

The MAC for Highly Reliable Packet Transmission with Deterministic Delay

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Abstract—we propose a new MAC which promises deterministic packet transmission delay and highly reliable communication in a convergecast network. Our MAC provides a higher communication success ratio in both line of sight and non line of sight environment. We compared the performance of our MAC to contention based MAC using CSMA/CA.

Keywords— MAC, Telematics, real time delivery

I. INTRODUCTION

A radio channel cannot be accessed simultaneously by two or more nodes that are in a radio interference range. Neighboring nodes may cause conflict or signal interference at some nodes if transmitting at the same time on the same channel. In wireless sensor networks (WSN), controlling access to the channel, generally known as multiple access control (MAC), plays a key role in determining channel capacity utilization, network delays, and power consumption.

The primary objective of WSN MAC has minimized power consumption. WSN serves applications having very light traffic load most of time such as fire monitoring, surveillance, and etc. Previous works [1], [2], [3], [4] have identified idle listening as a major source of energy wastage. It is often desirable to turn off the radio when a node does not participate in any data delivery.

S-MAC [5] provides a tunable periodic active/sleep cycle for sensor nodes. During sleep periods, nodes turn off radio to conserve energy. During active period, nodes turn on radio to Tx/Rx messages. Each active period is of fixed size, with a variable sleep period. The length of the sleep period dictates the duty cycle of S-MAC. At the beginning of each active period, nodes exchange synchronization information. Following the SYNC period, data may be transferred for the remainder of the active period using RTS-CTS to solve the exposed node and hidden node problem. T-MAC [6] improves on S-MAC's energy usage by using a very short listening window at the beginning of each active period. After the SYNC section of the active period, there is a short

window to send or receive RTS and CTS packets. If no activity occurs in that period, the node returns to sleep. By changing the protocol to have an adaptive duty cycle, T-MAC saves power at a cost of reduced throughput and additional latency. B-MAC [7] allows application to implement its own MAC through a well-defined interface. They also adopt low power listening (LPL) [8] and the clear channel sensing (CCA) technique to improve channel utilization. B-MAC is shown to have higher throughput and better energy efficiency than S-MAC and T-MAC.

Recently, in addition to energy efficiency, the requirement of highly reliable communication within a deterministic delay is getting more and more important in WSN. Emerging applications such as Intelligent Transportation Systems (ITS) require high reliability and deterministic communication delays. Out-of-date information is irrelevant and even leads to negative effects on the system.

However, the previous WSN MACs did not address and study reliable transport within a deterministic delay. S-MAC and T-MAC used CSMA/CA (carrier sense multiple access with collision avoidance) paradigm and duty cycle. CSMA/CA causes the communication delay to increase exponentially with an increasing number of nodes [9], and thus cannot guarantee the delay and packet error rate requirements. Low duty cycle is energy efficient but increases the packet delivery latency. Furthermore, the RTC and CTS packets to alleviate the hidden node problem incurs high overhead (40% ~ 75% of the channel capacity in sensor networks [10], [11]) because data packets are typically very small in sensor networks. Using low power listening approach in B-MAC, the receiver typically has to wait the full period until the preamble is finished before the data/ACK exchange can begin, even if the receiver has woken up at the start of the preamble. The LPL approach enormously increases packet transmission delay and wastes energy at both the receiver and transmitter.

In this paper we propose a new MAC which promises deterministic packet transmission delay and highly reliable communication in a convergecast network. Our new approach guarantees it by scheduling packet transmission. The proposed MAC assigns exclusive time slots to nodes in the wireless sensor network if they transmit latency or collision sensitive

packets. Furthermore, to provide highly reliable communication within a deterministic delay in a non line of sight environment, we introduce a data overhearing and forwarding scheme. 2.4GHz radio channel shows a low transmission success ratio when there is no direct line of sight

between the sender and receiver. If there is an obstacle between a sender and a receiver node, the signal hardly reaches to the receiver node. Nodes overhear a neighbor node's packet and forward it instead of neighbor node when the neighbor fails to transmit the packet. The overhearing scheme increases packet success ratio in delay without packet overhead.

The reminder of the paper, we will introduce the international WSN standard in section 2, our proposed MAC for highly reliable and real-time communication in section 3, and experimental results in section 4. Finally, we will conclude our paper.

II. REVIEW OF INTERNETIONAL WIRELESS SENSOR NETWORK SPECIFICATION

IEEE 802.15.4 [12], the standard for the wireless sensor network MAC, defines the protocol and interconnection of devices via radio communication in a personal area network (PAN). It uses the carrier sense multiple access with collision avoidance (CSMA/CA) medium access mechanism. The media access is contention based. However, using the optional superframe structure, time slots can be allocated by the PAN coordinator, the primary controller, to devices with time critical data.

