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CONTENTION RESOLUTION MECHANISM FOR RECEIVER-DRIVEN TDMA-BASED WIRELESS SENSOR NETWORKS*

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Abstract. *TDMA-based protocols that have been proposed for wireless sensor networks (WSNs) use two opposite strategies of assigning slots to nodes. The transmitted-driven slot assignment schemes, which assign slots to nodes for message transmission, eliminate collisions of data messages, but waste energy due to message overhearing. The receiver-driven schemes, which assign slots to nodes for message reception, eliminate message overhearing, but the neighbors of slot owners have to contend for the medium. The existing proposals of the receiver-driven TDMA protocols employ CSMA-based contention resolution mechanisms, which suffer from both hidden- and exposed-terminal problem, thus limiting the applicability of the protocol to low traffic load conditions. In this paper, we propose a contention resolution mechanism, named TONE, specifically designed for receiver-driven TDMA protocols, which alleviates both the hidden- and exposed-terminal problem, given that a reception slot is not reused within a 2-hop neighborhood. TONE resolves contentions in successive elimination rounds by using a two-phase tone-based signaling mechanism in every round. We also propose a group splitting algorithm, which governs the elimination process in the manner that minimizes the number of tone transmissions, thereby improving the energy-efficiency. Our analysis, verified by simulation results, demonstrates that TONE outperforms the CSMA-based contention resolution mechanism and it can greatly improve the performance of receiver-driven TDMA-based WSNs under heavy traffic load. Also, our simulations show that the receiver-driven TDMA protocol with TONE outperforms transmitter-driven TDMA protocol in energy-efficiency, although with a limited drop in data throughput.*

Key words: *wireless sensor network, MAC protocols, TDMA protocols, contention resolution mechanism*

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1. INTRODUCTION

A wireless sensor network (WSN) is a distributed system composed of a number of small, low-cost and battery-powered sensor nodes equipped with a low-power radio. WSN is built of a few to several hundreds or even thousands hundreds nodes, which are randomly deployed and have the ability to collect useful information from various environments, compute simple tasks and communicate with each other in a multi-hop manner in order to achieve some common objective, like environmental monitoring, military surveillance, target tracking, detecting hazardous chemicals and forest fires, and monitoring seismic activity [1]].

Because of the lack of a centralized control entity in WSNs, the sharing of wireless bandwidth among sensor nodes must be organized in a decentralized manner. Therefore, distributed Medium Access Control (MAC) protocol is a key component to ensure the successful operation of WSNs and it has obtained intensive research attention [3, 4]. A MAC protocol defines how and when nodes may access the shared medium in order to transmit their data and it tries to ensure that no collisions occur. MAC protocol controls the activity of nodes' radio transceiver directly, and therefore makes a strong impact on the network's overall performance and energy efficiency. MAC protocols for WSN usually trade off performance (delay, throughput, fairness) for cost (energy efficiency, reduced algorithmic complexity), while providing a good scalability and some limited adaptability for topology changes. Besides collisions, the network performance and energy efficiency are also affected by idle listening and overhearing. The idle listening occurs if a node listens to the medium when there is no transmission, whereas an overhearing happens when a node receives a data message transmission even if it is not the intended recipient of this transmission.

According to the underlying mechanism for collision avoidance, MAC protocols can be broadly divided into two groups: the contention-based protocols and the time division multiple access (TDMA) protocols. In order to achieve low power operation, contention-based MAC protocols incorporate some form of duty-cycling mechanism: each node keeps its radio transceiver turned off for most of the time and periodically switches it on for short periods to transmit and receive messages. One approach is to synchronize active and sleep periods of the neighboring nodes so that they are awake at the same time [5, 6]. A receiver only listens to brief contention period at the beginning of active phase, while senders contend during this period. Only nodes participating in data transfer remain awake after the contention period, while others go back to sleep until the next active period. For instance, S-MAC protocol employs a contention resolution mechanism based on Carrier Sense Multiple Access (CSMA) and the use of Request-To-Send/Clear-To-Send (RTS/CTS) control packets. Although the use of RTS/CTS handshake mechanism avoids most of the collisions, it incurs high control overhead due to small size of data messages in WSNs. Another contention-based strategy is the transmission of long wakeup preambles to bridge the gap between two consecutive checks performed by receivers [7-9]. This approach eliminates the need for duty cycle synchronization, but suffers from the overhearing problem, since the preamble also wakes up nodes which are not the intended receivers of a message.

