Contention Resolution using Signal Tones for Wireless Sensor Networks

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Abstract – **This paper deals with contention resolution using signal tones for Wireless Sensor Networks (WSNs). We give an overview of existing contention resolution mechanisms, and describe briefly representative protocols by stating their essential behavior and emphasizing their strengths and weaknesses.**

Keywords – **Wireless sensor networks, Energy efficiency, Medium access control, Contention resolution.**

I. INTRODUCTION

A wireless sensor network (WSN) consists of a number of autonomous sensor nodes, composed of sensors, a low-power radio transceiver, small amount of memory and processing capability as well as limited battery power supply [1]. The primary objective in WSN design is maximizing node/network lifetime, leaving the other performance metrics as secondary objectives. Since the communication of sensor nodes is more energy consuming than their computation, it is a primary concern to minimize communication while achieving the desired network operation.

MAC protocol defines how and when nodes may access the shared medium in order to transmit their data and tries to ensure that no collisions occur. The collisions can be resolved in two ways: statically, by assigning each node exclusive time slot and dynamically, by adding a contention period at the beginning of each data transfer period. During the contention period nodes contend for medium access by employing a suitable contention resolution mechanism (CRM). Only the node that wins the contention is allowed to transmit its message, while others go back to sleep until the next active period. There are two primarily sources of energy overhead associated with contention-based MAC protocols: 1) contention overhead, and 2) collision overhead. The contention overhead is a consequence of additional energy consumption during the contention period, which may involve energy for transmitting control packets, as well as the energy for carrier transmission and carrier sensing. The collision overhead is a consequence of data packet collisions that are not prevented by the CRM. In general, there is a trade-off: the more energy spent on contention resolution, the less energy will be lost due to collisions, and vice versa.

There are two main problems that lowers the networks energy efficiency and throughput: hidden terminal problem and exposed terminal problem. The hidden terminal problem causes collisions and the exposed terminal problem lowers the data throughput.

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CRM based on carrier sense multiple access (CSMA) protocol is often chosen due to its simplicity, low contention overhead and scalability [2]. With this scheme, sensor node randomly selects the moment of time in which it will starts with transmission, it senses the channel and withdraws if the channel is busy; or transmits the carrier signal otherwise. However, CSMA is susceptible to hidden- and exposed terminal problems, which lowers its energy efficiency and throughput. In order to combat the hidden terminal problem, a mechanism known as RTS/CTS handshake is widely used in wireless networks [3]. With RTS/CTS, signal tones are replaced with RTS and CTS control packets. Although the use of RTS/CTS mechanism avoids most of the data collisions, it is particularly unsuitable for WSNs because of high overhead due to control packets exchange [4]. Hence, the RTS/CTS is out of scope of this paper.

A class of CRMs based on exchanging unmodulated or modulated signals of short duration on the carrier frequency (so called tones) between the nodes offers a promising solution for collision-free communication with low contention overhead [5]-[7]. All of them provides the collision-freedom in a single-hop environment. In a multi-hop environment, the hidden-terminal problem may occur. To overcome this problem, several MAC protocols are proposed [8], [9]. Among others, a BCD-like contention resolution algorithm with tone-based signaling is proposed, which provides collision-free communication [10], [11].

In this paper, we give a survey of the tone-based CRM s for WSN. Section II explains the hidden- and exposed terminal problem end gives the overview of the existing tone-based CRMs and emphasizes their distinct features related to WSNs. Section III introduces TONE CRM, specifically developed for WSNs, which successfully eliminates hidden and exposed terminal problems.

II. CONTENTION RESOLUTION USING SIGNAL TONES

The main requirements for the wireless networks are energy efficiency and throughput, which are mainly affected by the limited range of the radio transceiver. There are two problems characteristic for wireless medium: hidden and exposed terminal problem.

The hidden terminal problem occurs when two or more nodes, not visible to each other (due to limited transmission range, presence of obstacles, etc.) intend to send their messages to the same receiver during a given active period. The energy consumed during the transmission and reception of collided data messages is wasted, and additional energy is required for the retransmission, which lowers the energy efficiency of the network.

The exposed terminal problem occurs when a node withdraws due to the ongoing transmission from one of its neighbors, although its transmission wouldn't collide with the ongoing. This causes unnecessary delay, thus lowering the throughput of the network.

