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A Control Channel based MAC protocol for Time Critical and Emergency Communications in Industrial Wireless Sensor Networks

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Abstract—**For time critical applications in industrial environments, failure in communication or unwanted delay can have devastating effects. It is therefore, important that Industrial Wireless Sensor Networks (IWSNs) offer reliable communication platform for time critical applications without violating the hard deadlines. In this paper, a MAC protocol for time critical and emergency communications is proposed. The proposed protocol, EE-MAC incorporates emergency communication and allows immediate channel access for such data. The paper presents mathematical model of the proposed protocol. For evaluation purposes, the performance of EE-MAC is compared to IEEE 802.15.4e LLDN. The results show that the proposed protocol offers up to 92% reduction in channel access delay of emergency communication at the cost of 5% to 15% increase in delay of non-critical and less time-sensitive data.**

Keywords— MAC; Time-critical; WSN; Industrial Wireless Sensor Networks; IWSNs; Reliability; WPAN; TDMA; Hybrid

I. INTRODUCTION

With the evolution of industries, new dimensions of research have surfaced. In recent years, the IWSNs have emerged as an effective and cost efficient solution for industrial automation and process control [1-3]. IWSNs in comparison to some wired networks with high cabling and maintenance costs (up to €4337 per meter [4]), offer a very nominal and cost-efficient solution. Apart from this, in terms of ease of deployment, IWSNs allow a significant reduction in deployment and network reconfiguration time. Furthermore, the recent improvements in Micro-Electro Mechanical Systems (MEMS) technology, have proved extremely influential in forming low cost smart networks. However, due to the critical nature of industrial applications the need for real-time and reliable communication is stressed more than ever [5].

IWSNs despite the benefits of scalability, self-organization, ease of deployment, localized processing, flexibility, self-healing abilities and cost effectiveness, still offer some uncertainties in terms of reliability and real-time communication of critical information. The condition is primarily credited to the unpredictable nature of the wireless medium. For the similar reasons the use of Wireless Sensor Networks (WSNs) are limited to monitoring applications where the time and reliability bounds are more flexible.

In the last decade the research on WSNs were more focused in improving the cost and energy efficiency of the sensor nodes. However, recently the use of WSNs in industrial applications is gaining much more attention. In the recent past many industrial protocols for IWSNs were introduced to offer suitable reliability and real-time communication. Some of the prominent industrial communication protocols include Zigbee [6], WirelessHART [7], ISA100.11a [8] Wia-PA and 6LowPAN [9]. Apart from this two IEEE standards, IEEE 802.15.4 [10] and IEEE 802.15.4e [11], were introduced, where the above stated protocols use one of these two standards as a baseline for defining the PHY and MAC layer. Since the IEEE802.15.4 uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as channel access method. Although the CSMA/CA based access schemes offer great potential for low delay but guaranteed channel access is usually compromised due to the uncertainty of collisions and lack of reliable channel access scheme. Due to the same reasons the suitability of the CSMA/CA based other industrial protocols is also questionable for critical processes. To address the reliability of channel access scheme and to significantly reduce the collisions IEEE 802.15.4e use Time Division Multiple Access (TDMA) as primary channel access mechanism where synchronized beacon enabled communication is established. IEEE 802.15.4e is primarily defined for industrial applications to offer reliable and timely channel access for the critical communication of the nodes.

In this paper, a MAC protocol for time critical and emergency communications is introduced. The proposed protocol, EE-MAC offers a mechanism for incorporating emergency information and provides immediate channel access for critical nodes. In the protocol, TDMA based time synchronized communication is established for collision avoidance and performance improvement. However, access to the critical or emergency communication is provided by adding special purpose communication slots between the two regular, consecutively scheduled time slots. The protocol allows the coordinator to adaptively include the urgently required information in the current transmission frame, which allows improved performance in meeting the critical time deadlines.

