A Low Latency Data Transmission Scheme for Smart Grid Condition Monitoring Applications

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Abstract—Condition monitoring of smart grid assets in a near real time manner is essential for the success of emerging smart grid applications. Wireless Sensor and Actor Networks (WSANs) are likely to be widely employed in a wide range of smart grid applications due to their various advantages. Transmitting delay-critical data from smart grid assets to the controller base station may require data prioritization and delay-responsiveness in condition monitoring applications. In this paper, we introduce a medium access scheme, namely delay-responsive, cross layer (DRX) data transmission that aims to address delay and service differentiation requirements of the smart grid. The DRX scheme is based on delay-estimation and data prioritization procedures that are performed by the application layer for which the MAC layer responds to the delay requirements of the smart grid application and the network condition. We provide a comprehensive performance evaluation of this scheme and show that DRX reduces the end-to-end delay and provide data prioritization to critical data. We outline the tradeoffs regarding this scheme and draw future research directions for robust communication protocols for smart grid condition monitoring applications.

Index Terms—Condition monitoring, delay-sensitive, smart grid, wireless sensor and actor networks.

I. INTRODUCTION

In the power grid, accurate and near real-time information collected from generators, transmission equipment, transformers, capacitor banks and substations becomes essential for a successful smart grid operation.

Wireless sensor and actor networks (WSANs) can be considered as favorable tools for monitoring and controlling smart grid assets. A WSAN is composed of a large number of low-cost, low-power, small and multifunctional sensor and actor nodes. Sensor and actor nodes communicate wirelessly over short distances. In a smart grid environment, sensor nodes can collect various kinds of data, e.g. voltage, current, frequency, etc. while actors perform tasks such as closing/opening circuit breakers, turning on/off loads, etc. WSANs are favored in condition monitoring applications due to their ability to work in extreme environmental conditions, in addition to having enhanced fault tolerance, low power consumption, self-configuration, rapid deployment and low cost. Furthermore, in environments where high voltages are in use, WSAN can also provide necessary insulation. Despite the various advantages of WSANs, they have not been widely utilized for monitoring critical smart grid assets. This is mostly due to the inherent limitations of WSANs in real-time data delivery. This real-time limitation is because WSANs use low power communication links in dense deployments which introduces low data rates and delays in channel access due to packet collisions.

The aforementioned limitations raise reliability concerns in the smart grid. In Wireless Sensor Network (WSN) literature, reliable data delivery has been extensively investigated, where the term “reliable” generally refers to ensuring that data is delivered from source to destination or sink. In the context of smart grid, reliability includes timeliness as well, since obsolete data or control signals may be as bad as or even worse than having no data or signals at the base station controller. For instance, in a scenario where partial discharge (PD) is being monitored in a high voltage (HV) transformer, delayed PD detection, could cause instability of the grid, or even failure of the HV transformer if no necessary actions take place immediately. In general the data transmitted by WSANs can be either event driven data or routine data. Event driven data transmission is triggered when a specific event takes place, on the other hand routine data transmission takes place periodically and they may not be critical for the operation of the system. Meanwhile, it is also apparent that, not all of the event driven data are significant in control actions. Some event driven data may tolerate minor delays and can be processed in a non-real-time manner. Therefore, providing Quality of Service (QoS) becomes essential for the smart grid setting.

In this paper, we present a protocol that aims to address data-prioritization and delay-sensitive data transmission for WSANs in the smart grid. The proposed protocol; delay-responsive, cross layer (DRX) data transmission uses application layer data prioritization to control medium access of sensor and actor nodes. DRX first performs delay estimation using a probabilistic model, if the estimated delay cannot meet the delay requirements of a specific smart grid application, then channel access of the node detecting the critical data is fast-tracked by reducing clear channel assessment duration. We compare the performance of DRX and existing QoS supporting mechanisms [1-2]. DRX achieves lower average end-to-end delay compared to the default IEEE802.15.4 MAC and the modified back off time (MBOT) scheme which has been presented in [2]. We also evaluate the performance of DRX in various smart grid environments with varying channel properties. Furthermore, we discuss a certain smart grid application with strict delay bounds and show that DRX satisfies the delay requirements of those applications.
The main contribution of this paper is to present an adaptive and cross layer scheme that prioritize critical data and ensure their timely delivery to the base station in a smart grid environment. We compare the performance of the DRX scheme existing QoS schemes that are used in WSNs. The impact of priority and delay awareness in medium access techniques on end-to-end delay, delivery ratio and energy consumption of the WSNs are presented. We further discuss the applicability of our priority and delay aware medium access scheme in the transmission of critical PD data in HV transformers.

