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A. Mehta, G. Bhatti, Z. Sahinoglu, R. Viswanathan, J. Zhang

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Abstract

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A Modified Beacon-Enabled IEEE 802.15.4 MAC Emergency Response Applications

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***Abstract*—IEEE 802.15.4 specification for MAC and PHY offers a standard for general purpose wireless sensor networks. The TG4e of IEEE 802.15 is currently engaged in defining a specification particularly suitable for industrial and commercial applications, which impose severe constraints of low latency and high reliability. In this work, we present a simple MAC scheme to address these requirements of emergency response sensing applications for wireless sensor networks. We evaluate the proposed scheme for varying channel and traffic load conditions using simulations. Our results show that the latency and packet loss rate performance of emergency response traffic, consisting of guaranteed time slot (GTS) frames, significantly improves in comparison with the performance of original IEEE 802.15.4 MAC. The proposed MAC was also evaluated for potential adverse impact on the non-critical traffic, which consists of frames that use contention access period (CAP) of the superframe. It is shown that under realistic load conditions, the impact on the CAP traffic is minimal.**

I. INTRODUCTION

Wireless Sensor Networks (WSN) have become an attractive choice for industrial sensing applications because of their low cost and reconfigurability [1]. However, some issues, such as high latency and low reliability, still need to be addressed for their use for emergency response sensing. The IEEE 802.15.4 is a MAC and PHY standard defined for WSNs [2]. But, IEEE 802.15.4 offers no guarantee for low latency and high reliability for the wireless traffic. This makes the standard ill-suited for time-critical emergency response applications. The latency performance limitations of IEEE 802.15.4 MAC are previously studied and reported in literature [3], [4]. We propose a modification to the IEEE 802.15.4 MAC superframe aimed at addressing these issues for emergency response traffic.

The latency issue in WSN can be addressed at two levels; an end-to-end (multi-hop) solution or dealing with it at a single hop level. In order to deal with end-to-end latency, time synchronized GTS transmissions for sequential hops have been proposed in order to reduce the end-node to coordinator node delay in WSN [6]. The scheduling of GTS transmission times of nodes for a single hop WSN can be optimized to avoid collisions and reduce transmission delays for all nodes [12], [14]. Another approach to reduce transmission delay in a WSN is to increase the channel utilization, as proposed in the hybrid MAC protocol Z-MAC [7]. [5], [9], [10] which investigate improving the coordination of WSN router nodes and avoid collisions of beacon frames to reduce end-node to coordinator node delay. Optimal channel assignments are also exploited to minimize collisions which result in the reduced end-node to coordinator-node delay [13]. Overall session latency can be reduced by sharing GTS among many nodes [15]. Theoretical analysis has also been used to quantify the latency and reliabilty performance of IEEE 802.15.4 MAC [4], [8], [11] and [16].

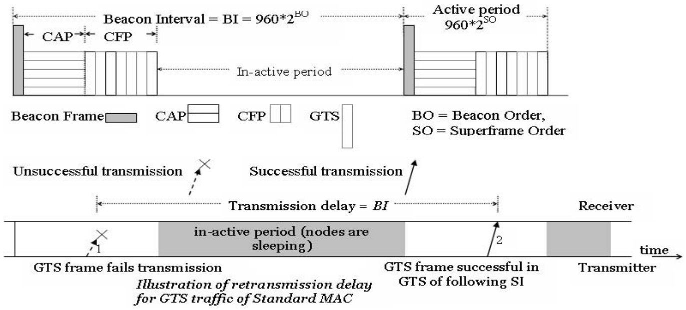

Fig. 1. Super-frame structure of IEEE 802.15.4 MAC

The work reported in this paper specifically focuses on low-latency and high reliability MAC for high-priority emergency response traffic (GTS) in a single-hop WSN. Contrary to the research approach discussed above, we consider error prone data frames. Our work extends on the work reported earlier in [1], where the position of contention free period (CFP) and that of contention access period (CAP) were swapped, and failed GTS frames were allowed retransmissions in the following CAP within the same superframe cycle. Intrinsically, that allocates more bandwidth resources to high-priority traffic under high channel errors, such a trade-off, however, may very well be desirable because the main purpose of such a WSN is to ensure timely emergency response [2]. The new superframe structure, as proposed in this paper, introduces an new period, named as Extended CFP (ECFP), to the MAC in [1]. The simplicity of the scheme is its novelty as will be clear below.

Section II presents our proposed MAC. Section III describes the simulation setup. Section IV discusses the reliability and latency performance via simulation results and presents comparative analysis. Finally, Section V gives the conclusions and