II. LITERATURE REVIEW

In the past few years a significant change in IWSN MAC protocols can be seen where the primary objectives of the protocols are much inclined to real-time and reliable communication. The gradual transition of the MAC objectives from network life time extension to a reliability and timely delivery of information has been seen. Due to increasing involvement of IWSNs in industrial processes, more researchers are trying to establish an equilibrium in increasing the energy efficiency along with the real-time and reliable data delivery [12].

For critical industrial automation and process control applications, IEEE 802.15.4e specifically defines Low Latency Deterministic Networks (LLDNs) framework which primarily targets at reducing the delay. IEEE 802.15.4e LLDN limits the maximum delay between consecutive channel access of a node to 10 milliseconds with an ability to incorporate up to 20 nodes in a single MAC-LLDN superframe [11]. Although LLDN and some other industrial protocols (WirelessHART and ISA100.11a), by incorporating TDMA, offer better reliability alongside minimizing the delay. However, due to sequential and slotted access, the delay is not efficiently optimized. Furthermore, the retransmission of the information is usually handled using CSMA/CA based channel access which adds uncertainty to the retransmission of the lost information.

In [13], authors present a TDMA based MAC protocol, ShedEx. This protocol targets the overall reliability improvements. The protocol offers a scheduling mechanism which repeats most rewarding slots to improve reliability. However, the protocol fails to offer priority based scheduling. Furthermore, individual latency bounds are not considered. In [14], a priority based MAC scheme is presented which considers four priority levels. In this scheme high priority traffic is allowed to overtake low priority traffic's communication slots which induces extended delays in low priority traffic. Furthermore, no scheduling mechanism is defined if multiple nodes with same priority level attempt to access the low priority node's timeslot. In [15], authors define an arbitration based MAC, where the preassigned arbitration frequency is used to provide the prioritized access to the channel. In this protocol, each node has to wait for arbitration request period to request channel. Apart from the fact that the protocol needs special coordinator to process orthogonal frequencies, the scheme also overlooks the need for number of orthogonal arbitration frequencies in case of large number of nodes. TDMA-MAC is presented in [16]. In TDMA-MAC the spatial information is utilized to reassign the TDMA slots where there is no interference. However, the scheme uses recursive solution which fails to eliminate conflicts effectively. Furthermore, in this protocol no mechanism is defined to accommodate high priority or emergency information. In [17], authors present a segmented shared slots assignment using the IEEE802.15.4e shared slot concept. The protocol offers a scheduling mechanism to offer improved shared slots placement in the superframe. However, apart from the retransmission improvement, the scheme fails to offer prioritized access.

III. SYSTEM MODEL

In the Industrial automation and process control, the communication link plays a very important role. The reliability of communication and timely delivery of information has great significance, especially in critical applications. It is therefore, preferred to use TDMA instead of CSMA/CA based channel access. The TDMA allows a collision free access to the channel and is a much more suitable alternate to CSMA/CA based channel access, especially in dense networks. However, by including TDMA, the overall channel access delay is significantly increased, especially for asynchronous and event driven critical communication.

In the proposed system, TDMA based channel access scheme is used as a baseline to ensure reliability and collision free communication. A hierarchical architecture is assumed to ensure a maximum two hop delay from sensor node to the control centre where the communication between the sensor nodes and the relevant coordinator node uses a star topology. The communication between the coordinator nodes and the control centre uses multichannel access scheme to establish parallel streams to meet the high data rates requirements and reduced delay.

