Delay-Aware Cross Layer Data Transmission Schemes for Wireless Sensor and Actor Networks

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***Abstract*— Wireless Sensor and Actor Networks (WSANs) are widely used in monitoring and control of critical systems. Data delivery in a timely manner is highly desired for various emerging application fields such as smart grid and e-health. For the resource constrained WSANs, transmitting time-critical data calls for data prioritization and delay-awareness. In this paper, we propose two delay-aware, cross layer (DRX) data transmission schemes for WSANs. Our approaches are based on delay-estimation and data prioritization steps that are performed by the application layer, in addition to the MAC layer parameters responding to the delay requirements of the application and the varying channel conditions in the network. Our results show that the proposed DRX schemes, particularly DRX_{CCA} is able to reduce end-to-end delay for data demanding timely delivery while maintaining acceptable performance in terms of throughput, packet loss and energy consumption.**

Keywords; Cross layer protocol, delay-awareness, IEEE802.15.4, wireless sensor and actor networks.

I. INTRODUCTION

In condition monitoring and control applications accurate and near real-time data delivery becomes essential for proper system operation. For instance, in e-health applications delivering vital signals in a timely manner from patients to the health personnel is of paramount importance. Another application field of low latency data delivery is the smart grid. In the smart grid, Distributed Energy Resources (DER) including Distributed Generation (DG), Distributed Storage (DS) and controllable loads are anticipated to engage in intensive interactions for the purpose of providing reliable, efficient and sustainable electrical services. The condition and capacity of these resources will vary in real-time while the applications built over them will desire accurate and timely information on their status.

Wireless Sensor and Actor Networks are composed of a large number of tiny, low-cost, low-power and multifunctional sensor and actor nodes. Sensor and actor nodes communicate wirelessly over short distances. Sensor nodes collect data on temperature, humidity and the physical condition of the environment, while actors perform various tasks in accordance with application requirements. WSANs are preferred due to their ability to work in extreme environmental conditions, in addition to having enhanced fault tolerance, low power consumption, self-configuration capability and low cost.

Despite the advantages of WSANs, they have not been fully integrated in delay critical applications targeting monitoring and control. This is mostly due to the inherent limitations of WSANs in real-time data delivery. WSANs use low power communication links in dense deployments which introduces low data rates and delays in channel access.

The abovementioned challenges introduce reliability concerns in critical applications, e.g. health or power grid. In fact, reliable data delivery has been widely studied in the Wireless Sensor Network (WSN) literature where the term generally refers to ensuring data delivery from source to destination or sink. In the context of critical applications that need near real-time decision, reliability needs to include timeliness as well, since obsolete data may be worse than having no data. For instance, when the blood sugar level of a patient suffering from diabetes, drops below a certain threshold, an alarm may be sent to the medical center. Delay in delivering such vital information can have serious impacts [1]. Delay-aware data transmission is also significant in smart grid applications. In the smart grid, WSN based demand control applications may require low latency data transmission [2]. Meanwhile, it is also apparent that, not all of the collected data by WSANs include vital signals or critical demand control actions. Therefore, providing service differentiation and quality of service (QoS) is also essential for WSANs in delay critical applications.

In this paper, we aim to provide service differentiation by proposing two delay-aware, cross layer (DRX) data transmission schemes. The proposed schemes implements application layer data prioritization techniques to control medium access of sensor and actor nodes. Our delay-aware approaches initially execute delay assessment in a certain node, if the estimated delay is higher than the delay requirements of a specific control and automation application, then that node is given higher priority to access the channel by either reducing its clear channel assessment duration (DRX_{CCA}) or reducing the minimum back-off exponent (DRX_{BE}). This approach is adaptive in the sense that when the in next round when delay estimation is done and the delay is found to be lower than the requirements, the parameters are set back to default. The DRX approach is also a cross layer approach; that is the application layer enforces parameters change at the lower layers to enforce QoS requirements. We show that our approach is able to improve the overall QoS requirements of a particular node, while not highly affecting its energy consumption. We also investigate the performance of our approach in different situations; this is done by considering different shadowing and multipath conditions that exist in real environments. Therefore the main contributions of this work is proposing a novel adaptive and cross layer approach to improve the QoS requirements in delay sensitive monitoring and control applications. To the best of our knowledge, MAC parameter tuning considering delay estimation and data prioritization has not been proposed before.