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 that is utilized by DRX. In Section IV, we introduce DRX in details and discuss the results in Section V. Finally, Section VI concludes the paper and gives future research directions.

II. RELATED WORK

In the literature, several studies have discussed using WSNs for monitoring utility assets and power grid equipment [3-7]. In [3], a condition monitoring system using WSN has been proposed to monitor PD activity in high voltage transformers where PD data was collected from individual sensors on the transformers and transmitted to the base station. The use of wireless multimedia sensor and actor networks in various smart grid settings, including electricity production facilities, transmission and distribution system and customer premises have been disused in [4]. In [5], the authors have evaluated using WSNs in customer premises for the purpose of pervasive demand response actions. Furthermore, the performance of WSNs in smart grid assets has been detailed in [6-7]. The study in [6], presents an assessment of the performance of WSNs in power substations, underground transformer vaults and power rooms. The authors focus on the impact of noise on the low power wireless links that are being used by WSNs. On the other hand, the effect of delay on smart grid applications has been investigated in [7], considering a WSN that is used for condition monitoring of a wind turbine.

Cross layer WSN design aspects have been investigated extensively in the general context of WSNs. In [8, 9], the authors have proposed 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 general WSN applications, end-to-end delay reduction has also been thoroughly investigated. In [10] the authors have proposed an Adaptive back off exponent (BE) management scheme for carrier sense multiple access with collision avoidance (CSMA/CA) of 802.15.4 and investigated its effects on power consumption of the node.

In addition to end-to-end delay reduction, QoS provisioning in WSNs has also been widely studied in the literature where high priority sensor data are aimed to be forwarded with less delay or higher reliability. In [1], the authors have suggested an adaptive mechanism by implementing back off exponent management to reduce packet collision. The proposed DRX scheme also uses an adaptive mechanism but with different cross layer techniques as will be explained later in this paper.

In [2], the authors have presented a QoS support technique in beacon enabled mode using CSMA/CA back-off time. In [11], the authors have discussed a distributed algorithm that satisfies specific application reliability and energy consumption requirements. In [12], the authors have proposed priority-based schemes to guarantee time-bound delivery of high priority packets in event-monitoring networks. In [12] the authors have proposed to reduce the number of clear channel assessments (CCA) performed in high priority nodes from two to one and perform frame tailoring to avoid collision. The proposed DRX scheme is different from [12], because DRX implements an adaptive process in modifying CCA duration. Note that it does not modify the number of CCA’s.

Furthermore, the effects of CCA methods such as energy detection and preamble detection have been extensively investigated in [13-14]. To the best of our knowledge, the impact of adaptive CCA duration has not been explored yet. DRX reduces the end-to-end delay by adaptively changing the duration of CCA of certain nodes and setting this parameter to default when prioritization is not required. The details of DRX is explained in the following sections.

III. DELAY ESTIMATION MODEL

We follow the general analytical model for the slotted carrier sense multiple access with collision avoidance (CSMA/CA) mechanism of beacon enabled mode of the IEEE 802.15.4 presented in [15]. In this model, we use a star topology where all nodes in the Personal Area Network (PAN) use contention to acquire channel access and transmit the data to the PAN coordinator. In [15], accurate and approximate models were derived; both models solve a set of highly nonlinear equations using numerical methods. In this paper, we utilize several mathematical and algebraic approaches to derive the formulas below; however we do not report all the computations due to limited space. We found that the accurate analysis is not suitable for use in the limited resources sensor devices, since it is computationally demanding and requires high processing power. In this paper, we utilize the approximate model. It is worth to note that, in this paper, we are using the analytical model of [15] to estimate the end-to-end delay which will activate the operation of the prioritization and delay reduction schemes in MAC sub-layers.