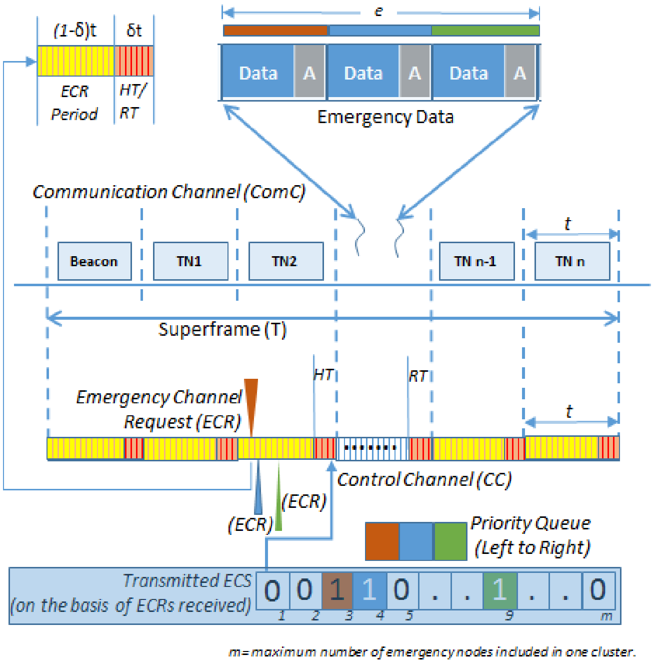

Figure 1 EE-MAC Operation

In order to ensure real time and reliable communication of critical and emergency information, the proposed MAC protocol, EE-MAC is listed as follows.

A. EE-MAC

Emergency Enabled MAC (EE-MAC) allows the nodes with critical/emergency information to request the channel access. Since the occurrence of the emergency communication is asynchronous and is relatively rare so a hybrid scheme is introduced where the regular communication continues in a TDMA based superframe.

In case of emergency, a slotted request mechanism using control channel is introduced which allows the coordinator to halt the regular TDMA based transmission and initiate emergency communication by inserting appropriate number of time slots in the TDMA frame. In case of multiple emergency requests triggered in a particular time a queuing function is used to allocate the resources sequentially. For such cases the communication of regular TDMA can be stopped for multiple timeslots. To ensure the collision free transition, a halt (*HT*) and reinitiate (*RT*) sequence is defined which informs the nodes to stop and resume communication when needed. *HT* and *RT* sequences are initiated by the coordinator to stop regular time frame communications and resume these communications respectively. A minimum halt duration is also included in *HT* sequence to improve energy efficiency of the network.

In Figure 1, superframe structure of EE-MAC and other related details are presented. As represented in figure each superframe is divided in *n* timeslots, each of duration *t*. Each timeslot is further divided in communication and acknowledgement window of duration $(1-\delta)\times t$ and $\delta \times t$ respectively. The control channel is also synchronized with communication channel and in control channel each time slot of duration *t* is divided in the Emergency Channel Request *(ECR)* period and halt/Reinitiate (*HT/RT*) communication Period. In the ECR period, a slotted access is used where the ECR period is divided into *m* slots. Each emergency node is provided one of these *m* slots to initiate ECR (The division of these slots among the emergency nodes can be overlapping to accommodate larger number of emergency nodes with more frequent channel request opportunity). At the completion of the ECR period if one or more channel requests are received, the coordinator initiates *HT* during *HT/RT* period to halt the ongoing regular communication. By default, the regular communication is stopped for single time slot but if more than one emergency communication requests were received during *ECR* period, the halt duration is extended accordingly and this duration is communicated during *HT* sequence transmission along with the Emergency Communication Sequence (ECS) (See Figure 1 for the ECS based on the ECRs received in the ECR period). This allows the regular communication nodes to go to sleep mode for the halt duration (*HD*) to conserve energy. Furthermore, the regular communication nodes in the network only need to stay active during the timeslots when these nodes are communicating. Whereas the nodes will be in passive listening mode during the beacon and *HT/RT* period (passive listening can be adjusted to alternative slots as any one of *HT* or *RT* sequence transmission, if received, will be enough to adjust the listening node's transmission slot) and sleep mode for the rest of the time. For evaluation purposes Table I, represents the selected values of different parameters.

The performance of the EE-MAC protocol is compared with the IEEE 802.15.4e, Low Latency Deterministic Networks (LLDNs) framework, specifically defined for the critical industrial applications. Mathematical model for the proposed EE-MAC protocol is also presented.