The rest of the paper is organized as follows. In Section II we present the related work. In Section III we present the analytical model for delay estimation. In Section IV we introduce the proposed approach and discuss the results in Section V. Finally, Section VI concludes the paper.

II. Related Work

In the literature, cross layers protocols for WSNs have been widely studied. In [3, 4] the authors propose a cross layer protocol to combine the functionalities of medium access, routing, and congestion control and address receiver-based contention, congestion control, and duty cycling in WSNs. In [5], the authors have proposed a cross layer protocol for target tracking applications. In [6] the authors have proposed an Adaptive back off exponent (BE) management scheme for CSMA/CA of 802.15.4 and investigated its effects on power consumption of the node. Furthermore, in [7], the authors have proposed a distributed algorithm that meets the application-specific reliability and energy consumption. In [8] he authors propose an adaptive mechanism to the implementation of the back off exponent management, based on a decision criterion to optimize the energy consumption. In [9] the authors propose a priority-based scheme, using frame tailoring and priority toning, to guarantee time-bounded delivery of high priority packets in event-monitoring networks. Besides generic delay reduction, QoS has also been studied in the literature where high priority sensor data are aimed to be forwarded with less delay or higher reliability. In [10], the authors have proposed to exploit packet priority to temporally separate the medium access of different groups of nodes which is established by configuring sleep and active periods accordingly. The impact of delay on smart grid applications has been initially investigated in [11], considering a WSN that is used for condition monitoring of a wind turbine.

Following the work presented in [7], our work uses a probabilistic delay estimation model. This model estimates the delay based on different number of nodes and traffic conditions and then reduces the end-to-end delay to meet the delay requirement of a specific application. In addition to that our scheme also offers priority to certain nodes that are transmitting delay critical data. Furthermore, we aim at reducing the end-to-end delay by adaptively changing the duration of clear channel assessment of certain nodes and setting this parameter to default when prioritization is not required.

III. Analytical Model for Delay Estimation

The IEEE 802.15.4 standard specifies MAC and physical layers [12]. In this standard the CSMA/CA is used with a slotted binary exponential backoff scheme to reduce collisions by randomizing the channel access. The IEEE 802.15.4 standard defines two channel access techniques; namely the beacon-enabled mode, which uses a slotted CSMA/CA and exponential back-off, and a simpler unslotted CSMA/CA without beacons.

The standard defines three bands for operation: 868MHz, 902MHz and 2.4GHz. The 2.4 GHz band provides a data rate of 250 kbps by using one of 16 pseudo-orthogonal PN codes of length 32 chips to represent 4 bits of information. According to the standard CCA may be performed using either energy detection or carrier sensing or a combination of the two. It further specifies the CCA detection time as 8 symbol periods; that is, the PHY layer has to finish its CCA and report its findings to MAC within 128µs. There is however a possibility of a false alarm which prevents an otherwise possible transmission. On the other hand, missed detection that could potentially cause collisions impacts the overall system performance. The CCA methods vary greatly in their ability to detect signal presence reliably and in power consumption. As a result, the particular choice of the CCA method and parameters has a substantial impact on the performance of MAC sub-layer metrics such as throughput, delay and energy efficiency. In many cases these MAC sub-layer metrics are contradictory and require careful optimization of CCA parameters to attain a reasonable trade-off [13].

A generalized analytical model of the slotted CSMA/CA mechanism of beacon enabled IEEE 802.15.4 is proposed in [14]. The model uses a Personal Area Network (PAN) coordinator with N nodes and beacon-enabled slotted CSMA/CA and ACK. All nodes may contend to send data to the PAN coordinator where the behavior of a single node is modeled using a Markov chain.

