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Priority-Based Adaptive MAC Protocol for Wireless Sensor/Actuator Networks

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Abstract- The recent progresses made in microelectronics, embedded systems and wireless communications led to the emergence of wireless sensor/actuator networks (WSANs) in variety of applications. WSANs demand energy efficient, reliable and timely data gathering. Beyond that, there may be need to rapidly respond to observed events. IEEE 802.15.4 standard does not have any prioritization mechanism and all data flows are received with the same priority. This paper presents an adaptive MAC protocol with priority-based TDMA scheduling algorithm by using modified IEEE 802.15.4 superframe structure for time-critical WSAN applications. Proposed MAC protocol with event-aware scheduling enables the prioritization of data flows from sensor nodes with respect to reliability and timely reaction requirements. Simulation results demonstrate that the effectiveness of proposed strategy to reduce the redundant traffic load in data gathering process from distributed sensor nodes.

Keywords- *priority, TDMA schedule, MAC protocol, WSAN*

I. INTRODUCTION

The key part of the Industry 4.0 is the Cyber-Physical Systems (CPSs) that interact with physical world in real-time. A typical CPS is usually composed of a group of networked embedded devices that collect information from their environments through sensors and control the process via actuators. The sensor and actuators pairs are connected to controller with communication network [1]. The controller may be may be centralized or distributed depending on the nature of physical system where it operates. Traditional wired networks usually do not provide adequate mobility, flexibility and scalability requirements of CPS applications. The integration of cyber (computation and networking) objects and physical processes can be enabled through wireless sensor/actuator networks (WSANs) as an extension of wireless sensor networks (WSNs) [2].

A typical WSAN consists of different type wireless devices that have heterogenous characteristics, often called sensor nodes (SNs) and actuator nodes (ANs). The ANs can be wire powered or deployed with an external energy source. On the contrary, the on-board battery powered SNs have limited energy supply and stringent computing resources [3, 4]. Theoretically, WSAN is a closed-loop control system to detect and control the physical world around it. The control loops comprise the end nodes (SNs and ANs) that connected with controller [5]. The SNs cooperates each other to perform distributed sensing over large areas. In order to achieve the long-time plant monitoring, the SNs' energy consumption should be reduced as much as possible. The RF transceiver often consumes the largest amount of energy among all hardware components. Energy consumption of transceiver can be reduced with proper optimization of physical (PHY) and media access control (MAC) sublayer of the data link layer [6].

The MAC layer is responsible for organizing the shared channel access of all nodes with efficient scheduling. MAC protocols often use Time Division Multiple Access (TDMA) or Carries Sense Multiple Access with Collision Avoidance (CSMA/CA) techniques to allocate the channel among nodes. TDMA provides improved energy efficiency, since nodes are active only during their transmission time, otherwise they remain in sleep mode [7]. On the other hand, control loops in WSANs demand high reliability and low latency to avoid undesired or dangerous states. This means that the data must be transmitted accurately and without unacceptable delay between the controller and field devices [8, 9]. But, wireless data links are inherently unreliable due to the multipath fading, interference, moving obstacles and weather conditions, especially in industrial environments [1, 10].

TDMA divides the channel into frames where each frame consists of multiple time-slots of fixed or variable length. Time slots are allocated to end nodes according to scheduling policy and priority constraints. If required, multiple time slots can be assigned to a single node depending upon instantaneous data traffic load. Time-slot assignment is an important problem to guarantee the quality of service (QoS) requirements. In TDMA mechanism, the channel access is bounded by superframe structure that has critical importance in the design of MAC protocols [6]. The superframe of IEEE 802.15.4 standard does not provide adequate capability to meet high reliability and time-critical communication challenges of WSAN applications [11]. The scheduling optimization improves the network performance, especially in industrial control applications [12, 13]. This study presents an adaptive MAC protocol with modified superframe structure that is developed for WSANs. The main aim is to enable to provide real-time communication with deterministic delay and no packet loss by efficient utilization of TDMA schedule in data gathering process.

