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Performance Comparison on Light Weight Delay and Data Transmission Medium Access Approaches For Smart Grid Applications

T.Mythili[1], R.T.Narmadha[2], Dr.J.Ramesh[3]

[1, 2] Info Institute of Engineering, Coimbatore, India

[3] PSG College of Technology, Coimbatore, India

ABSTRACT: A comprehensive delay performance measurement and analysis in a large-scale wireless sensor network is performed. A lightweight delay measurement system is built and a robust method to calculate the per-packet delay is presented. The method can identify incorrect delays and recover them with a bounded error. Wireless Sensor and Actor Networks (WSANs) are widely utilized in a wide range of smart grid applications along with their successful adoption in various critical areas including military and health. Delay-responsive, cross layer (DRX) data transmission, and fair and delay-aware cross layer (FDRX) data transmission medium access approaches that aim to address delay and service requirements of the smart grid are introduced here. DRX reduces the end-to-end delay while FDRX has lower collision rate.

KEYWORDS: Light weight delay measurement, Wireless Sensor and Actor Network, Delay – responsive cross layer, Fair and delay – aware cross layer

I. INTRODUCTION

We build an infrastructure for delay measurement in CitySee, a large-scale WSN consisting of 1200 nodes. The infrastructure does not rely on network synchronization and thus does not introduce additional overhead. We present basic statistical characteristics based on the collected data. We quantitatively calculate the correlation between different impacting factors and the delay performance. Based on those important factors, we build a practical delay model and validate the model using the collected data trace. Finally, we revisit three important protocols based on the measurement results and propose a practical delay model.

Wireless sensor and actor networks (WSANs) are considered as potential tools for monitoring and controlling the smart grid. 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. Sensor nodes can collect various kinds of data, e.g. voltage, current, frequency and etc. while actors perform tasks such as closing/opening circuit breakers, turning on/off loads, etc. 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, rapid deployment and low cost.

We present two protocols that aim to address data-prioritization and delay-sensitive data transmission for WSANs in the smart grid. The first approach; delay-responsive, cross layer (DRX) [1] uses application layer data prioritization to control medium access of sensor and actor nodes. DRX first performs delay estimation, if the estimated delay cannot meet the delay requirements of the smart grid application, then channel access of the node is fast-tracked by reducing clear channel assessment (CCA) duration. The second approach, namely fair and delay-aware cross layer (FDRX) data transmission incorporates fairness into delay-sensitive data transmission [2]. Similar to DRX, FDRX initially executes delay assessment, if the estimated delay is higher than the delay requirements of the application, then the node is given

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higher priority to access the channel. To provide fairness, the node periodically yields to the other nodes in the WSAN. Hence, FDRX provides fairness by periodically allowing other nodes in the personal area network (PAN) to contend fairly to access the channel.

II. RELATED WORK

Delay Analysis: There are extensive works for delay performance analysis in WSNs. First, probabilistic delay bounds are proposed in [3] by extending network calculus. In the second category, stochastic delay models are proposed. For example, in [4], different models are proposed by combining real-time theory and queuing theory. In those models, unreliable networks with heavy traffic are considered. There are some empirical network delay models proposed for end-to-end delay measurements. A delay model based on Discrete Markov Processing in the network is proposed in [5]. However, those works proposed in WSNs are often based on assumptions—e.g., traffic or routing path—and not evaluated in a real large-scale network. In this paper, we are the first to propose a lightweight delay measurement and analysis in an operational LPL WSN.

Time Synchronization: There are also many global time synchronization methods in wireless sensor networks, e.g., [6], [7], and [8]. Those methods can synchronize all nodes in the network and provide synchronized timestamps. Our measurement method is different from those methods in two aspects. First, our method does not require time synchronization among all nodes in the network. We recover the timestamp at the sink side. Thus, this reduces the message exchange overhead among all nodes. Second, our method does not need to maintain a synchronized timestamp all the time. Therefore, our method does not require periodical message exchange.

Large-Scale Sensor Network Deployment: There are many sensor network deployments in the world. Cross layer protocols have been studied in the general context of WSNs. 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 are proposed. Reducing the end-to-end delay of a WSN has been also studied for more general applications.