The derived model uses an accurate and an approximate model; both of which solve a set of three nonlinear equations using certain numerical methods. The exact analysis may be computationally challenging and not suitable for use in sensor devices. Thus, we focus on the implementation and evaluation of the approximate model. In the approximated model nodes utilize local measurements to estimate the delay.

The main idea behind the model is that sensor nodes can easily estimate the busy channel probabilities ρ, σ and ω. Where ρ is the probability that the first clear channel assessment CCA_1 is busy, σ the probability that CCA_2 is busy and ω is the probability that a node attempts a first carrier sensing CCA_1 in a randomly chosen time slot.

The probability ω further depends on the probability that a transmitted packet encounters a collision P_{co}, ρ and σ. P_{co} is the probability that at least one of the *N-1* remaining nodes transmits in the same time slot. If all nodes transmit with probability ω, P_{co} is given by:

$$P_{co} = 1 - (1-\omega)^{N-1} \tag{1}$$

where *N* is the number of nodes. The probability of having CCA_1 busy (ρ) is given by the summation of the probability of finding a channel busy during CCA_1 due to data transmission (ρ_1) and the probability of finding a channel busy during CCA_2 due to ACK transmission (ρ_2):

$$\rho = \rho_1 + \rho_2 \tag{2}$$

where

$$\rho_1 = L(1-(1-\omega)^{N-1})(1-\rho)(1-\sigma) \tag{3}$$

and

$$\rho_2 = L_{ack}\frac{N\omega(1-\omega)^{N-1}}{1-(1-\omega)^N}(1-(1-\omega)^{N-1})(1-\rho)(1-\sigma). \tag{4}$$

Here L_{ack} is the length of the acknowledgement. The probability that CCA_2 is busy is given by:

$$\sigma = \frac{1-(1-\omega)^{N-1}+N\omega(1-\omega)^{N-1}}{2-(1-\omega)^{N}+N\omega(1-\omega)^{N-1}} \tag{5}$$

$$\omega = (1+a)(1+b)p_{0,0,0} \tag{6}$$

and

$$a = \rho + (1-\rho)\sigma \quad and \quad b = P_{co}(1-a^{m+1}) \tag{7}$$

$p_{0,0,0}$ is the approximate stationary distribution of Markov chain and given by the following expression [14]:

$$p_{0,0,0} = \Big[\frac{Wo}{2}(1+2a)(1+b) + L_s(1-a^2)(1+b) +$$
$$Yo(Pco1-a22Pco1-a2n-1+1+1-1 \tag{8}$$

where $m = MaxBackoffs$, $W_o = 2^{MinBE}$, $n = MaxFrameRetries$, L_s is the time period of successful transmission and is given by the following relation:

$$L_s = L + t_{ack} + L_{ack} + IFS \tag{9}$$

Here *L* is the total length of the packet including overhead and payload, t_{ack} is the acknowledgment waiting duration, L_{ack} is the length of the acknowledgment frame and *IFS* is the inter-frame spacing.

$Y_o = \frac{L_o p_o}{(1-p_o)}$,where L_o is idle state length and p_o is the probability of going back to the idle state.

Equations (2), (5) and (6) can be solved to find the values of ρ, σ and ω.

The average estimated delay is given by

$$\mathbf{E}[\mathrm{D}] = \mathbf{P}^{\mathrm{T}}\mathbf{D} \tag{10}$$

where $\boldsymbol{P} = [\Pr(X_0|X_t) \ldots \Pr(\mathrm{X_n}|X_\mathrm{t})]^{\boldsymbol{T}}$, $\mathbf{D} = [\mathrm{d_0} \ldots . \mathrm{d_n}]^{\mathrm{T}}$, $\mathrm{d_j} = \mathrm{T_s} + jT_c + (j+1)\boldsymbol{E}[T]$

$$\Pr(\mathrm{X_j}|X_\mathrm{t}) = \frac{(1-\mathrm{P_{co}}(1-a^{\mathrm{m}+1}))\mathrm{P_{co}^{j}}(1-a^{\mathrm{m}+1})^{\mathrm{j}}}{1-(\mathrm{P_{co}}(1-\mathrm{a^{m+1}}))^{\mathrm{n}+1}} \tag{11}$$

$\mathrm{T_s}$ and $\mathrm{T_c}$ are time durations of successful and collided packet transmissions respectively.