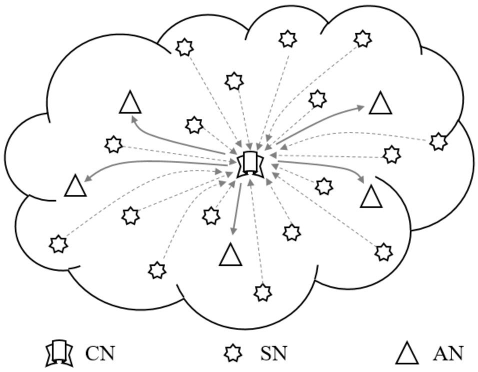

Figure 1. System model of proposed WSAN based CPS.

The rest of paper is organized as follows: Section II depicts the network model and introduces the background. Section III describes the proposed MAC protocol. Section IV presents the simulation results. Finally, Section V draws some conclusions.

II. NETWORK MODEL

The network of interest is a WSAN with star network topology that consists of multiple end nodes as shown in Fig. 1. In a semi-automated architecture, single controller node (CN) operates as common sink and makes decisions about the control of its environment. The CN also coordinates the data gathering and actuation tasks of control loops. It is assumed that the CN is close to sensor/actuator pairs and then clearly one-hop communication can be applicable practically. The CN has a connection to the monitoring node via wired or wireless links. The monitoring node connects the complete WSAN to the remote-control center. The operator manages the whole system via human-node interface.

The number of end nodes highly depends on the application requirements. A group of SNs (few tens to hundreds) sense the physical variables (pressure, temperature, flow rate, etc.) around their sensing range and report them to the CN directly. The CN evaluates all collected data by comparing the set point which is predefined by operator. If required, it sends control signals to the ANs that are regularly deployed over the field. The ANs convert control signals to commands and drive the actuator devices (motors, valves, pumps, etc.) to perform appropriate actions on the plant. The block diagram of the WSAN based closed-loop control system is shown by Fig. 2.

It is assumed that the ANs are energy unconstrained devices that are powered by AC lines and powerful RF transceiver that can communicate with the CN. The CN is also equipped with powerful computing capabilities, long battery life, renewable energy source (e.g., solar panel) and uninterruptible power supply (UPS). Therefore, the lifetime of network dominantly depends on the SNs' battery life. On the other hand, since the SNs are densely deployed over the environment, the redundancy of sensor nodes results in correlated data transmissions from SNs to the CN. So, unnecessary data transmissions cause extreme network traffic in data gathering and delayed response to observed events in actuation process.

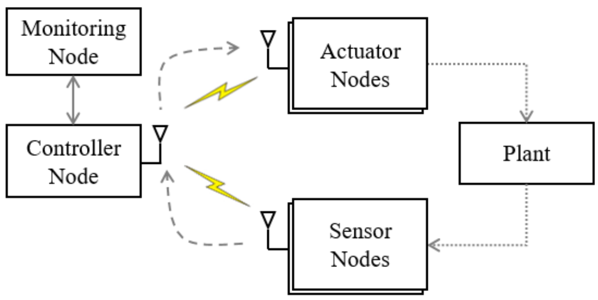

Figure 2. Block diagram of closed loop control system over WSAN.

III. PROPOSED MAC PROTOCOL

Resource efficiency is one of the most important design criterion that should be considered when developing a MAC protocol. In WSAN based applications, MAC protocol aims to maximize the network lifetime without consume too much energy and minimize the channel access delay in data transmission. Beacon-enabled mode of IEEE 802.15.4 standard offers slotted channel access mechanism where the slots of superframe are divided into two phases: contention access period (CAP) and contention free period (CFP). In the CFP phase, the SNs are assigned guaranteed time slots (GTS) for data communication. Proposed MAC protocol modifies the superframe structure of IEEE 802.15.4 standard and utilizes the TDMA scheduling in CFP to simultaneously reduce the energy consumption and enables meeting the delay requirements of real-time data flows. As shown in Fig. 3, time axis is divided into two main portions: active and inactive periods for SNs. Active period is further divided into two phases: setup and data gathering. Inactive period also divided into two phases: actuation and unused slots.