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 [11], the authors propose an adaptive mechanism by implementation of the back off exponent management to reduce packet collision. DRX and FDRX also use an adaptive mechanism but with different cross layer techniques. In [12], the authors present a QoS support mechanism in beacon enabled mode using CSMA/CA back-off time. Priority-based schemes to guarantee time-bounded delivery of high priority packets in event-monitoring networks have been proposed. The authors propose 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.

In addition, the impact CCA methods such as energy detection and preamble detection have been thoroughly investigated. However, the impact of adaptive CCA duration has not been explored. DRX and FDRX basically aim to reduce 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.

III. SYSTEM OVERVIEW

A. Network

The primary goal of CitySee is to precisely measure CO emissions in a citywide area. Fig. 1 shows an overview of the network. Totally, we have deployed 1200 nodes. The network employs a tiered architecture with three kinds of nodes, i.e., normal telosB nodes, CO nodes, and mesh nodes. In the network, each normal sensor node reads the sensing data and records system status. CO nodes can also read the CO concentration. The CO sensing component is connected to the main board through the UART connection. The normal nodes and CO nodes form a network and deliver their data to a sink node (normal node) in the network. Fig. 2 shows the sensor nodes in our network. The mesh nodes have a high bandwidth of several megabytes per second and a long transmission distance. They comprise the network backbone. Sink nodes of different subnets are connected to the network backbone in order to deliver packets to the base station. Fig. 3 illustrates the overview of the system architecture.

B. Protocols

1) Low Power Listening: Low power listening (LPL) is widely adopted in WSNs to save energy. In LPL, each node switches between awake and sleeps state to save energy. Most LPL protocols share the similar principle as shown in Fig. 4. Each node samples the channel for a short duration in each cycle. If energy is detected, the node stays awake for another short duration to receive packets. Otherwise, the node turns off the radio and in the next cycle (e.g., 500 ms later) resample's the channel. To transmit a packet, the sender continues sending packets as preambles until the receiver wakes up. For broadcast, the preamble lasts for cycle duration in order to ensure that all neighboring nodes wake up once. Another type of LPL protocol is receiver-initiated low-duty cycle protocol. Each node periodically wakes up and sends probe packets to see if there are transmissions intended for it. If a node has packets to send, it will keep awake and send the packets once receiving a probe packet from the receiver. Since a sender may begin to send packets at any time, the time the sender needs to wait is randomly distributed in the cycle. This introduces randomness to packet delay.

2) Collection Tree Protocol: Collection Tree Protocol (CTP) is used to build a routing tree in the network. CTP adopts the ETX metric, the expected transmission count, as the path quality metric. Each node selects a path with minimum ETX. The ETX of a link is calculated as, where is the packet reception ratio. The path ETX is calculated as the sum of all link ETXs along the path.

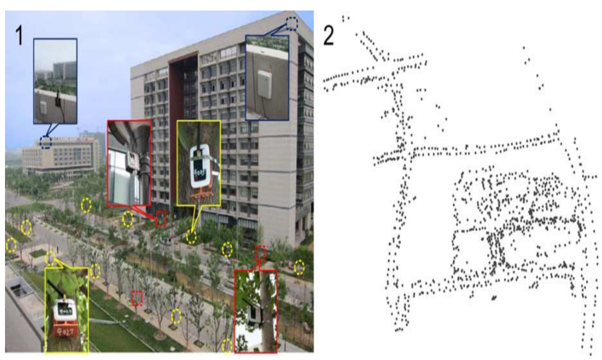

Fig. 1. Deployment and sensor nodes in CitySee: 1) overview of the deployment area; 2) node locations in the network.

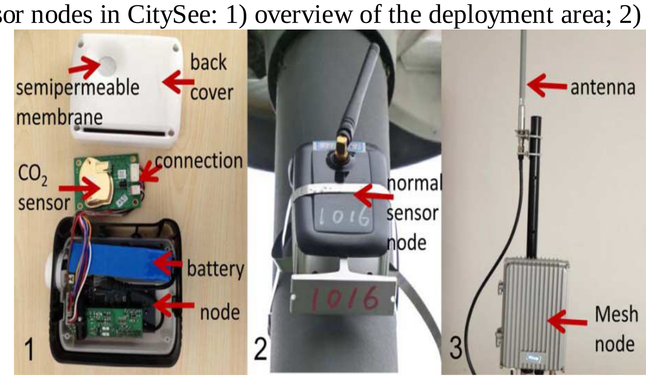

Fig. 2. Sensor nodes in CitySee: 1) CO sensor node, 2) normal sensor node, and 3) mesh node.

