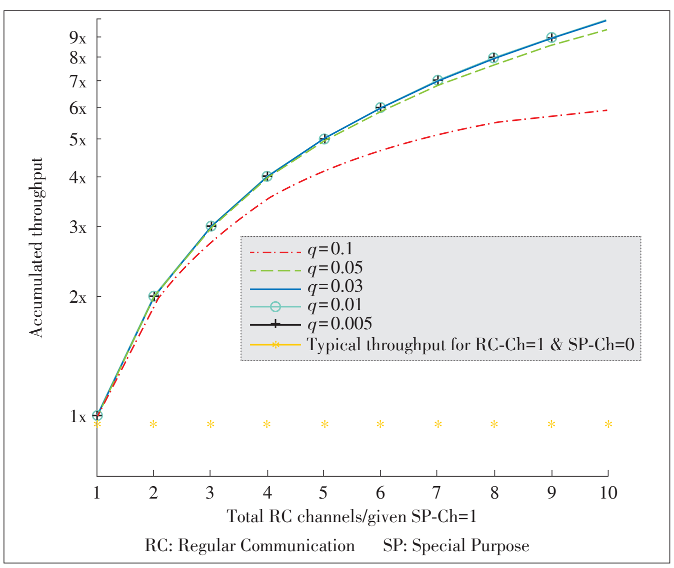
▲Figure 8. Frame error rate for proposed scheme with three RC channels and one SP channel.



▲Figure 9. Frame error rate for proposed scheme with five RC channels and one SP channel.



▲**Figure 10. Frame error rate for proposed scheme with ten RC channels and one SP channel.**



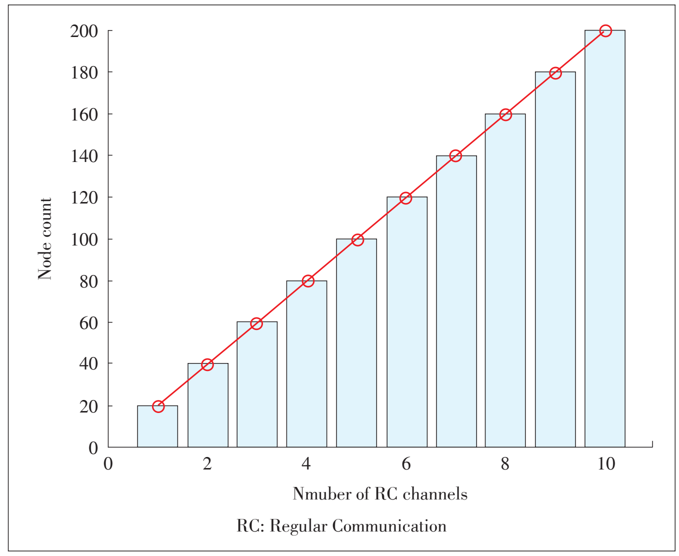
▲**Figure 11. Accumulated throughput of the proposed multi-channel scheme with reference to single channel low data-rate WPAN.**

is presented in **Fig. 12**. Since the short burst communication is used for urgent delivery of information, the time duration of superframe T is limited to 10 ms. A communication overhead of 3.84 ms is considered, leaving the connected nodes a relatively short duration for communication. Each node in a cluster is assigned at least one time-slot in the 10 ms window enabling fast, frequent, and reliable communication to the central control unit, well within the specified times.

5 Conclusions and Future Directions

The paper presents a multi-channel performance and throughput enhancement scheme for IWSNs. The primary objective of the scheme is to enhance the reliability of the communication between the sensor nodes and the cluster-head. A SP channel is also defined which ensures suitable reliability enhancement in the communication over the traditional single channel schemes. In the scheme, the performance is evaluated using throughput, reliability and the number of nodes accommodated in a cluster. The scheme offers a notable increase in the reliability and throughput over the existing IEEE802.15.4e standard. The overall improvement in reliability is directly dependent on the SP channels to RC channels ratio. The throughput however is more dependent on the number of RC channels and the probability of successful communication.

For the evaluation purposes, the scheme considers one SP channel and can further be realized for multiple SP channels and give a more suitable venue for performance improvement. In this paper the SP/RC channels ratio is limited to the cases ranging from 1:1 to 1:10. However, a more generic approach may be considered, where ratios 1:1 to 10:1 are evaluated for study purposes. Investigating the whole range of channel ratios enables the use of the scheme in different challenging scenarios and a predefined projected or predicted output can also be formulated to better meet the desired requirements.



▲**Figure 12. Total number of affiliated nodes to a cluster-head.**

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