The signal tone is a radio signal of limited duration that carries no information. It is used for binary indication of transmitter's state. There are several ways the MAC protocols can use signal tone: in form of a busy tone, jamming signal and binary-countdown (BCD) procedure.

A. Busy Tone

MAC protocols based on a busy tone uses two frequency channels: data channel and control channel. The busy tone is transmitted on the control channel by receiver, during the reception of the data on the data channel. In this way, by transmitting the busy tone node prevents its neighbors to initiate new transmission which would cause collisions. Although the use of the busy tone efficiently eliminates collisions, the increased energy consumption due to the long tones and increased price and consumption of the radio transceiver makes it unsuitable for use in WSNs. There are several existing MAC protocols that use busy tone.

BTMA protocol is designed for single-hop networks with central base station [5]. Base station transmits the busy tone in case that the carrier is detected on the data channel. The sensor node that has packet to transmit firstly senses the control channel and transmits only if the busy tone is not sensed, otherwise retreats for an arbitrary period of time. Although it eliminates the hidden terminal problem in single-hop networks, BTMA cannot deal with the hidden and exposed terminal problem in multi-hop networks.

RI-BTMA also uses separate control channel [12]. Sensor node that has packet to transmit firstly senses the control channel. In case that the busy tone is not sensed, node transmits the RTS packet containing the recipients address on the data channel, and waits the recipient's response in form of a busy tone on the control channel. The recipient that detects its address on the data channel transmits the busy tone until the end of the data reception. In the absence of the busy tone, the transmitter retreats for an arbitrary period of time. In this manner the busy tone acts as the reservation ton and CTS packet, in which way it deals with the hidden terminal problem.

DBTMA protocol is a distributed solution intended for the ad hoc networks [13]. This protocol uses two busy tones on two separate channels: the receive busy tone, transmitted by receiver during data reception, and the transmit busy tone, transmitted by transmitter during transmission of the RTS packet. The node that has message to send first senses both control channels. In case that at least one channel is occupied, it retreats and tries later; otherwise, it initializes the procedure by sending the RTS packet on the data channel, together with the transmit busy tone on the control channel. After that, the transmitter stops sending the transmit busy tone and waits for the receive busy tone. Potential receiver that senses the transmit busy tone starts transmission of the receive tone, until the period intended for reception of the whole data packet. The transmitter sends its data packet after it senses the receive busy tone. In this manner DBTMA successfully eliminates hidden and exposed terminal problem, with the cost of the additional hardware and additional delay due to generation and detection of the additional busy tone on the second control channel.

B. Jamming Signal

The jamming signal is used by the nodes during contention for the channel access [6]. All the nodes that have message to send simultaneously start to transmit the jamming signal of a different length. After that, they sense the channel. If the medium is still occupied, the node lost contention and retreats. In this manner, the node with the longest jamming signal is the winner and starts with the data transmission.

Black-Burst protocol is designed for the single-hop networks. It divides nodes in to two groups: nodes with the high and with the low priority [6]. The jamming signal is used by the nodes with the high priority: the node with message to send senses the channel and, in case it's free, begins to transmit the jamming signal. Duration of the jamming signal is set by each node individually and corresponds to its delay in the network. After the transmission ends, the node samples channel ad retreats in case it's busy. In this case, the winner is always the node with the longest jamming signal, i.e. the highest delay. The nodes in the group with the low priority uses regular CSMA/CA contention mechanism in case there are no nodes with the high priority interested in transmission.

Priority MAC protocol within the ad-hoc networks implements priorities similarly to the Black-Burst [7]. In the network that offers K different classes of services, each class is assigned different duration of the jamming signal, proportional to its priority. This provides the node with the highest priority to be the winner, since it has the longest jamming signal.

C. The Binary-Countdown, BCD

BCD-based MAC protocols for wireless networks implement arbitration concept from the CAN busses (*Controller Area Network*). CAN bus for the wired networks implements bit-dominant arbitration [14]. The node priority is coded with the unique binary sequence. The CAN arbitration concept provides the access to the medium to the node with the highest (or the lowest) binary sequence. The arbitration functions as follows: the percipient nodes sends synchronously their binary sequences bit by bit in fixed time moments. The logical one (or zero) is coded using dominant signal and the logical zero (or one) using recessive signal. In case there is at least one dominant signal transmitted, the resulting signal on the communication line will be dominant. The resulting signal is recessive only if all the transmitted signals are recessive. The nodes that have sent the dominant signal continues with the contention, all the others retreat.