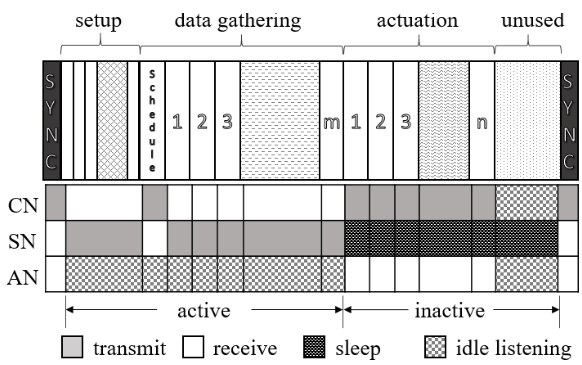

Figure 3. Superframe structure of proposed adaptive MAC protocol.

Data gathering and actuation phases divided into *m* and *n* numbers of equal time-slots which have sufficient duration. The total number of time-slots in data gathering and actuation phases are optimized to provide real-time control in superframe structure. TDMA technique requires time synchronization among nodes for collision-free operation. At the beginning of each frame, periodic beacons are broadcasted by the CN for synchronization. In setup phase, the SNs which have received beacon signal report their IDs to the CN by using the CSMA/CA technique in CAP. Thus, the SNs are attached to the CN and then the network setup is completed.

In data gathering phase, the CN creates TDMA schedule according to selected scheduling algorithm and broadcasts it to the SNs for collision-free data transmission. So, the SNs only wake up in specified time-slots according to their unique schedule. The scheduling algorithm may be applied to give fixed or dynamic priority to the different data flows. In fixed priority, each data flow has a certain priority. On the contrary, dynamic priority changes precedence of different data flows adaptively with predefined criterion. Proposed MAC protocol can be applied with both the fixed and dynamic priority scheduling. At this point, it can be considered that the employment of three different scheduling approaches: Round Robin, channel-aware (opportunistic) and event-aware.

- Round Robin scheduling algorithm gives same priority to the SNs and allocates time-slots in turn.
- Due to the time-varying channel conditions, wireless link between the CN and SNs may not be always available. Packet loss probability depends on the channel quality of scheduled SNs. To improve the reliability of transmitted data, an effective strategy is gives priority to the SNs with better channel quality. Channel-aware scheduling algorithms takes advantage of favorable channel conditions in assigning time-slots to the SNs. The channel quality often is measured by signal-to-noise ratio (SNR). The CN broadcasts a pilot signal with beacon and the SNs estimate their channels. The SNs which have the channel quality over the predefined threshold report their IDs to the CN. Moreover, the CN arranges the channel access among all powerful SNs when they feed back their channel quality with node ID. In general, the channel quality is quantized at the SNs before it is feedbacked to the CN.
- In WSANs, depending on the application there may be a need to rapidly respond to emergency events. Therefore, the SNs should be capable of sensing abnormal conditions over a reasonable time interval. Channel access delay can be minimized by optimizing the packet generation rates of the SNs. Event-aware scheduling algorithms gives priority to the SNs which have emergency data flow rather than regular data flows. To reduce the response time to the events, an effective strategy is gives priority to the SNs which have emergency data flow. Abnormal sensor measurements can be detected as event by using threshold based packet transmission strategy. In proposed MAC protocol, it is considered two different methods to give priority to the emergency data flow.
    - The SNs calculates the difference between the previously forwarded sensor measurements and the actual sensor values. If difference is greater than the predetermined threshold, the SNs report their IDs to the CN.
    - The SNs report their IDs to the CN only if the sensor measurements are outside of the upper / lower limits.