TDMA-based protocols establish a schedule wherein each node is assigned one (or possibly multiple) slots within a global time frame. By letting nodes turn-off their radios alternately, rather than simultaneously, TDMA-based protocols significantly reduce communication grouping. In this way, collisions within individual slots are reduced or completely eliminated. Traditional TDMA protocols for WSNs, like [10-13], assign each node a fixed slot to transmit one message in each frame. To prevent transmissions to interfere with each other, this *transmitter-driven* TDMA approach allows slots to be reused only beyond 2-hops so that nodes within interference range transmit at different times. Such a scheme is thus able to reduce energy wastes due to contention, collisions and idle listening, while providing guaranteed bandwidth of one transmitted message per frame for all nodes in the network. The only remaining sources of energy overhead in transmitter-driven TDMA protocols are channel sampling and message overhearing. Both are consequence of the requirement that each node must wake up in every slot owned by one of its neighbors in order not to miss incoming messages, and both are particularly evident in dense networks. A common critique of the TDMA-based protocols is that the 2-hop exclusive slot assignment usually requires a frame with a large number of slots, which may lead to a significant message delay, and pour channel utilization. In addition, changing the frame length and/or the slot schedule dynamically according to the unpredictable variations of network topology is usually hard for TDMA-based schemes. Nevertheless, the transmitter-driven TDMA scheme is attractive for high data rate WSNs because it is energy-efficient and may provide higher throughput than contention-based protocols.

Other variations on the basic TDMA scheme are possible. Rather than scheduling slots for node transmissions, slots may be assigned for reception with contention resolution procedure conducted at the beginning of each slot [14-18]. With respect to the transmitter-driven TDMA scheme, the main benefit of this *received-driven* TDMA scheme is that it avoids data messages being overheard by non-intended receivers, thereby additionally reducing the energy overhead. Moreover, the receiver-driven approach can be more energy-efficient under light traffic conditions, because each node checks for the incoming data messages only in its own receive time slots. However, in order to provide a valuable alternative to transmitter-driven TDMA protocols, the receiver-driven TDMA protocols need to be coupled with a contention resolution mechanism (CRM) that is efficient in both time and energy demands, and highly effective in avoiding collisions. The CRMs for receiver-driven TDMA protocols are our focus in this paper.

Commonly used CRMs in receiver-driven TDMA protocols are based on CSMA [14, 16], where the transmitter first senses the channel before transmitting. The CSMA-based CRM is both fast and energy-efficient. However, even in the context of receiver-driven TDMA with 2-hop exclusive slot assignment the CSMA is vulnerable to the well-known hidden- and exposed-terminal problems. At low traffic, when hidden and exposed terminals occur rarely, the receiver-driven TDMA with CSMA-based CRM provides significant improvement in energy-efficiency over transmitter-driven TDMA. However, as traffic load increases, the combined effects of hidden and exposed terminals severely degrade the overall performance.

In this paper, we propose a CRM, that we named TONE, which is specifically designed for receiver-driven TDMA networks. The key feature of TONE is that it solves both the hidden- and exposed-terminal problem, given that each node is assigned a 2-hop exclusive slot for data reception. By effectively avoiding collisions, TONE overcomes the main cause of CSMA's inefficiency under high traffic load conditions, thereby considerably extending the applicability of received-driven TDMA protocols. The basic premise of our strategy for CRM is that the problem of resolving contentions in a receiver-driven TDMA-based network can be characterized as a problem of searching for an intended sender in a set of neighbors of the slot owner. In TONE, this search is conducted in successive elimination rounds narrowing the number of contending nodes until the winner is selected. The elimination procedure is simple: at the beginning of each competition round, the set of non-eliminated contenders is divided into two groups. Then, it is checked whether the first group contains at least one intended sender, and if true the first group wins the round while the second group is eliminated; otherwise, the second group enters the next round and the first group is eliminated. The interaction between two groups of contending nodes is accomplished via a two-phase tone-based signaling mechanism. In the first phase, intended senders from the first group (if any) transmit tone signals of short duration, while the receiver node (i.e., slot owner) detects the presence of a tone. In the second phase, the receiver node retransmits the tone to contending nodes in the second group.