The superframe duration of LLDN is represented as T_{LLDN}, whereas in case of the EE-MAC the superframe duration of $T_{EE\text{-}MAC}$ is given by

$$T_{EE-MAC} = T_{LLDN} + e \tag{1}$$

Where *e* is the duration of the average additional timeslots, each of duration *t*, added to the superframe to compensate emergency communication. It also considers the deviation (Δ) from the mean duration. Since the emergency communication in industrial environments is asynchronous and event driven, therefore it is modelled as a Poisson (α) distribution. The duration of timeslot (*t*) is presented in equation 2 whereas the PMF of the Emergency occurrences (x) in ECR period (1-δt) is presented in equation 3.

$$t = \frac{T_{LLDN} - D_{PL}}{n} \tag{2}$$

$$P_X(x) = \begin{cases} \dfrac{\frac{\alpha^x e^{-\alpha}}{x!}}{\sum_{y=0}^{m} \frac{\alpha^y e^{-\alpha}}{y!}} & where\ x = 0,1,2,\dots,m \\ 0 & otherwise \end{cases} \tag{3}$$

TABLE I. DESCRIPTION OF VARIABLES USED AND SELECTED VALUES

Parameters	Variable(s)	Value(s)
Total Time slots in IEEE802.15.4e LLDNs superframe	*n*	20
Number of emergency nodes included in a cluster	*m*	1,2,…10
Packet Payload bits	*Payload_bits*	960 bits
Payload transmission time	*MAC_payload (PL_delay), D_{PL}*	3.84ms
Superframe time duration (LLDN)	T_{LLDN}	10ms
Data Rate	R_b	250Kbps
Probability of successful communication	*p*	0.7-0.999
Emergency traffic Arrival rate per second	*λ*	1-500
Number of emergency requests	*α*	-
Time slot duration	*t*	≅300μs
Access Delay	*d*	-
Average successful communication delay	*d_success*	-

Here *m* refers to the number of emergency nodes included in a cluster and α=λ*t*. The time duration of the emergency slots within a superframe (*e = duration of average no. of emergency slots* ± Δ) is given by

$$e = t \times \left\{ \left(\sum_{x=0}^{m} \left(x \times \frac{\frac{\alpha^x e^{-\alpha}}{x!}}{\sum_{y=0}^{m} \frac{\alpha^y e^{-\alpha}}{y!}} \right) \right) \pm \left(\sum_{x=0}^{m} \left(x - \sum_{x=0}^{m} \left(x \times \frac{\frac{\alpha^x e^{-\alpha}}{x!}}{\sum_{y=0}^{m} \frac{\alpha^y e^{-\alpha}}{y!}} \right) \right)^2 \right) \right\} \tag{4}$$

In equation 4, α=λT_{LLDN}. The occurrence of emergency communication is considered random and in reference to a particular superframe, it can occur anywhere during the frame with equal probability. Therefore, occurrence time of the emergency communication is modelled as uniform distribution. The access delay between the time when, need for emergency transmission is developed to the time when the transmission is started, has great significance in emergency communications. For LLDNs, it is ensured that the maximum channel access delay is kept fixed to T_{LLDN}, however, for evaluation purposes the average access delay (*d*) is used for both EE-MAC and LLDNs.

Average access delay of LLDNs (d_{LLDN}) and Average access delay of EE-MAC ($d_{EE\text{-}MAC}$) for emergency data is presented in equation 5 and equation 6 respectively.

$$d_{LLDN} = \frac{1}{2} T_{LLDN} \tag{5}$$

$$d_{EE-MAC} = \sum_{x=1}^{m} \left[\left(\delta t + \frac{1}{2} t + (x-1) \times t + \left(\frac{x}{n} \times D_{PL} \right) \right) \left(\frac{\alpha^{x} e^{-\alpha} / x!}{\sum_{y=1}^{m} \alpha^{y} e^{-\alpha} / y!} \right) \right] \tag{6}$$