The analytical model assumes that sensor nodes can estimate the probabilities of a busy channel $\rho$, $\sigma$ and $\nu$. Where $\rho$ is the probability that the first clear channel assessment (CCA) is busy, $\sigma$ is the probability that CCA is busy and $\nu$ is the probability that a node attempts first carrier sensing (CCA) in a randomly selected time slot. The probability $\nu$ depends on $\rho$ and $\sigma$ and on the probability that a transmitted packet encounters a collision $P_{co}$. $P_{co}$ 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 $\nu$, $P_{co}$ is given by:

$$P_{co} = 1 - (1 - \nu)^{N-1} \quad (1)$$

where $N$ is the number of nodes. The probability of having $CCA_1$ busy $\rho$ is given by the summation of the probability of finding a channel busy during $CCA_1$ due to data transmission ($p_1$) and the probability of finding a channel busy during $CCA_2$ due to ACK transmission ($p_2$):
\[ \rho = \rho_1 + \rho_2 \]  

(2)

where

\[ \rho_1 = L(1 - (1 - \nu)^{N-1})(1 - \rho)(1 - \sigma) \]  

(3)

and

\[ \rho_2 = L_{\text{ack}} \frac{Nv(1-\nu)^{N-1}}{1-(1-\nu)^N} (1 - (1 - \nu)^{N-1})(1 - \rho)(1 - \sigma) \]  

(4)

where \( L_{\text{ack}} \) is the length of the acknowledgement. The probability that \( \text{CCA}_i \) is busy is given by:

\[ \sigma = \frac{1-(1-\nu)^{N+1}+Nv(1-\nu)^N}{2-(1-\nu)^N+Nv(1-\nu)^{N-1}} \]  

(5)

where

\[ v = (1+a)(1+b)p_{0.0.0} \]  

(6)

and

\[ a = \rho + (1 - \rho)\sigma \quad \text{and} \quad b = P_{0.0}(1 - a^{m+1}) \]  

(7)

\( p_{0.0.0} \) is the approximate stationary distribution of Markov chain and given by [15]:

\[ p_{0.0.0} = \left[ \frac{\nu}{2} (1 + 2a)(1 + b) + L_s(1 - a^2)(1 + b) + Y_o ((P_{0.0}(1 - a^2))^{n-1} + 1) + 1 \right]^{-1} \]  

(8)

where \( m = \text{MaxBackoffs}, \; W_o = 2^{\text{MaxBE}}, \; n = \text{MaxFrameRetries}, \; L_s \) is the time period of successful transmission and is given by the following relation:

\[ L_s = L + t_{\text{ack}} + L_{\text{ack}} + IFS \]  

(9)

Here \( L \) is the total period of the packet including overhead and payload, \( t_{\text{ack}} \) is the acknowledgment waiting duration, and \( IFS \) is the inter-frame spacing.

\( Y_o = \frac{L_o}{1-p_o} \), 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 \( \rho, \sigma \) and \( a, b \).

The average estimated delay is given by:

\[ E[D] = P^TD \]  

(10)

where

\[ P = [Pr(X_0|X_0) \ldots Pr(X_n|X_0)]^T, \; D = [d_0 \ldots d_n]^T, \]

\[ d_j = T_s + jT_c + (j + 1)E[T] \]

\[ Pr(x_j|x_i) = \frac{(1-P_{0.0}(1-a^{m+1}))(a^{m+1})}{1-(P_{0.0}(1-a^{m+1}))^{n+1}} \]  

(11)

\( T_s \) and \( T_c \) are time durations of successful and collided packet transmissions respectively.

\( x_i \) is occurrence of successful packet transmission at time \( j+1 \) given that at time \( j \) the transmission is unsuccessful; \( x_i \) is the occurrence of successful packet transmission within \( n \) attempts.

\[ E[T] = 2T_s(1 + \bar{P}T) \]  

(12)

where

\[ \bar{P} = [\bar{P}(B_0|B_t) \ldots \bar{P}(B_m|B_t)]^T, \; T = [t_0 \ldots t_m]^T \]

\[ t_i = [(2i+1 - 1)W_o + 3i - 1]/4 \]

\[ B_i \] is occurrence of a busy channel for the \( i \)-th time then an idle channel at the \( i+1 \)-th time, \( B_i \) is the successful sensing event in \( m \) attempts. The estimated delay from this analytical model that has been initially proposed in [15] is utilized by the medium access schemes described in the following section.