Using tones in MAC design is not new. Several previous MAC protocols are based on exchange of short tones and/or use similar iterative elimination concept as TONE. Most relevant to our work is the class of MAC schemes based on a binary-countdown approach [19]. The basic idea of binary countdown lies in selecting the winner based on a k -bit binary number $(b_{k-1},...,b_0)$. An intended sender (say u) with $b_i = 1$ transmits a short tone signal during i^{th} slot of the contention period. Otherwise, if $b_i = 0$, node u listens to the channel, and gives up its attempt of gaining access to the channel if the channel is busy. If each node uses a distinct binary number, only one node survives at the end of the contention period. This simple scheme guarantees the collision-freedom if all nodes are within a single broadcast domain [20, 21]. However, in a multi-hop network, it is prune to hidden-terminal problem. To overcome this shortcoming, enhanced WiDom protocol [22] transmits each bit in two stages. In the first stage, nodes with $b_i = 1$ transmits a tone; in the second stage, nodes with $b_i = 0$ retransmits the tone detected in the first stage. If a node detects a tone in one of two stages it withdraws from the competition. By ensuring that only one intended sender within a 2-hop domain can win, this scheme overcome the hidden-terminal problem. However, it introduce exposed-terminal problem, leading to bandwidth under-utilization.

In contrast to previous solutions, TONE relays on pre-established TDMA frame with 2-hop exclusive receiver-driven slot assignment providing the minimum distance of 3-hops between any two simultaneously active receiver nodes. In such setup, the contention resolution can be narrowed down to 1-hop domains of the slot owners, allowing the two-phase tone-signaling mechanism to avoid both hidden and exposed terminal problem completely. In addition, TONE replaces the binary countdown approach with a group splitting algorithm, which divides the set of non-eliminated contenders during the individual competition rounds in a way which minimizes the number of tones transmitted during the entire competition session. To the best of our knowledge, to date, our work is the first one to deal with the energy-efficiency of tone-based CRMs through the minimization of the number of transmitted tones.

The remainder of the paper is organized as follows: In Section 2, we first outline the system model and assumptions used through the rest of the paper, and then we discuss various aspects of TDMA-based protocols, including channel access mechanism. Section 3 provides a description of the proposed contention resolution scheme, followed by evaluation in Section 4. Section 5 concludes the paper.

2. TDMA-BASED MAC PROTOCOLS

2.1. System model and assumptions

A WSN is composed of a set V of nodes. Nodes are equipped with low-power radios, so each node $v \in V$ can communicate with a subset $N_1(v) \subseteq V$ of nodes determined by the radio range. Each node $u \in N_1(v)$ is called the 1-hop neighbor of v. We assume that communication capability is bidirectional, i.e. $u \in N_1(v)$ if $v \in N_1(u)$. The size of set $N_1(v)$ is known as the degree of node v, denoted by $\delta(v)$. We use δ_{max} and δ_{avr} to denote the maximum and the average node degree in the WSN, respectively. Two nodes having a common 1-hop neighbor are called 2-hop neighbor to each other.

A single frequency channel is shared spatially by all nodes in WSN, and communication is half-duplex, i.e. node cannot send one message and receive another simultaneously. All node clocks are synchronized to a common global time, and time is slotted. A slot is the smallest time unit for transmitting one complete data message. Slots are grouped into periodic frame, with L slots per frame. Nodes access the channel according to the predetermined TDMA schedule which specifies in details which nodes are to send and which are to receive in each slot of the frame.

2.2. Classification of TDMA-based protocols

Two types of TDMA scheduling problems have been investigated in the literature: node scheduling and link scheduling [23]. In node scheduling, the slots are assigned to nodes, whereas in link scheduling the slots are assigned to links through which pairs of neighboring nodes communicate. In this paper, we assume a node scheduling model in which each node v is assigned a single slot $S(v)$ in the frame. We say that node v owns slot $S(v)$. In large TDMA-based multi-hop WSNs, slots within a fixed-length frame need to be spatially reused, that is, shared among several (geographically separated) nodes. We assume 2-hop exclusive slot assignment in which slot $S(v)$ is not reused in node's v 2-hop neighborhood. Depending on how nodes use assigned slots, two slot assignment schemes can be identified: (a) transmitter-driven TDMA (TD-TDMA) in which a node v uses slot $S(v)$ to send data messages to its 1-hop neighbors, and (b) receiver-driven TDMA (RD-TDMA) in which a node v uses slot $S(v)$ to receive data messages from its 1-hop neighbors.