The format of the superframe is defined by the coordinator. The superframe is bounded by network beacons sent by the coordinator and is divided into 16 equally sized slots. The beacon frame is transmitted in the first slot of each superframe. The beacons are used to synchronize the attached devices, to identify the PAN, and to describe the structure of the superframes. Any device wishing to communicate during the contention access period (CAP) between two beacons competes with other devices using a slotted CSMA-CA mechanism.

For low-latency applications or applications requiring specific data bandwidth, the PAN coordinator may dedicate portions of the active superframe to that application. These portions are called guaranteed time slots (GTSs). The GTSs form the contention-free period (CFP), which always appears at the end of the active superframe starting at a slot boundary immediately following the CAP. The PAN coordinator may allocate up to seven of these GTSs, and a GTS may occupy more than one slot period. However, a sufficient portion of the CAP remains for contention-based access of other networked devices or new devices wishing to join the network. All contention-based transactions are completed before the CFP begins. Also each device transmitting in a GTS ensures that its transaction is complete before the time of the next GTS or the end of the CFP. In IEEE 802.15.4, only a PAN coordinator can assign a GTS to this child node.

Nodes which are more than 2 hops away from PAN coordinator access medium during CAP. However, the transmitting delay during CAP is increasing exponentially with an increasing number of nodes. IEEE 802.15.4 cannot guarantee the delay and packet error rate requirements. Moreover, the Zigbee specification [13] uses a time division approach for beacon scheduling in a multi-hop WSN. Each coordinator selects a start time for its beacon transmission and superframe duration. The beacon is transmitted while the other coordinators are in sleep mode. However, the approach causes a large transmission delay, n*superframe, if the node in a tree level n tries to transmit data to the top level node.

III. OUR PROPOSED MAC

Our Proposed MAC targets convergecast network. Convergecast refers to a communication pattern in which the flow of data from a set of nodes to a single node in the network. Many sensor network applications require convergecast for data collection. For example, consider a sensor network deployed to determine the location of a sniper in an urban environment. In general sensor nodes have limited computational capability. As a result, they cannot execute sophisticated algorithms to determine the location from which the shot was fired. In such applications all the packets generated in the network have to reach the base station for further analysis.

A. Collision Avoidance

Wireless sensor networks are normally composed of clusters as following figure 1. In each cluster, several sensor nodes are associated to a cluster header which coordinates the cluster and routes packets among clusters. The sensor node communicates with a node in other cluster through the cluster header. The cluster network enables routing information to be handled efficiently. Only the cluster header maintains routing and scheduling information of sensor nodes in other clusters. For low power communication, sensor nodes periodically are in an active state enabling communication. The cluster header maintains the active period scheduling information. It allows limited numbers of high resource cluster headers to establish and coordinate whole WSN. The poor resource sensor nodes focus on sensing and one hop communication with its cluster header. In addition, the cluster header coordinates its cluster. It allows sensor nodes to join its cluster and manages inter cluster communication.

One of the cluster headers should be a PAN coordinator. Generally the first cluster header establishing the WSN becomes the PAN coordinator. In figure1, there are four cluster headers, A, B, C, and D. The cluster header A also operates as the PAN coordinator. In the network all packets converge into the PAN coordinator A.

Scheduling packet transmission realizes highly reliable communication within a deterministic delay in the convergecast network. Our MAC schedules packet transmission and thus collisions, which induce communication failure, are avoided.

The MAC assigns exclusive time slots for transmitting nodes which try to transmit latency sensitive packets and prevent packet collision. Only a node having authority to use the time slot transmits its data in the given time slot. The scheduling information is transmitted to the network using beacon frames. All cluster headers periodically broadcast its beacon frames into its cluster.

Fig. 1 shows the assigned transmitting time slot. At the beginning of the superframe, Our MAC assigns time slots for beacon frames. The parent cluster header has faster beacon time slot than the child cluster header. The beacon frame may include some information from its parent beacon frame. The sequential beacon time slot assignment minimizes beacon information propagation delay. The delay is shorter than an active period. Our MAC assigns time slot 1 - 4 as beacon time slots for node A to D.