In the wireless networks that implement BCD algorithm, the CAN arbitration is implemented in the following manner: the dominant bit is implemented as signal tone of certain duration, and the recessive as the absence of the signal tone.

The nodes in wireless network usually cannot simultaneously transmit and receive, so this way of coding allows the nodes with the recessive signal to sample the channel, in order to detect the dominant signal. The Fig. 1 shows an example of the arbitration using BCD algorithm. There are three nodes participating the arbitration, each with the different priority. The binary zero is coded as dominant bit and the binary one as recessive bit. The consequence of this type of coding is that the higher priority is coded using lower binary number. During the first two contention rounds, all three nodes transmits the bit of the same priority (i.e. transmit the signal tone in case of the binary zero, or samples the channel in case of the binary one). So, during the first round, all the nodes transmits, so no one hears signal tone, and during the second all the nodes samples, but there's no signal tone, so they do not retreat. Then, during the third round the node no. 2 hears the dominant bit and retreats, as well as the node no.1 two rounds later. The end of the arbitration reaches only note no. 3, and it is the winner.

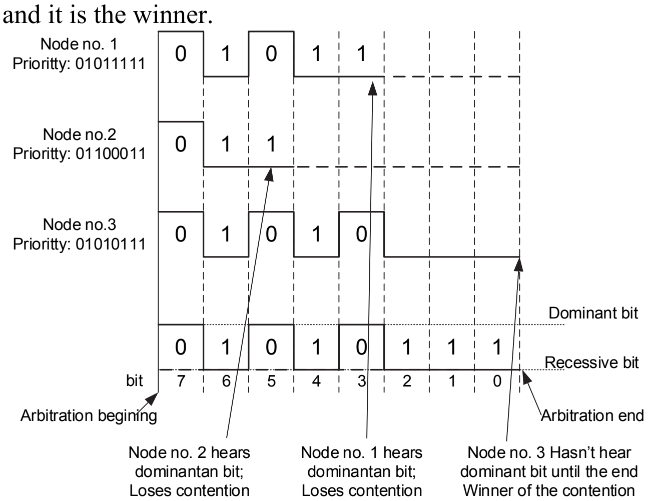

Fig. 1. Example of the CAN arbitration

The BCD algorithm is used with the protocols CSMA/IC [8] and WiDom [15]. Since these protocols can provide deterministic arbitration only within single broadcast wireless networks, they cannot be used for the multiple broadcast domains, like multi-hop WSNs and 1-hop star networks, due to the hidden terminal problem.

The further improvement of the CSMA/IC [5] suggests introduction of the control channel and increasing of the signal tone strength (or increasing of the receiver sensitivity), in order to extend its scope to the 2-hop neighborhood. However, this solution doesn't deals with the hidden terminal problem due to the physical obstacles, and increases the price and consumption of the radio transceiver. The extension of the WiDom for multiple broadcast domains suggests the two-phase signaling [5]. During the first phase the dominant bit is transmitted and during the second phase it is reemitted. Thou this approach successfully deals with the hidden terminal problem, it still suffers from the exposed terminal problem.

III. The Use of Signal Tones in WSN

The WSNs are specific kind of networks in terms that they involve high number of sensor nodes organized in multi-hop manner. Hence, each node competes with potentially high number of neighbors, and overhears a potentially high number of other competitions. This means that the CRM for the WSN must be very efficient in terms of dealing with hidden- and exposed terminal problems. The commonly used CRM is CSMA, due to its simplicity, but it is highly inefficient so the new CRMs are proposed, such as TONE.

A. TONE

TONE is an energy-efficient intra-cluster tone-based CRM for WSNs [11]. The cluster consists of a central node called cluster head (CH) and arbitrary number of cluster members (CMs). TONE provides collision-free data communication between CMs and CH. TONE CRM can also be applied in multi-hop WSNs with receiver-driven TDMA MAC protocol [10]. At each time slot, multiple clusters are formed within the network, with slot owners acting as CHs, and their immediate neighbors acting as CMs. The 2-hop exclusive slot assignment provides that the clusters are mutually isolated (Fig. 2), so each cluster can apply intra-cluster CRM TONE at the beginning of the slot, in order to select one CM for each CH.