In emergency communications, Average delay time when, need for emergency transmission is developed to the time when the transmission is successfully completed for LLDN and EE-MAC ($d\_success_{LLDN}$, $d\_success_{EE\text{-}MAC}$) is presented in equation 7 and equation 8 respectively.

$$d\_success_{LLDN} = d_{LLDN} \times \sum_{w=1}^{\infty} w \times p(1-p)^{w-1} \tag{7}$$

$$d\_success_{EE-MAC} = d_{EE-MAC} \times \sum_{w=1}^{\infty} w \times p(1-p)^{w-1} \tag{8}$$

Here p is the probability of successful transmission and w is the count of transmissions until the successful communication takes place.

IV. RESULTS AND DISCUSSION

The performance of the EE-MAC is judged in comparison to the IEEE802.15.4e LLDN, where the performance of EE-MAC is represented in terms of access delay, average timeframe extension and average delay till emergency communication to be successfully completed.

In Figure 2, the average access delay for MAC LLDN and EE-MAC is presented as a function of number of emergency nodes. Since the LLDN offers a TDMA based access so the emergency nodes are provided with uniform access delay represented in the figure. On the other hand, since EE-MAC provides on demand channel access, therefore the access delay for the EE-MAC is relatively lower to that of the LLDN. The figure shows that the EE-MAC even under extreme conditions (m=10, λ=500 emergency communication requests per second (on average)) manages to offer a 50% reduction in the access delay. The average access delay for less extreme cases is evaluated to be under 0.6 milliseconds. The overall reduction in the access delay by EE-MAC can range from 50% to 60% for relatively extreme conditions and 88% to 92% for less extreme conditions.

To further investigate the delay in emergency communication, the average delay till successful communication for the different values of λ (the number of emergency communication requests per second) and *m* (number of emergency nodes) is presented in Figure 3. The figure shows that the EE-MAC under poor channel conditions (p = 0.7) and high number of emergency requests (500 requests per second, on average) still manages to reduce the average delay to 4.89 milliseconds.

The average delay for less extreme cases is estimated to be less than 1.2 milliseconds. The presented analysis show that EE-MAC manages to reduce the average delay till the successful communication of emergency information by 31% in extreme circumstances. However, in less extreme circumstances ($p > 0.9$ & λ<100) delay reduces by 84% to 91.5%. It can be seen that the access delay(d) and average successful communication delay ($d\_success$) are not the same as the scheduling failures are also considered in the evaluation. For evaluation purposes the channel is considered to be symmetric.

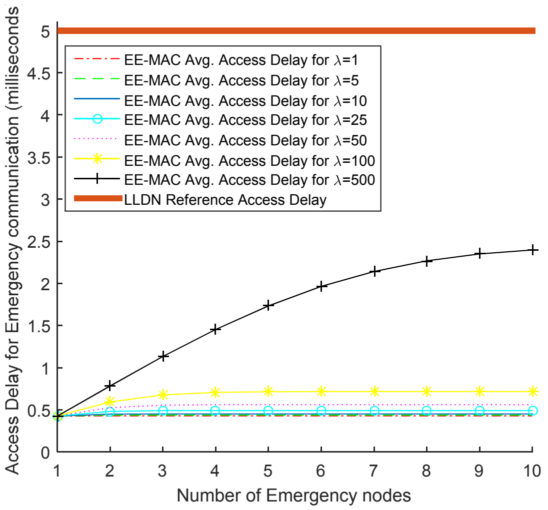

Figure 2: Access Delay to acquire channel as a function of number of emergency nodes (m)