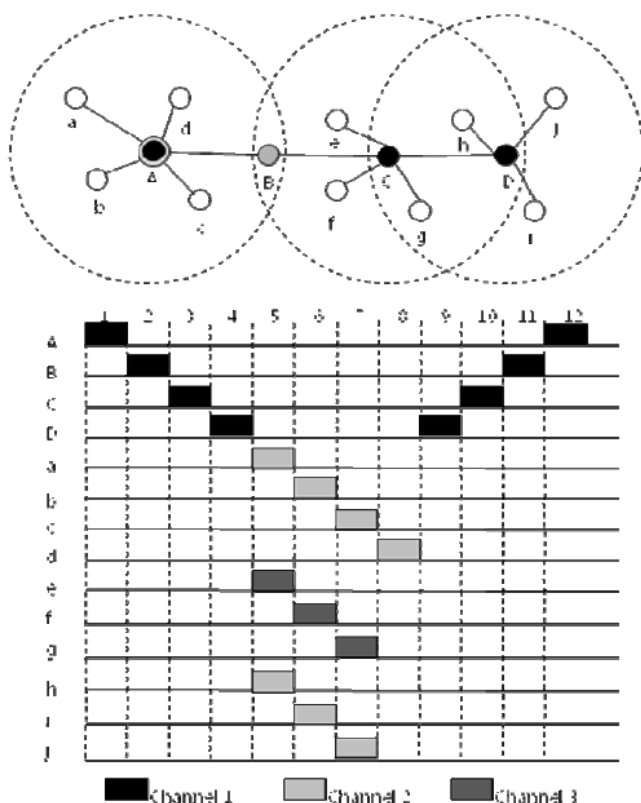


Figure 1. Slot assignment for high reliable communication within deterministic delay

The cluster header assigns its child nodes to different individual time slots for transmitting data frames. A node using its assigned data time slot doesn't disturb neighbor node's data frame transmission because the transmission in a cluster is coordinated and never try to transmit the frame at the same time.

A node's communication gets interfered while its neighbor nodes within two-hop away are transmitting. A neighbor cluster header reassigns used time slot in a neighbor cluster

to its child nodes but the channel is different. The channel differentiation and slot reuse reduces communication delay without interference. The cluster header which is more than two-hop away can reassign used time slot on used channel. It makes to minimize delay with limited radio resource.

In Fig. 1, the cluster header A assigns slot from 5 to 8 to its child node a to d on channel 2. The cluster header D reassigns used time slot to its child node on the same channel 2 because they are three-hop away. However, the cluster header C assigns the time slot on the different channel 3.

To reduce end-to-end delay, our MAC organizes the time slots in a sequence so that the packets flow continuously from the leaf level cluster header D to the PAN coordinator A shown in Fig. 1. The cluster header which is on the leaf level is assigned the more recent time slot than parent cluster header. The assignment sequence lets the PAN coordinator acquire all data in one superframe duration.

B. Overhearing and Forwarding Scheme

2.4GHz radio channel shows a low transmission success ratio when there is no direct line of sight between the sender and receiver. If there is an obstacle between a sender and a receiver node, the signal hardly reaches to the receiver node. Namely, an obstacle affects the radio channel status. The channel is unstable, as an obstacle blocking the line of sight (LOS) deteriorates the communication success ratio. When the obstacle is far from the LOS, the communication reliability is increased. If we cannot guess the movement of the obstacle, it is difficult to determine the channel status.

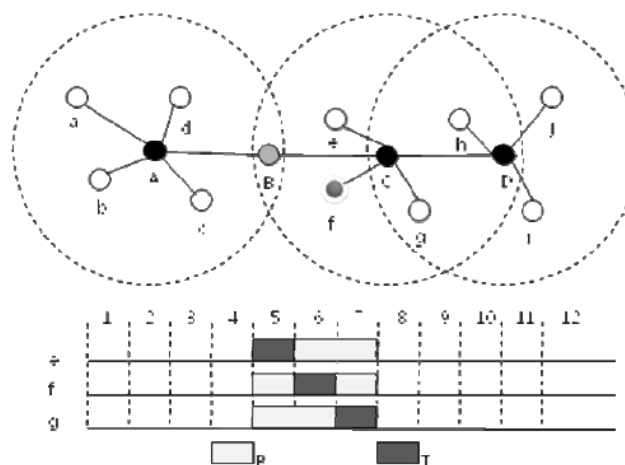


Figure 2. Scheduling on non-LOS environment

To provide highly reliable communication within a deterministic delay in a non-LOS environment, we introduce a data overhearing and forwarding scheme. Nodes transmit latency sensitive data packets to their parent nodes in the assigned data time slot. The packets transmitted with acknowledgement requests are to be acknowledged by the recipient. If the intended recipient correctly receives the packet, the transmission of the acknowledgement commences. If an

acknowledgement is not received or if the acknowledgement is corrupted, a neighbor node which overheard the data packet forwards it to the intended recipient instead of original sender. Normally, nodes drop overheard packets which is not destined for it. Our MAC, however, keeps the packet and forwards it to the recipient when the original packet fails to be transmitted and the deadline for transmission has not been exceeded.

The overhearing neighbor node implicitly recognizes original packet transmission failure if it receives only the data packet. The original sender also knows one of its neighbor forwards the data packet failed transmission originally by overhearing. The original sender activates its transceiver to overhear its neighbor node packet only when it recognizes its packet transmission failure. After one of the neighbor nodes forwards its packet which is failed to be transmitted originally, the original sender invalidates the original transmission failure packet. The forwarding neighbor node is obligated to successfully transmit the packet instead of original sender.