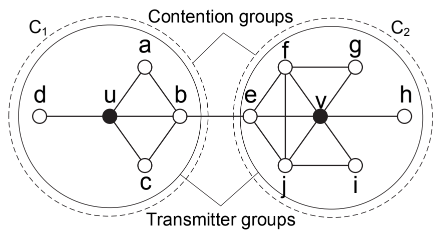

Fig. 2. Separated clusters in receiver-driven TDMA MAC based WSN. **Notice**: nodes *u* and *v* are owners of the current time-slot

TONE intra-cluster CRM is based on an elimination process that divides the initial group of CMs recursively in two subgroups, AC (group of active contenders) and SC (group of silent contenders), eliminates one subgroup and continues the procedure until a subgroup is of size 1. There are two main components of the TONE: the tone-based signaling mechanism and the group splitting algorithm.

Tone based signaling mechanism is used for testing the presence or absence of intended senders in AC group and presenting this information to intended senders in SC group. The contention period is divided in contention rounds (CR). Each CR is divided into two phases (Fig. 3). During the first phase, intended senders in AC group transmit their tones. During the second phase, CH retransmits the tone. In this way, CH is actively involved in the contention resolution process, ensuring that each tone transmission reaches all CMs in the cluster. Note that tones may collide with one another without affecting their functionality, because what is important is the presence of the tone.

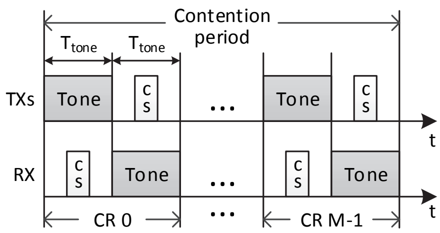

Fig. 3. Two-phase signaling in TONE

Two phase operation of tone-based signaling mechanism is crucial for avoiding both hidden- and exposed terminals in TONE. Hidden terminals are avoided because all the intended senders are merged into single contention group by means of CH node that acts as a tone repeater. Exposed terminals are avoided since clusters are isolated, so there no simultaneously active potential senders from different clusters.

The group splitting algorithm determinates how a group of non-eliminated contenders is partitioned into AC and SC group at the beginning of each CR. It is performed locally by each non-eliminated intended sender, and it does not require any communication among nodes.

TONE uses novel group-splitting mechanism, based on BCD, which aim to minimize the size of the AC group at each CR. By lowering the size of the AC group, TONE decreases the number of tone transmissions, thereby improving the energy efficiency.

If *c* is the size of the current contention group and the *r* is the number of the remained contention rounds, TONE computes the size of the AC group as in Eq. (1):

$$g = \begin{cases} 1 & if \quad c \le 2^r \\ c - 2^r & else \end{cases} \qquad (1)$$

Using the concept of contention interval, the proposed group splitting mechanism does not need to explicitly determine which nodes belong to which subgroup. Knowing its own competition number, the boundary values of contention interval, and the size of AC group, every contending node can individually determine to which subgroup it belongs.

By eliminating hidden- and exposed terminal problem, TONE CRM improves energy efficiency and throughput, while providing collision-free data communication in multi-hop WSN.

IV. Conclusion

In this paper we presented the overview of the contention resolution mechanisms that use signal tones employed in current MAC protocols for WSNs. The use of signal tones can certainly simplify contention resolution and lower the energy consumption. There are several efficient solutions that use signal tones in centralized wireless networks. However, due to hidden- end exposed terminal problems, generalization of these schemes to multi-hop networks is not always possible, or comes with the cost of increased protocol complexity. We identified the TONE protocol as the most promising contention resolution mechanism based on signal tones for the use in multi-hop WSNs. When integrated in receiver-driven TDMA MAC, the TONE provides collision-free data communication. Design of an efficient signal tone-based contention resolution mechanism for other categories of MAC protocols (e.g. MAC with common active period) is still an open problem, since so far there are no defined communication standards for WSNs based on signal tones.

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