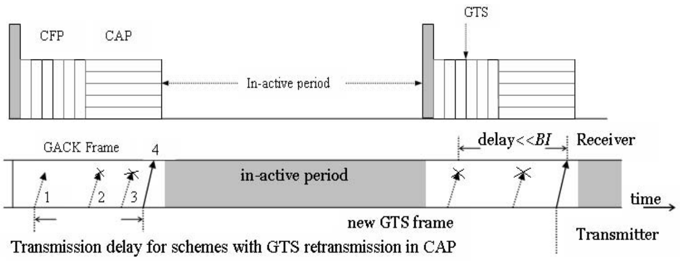

Fig. 2. Super-frame structure with swapped periods

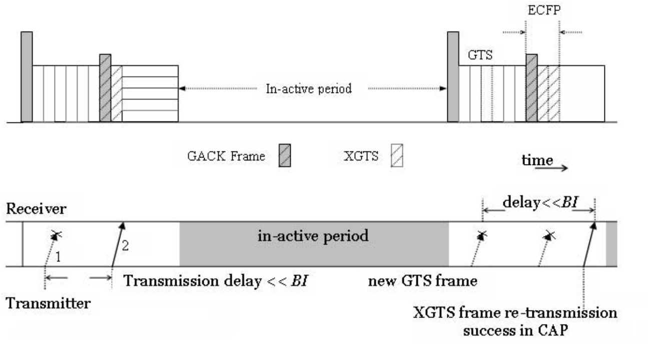

Fig. 3. Proposed EGTS MAC as an enhancement to the IEEE 802.15.4 MAC to provision low latency for time-critical GTS transmissions.

summarizes future work.

II. System description and proposed modifications

The IEEE 802.15.4 standard offers two modes of operation for WSN: beacon-enabled and beaconless [2]. We use the beacon-enabled mode because it facilitates time synchronized transmissions by using gurantteed time slots and is well-suited for emergency response applications. Fig. 1 shows the beacon-interval (BI), which is the time between successive beacon frame transmissions, in a superframe. Beacon frames are sent in periodic time intervals specified by beacon-order (BO). Each BI comprises of an active period and an inactive period. The length of of the active period is determined by a parameter, called superframe order (SO). During inactive period, a node may opt to switch over to a power-saving mode or passively scan the channel and receive frames. The active period, on the other hand, is divided into CFP and CAP intervals. The CFP and CAP data are normally segregated and CFP cannot use CAP time slots for GTS frame transmissions [2]. Detailed description of the standard is given in [2]. Fig. 1 illustrates the transmission delay incurred by failed GTS frames.

A. Proposed Extended CFP Mechanism

Previously in [1], the CAP and CFP were swapped, as illustrated in Fig. 2, and failed GTS frames were allowed retransmissions in CAP in order to reduce the GTS frame transmission delay. As is obvious in Fig. 2, GTS retransmissions will have to compete with CAP traffic, which results in increased contention in the CAP. Our proposed ECFP MAC scheme extends on these modifications. We add an ECFP at the end of the CFP as illustrated in Fig. 3. Like CFP, the ECFP too consists of GTS slots called as Extended GTS (XGTS), which are allocated by the PAN coordinator (PANC), only on demand, and used by GTS traffic. The XGTS, in the ECFP, are allocated for retransmission of failed GTS transmissions in the preceding CFP. The ECFP allows for segregating the GTS retransmissions from the CSMA traffic of the CAP thus allowing a contention-free channel access as illustrated in Fig. 3.

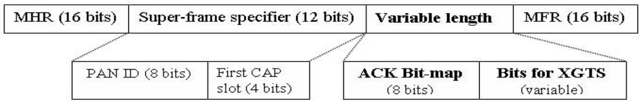

Fig. 4. Structure of GACK frame

Further, even if the retransmission attempt fails, the same frame can attempt for another retransmission in the following CAP of the same superframe. Hence, our proposed ECFP MAC structure offers an increased probability of the GTS frame transmissions succeeding in a superframe. The use of ECFP also limits its impact on non-critical CAP traffic by allocating slots in ECFP only on demand.

B. Group ACK Structure

The ECFP can be characterized by an Group Acknowledgement (GACK) frame as shown in Fig. 4. GACK is transmitted by the PANC following the CFP but prior to the start of ECFP, Fig. 3. The GACK provides a variable length field containing the ACK bitmap field, i.e. 1 bit for each GTS frame transmission in the CFP. We assume that one frame is transmitted in every allocated GTS in the CFP. The bitmap field is used to acknowledge uplink transmissions. The GACK frame also contains information about the GTS allocation in the ECFP. Slave nodes are assumed to listen for the GACK frame and determine the status of their GTS transmission during the CFP. A slave node can determine if its GTS transmission failed and that if it has been allocated a GTS in ECFP by looking at the bitmap. Besides, each time slot number in the ECFP is defined by 4 bits and XGTS are allocated in the same sequence order as of the GTS allocations in the CFP. If the count of 4 bit words is $\leq$ the XGTS slot allocated to the node, then it has an assigned XGTS. If XGTS allocation exceeds the maximum length allowed as specified by the standard [2], slave nodes will not be assigned any more XGTS. In case the GACK does not allocate an XGTS for a node with failed GTS transmission, the node waits for the following CAP to send its GTS frames. Duration of ECFP changes in each BI as XGTS are allocated on a need basis. In the case all GTS transmissions are successful, there would be a full length CAP available for CSMA traffic.

III. Simulation Setup

We simulate a star network with one PANC node and $N = 27$ leaf nodes (slaves). We assume nodes generate packets with a Poisson distribution given as $p_K(k) = \lambda^k e^{-\lambda}/k!$, where λ is the mean arrival rate and k is the number of arrivals in one second. Each one of seven slaves generate CFP traffic with Poisson arrival rate of λ_g packets per second, and each one of 27 slaves generate CAP traffic with Poisson arrival rate of λ_c packets per second. We assume seven CFP slave nodes as it is the maximum allowed by the IEEE 802.15.4 standard, [2]. Slave nodes transmit periodic emergency data packets up-stream to the PANC, uplink. The PANC transmits individual ACKs for the CAP transmissions, and one GACK for all the GTS transmissions. No ACK is sent for erroneous CAP frames, allowing them to time out and be retransmitted. The same probability of error, P_e, is assumed for all transmissions. We further assume an error-free transmission for ACK frames and control frames, and since our focus is on emergency response, we assume that the nodes transmit the latest information they have for GTS traffic and discard all but the most recent frame at the start of every GTS. These assumptions impact all schemes considered and hence do not impact our comparative analysis.