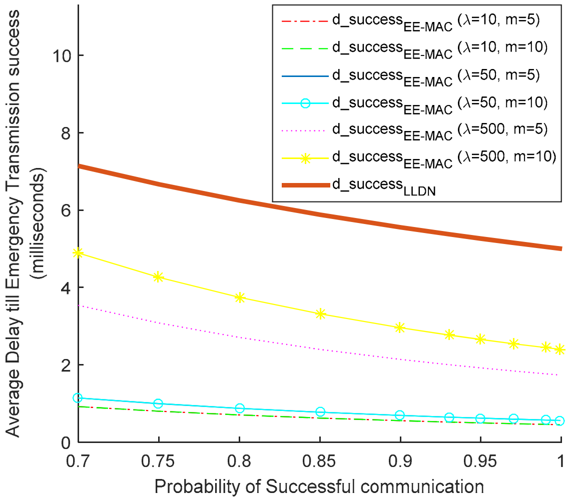

Figure 3: Average delay till successful communication for different channel conditions (p)

The improvements in the average delay of emergency communications was achieved with the insertion of additional slots to the MAC superframe, which extends the superframe duration and the average access delay of non-emergency communication. In Figure 4, the average superframe duration for both IEEE802.15.4e LLDN and EE-MAC for different number of emergency nodes is presented. It can be seen that the average access delay in EE-MAC is increased by 1.5 milliseconds for extreme conditions (m=10, λ=500). Since the delay is added to the communication nodes with less stringent time constraints and an overall increase in average delay is below 7% for most of the cases which is considered non-critical. Apart from this a reduction of up to 92% in the emergency transmission delay is achieved.

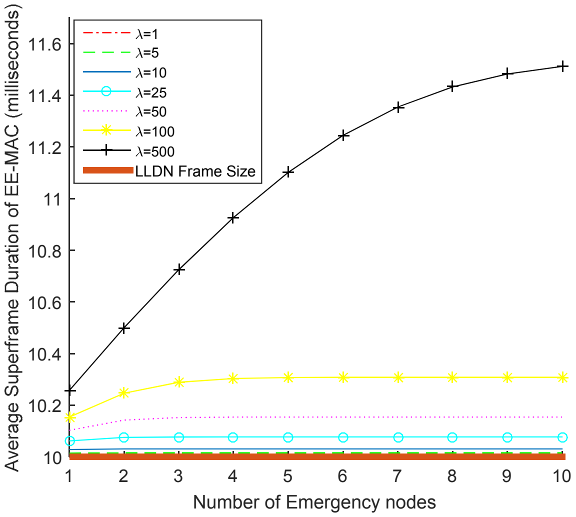

Figure 4: Average Duration of superframe as a function of number of emergency nodes (m)

V. CONCLUSION AND FUTURE DIRECTIVES

In recent years, IWSNs have emerged as a popular research theme with applications spanning a wide range of industries including automation, monitoring, process control, feedback systems, automotive and emergency response. Due to the critical nature of these processes and stringent time constraints on certain emergency and control information, the delay in such communications is unacceptable. In this paper a MAC protocol, EE-MAC is proposed to improve the overall delay of the critical and emergency information. A mathematical modelling for EE-MAC is presented and the performance of the EE-MAC is compared with the IEEE 802.15.4e LLDN framework. It can be seen from the results that EE-MAC offers a 31% decrease in average delay till successful transmission (*d_success*) of emergency communications in harsh conditions whereas, in less harsh circumstances the *d_success* is decreased up to 84% to 91% compared to the IEEE 802.15.4e LLDN. The access delay (d) for emergency communication was also reduced from 50% to 92% at the cost of under 7% increase (for majority of the cases) in delay of non-critical communication taking place in the network.

As a future aspect of the presented research, the proposed MAC protocol can be extended for multi-channel scenario with parallel communication streams. Increase in reliability can also be achieved as a reliability delay tradeoff where the delay is set to maximum allowable limit to increase reliability. To offer better scalability and to diversify the intended application area, adaptive transition mechanism can also be introduced where the proposed protocol could be adaptively adjusted for underlying application. This would extend the proposed MAC protocol for regulatory control applications and deadline based applications. Furthermore, the proposed protocol can be expanded using the Internet of Things (IoT) with Internet enabled devices (IEDs) used as coordinators. This can offer a high speed link between clusters and control centre.

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