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In DRX, 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).

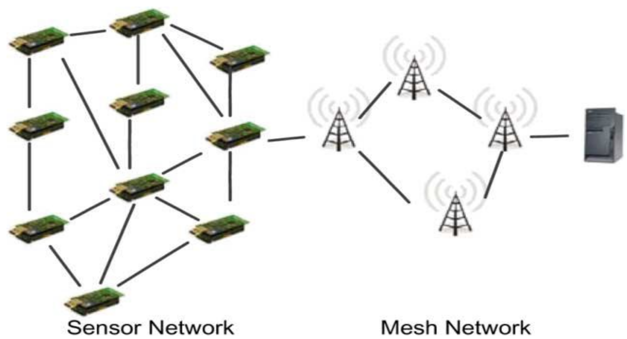

Fig. 3. Overview of network architecture.

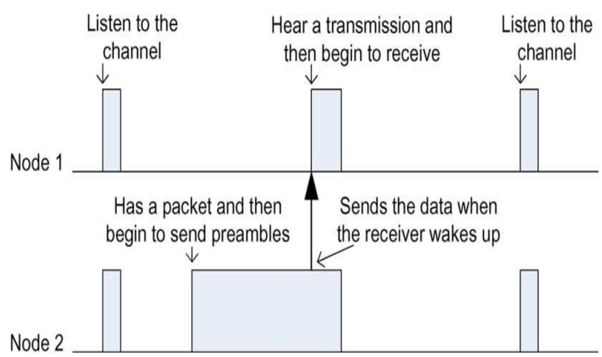

Fig. 4. Basic mechanism of LPL protocols.

In doing so, the physical layer senses the channel in half of the regular CCA duration and reports the results to the MAC sub-layer. Thus, this node can acquire the channel and get to transmit its data before other contending nodes. If the node finds the channel busy, it invokes the back-off algorithm. In this scheme, we assume that there are no devices transmitting at the same frequency band other than the IEEE 802.15.4 nodes, to avoid any possible coexistence problems. Algorithm 1 describes the DRX scheme. Initially the application layer evaluates the captured data and decides if the priority of the monitored parameter value Φ is beyond an acceptable threshold, then the algorithm invokes the delay estimation process $\boldsymbol{E}[D]$. If the estimated delay is found to be higher than the threshold τTH value (different delay thresholds for deferent smart grid applications are obtained and used later in the performance evaluation section) then the CCA duration is divided by two, otherwise the algorithm does not make any changes on the physical layer parameters and transmits the data using regular CCA duration process.

Algorithm1: DRX Scheme

1 MEASURE THE VALUE OF Φ
2 **if** Φ > ΦTH **then**
3 // Invoke delay estimation algorithm
4 $E[D]=PTD$
5 **if** *E[D] > τTH* **then**
6 // Insert a flag in application layer header
7 APP Header = APP Header*
8 CCAduration = CCAduration/2

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MAC_CSMA-CA( )
else
CCAduration = 8 symbol durations
MAC_CSMA-CA( )

else
CCAduration = 8 symbol durations
MAC_CSMA-CA( )
if CCA = successful **then**
Transmit Packet
else
if NB < MaxCSMABackoffs
go to 8 // repeat the CSMA-CA
else drop packet

The second presented scheme includes an improvement to the DRX scheme. The DRX scheme aims to reduce the end-to-end delay without taking other nodes in the PAN into consideration. The proposed FDRX scheme can achieve the delay reduction and additionally allow other nodes to transmit fairly. Similar to the DRX scheme, the FDRX scheme initially implements the delay-estimation algorithm. Based on the resulting values of the delay estimation, the MAC layer responds to the delay requirement of the application. The main difference between the DRX and the FDRX schemes is that the latter yields to other nodes in the PAN periodically to allow them to transmit. Thus, FDRX is fairer to other nodes. In the FDRX scheme, 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). This request is done based on a predefined yielding intensity, α. The value α varies from zero to one, zero means the node is not yielding to other nodes (corresponds to DRX) and one means that node uses the default IEEE802.15.4 MAC settings.