We simulate 5 hours of transmission time and average the delay and drop rate over 5 runs with different seeds. OPNET simulation software is used for simulating the WSNs. We focus our simulations on 3 schemes, (1) Standard IEEE 802.15.4 MAC or referred just as 'Standard', (2) the proposed ECFP MAC and (3) Standard with retransmissions and swapped periods. For performance of other schemes refer [1].

The WSN MAC parameters are set same as in [1]. Namely, $BO = 5$, $SO = 2$, maximum backoff exponenet $aMaxBE = 5$, maximum number of retries allowed is $aMaxFrameRetries = 3$. The PHY data rate is 250 Kbps. QPSK modulation with symbol size of 4 is used and channel frequency is 2.4 GHz [2]. We assume a static wireless channel with varying P_e for various simulation runs. The superframe duration is set to 61.44 ms with CAP as 33.94 ms and CFP as 26.8 ms. Each GTS time slot has a duration of 3.84 ms and can accommodate one GTS transmission. The Beacon frame duration and GACK transmission time are 0.7 ms reducing the CAP to 33.24 ms. The durations for the CFP, the active period, SI, BO and SO remain the same for each superframe. The CSMA back-off exponent and inter frame spacing are assigned default values as specified in the IEEE 802.15.4 standard. We set each data frame as a fixed size packet of 304 bits, typical WSN, including the MAC and PHY headers.

IV. RESULTS AND DISCUSSIONS

We study comparative performance of MAC schemes by analyzing the GTS frame drop rate, GTS frame transmission delay, CSMA/CA frame transmission delay and CSMA/CA frame drop rate. Reliability and latency metrics are plotted for various λ_c and P_e for both GTS and CAP traffic.

A. Impact of λ_c on QoS of the GTS traffic

This subsection holds the true advantage of using ECFP scheme for emergency response. We first set $P_e = 0.1$ and $\lambda_g = 0.5$ and vary λ_c from 0.125 to 3 frames/second/node, for each of 27 slaves, for analyzing the effect of λ_c on the performance. Fig. 5 plots GTS frame drop probability as a function of the total CSMA frame arrival rate λ_{cT}, where $\lambda_{cT} = \sum_{i=1}^{N} \lambda_c(i)$. Here we assign all $\lambda_c(i)$ (hence reference to as λ_c) to be same. From Fig. 5, the proposed ECFP scheme performs better than both 'Standard with retransmissions and swapped periods' and Standard MAC schemes, for all values of λ_{cT}. The GTS drop rate for proposed ECFP scheme is around 10% at low λ_{cT} and increases to a maximum of 11% as λ_{cT} increases. This is a performance gain of $\geq$ 10% for all CAP arrival rates. Also, even at very high λ_c ($\lambda_c \geq 1$ or $\lambda_{cT} \geq 27$), the proposed ECFP MAC still shows around 12.6% lower GTS drop rate than the remaining schemes discussed above. This is due to the contention free retransmissions provided by the XGTSs in ECFP.

Fig. 6 shows the GTS frame transmission delay versus λ_{cT} for a $P_e = 0.1$. This graph holds the true advantage of using ECFP scheme. The ECFP MAC scheme vastly outperforms all other schemes with almost constant average delay for all values of λ_{cT}. Only 'Standard with retransmissions and swapped periods' shows comparable performance and at very low λ_{cT}, ≤ 8.1. This increases as λ_{cT} is increased. It is apparent in Fig. 6 that the ECFP scheme outperforms the other schemes because it allows a retransmission in contention-free time slot that is unaffected by the variations in λ_{cT}, comparing Figs. 2 and 3. The slight increase in the GTS frame transmission delay for proposed ECFP scheme as λ_{cT} is increased, is due to the marginal number of failed GTS frames which also fail their XGTS transmissions and are tried in the following CAP or the next superframe. Assuming each failed GTS frame gets an XGTS transmission, the number of GTS frames suffering moderate to extremely high frame transmission delay averages at $100\text{x}P_e^2 = 1\%$, for Fig. 6, as compared to 10% for all other schemes. The GTS frame transmission delay is constant for Standard MAC because in the Standard MAC CFP data is unaffected by CAP traffic due to isolation of CAP and CFP traffic [2].

B. Impact of P_e on QoS of the GTS traffic

The impact of P_e on GTS traffic is quantified in graphs shown in Figs.7-12. In these graphs, $P_e = [0.01, 0.9]$ while $\lambda_g = 0.5$ frames/second/node. Performance curves for $\lambda_c = 0.125$ and $\lambda_c = 1.0$ frames/second/node are shown in Figs. 7, 8 and 10, 11 respectively. 3-D graphs are also shown to compare the performance of ECFP scheme with the Standard scheme for all values of P_e and λ_c simultaneously in Figs. 9 and 12.