IV. DELAY-RESPONSIVE, CROSS LAYER (DRX) DATA TRANSMISSION

We propose an adaptive scheme for a WSAN that is used for monitoring and controlling delay critical data in a specific smart grid application. We assume that at a certain point of time, the data collected by any sensor node would have high priority, and should be delivered to the base station with minimum end-to-end delay.

We present a scheme that includes an adaptation module that enables the interaction of the application layer with the MAC and physical layers. The objective of this priority and delay-aware technique is to reduce the end-to-end delay and provide QoS. This is achieved by allowing each node in the PAN to initially implement the delay-estimation algorithm \( (E[D]) \) that estimates the expected delay based on the model described in Section III. Then, a node makes a decision based on the delay estimation algorithm, by making the MAC sub-layer respond to specific delay requirement of the application.

The application layer independently activates \( E[D] \) if the measured data trigger an alarm indicating high priority. If \( E[D] \) is found to be higher than a predefined threshold \( \tau_{TH} \) then the application layer places a flag in the application layer header indicating that lower layers should treat these packets differently. Thus, upon the arrival of those packets to the MAC sub-layer, it requests the physical layer to make changes in its parameters.

In DRX, upon the arrival of the flagged packets to the MAC sub-layer, it requests the physical layer to decrease the CCA length from 8 symbol periods to 4 symbol periods (from 128μs to 64μs). By reducing the CCA duration, the physical layer will sense the channel in half of the normal CCA duration and report the results to the MAC sub-layer. Therefore, this node will have a higher probability to acquire the channel and transmit its data before other contending nodes. However, if the node finds the channel busy, it invokes the back-off algorithm as described in [16]. In the DRX scheme, we assume that there are no devices transmitting at the same frequency band other than the IEEE 802.15.4 nodes, to reduce coexistence problems. In algorithm 1, we describe the DRX scheme in details. The priority of captured data is initially evaluated by the application layer, and if the priority of the monitored parameter value \( \Phi \) is beyond an acceptable threshold (i.e. higher or lower than normal limit values [17]), then the algorithm invokes \( E[D] \). If the estimated delay is found to be higher than the threshold \( \tau_{TH} \) value, (each smart grid monitoring application has different \( \tau_{TH} \) [17]) then the CCA duration is reduced, otherwise the algorithm does not make any changes on the physical layer parameters and transmits the data using regular CCA duration process.
We use QualNet [18] network simulator platform to implement the DRX scheme. We test the priority and delay-aware medium access scheme with different number of nodes and traffic conditions. In addition to that, we investigate the performance of the DRX scheme in a realistic smart grid environment; we do this by considering smart grid condition monitoring situation with specific shadowing deviation and path loss properties. Furthermore, we select the simulation parameters similar to that of the analytical model described in Section III. As mentioned before, we use a beacon enabled star topology having N nodes and a coordinator, where N varies from 10 to 40 in each simulation scenario. We assume that all nodes are operating in the 2.4 GHz band with a maximum bit rate of 250 Kbps. All nodes transmit constant bit rate traffic (CBR). To evaluate the performance of the DRX scheme, we assume that one node receives high priority packets during the simulation time. We set the transmission range of all nodes to 50m, and configure all nodes in the same PAN. We run each simulation for 300 seconds and repeat each simulation 10 times. In the initial simulations, we set the delay threshold $\tau_{TH}$ of the DRX scheme to 0.400 second (following actual delay requirements presented in [17]). We assume that all nodes transmit with sufficient power, i.e. all nodes can hear each other. We also assume that the noise level is constant throughout the entire simulations (i.e. constant noise factor). Table I shows the default parameters used in the simulations; we take the rest of the simulation parameters from [16]. We compare the performance of the DRX scheme with an existing QoS supporting mechanism [2] in terms of end-to-end delay and the packet delivery ratio. The mechanism presented in [2] reduces the back off time of a contending node to make it back off for a shorter period then the rest of the nodes. The authors reduce the back off time by reducing the value of the back off exponent (BE) [16].
Condition monitoring of HV transformers demands critical operational reliability and service restoration time. WSNs have been proposed previously to remotely monitor PD pulses in HV transformers [3]; which is useful to track when and where a transformer has failed or is giving signs of failure, in a near real time fashion. This can intensely promote system reliability and efficiency. In HV transformers, a PD is a localized breakdown of the dielectric insulation system under HV stress, which does not bridge the space between two conductors. PD causes progressive deterioration of insulating materials, eventually leading to complete transformer failure. The effects of PD within HV transformers are very serious and can ultimately lead to complete system failure if not immediately treated.