Fig. 2 shows transceiver active duration. While a node f is transmitting a packet during time slot 6, its neighbor nodes e and g turn on their transceiver to overhear a packet from f. one of e and g will forward the packet if the node f fails to transmit the packet.

C. Low Power Consumption

Low power consumption is one of the main requirements in the WSN. Our MAC knows the time when the nodes are required to be awake for communication. Thus all nodes stay in a low-power sleep mode and awake when required.

For upstream communication, nodes awake during its given time slot if it has data to transmit and its neighbor's time slot for overhearing. We assign data time slot for upstream data packet which is more delay sensitive than downstream packet. The node awakes to get downstream data packets during the contention period if the parent node wants to send it. At the end of every assigned time slot, our MAC assign contention period which every node are allowed to access the channel if they want. During contention period, basically nodes are in sleep mode. They activate its transceiver when it receive a beacon frame indicating that its parent node will transmit a downstream packet. The parent node adds the child node address in its beacon frame subfield if it want to transmit downstream packet.

IV. EXPERIMENTAL RESULTS AND PERFORMANCE ANALYSIS

In this section, we present experimental results. We implemented a prototype sensor network using our reliable and delay guaranteeing MAC protocol. The sensor nodes used in the experiment are presented in Fig. 3. They use the MSP430F1611 MCU, whose modular architecture allows powering down peripherals and the CPU when not in use,

reducing the power consumption. The sensor nodes communicate with other nodes using the Chipcon CC2420 transceiver operating on 2.4GHz. The nodes are powered by a 3.6V battery.

For the experiment, we designed a wireless sensor network with 2 clusters. Fig. 4 shows the network topology and slot assignment for the performance test. Our MAC assigns first and second slot to beacon time slot of node A and B. From 3rd to 6th slot, child nodes of each cluster allow to transmit data packet and node B can forward the packet to node A during slot 7. We compare our MAC with CSMA/CA MAC.



Figure 3. Sensor node

During the test, each child node simultaneously tries transmitting 4 bytes of MAC payload data to its parent node in 250msec intervals. The cluster header B instantaneously relays the data to the cluster header A.

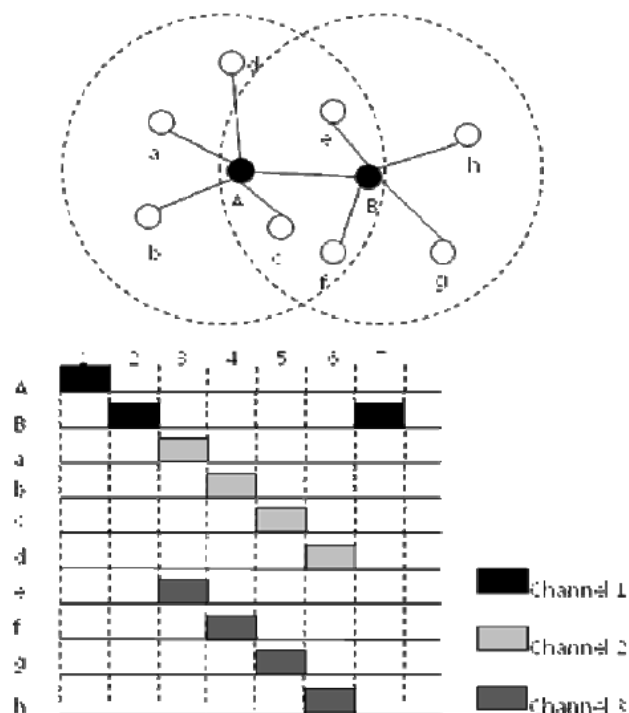


Figure 4. Network topology and slot assignment for the performance test

TABLE I compares the end-to-end transmission success rate within guaranteed delay 250msec of our MAC with contention based MAC using CSMA/CA. Our MAC provides a larger transmission success ratio compared to CSMA/CA. The successful transmission rate for packets sent from the sender node to node A in a LOS environment is 61% for nodes using CSMA/CA and 98.7% for nodes using our MAC. In a non-LOS environment, the transmission success ratio is 2.57% for nodes using CSMA/CA and 75.01% for nodes using our MAC. Furthermore, power consumption can be reduced, as the packet receiving time slot is deterministic, and the nodes can only enter Rx mode when they are expecting to receive a packet.

Table 1. Experimental result

	LOS	Non-LOS
CSMA/CA	61 %	2.57%
OUR MAC	98.7 %	75.01%

V. CONCLUSIONS

We designed and implemented a new MAC promising hard real-time and reliable communication both a LOS and a non-LOS environment in 2.4GHz ISM band. The protocol can be used in real-time systems and offers advantages over contention based MAC using CSMA/CA mechanism in terms of the packet delivery success rate and power consumption.

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