The threshold and upper/lower limit values can be determined by examining the operating range of the controlled system.

The SNs collect critical and reliable information in a timely manner. After that, the gathered information is sent to the CN. By periodically changing the scheduling algorithm in data gathering phase, the CN gathers both regular and emergency data flows with different reliability levels. The CN inform the SNs about the valid scheduling algorithm via beacon message broadcast at the start of each frame. In actuation phase, the CN evaluates the received data and sends control signals to the ANs. The ANs only receive control commands and do not send any feedback messages to the CN. The SNs remain in sleep mode during inactive period to avoid extra consumption of energy. Unused slots are added at the end of the actuation phase to adjust the duty cycle. So, energy consumption of SNs can be minimized by lowering the duty cycle.

IV. Simulation Results

In this section, the performance of event-aware scheduling methods is evaluated on the WSAN based industrial control scenario. MATLAB is used to perform the statistical (Monte Carlo) simulations, rather than well-known network simulators. The system gathers the temperature measurements from M number of SNs and then makes decisions where to send control commands to N number of ANs. It is assumed that ($M \geq m$) and time-slot duration is chosen to be equal to the packet transmission time. In this setup, the initial temperature values are randomly generated in 20-24°C interval at the beginning of each repetition. Similarly, the instantaneous temperature variations are randomly generated with Gaussian distribution in each time-slot.

Fig. 4a shows that the sensor measurements for three independent SNs. In traditional Round Robin scheduling, the SNs send their data packets in each time-slot as shown in Fig 4b. On the contrary, only certain SNs which have abnormal measurements send their data packets in event-aware scheduling. In Fig. 4c, the SNs access the channel when the difference between their two successive measurements is greater than the threshold. Similarly, Fig. 4d shows the channel access of SNs which have measurements beyond the upper / lower limits. An initial analysis showing how the channel access delay depends on the priority of scheduling method.

Fig. 5 shows that the TDMA schedules of Round Robin and event-aware scheduling algorithms. In Round Robin scheduling, all of the SNs transmit data packets in turn. Event-aware scheduling with threshold enables to transmit data packet when the SNs detect abnormal deviation in collected data. Event-aware scheduling with upper / lower limits restrict the channel access of the SNs when their measurements are within desired bounds. It is clear that event-aware scheduling strategy may significantly reduce the number of channel access and also the redundant traffic load in data gathering phase. By this way, the SNs spend most of their time in sleep mode, so that the network lifetime can be extended drastically.

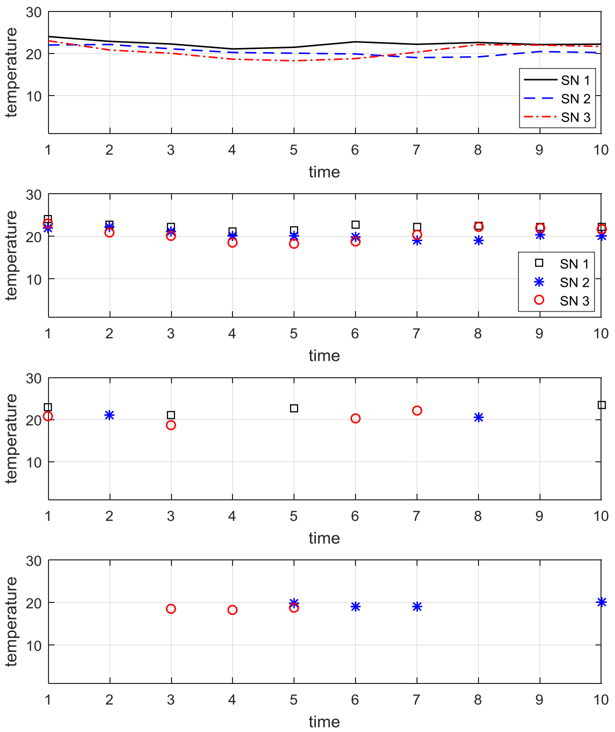

Figure 4. Temperature monitoring of industrial control application.