1) Impact of P_e on GTS frame Drop Rate: Fig. 7 shows GTS frame drop rate versus P_e for various schemes at $\lambda_c = 0.125$ frames/second/node. For a very low P_e, $< 10\%$, all schemes show similar GTS frame drop rate with only marginal gains by the ECFP scheme. As P_e is increased, the ECFP scheme shows significant gains, up to 60%, in GTS frame drop rate as compared to the Standard IEEE 802.15.4 scheme. This is again because of the use of XGTS in our scheme. Since nodes transmit only the newest GTS frame, while dropping all the previously buffered ones, the longer a frame stays

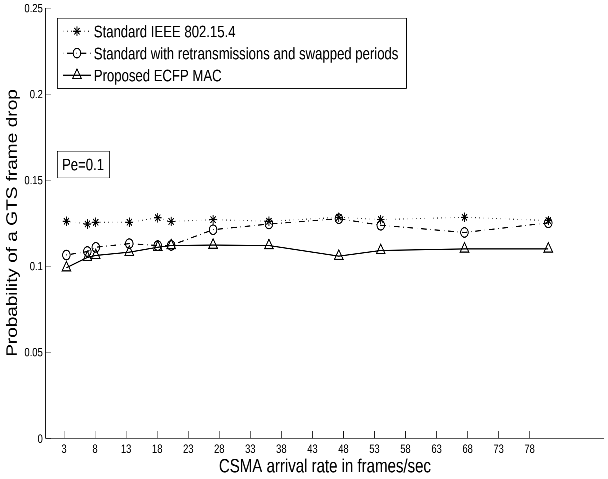

Fig. 5. GTS frame drop rate vs CSMA load

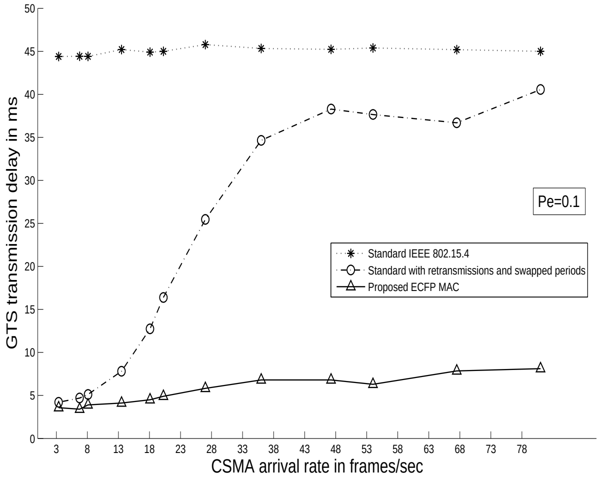

Fig. 6. GTS frame transmission delay versus CSMA load

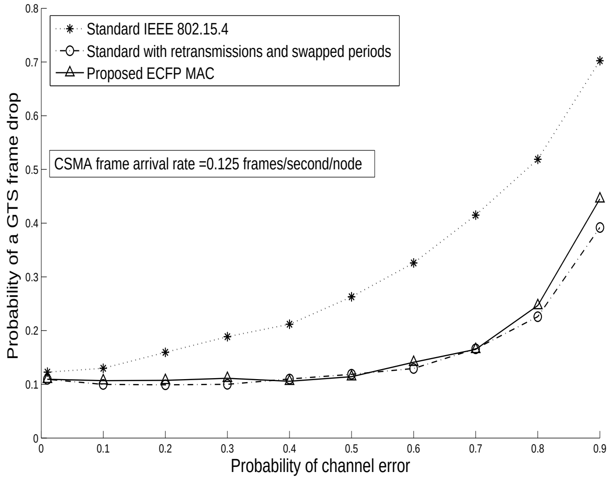

Fig. 7. GTS frame drop rate vs Probability of frame error

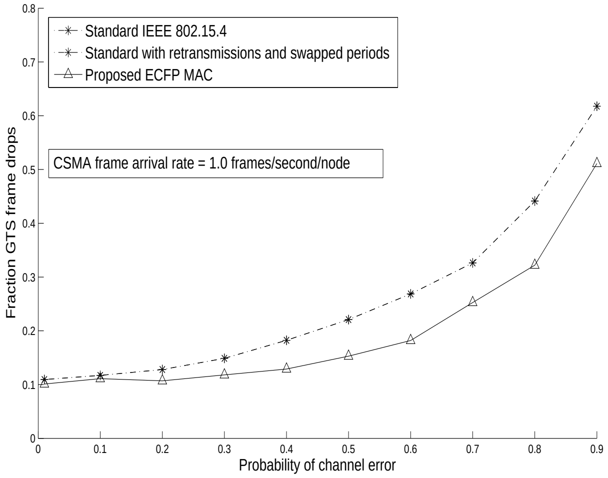

Fig. 8. GTS frame Drop Rate vs Probability of frame error

unsuccessfully transmitted, for high P_e values for example, the higher its change of being dropped. Probability of a frame drop for high P_e values is lower in our ECFP MAC and hence lower wait time in the node's buffer.