X_j is occurrence of successful packet transmission at *j+1* given that *j* transmission is unsuccessful; X_t is the occurrence of successful packet transmission within n attempts.

$$\boldsymbol{E}[T] = 2T_s(1+\widetilde{\boldsymbol{P}}^T\boldsymbol{T}) \tag{12}$$

where $\widetilde{\mathbf{P}} = [\tilde{P}(B_o|B_t) \ldots . \tilde{P}(B_m|B_t)]^T$, $\mathbf{T} = [\mathrm{t_0} \ldots . \mathrm{t_m}]^{\mathrm{T}}$

$$t_i = [(2^{i+1}-1)W_o + 3i - 1]/4$$

$$\tilde{P}(B_i|B_t) = \frac{\max(\rho,(1-\rho)\sigma)^i}{\sum_{k=0}^{m}\max(\rho,(1-\rho)\sigma)^k} \tag{13}$$

B_i is occurrence of a busy channel for the *i-th* time then an idle channel at the *i+1th* time, B_t is the successful sensing event in *m* attempts.

IV. The Proposed Scheme

The proposed scheme can be implemented in a number of WSN scenarios such as in the smart grid, telemedicine and in military based applications. In these scenarios monitoring and control of delay critical data is required. Therefore, we assume that the data collected by certain sensors have high priority and should be delivered with minimum end-to-end delay.

The proposed scheme includes an adaptation module which facilitates the interaction of the application layer with the MAC and physical layers of the sensor network protocol stack. Our delay-aware technique aims to reduce the end-to-end delay by estimating the delay of critical data, and then insuring that this data is delivered to the destination with minimum delay. We first implement the delay-estimation algorithm that estimates the expected delay based on the probabilistic model explained in Section IV. Based on the resulting values of the delay estimation, the MAC layer responds to the delay requirement of the application.

The delay estimation algorithm is executed by individual sensor nodes based on the priority of the data. If a node finds out that the estimated delay is higher than a set threshold then the application layer places a flag indicating that lower layers should treat the packet accordingly. Thus, upon arrival of the frames to the MAC sub-layer, it makes changes in its own parameters or that of the physical layer based on two proposed schemes.

In the first proposed scheme, namely $\mathrm{DRX_{CCA}}$, the MAC sub-layer requests the physical layer to reduce the CCA duration from 8 symbol periods to 4 symbol periods (from 128µs to 64µs). In doing so, the physical layer senses the channel in half of the regular CCA time and reports the results to the MAC layer. Thus, this node gets to transmit its data before the other contending nodes. If the node finds the channel busy, it invokes the back-off algorithm as described in [10]. In this scheme, we assume that there are no other devices transmitting at the same frequency band to avoid any possible coexistence problems. Algorithm 1 describes the DRX_{CCA} scheme, initially the application layer evaluates the captured data and decides if its value is above the threshold ($V > V_{threshold}$); if so, then the algorithm invokes the delay estimation process. If the delay is found to be higher than the threshold value then the CCA duration is divided by 2, otherwise the algorithm does not make any changes in the MAC or physical layer and transmit the data using the normal process.

Algorithm1: DRX_{CCA} Scheme

if $V > V_{threshold}$ **then**
    $E[D] = P^T D$
    if $E[D] > D_{threshold}$ **then**
        CCAdurration = CCAduration/2
else

Although CCA is a physical layer parameter, it has a direct impact on the performance of the MAC sublayer of the WSN as can be seen in the presented results. Several previous studies has discussed the effect of the CCA on the perfomance of the MAC sublayer [15], [16]. However a cross layer approach has not been adopted in those studies.