Most existing designs of TDMA-based MAC protocols are founded on TD-TDMA model. In this scheme, 2-hop exclusive slot assignment ensures that nodes assigned with the same slot do not have common neighbors. Therefore, collision in case of their concurrent transmissions cannot occur. In RD-TDMA, each node is assigned a 2-hop exclusive slot to receive messages. During the slot owned by a node v, a multipoint-to-point (star-based) wireless network is created around v. In this temporal network, the node v acts as a receiver node, and nodes in $N_1(v)$ act as transmitter nodes. Any message transmission is successful if no other node, among nodes in $N_1(v)$, transmits to v in the given slot. A collision occurs if multiple transmitter nodes attempt to transmit simultaneously. In order to avoid collisions, or at least decrease collision probability, transmitter nodes use CRM to cooperatively elect one of them as the next transmitter. In this paper we investigate two RD-TDMA variants: (a) RD-TDMA/CSMA – receiver-driven TDMA with CSMA-based CRM, and (b) RD-TDMA/TONE – receiver-driven TDMA with our proposed tone-based CRM.

2.3. Channel access

In general, each slot of the TDMA frame is divided into three time intervals: a) the contention period, b) the data transfer period, and c) the acknowledgement (ACK) period. Not all slot sections are required for all TDMA protocol variants as indicated in Fig. 1. The contention period is included in RD-TDMA protocols to provide the time needed for the contention resolution procedure. The data transfer period is common for all protocol variants. The length of this period is fixed depending on the channel bandwidth and data message size. With RD-TDMA/CSMA scheme, a receiver node immediately responds with an ACK packet after the successful reception of a message; the absence of ACK is the sender's only indication of a collision. Both TD-TDMA and RD-TDMA/TONE protocol guarantee collision-freedom in the data transfer period, and thus ACK packet is not necessary for their correct operation.

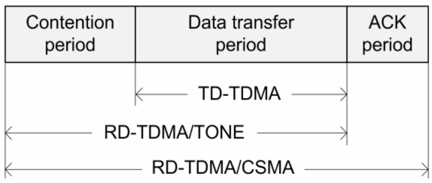


Fig. 1 TDMA slot structure.

2.3.1. Data transfer period

Fig. 2 depicts activities performed by sender and receiver nodes during the data transfer period of slot. The sender node begins transmission in data transfer period with a short tone signal (or stretched preamble). The tone is implemented either as a continuous un-modulated carrier signal of pre-specified duration, or as a signal modulated with a random bit sequence of specified length. In order to avoid unnecessary long idle listening when the sender node does not have data to send, the receiver briefly samples the channel at the middle of tone interval, just long enough to detect a signal above the noise threshold. If there is no message to be sent, the receiver will detect a clear channel and it goes to sleep immediately. Otherwise, if the channel is determined to be busy, the receiver stays awake to receive the incoming data message. The length of tone, T_{tone}, depends on the tolerance of clock, Θ, the periodicity of maintaining synchronization, t_{sync}, and the time needed for channel sampling, T_{CS} [26]:

$$T_{tone} = 4\Theta t_{sync} + T_{CS}$$

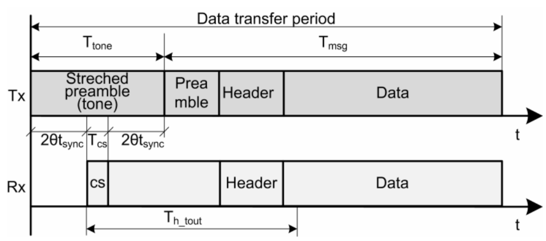


Fig. 2 Data transfer period of slot

Note that the computed value of T_{tone} ensures the overlapping of tone signal with the channel sampling at the maximum drift between sender and receiver clocks.

In order to prevent the idle listening of receiving node in the case of collision, the node stops the reception and switches-off the radio if it does not receive the header of a data message for timeout period of T_{h_tout} after channel sampling. To avoid unnecessary overhearing of complete data messages, the receiver examines the destination address of a message immediately after receiving its header. If a data message is destined to another node, it immediately stops the reception and switches-off the radio.