We also observe from Fig. 7 that 'Standard with retransmissions and swapped periods' shows comparable drop rate performance to the ECFP MAC, and for extremely high $P_e = 0.9$ shows slightly improved performance than ECFP MAC. This is since Fig. 7 plots for low $\lambda_c = 0.125$, and coupled with the fact that the CAP in the ECFP scheme is relatively shorter due to carving out of ECFP. A failed GTS frame finds a smaller CAP with potentially higher contention in our scheme at high P_e values. This accounts for the marginal loss in performance for non-critical CSMA traffic. This however is not an issue as timely delivery of highly critical GTS frames, as opposed to dropping some non-critical CSMA frames under high P_e, is a valuable trade-off.

Fig. 8 plots GTS frame drop rate versus P_e for $\lambda_c = 1.0$ frames/second/node. Here we see a contrast to Fig. 7 when $\lambda_c = 0.125$. Here the GTS frame drop rate for the ECFP scheme is superior to all the other schemes, even at very high values of P_e, $P_e \geq 0.8$. From Fig. 8 we see that the performance of 'Standard with retransmissions and swapped periods' is now the same as Standard MAC, for all values of P_e. This is because when λ_c is increased, the contention in CAP is increased effecting GTS retransmissions. However thsi effect is not significant in our ECFP scheme.

Fig. 9 shows the overall GTS frame drop rate performance

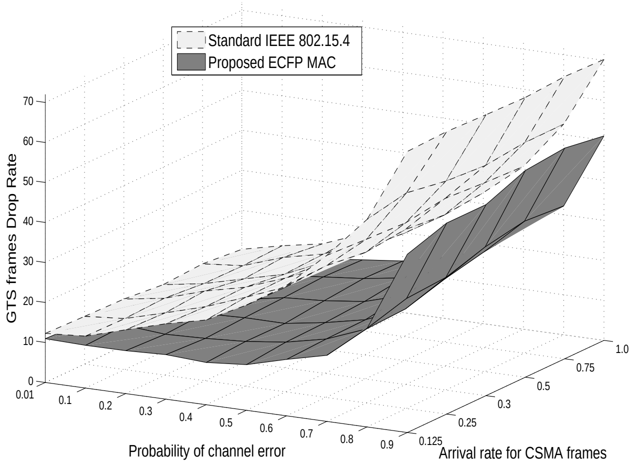

Fig. 9. GTS frame Drop Rate versus Probability of frame error and CSMA load

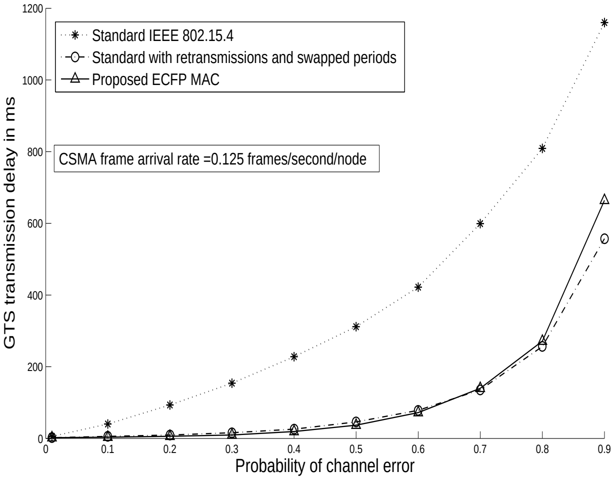

Fig. 10. GTS frame transmission delay vs Probability of frame error

of ECFP MAC and Standard MAC, for all values of P_e and λ_c. Apart from extremely low values of P_e and λ_c, the ECFP MAC outperforms Standard MAC scheme by a significant margin. For $P_e = 0.5$ and as λ_c is increased from 0.125-2.0, the Standard MAC shows a constant drop rate of 26% while ECFP MAC increases only from 11-15%. Hence even as λ_c is increased significantly the GTS frame drop rate of ECFP MAC is approximately half of Standard MAC. As P_e is increased from 0.5-0.9, we see a gain of 56% in GTS frame drop rate performance at $P_e = 0.6$ for low λ_c, and 42% as λ_c is increased. At $P_e = 0.9$, we see a gain of 38% at low λ_c and 30% as λ_c is increased. As λ_c and P_e both are increased, upper-right corner of Fig. 9, ECFP MAC out performs Standard scheme by a significant margin.

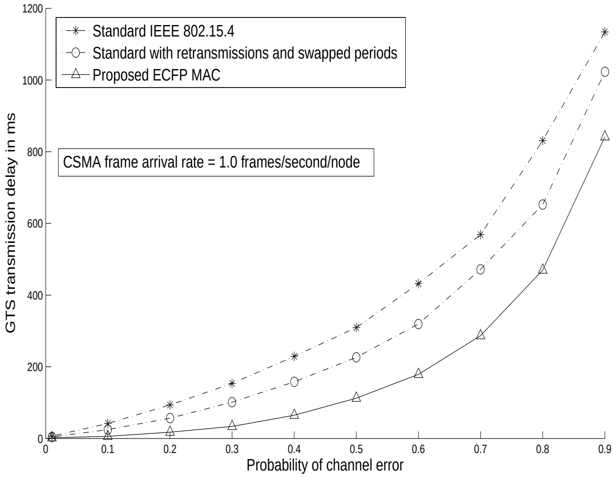

Fig. 11. GTS frame transmission delay versus Probability of frame error

2) Impact of P_e on Transmission Delay of GTS traffic: Fig. 10 shows GTS frame transmission delay versus P_e for various schemes for $\lambda_c = 0.125$ frames/second/node. The ECFP scheme outperforms the other two schemes, especially the Standard MAC scheme, when P_e is increased from 0.01 to 0.7. The ECFP scheme outperforms 'Standard with retransmissions and swapped periods' by approximately 40% at $P_e = 0.2$ and by approximately 10% at $P_e = 0.6$. For $P_e \geq 0.8$, the ECFP scheme experiences slightly higher transmission delay than 'Standard with retransmissions and swapped periods' due to smaller CAP at high P_e values, as discussed in earlier sections.