In the second proposed scheme, namely $DRX_{BE,}$ the application layer follows the same procedure of evaluating the threshold explained above. If delay reduction is required, then the application layer requests the MAC sub-layer to reduce the value of the minimum back-off exponent *minBE* by two. The idea of modifying the MAC parameters to improve the performance of the WSN was presented in [5] and [7]. However, our shceme facilitates cross layer information. Algorithm 2 describes the DRX_{BE} scheme.

Algorithm2: DRX_{BE} Scheme

if $V > V_{threshold}$ **then**
    $E[D] = P^T D$
    if $E[D] > D_{threshold}$ **then**
        MinBE = MinBE-2
else

V. PERFORMANCE EVALUATION

To evaluate the performance of the analytical system a simulation model is built and simulated using QualNet [17] network simulator. The WSN is tested with different number of nodes and traffic conditions. Furthermore, to investigate the performance of the proposed scheme in different environments we simulate our WSNs in outdoor, indoor. The simulation parameters are selected similar to that of the analytical model. We use a beacon enabled star topology having N nodes and a coordinator, where N varies in each simulation scenario. The ACK mechanism is not used to reduce the energy consumption. We assumed that the IEEE 802.15.4 MAC protocol is operating in the 2.4 GHz band with a maximum bit rate of 250 Kbps. The transmission range was set to 40m and all the nodes are in the same PAN. Each simulation was run for 3000 second and each result represents an average of 10 runs. Table I shows the default parameters used in the simulations, the remaining parameters are taken from [12].

TABLE I. INITIAL SIMULATION PARAMETRES

Parameter	**Value**
Acknowledgment mechanism	Disabled
Transmission power (dBm)	3.0
CCA mode	Carrier sense
Noise factor (dB)	10.0
Contention window	2
Routing-protocol	AODV
Packet size	128B
Beacon order	3
Super frame order	3

Fig. 1 shows the relation between the average end–to–end delay and the number of nodes in the simulation environment and the estimated delay using the analytical model of Section IV. From Fig. 1 it can be seen that there is an agreement between the estimated value of the delay and the actual simulated delay which is a good indicator that the analytical model can be utilized by the proposed scheme. Note that, as the number of nodes increases, the difference between the simulated and the estimated delay slightly increases, this is because of the approximation nature of the mathematical model. In the subsequent evaluations we select N=10 nodes which gives a difference of 2.1% between the simulated and the estimated delay. The general trend of the end-to-end results presented here agrees with the results of [14].

Fig.2 presents the average end-to-end delay versus the number of nodes from the simulated WSN. We can see that using DRX_{CCA} has higher impact on delay reduction than DRX_{BE}. This delay reduction becomes more significant as the number of nodes increase.

We also investigate the effect of implementing the DRX_{CCA} scheme on the application layer throughput which represents the total number of bits (in bits/sec) forwarded from the application layer to lower layers. As seen in Fig. 3, the throughput in the DRX_{CCA} implementation is higher than the throughput in the default case in all number of nodes.

Fig. 4 shows the percentage of data packet received by the PAN coordinator from an individual node versus the number of nodes. As seen from the results DRX_{CCA} scheme outperforms the default parameter setup in terms of the percentage of data packets received. We also observe that the

DRX_{BE} scheme also has higher percentage of data packet received compared to the default scheme. Packet delivery ratio drops as the number of nodes increase as expected.

Fig. 5 shows the effect of DRX_{CCA} scheme on the energy consumption of sensor nodes. It is seen that the energy consumed in the transimit mode is slightly higher when we implement the DRX_{CCA} scheme, this is because the node implementing this scheme will be transmitting more often than its nieghbouring node. The increase in energy consumption is not significant (only 0.9%) compared to the increase in the thoughput, packet reception ratio and the reduction end-to-end delay.