2.4. Contention resolution for RD-TDMA protocols

The following three concepts are important in the context of contention resolution in RD-TDMA protocols: the transmitter group, the intended sender, and the contention group. A *transmitter group* is a set of nodes with the common intended receiver node. In RD-TDMA based WSNs, the transmitter group equals the 1-hop neighborhood of the slot owner. Note that due to 2-hop exclusive slot assignment each node can be a member of at most one transmitter group in any slot. *Intended sender* is a node in a transmitter group with a message to send to the slot owner. Any simultaneous transmission of two or more intended senders in the same transmitter group causes collision at the receiver node. A *contention group* is defined as a maximal set of transmitter nodes that can mutually contend. The purpose of the CRM is to elect at most one intended sender among members of contention group in a fully distributed manner.

Because the contention resolution is localized to individual contention groups, the collision-free data transmission can only be guaranteed if all nodes in the same transmitter group participate in a single contention group. Otherwise, winners in different contention groups will transmit their data messages simultaneously causing collision at the receiver node. This is known as hidden terminal problem. Also, it is possible that one contention group includes nodes from two or more neighboring transmitter groups. This leads to the exposed terminal problem, when an intended sender that loses competition for the medium refrains from transmission even though it would not have interfered with the transmission of the winning node. Therefore, only a CRM with one-to-one relationship between transmitter groups and contention groups can fully avoid collisions and alleviate exposed terminal problem.

2.4.1. CSMA-Based Contention Resolution

In RD-TDMA/CSMA, the contention period is divided into many short contention slots. An intended sender randomly selects a slot within the contention period to perform channel sampling. An idle channel allows the node to proceed by transmitting a tone signal that covers the rest of contention period until the end of time interval reserved for the stretched preamble in data transfer period. Otherwise, if the node detects a busy channel (which happens when another nearby intended sender first started transmitting the tone), it gives up its attempt to transmit and switches-off the radio. Note that in RD-TDMA/CSMA a node that is scheduled to receive in particular slot does not participate in contention resolution and remains in low power mode during the contention period.

In CSMA-based CRM, the contention group is defined as a maximal set of transmitter nodes with the property that any two nodes in the group are 1-hop neighbors. As a consequence, the contention group may include nodes from different transmitter groups due to minimal distance of 2-hops between two simultaneously active receiver nodes. Also, nodes in the same transmitter group may be distributed over several contention groups due to maximum distance of 2-hops between two nodes in the same transmitter group. For instance, seven nodes in the transmitter group around receiver node v in Fig. 3 are partitioned into four contention groups. Because the contention resolution is narrowed down to the individual contention groups, there might be as many as four winner nodes in every contention session; two are enough to cause a collision. Note also that nodes f, e and j from the transmitter group around the receiver node v share the contention group with node b from another transmitter group. Whenever the winner of the competition in this contention group is any of nodes f, e and j, node b will be prevented to transmit although its transmission will not collide with the transmission of the winning node. Similarly, when node b wins, no one of nodes f, e and j will be allowed to send its data message.

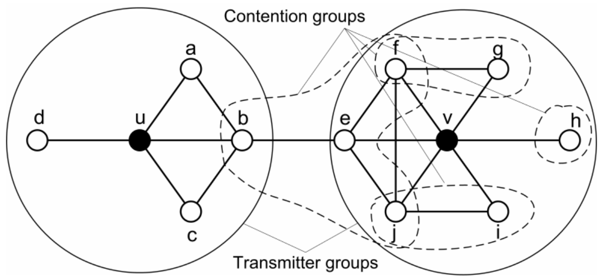


Fig. 3 Transmitter and contention groups in RD-TDMA/CSMA

As a consequence of the possibility of collision, the sender has to buffer each sent data message until it receives an ACK for that message. If an ACK packet is not received for a data message (which indicates a collision), then the sender node retransmits the same data message. To prevent repeated collisions of retransmitted data messages, the node waits a random number of frame periods (so called back-off delay) before attempting to retransmit the message.