IV.PERFORMANCE EVALUATION

Several kinds of information are presented here: 1) The delay distribution exhibits randomness. 2) Though the delay of different nodes varies in a large range, the median delays are evenly distributed between 0–2 s. 3). There exist many large delays for most nodes given in Fig. 5.

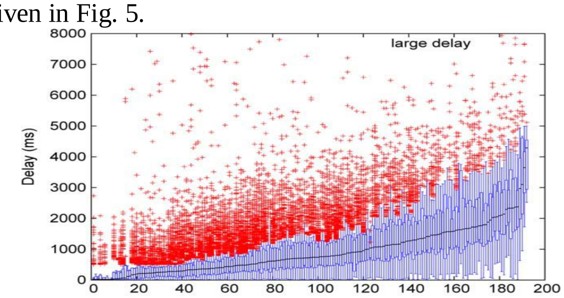

Fig. 5. Delay distribution for all nodes.

We investigate the effect of the DRX and FDRX schemes on the energy consumption of sensor nodes. In Fig. 6, the energy consumed in the transimit mode is slightly higher for DRX and FDRX schemes than the default settings since nodes implementing these schemes will have the opportunity to transmit more often than their neighboring nodes. However, the increase in energy consumption is not significant (only 0.9%) compared to the increase in the packet delivery ratio and the reduction in the end-to-end delay. The value of α can be adjusted according to the power requirments of individual nodes. Fig. 7 shows the effect of α on the energy consumed in the transmission mode.

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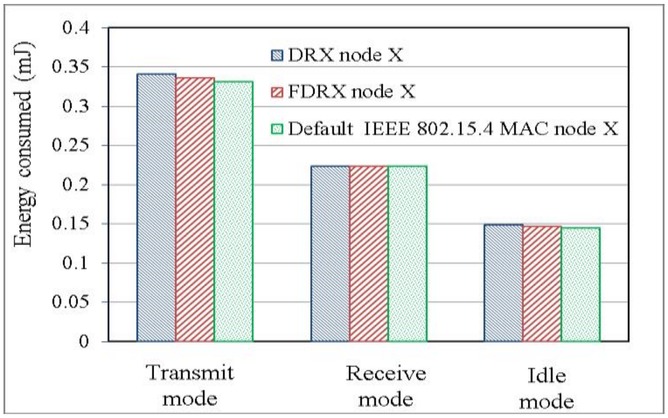

Fig.6. The effect of the DRX and FDRX schemes on the energy consumption.

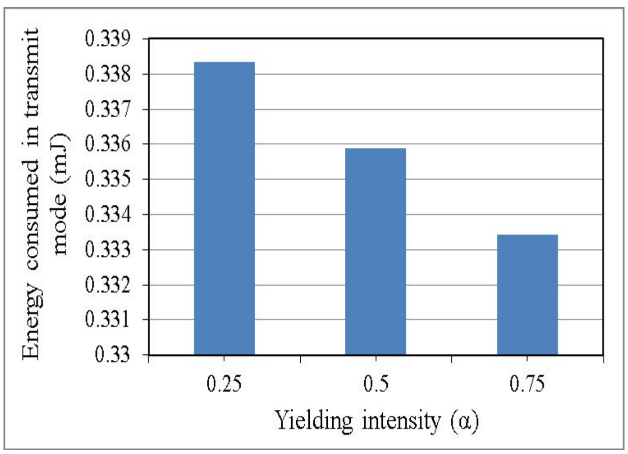

Fig.7. The effect of the yielding intensity α on the energy consumed.

V. CONCLUSION

We propose a lightweight delay measurement method to efficiently calculate delay without time synchronization, which is applicable to operational networks. The first scheme, namely DRX first estimates the end-to-end delay. If the packet is from a critical smart grid application that has high priority and if the estimated delay cannot meet the delay requirements of this application, then DRX reduces the clear channel assessment duration, in order to allow the high priority packet to access the medium. The second approach, namely FDRX incorporates fairness into delay-sensitive data transmission by yielding other nodes periodically. Our results show that DRX and FDRX schemes are able to reduce delay for high priority data while maintaining acceptable packet loss values. The DRX scheme has a higher effect on the end to end delay reduction compared to the FDRX. DRX scheme does not take fairness into consideration. FDRX shows more flexible results and provides fairness to other nodes WSAN.

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