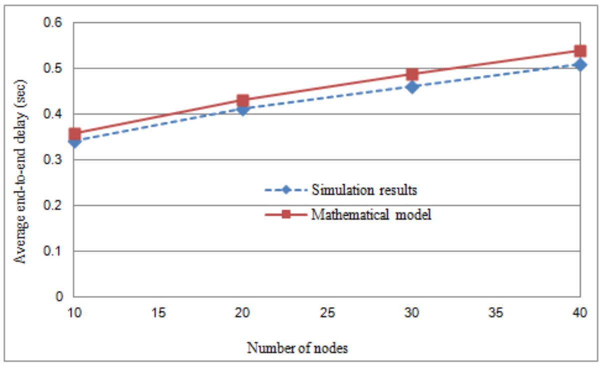

Fig.1 Simulated and estimated end-to-end delay.

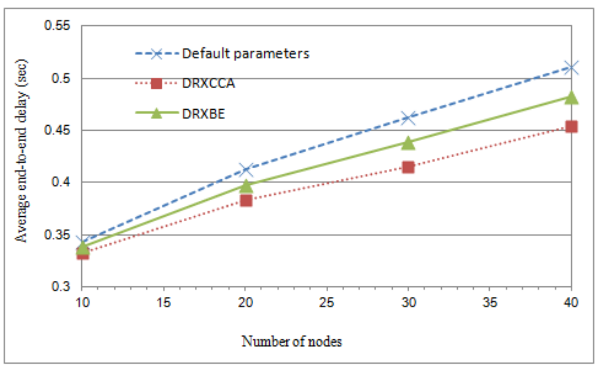

Fig.2 The average end-to-end delay of DRX_{CCA}, DRX_{BE} and default values.

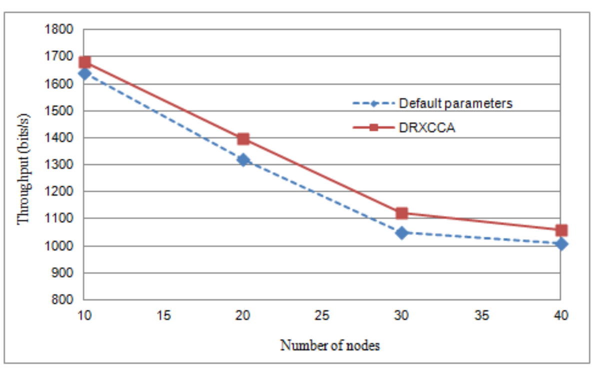

Fig. 3 The throughput (bit/s) comparison of DRX_{CCA}.

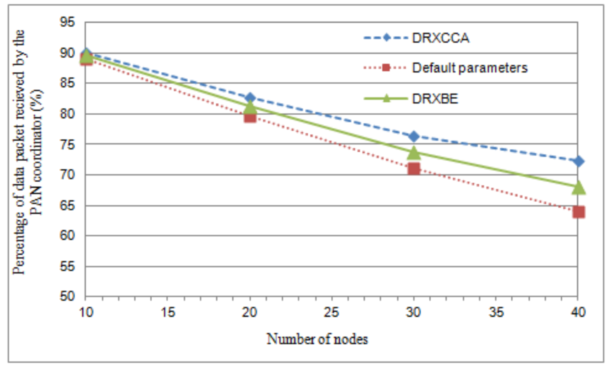

Fig. 4 Data delivery performance of DRXCCA, DRX_{BE} and the default case.ata packet received by the PAN coordinator.

We further elaborate on the performance of the DRX_{CCA} scheme in different environments. We assumed that the WSN system is deployed in various environments with a log-normal channel parameters for different values of shadowing deviation. We also simulated the DRX_{CCA} scheme in a free space model and a two-ray model. The free space and the two ray models represent the communication range as an ideal circle. In real environment, the received power at certain distance is a random variable due to multi path propagation effects, which is also known as fading effects. A more general and widely-used model is called the shadowing model. Table II shows some typical values of shadowing deviation in dB which we used to simulate our WSN in various environments [18].