The ability of the ECFP scheme to behave gracefully under high λ_c is seen again in Fig. 11, where $\lambda_c = 1.0$ frames/second/node. As we increase λ_c, we see significant gains in performance by employing ECFP scheme as opposed to all other schemes in Fig. 11. Reason for this again is because failed GTS frames have contention free retransmissions in XGTS and are more resistant to increase in λ_c, unlike schemes which employ retransmissions in CAP. From Fig. 11, we see $\geq$ 80% gain in GTS transmission delay over other schemes when $P_e = 0.2$. For $P_e = 0.3$ the closest performance to ECFP MAC is of 'Standard with retransmissions and swapped periods', to which ECFP scheme shows 60% reduced delay and 85% less delay as compared to Standard scheme. At $P_e = 0.5$ these gains are 60% and 75% respectively and gradually go down to 33% and 50% at $P_e = 0.8$. Finally, at $P_e = 0.9$ we still see gains close to 20% over schemes with retransmission and 30% over Standard schemes.

We now analyze GTS frame transmission delay for all values of P_e and λ_c. Fig. 12 compliments Figs. 10 and 11 by giving an overall picture of ECFP performance comparison with Standard 802 MAC scheme. From Fig. 12 we see that the GTS frame transmission delay for ECFP MAC is significantly less than that of Standard MAC scheme for a vast majority of P_e and λ_c values. For low values of $P_e = 0.01$, the performance

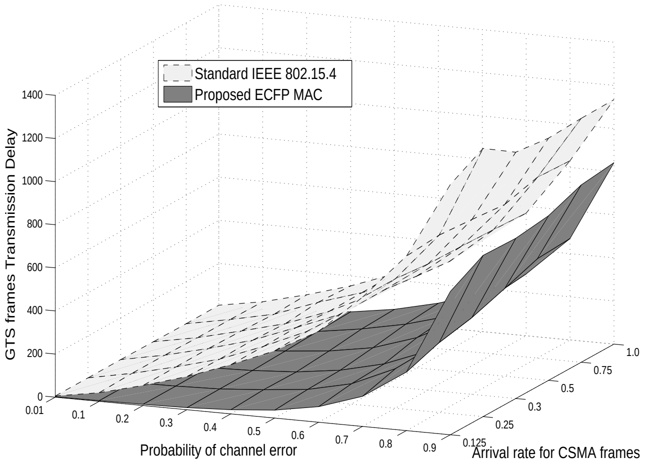

Fig. 12. GTS frame transmission delay versus P_e and λ_c

of other schemes is comparable to ECFP MAC. As P_e is increased to 0.1, ECFP begins to out perform Standard MAC by $\geq 90\%$ less delay. This gain stays above 85% for $\lambda_c = 0.125$ and 70% for $\lambda_c = 1.0$. For $P_e = 0.9$, ECFP MAC out performs Standard MAC by 50% for $\lambda_c = 0.125$ and 30% for $\lambda_c = 1.0$ and significantly for $\lambda_c = 2.0$.

C. Impact of ECFP Super-frame Structure on CSMA Traffic

Impact of ECFP on the CSMA traffic is analyzed by plotting CSMA frame transmission delay and CSMA frame drop rate performance versus λ_c and P_e. Comparison is drawn between the corresponding gains achieved in GTS performance for same values of λ_c and P_e. We see that under high λ_c and P_e, i.e. unfavouring channel conditions, sacrificing latency and reliability for non-critical CSMA traffic for significant gains in emergency response critical GTS traffic is a valuable trade-off.

Fig. 13 shows the CSMA frame drop rate versus λ_{cT} for $P_e = 0.1$. From Fig. 13 we can draw comparative analysis with Fig. 5 which shows GTS frame drop rate versus λ_{cT}. It is clear from Fig. 13 that CSMA frame drop rate performance shows variation as λ_c is increased beyond 0.5, $\lambda_{cT} \geq 20$. For extremely high λ_c, $\lambda_c \geq 2.0$, $\lambda_{cT} \geq 54$, the CSMA drop rate of the schemes with retransmissions is significantly higher than the Standard schemes. The CSMA frame drop rate for ECFP MAC is same as that for schemes which employ retransmissions. Hence comparing with Fig. 5, we see that we gain in GTS frame drop rate performance for no loss in CSMA performance for resonable channel conditions.

Fig. 14 shows CSMA frame transmission delay against λ_{cT}. For $\lambda_{cT} \leq 34$ frames/second, all schemes show the same delay and as λ_{cT} is increased, $\lambda_{cT} \geq 54$ frames/second or $\lambda_c = 1.0$ frame/second/node, our ECFP scheme shows nearly 5% more delay, which is about 5ms more than standard based schemes.