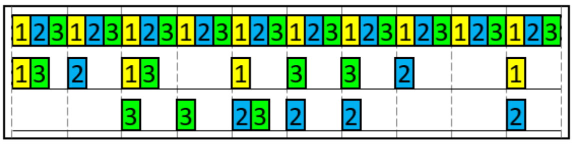

Figure 5. TDMA schedules of different scheduling algorithms

The analysis is extended to the investigate the effect of threshold and limit values on the event-aware scheduling. Fig. 6 shows that the variation of channel access with different threshold values. When the threshold value increases, the number of channel access reduces in event-aware scheduling with threshold. Similarly, Fig. 7 shows the variation of channel access with the upper/lower limits. When the distance between the limit values increases, the number of channel access also reduces in event-aware scheduling with upper and lower limits.

V. CONCLUSION

In WSANs, the ANs need accurate event data from the SNs to perform required control actions. This paper focus on the design of an adaptive MAC protocol to improve the QoS requirements like energy efficiency, reliability, timely data gathering and fast emergency response in WSANs. In this context, it is considered that the priority of data flows from several SNs. Proposed MAC protocol exploits the dynamic priority based scheduling approach to reduce the excessive channel access delays in data gathering due to the congestion. To perform priority based TDMA schedule, the modified superframe of IEEE 802.15.4 standard is used through event-aware scheduling algorithms. Simulation results show that the prioritized scheduling approach accelerates the transmission of event data packets. It is hoped that the findings from this study will serve as a pioneer for future research to be conducted on priority-based MAC protocol design.

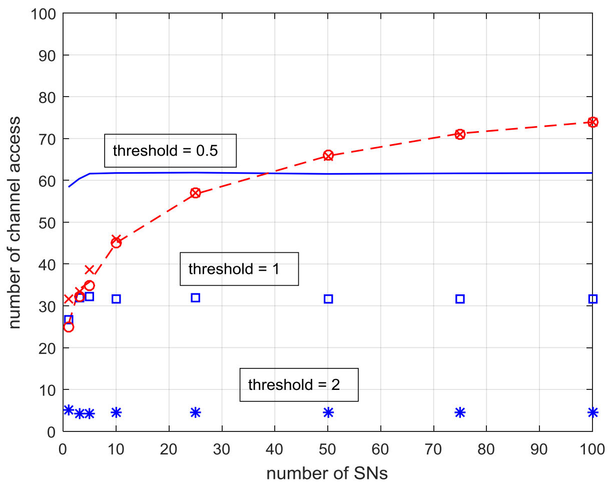

Figure 6. Variation of the channel access numbers with threshold

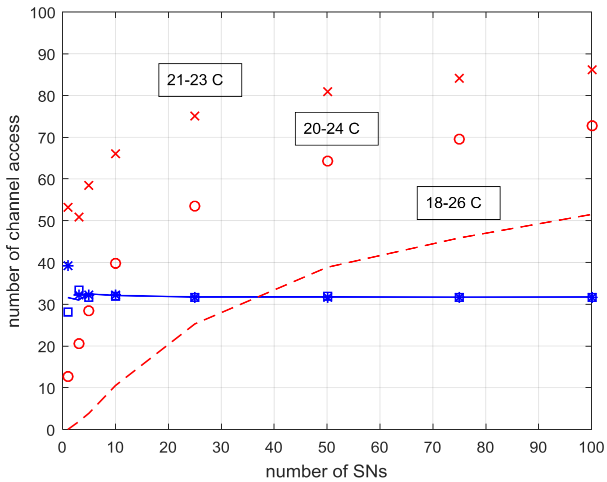

Figure 7. Variation of the channel access numbers with upper/lower limits

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