TABLE II. TYPICAL VALUES OF SHADOWING DEVIATION IN DB

Environment	**σ_{dB} (dB)**
Outdoor	4 to 12
Indoor, hard partition	7
Indoor, line-of-sight	3 to 6
Indoor, obstructed	6.8

Fig. 6 and Fig.7 show the relation between the average end-to-end delay of node 2 (where the DRX_{CCA} is implemented) as a function of shadowing deviation in a two ray and free space models respectively. We can see that the DRX_{CCA} outperforms the default parameter scheme in all values of shadowing deviations and in both propagation models.

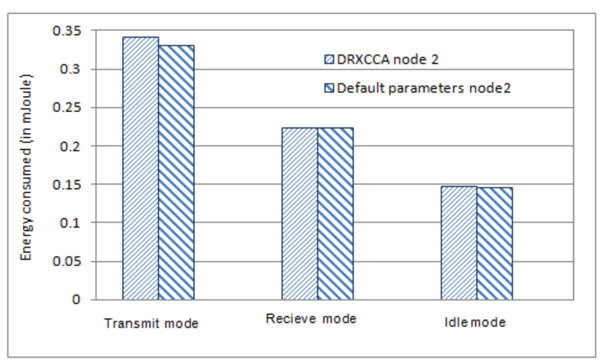

Fig. 5 Energy consumption of DRX_{CCA} .

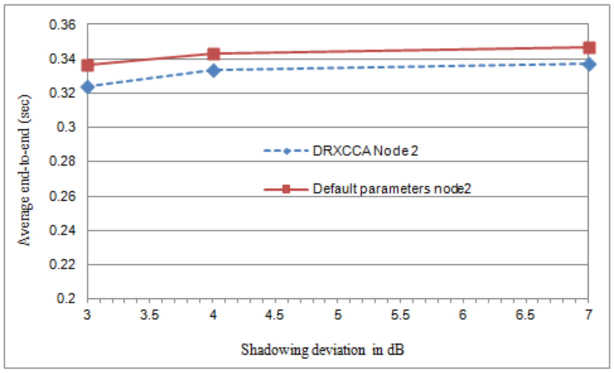

Fig.6 Average end-to-end delay under various shadowing deviation values in a two ray model.

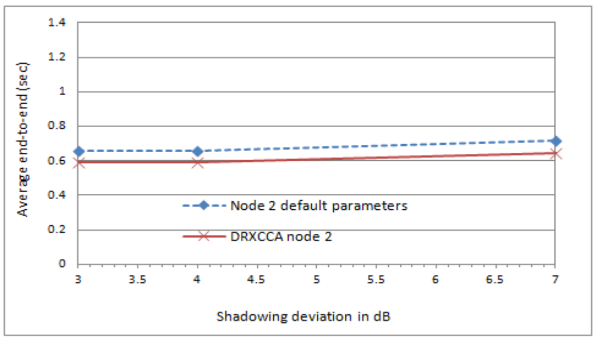

Fig. Average end-to-end delay under various shadowing deviation values in a free space model.

VI. Conclusions

It is essential to achieve certain levels of reliability in monitoring and controlling delay critical applications. In applications such as monitoring patients in a hospital or controlling the smart grid, delay is considered to be a fundamental issue to be addressed.

In this paper, we proposed two schemes that respond to the delay requirements of the application by predicting the end-to-end delay and creating cross layer measures. Our schemes achieve delay-awareness by modifying the parameters in the lower layers, i.e. MAC and physical layers. The results show that the proposed schemes are able to reduce delay for high priority data while maintaining acceptable throughput and packet loss values. The first scheme, DRX_{CCA} slightly performs better than the second scheme DRX_{BE} in terms of end-to-end delay. The delay reduction achieved by the proposed schemes will enhance the monitoring operation in situations where sudden changes in the monitored data take place. Furthermore, the proposed schemes do not increase energy consumption of the WSN significantly.

As a future work we plan to investigate the effects of the modified CCA duration on coexistence with other wireless protocols such as Wi-Fi.

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