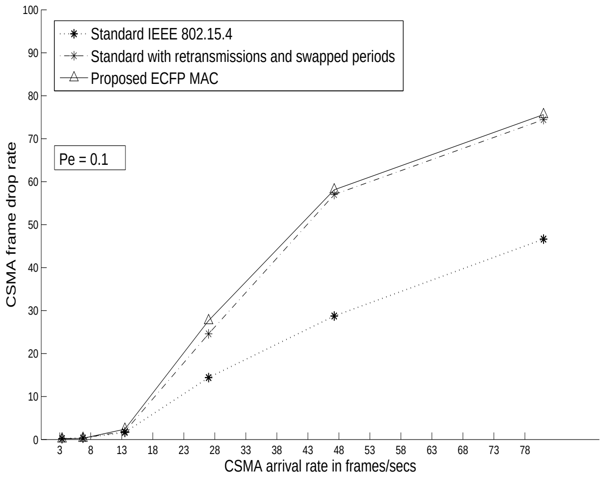

Fig. 13. CSMA frame drop rate versus CSMA arrival rate

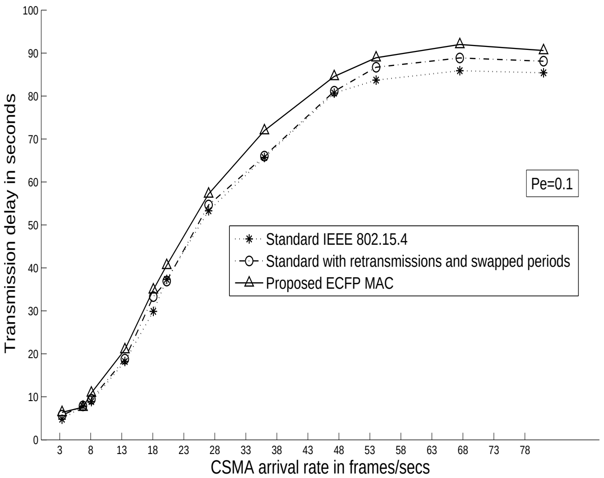

Fig. 14. CSMA frame transmission delay versus CSMA load

Fig. 15 plots CSMA frame drop rate versus P_e for $\lambda_c = 0.125$ frames/second/node. From Fig. 15 we see that only for extremely high $P_e \geq 0.7$, there is a difference in the CSMA frame drop rate performance of the Standard 802 MAC versus other two schemes. Moreover, from Fig. 15 the ECFP scheme shows the same level of performance as ‘Standard with retransmissions and swapped periods’. This compared with Figs. 7, 8 and 9, we see that the relative gains in GTS frame drop rate is at no extra CSMA performance cost, as compared to retransmission schemes and at minimal penalty as compared to Standard 802 MAC schemes. This will change for higher λ_g, however we expect the same trend unless for extremely high λ_g, when all schemes will deteriorate in performance.

Fig. 16 shows CSMA frame transmission delay versus P_e, for $\lambda_c = 0.125$. As can be seen from Fig. 16, the ECFP scheme closely follows the transmission delay of all other schemes for $P_e \leq 0.4$. Between $0.4 < P_e \leq 0.7$, the ECFP scheme shows comparable performance to ‘Standard with retransmissions

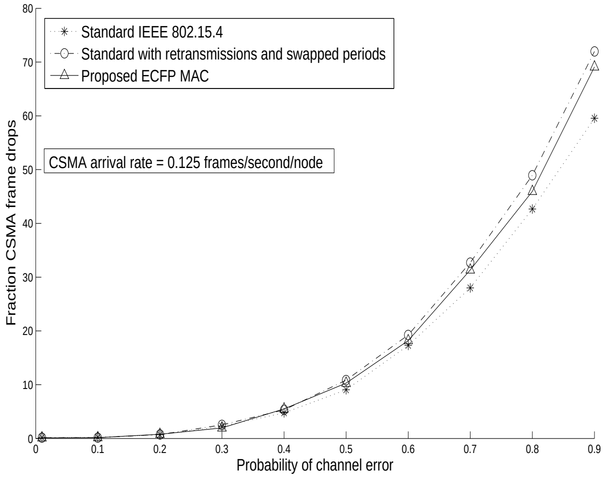

Fig. 15. CSMA frame drop rate versus Pe

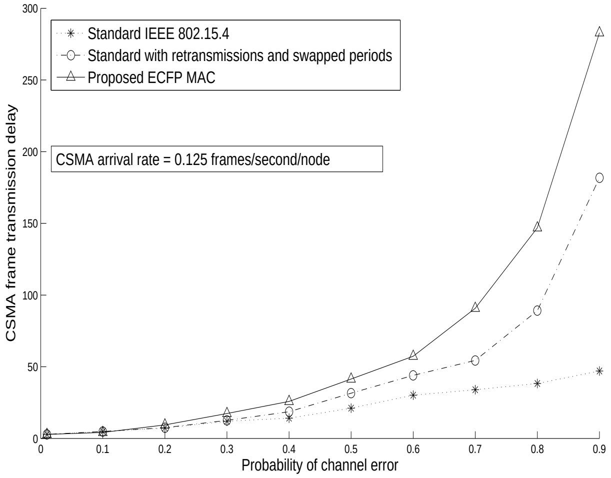

Fig. 16. CSMA frame transmission delay versus Pe

and swapped periods', and noticeably higher as compared to Standard 802 MAC schemes. For extremely high P_e, $P_e \geq 0.8$, the ECFP scheme shows a relatively higher CSMA frame transmission delay than all other schemes. The actual CSMA delay value, however, is still of the order of ms making the overall impact on CSMA best-effort traffic marginal. Comparing Fig. 16 to plots of GTS frame transmission delay versus P_e, especially Fig. 10, we see that the gains provided by ECFP scheme as compared to other schemes presented, for reasonable channel conditions, well out weigh its CSMA performance.