As a case study, we consider using a WSAN with the DRX scheme for HV transformer condition monitoring as a typical smart grid monitoring application that requires strict end-to-end delay requirements. We obtained the functional requirements for this application from [17].

To investigate the performance of the DRX schemes in environments where HV transformers are deployed, we take the effect of path loss and shadowing deviation in such environment in to consideration. We follow the work presented in [6], where the authors have conducted a series of experiments with sensor nodes to measure the link quality indicator (LQI) and the received signal strength indicator (RSSI) under certain radio propagation parameters for different electric power system environments. We simulate the DRX scheme in outdoor 500-kV substation, indoor main power room and underground transformer vault environments. We use the following values for channel propagation parameters, for outdoor substation: (path loss = 3.51, shadowing deviation = 2.95), for indoor main power room: (path loss = 2.38, shadowing deviation = 2.25) and finally for underground transformer vault: (path loss = 3.15, shadowing deviation = 3.19). We assume that the channel is having lognormal shadowing model with shadowing mean of 2.25 dB and all sensor nodes are operating in non-line of sight (NLOS) mode.

In Table II, we show the percentage of data packets lost due to collision at the sink for the above mentioned electrical power environments using the default IEEE 802.15.4 MAC settings and the DRX scheme. In this scenario, we used 15 nodes and overloaded the nodes with CBR traffic to test the scheme in extreme traffic conditions. We observe that the DRX scheme slightly outperforms the default settings in terms of the percentage of lost packets due collision.

### Table II

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**A. Case Study: Transformer monitoring**

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Specific reliability requirements including minimum data monitoring latency is given in [6]. To show the significance of using the DRX scheme in achieving these reliability requirements, we consider the performance of a WSAN with the DRX scheme for transformer monitoring. We consider a WSAN with 40 nodes in a star topology where sensor nodes monitor PD activity and transmit the data to a PAN coordinator. We assume that the PAN coordinator is connected to a high-speed network, e.g., Ethernet Passive Optical Network (EPON), hence the delay from the PAN coordinator to the user is negligible. We simulate the WSANs using the default IEEE802.15.4 MAC settings and the DRX scheme. In Table III, we show that the default IEEE802.15.4 MAC setting has higher latency than the functional requirements of transformer monitoring as specified in [17], while the DRX scheme succeeds in reducing the latency below the functional requirements (500 ms). The DRX scheme is able to reduce the end-to-end delay by 60 ms. This delay reduction is significant in such sensitive condition monitoring application.

### Table III

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<th>Smart Grid Application</th>
<th>Functional Requirements (Min Latency)</th>
<th>Default IEEE802.15.4 Settings</th>
<th>DRX</th>
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<td>Transformer monitoring</td>
<td>500 ms</td>
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VI. Conclusions

In this paper, we introduced the delay-responsive, cross layer (DRX) data transmission scheme which is a light weight algorithm that responds to the delay requirements of smart grid applications by predicting the end-to-end delay and creating cross-layer measures. This scheme achieves delay-responsiveness by modifying the parameters of the physical layer of the IEEE802.15.4 protocol. The DRX scheme estimates the end-to-end delay, if the packet is having critical data. If the estimated delay cannot meet the delay requirements of a smart grid monitoring application, then DRX reduces the clear channel assessment duration, in order to allow the high priority packet to access the medium before other contending packets.

Simulation results show that the DRX scheme is able to reduce the delay of high priority data while preserving acceptable packet loss values. This delay reduction which is achieved by DRX enhances the smart grid condition monitoring operation in situations where sudden defects or changes in loads or the generation cycle take place.

We performed a case study to show the effectiveness of the DRX scheme in reduction of the latency of transformer monitoring reliability functional requirements. In the case study, we considered actual shadowing and path loss values of electric power systems. The results of this evaluation showed that the DRX scheme outperformed IEEE 802.15.4 with the default settings.

As a future work, we plan to study the performance of the proposed scheme in multi-hop scenarios and study the effect of interfering nodes such as WiFi devices. Furthermore, we plan to implement this scheme in an actual testbed in a smart grid environment.