V. CONCLUSION

In this paper we propose modifications to existing IEEE 802.15.4 MAC to provision low-latency and high reliability for time-sensitive transmissions for emergency response. Our scheme extends on previously proposed modifications to the IEEE 802.15.4 MAC. In the overall sense, the ECFP scheme shows significantly lower GTS frame drop rate and GTS frame transmission delay: for moderate to high values of CAP arrival rate, 75% reduced latency and 12.5% reduced GTS frame drop rate than the other compared schemes. When the CAP arrival rate is increased, the ECFP scheme has an increased performance for GTS frame transmission delay and drop rate for a full spectrum of probability of channel errors. The results show that there is negligible impact on the QoS of CAP traffic, except for very high probability of channel errors or extremely high CSMA frame arrival rates. It is also evident that for emergency response applications, trading the performance of best effort CSMA traffic for significant gains in guaranteed traffic performance under extreme conditions is acceptable. Future work will address theoretical analysis of the ECFP.

REFERENCES

[1] *G. Bhatti, A. Mehta, Z. Sahinoglu, J. Zhang, R. Viswanathan, Modifed Beacon-Enabled IEEE 802.15.4 MAC for Lower Latency*, Globecom 2008

[2] *IEEE 802.15.4 Standard on Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications for Low Rate Wireless Personal Area Networks*, IEEE 2003.

[3] J. Misic, S. Shafi and VB. Misic, *Performance limitations of the MAC layer in 802.15.4 low rate WPAN*, COMPUTER COMMUNICATIONS, AUG 21 2006, 29 (13-14): 2534-2541

[4] J.S. Lee, *Performance evaluation of IEEE 802.15.4 for low-rate wireless personal area networks*, IEEE TRANSACTIONS ON CONSUMER ELECTRONICS, AUG 2006 52 (3): 742-749

[5] G. Chalhoub, E. Livolant, A. Guitton, A. van den Bossche, M. Misson and T. Val, *Specifications and Evaluation of a MAC Protocol for a LP-WPAN* AD HOC and SENSOR WIRELESS NETWORKS, 2009, 7 (1-2): 69-89.

[6] C.W Chen, Weng CC (Weng, Chuan-Chi)1, Ku CJ (Ku, Chang-Jung)1, *Design of a low power and low latency MAC protocol with node grouping and transmission pipelining in wireless sensor networks*, COMPUTER COMMUNICATIONS, SEP 2008, 31 (15): 3725-3738.

[7] I . Rhee, A. Warrier, M. Aia, J. Min, M.L Sichitiu, *Z-MAC: A hybrid MAC for wireless sensor networks*, WIRELESS NETWORKS, JUN 2008, 16 (3): 511-524.

[8] W.T.H. Woon, T.C. Wan *Performance evaluation of IEEE 802.15.4 wireless multi-hop networks: simulation and testbed approach* INTERNATIONAL JOURNAL OF AD HOC AND UBIQUITOUS COMPUTING, 2008, 3 (1): 57-66.

[9] A . Van den Bossche, T. Val, E. Campo *Modelisation and validation of a full deterministic medium access method for IEEE 802.15.4 WPAN* AD HOC NETWORKS, 2009, 7 (7): 1285-1301.

[10] C.V. Joshi, M.S. Sutaone, A. Yadav, M. Bhoyar, A. Barve *A Review of the Challenges in the Implementation of Next-Generation ZigBee Networking* IETE TECHNICAL REVIEW, 2008, 25 (4): 161-167.

[11] PK Sahoo, JP Sheu, YC Chang *Performance evaluation of wireless sensor network with hybrid channel access mechanism* JOURNAL OF NETWORK AND COMPUTER APPLICATIONS, 2009, 4 (32): 878-888.

[12] I. Gragopoulos, I. Tsetsinas, E. Karapistoli, F.N. Pavlidou *FP-MAC: A distributed MAC algorithm for 802.15.4-like wireless sensor networks* AD HOC NETWORKS, 2008, 6 (6): 953-969.

[13] K.R. Chowdhury, N. Nandiraju, P. Chanda, D.P. Agrawal, Q.A. Zeng *Channel allocation and medium access control for wireless sensor networks* AD HOC NETWORKS, 2009, 7 (2): 307-321.

[14] C. Na, Y.L. Yang, A. Mishra *An optimal GTS scheduling algorithm for time-sensitive transactions in IEEE 802.15.4 networks* COMPUTER NETWORKS, 2008, 52 (13):2543-2557.

[15] A. Koubaa, M. Alves, E. Tovar, A. Cunha *An implicit GTS allocation mechanism in IEEE 802.15.4 for time-sensitive wireless sensor networks: theory and practice* REAL-TIME SYSTEMS, 2008, 39 (1-3): 169-204.

[16] *A. Mehta, G. Bhatti, Z. Sahinoglu, R. Viswanathan, J. Zhang, Performance Analysis of Beacon-Enabled IEEE 802.15.4 MAC for Emergency Response Applications*, ANTS 2009