3. TONE-BASED CONTENTION RESOLUTION MECHANISM

The proposed CRM, that we named TONE, is based on an elimination process that divides an initial transmitter group recursively into two subgroups, eliminates one subgroup and continues the procedure until a subgroup is of size 1. The basic concept behind TONE is illustrated in Fig. 4. The figure presents a transmitter group with seven nodes among which four are intended senders (represented with dark dots). The competition takes three *competition rounds* (CRs). At the beginning of each CR, the set of non-eliminated transmitter nodes is split into two groups: the group of active contenders (AC), and the group of silent contenders (SC). Then, it is tested whether the AC group contains at least one intended sender. If AC group is not empty (i.e. it does contain at least one intended sender), the SC group is eliminated, and all intended senders in this group (if any) are instructed to withdraw from the competition. Otherwise, the algorithm eliminates the

AC group and keeps the SC group. The algorithm finishes when the survived group of contenders contains one node only. This node is the winner of the competition.

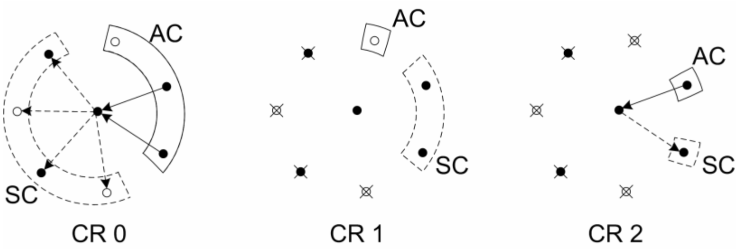


Fig. 4 Contention resolution with TONE

The two main components of TONE are: (a) the tone-based signaling mechanism, and (b) the group splitting algorithm. The group spitting algorithm determines how a group of non-eliminated contenders is partitioned into AC and SC groups at the beginning of each CR. In TONE, this operation is performed locally by each non-eliminated intended sender, in a sense that it does not require any interaction among contending nodes. The tone signaling mechanism provides means for testing the presence or absence of intended senders in AC group and presenting this information to intended senders in SC group. In TONE, this is achieved by exchanging a short tone signals between intended senders and the receiver node, as explained below.

3.1. Tone-based signaling mechanism

The tone-based signaling mechanism is used during each CR of the contention period with the goal to notify intended senders in SC group about the presence of intended senders in AC group. This mechanism is implemented in two phases and directly involves the receiver node (Fig. 5). In the first phase (corresponds to the first mini-slot of CR), active intended senders (i.e. those in AC group) announce their presence to the receiver node. In the second phase (corresponds to the second mini-slot), the receiver node notifies silent intended senders (i.e. those in SC group) about the presence or absence of intended senders in AC group. In order to reveal its presence, an active intended sender transmits a short *transmitter-tone (T-tone)* during the first mini-slot; then it skips the second mini-slot, and continues the competition in the next CR. During the first mini-slot, the receiver node receives the tone. Receiving a tone means detecting the presence of a tone signal. Therefore, to receive a tone, the receiver node should sample the channel at the middle of mini-slot. Note that T-tones may collide with one another without affecting their functionality, because what is important is the presence of the tone. In essence, the receiver node receives the "or" of the T-tone transmissions of all active intended senders. When the receiver node senses a T-tone, it will broadcast a *receiver-tone (R-tone)* during the second mini-slot; otherwise, the receiver node stays silent. Intended senders from SC group listen for a R-tone during the second mini-slot. When a silent intended sender senses a R-tone it will withdraw from the competition (because it knows that there is at least one intended sender in AC group). Otherwise, it will proceed to the next CR. Note that solid arrows in

Fig. 4 represent individual transmissions of T-tones, while multiple dashed arrows represent transmission of a single R-tone.

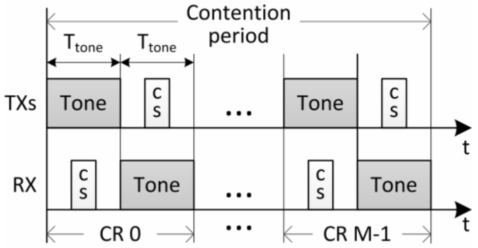


Fig. 5 Contention period in RD-TDMA/TONE

The two phase operation of the tone-based signaling mechanism is crucial for providing one-to-one relationship between transmitter and contention groups in TONE, thus fully avoiding both hidden- and exposed terminals (Fig. 6). Hidden terminals are avoided because all nodes in the transmitter group are merged into a single contention group by means of receiver node that acts as a tone repeater. To explain how the exposed terminals are eliminated let us consider Fig. 6 that depicts two neighboring transmitter groups, C_1 and C_2, with receiver nodes u and v respectively, owning the same slot. Because of the minimum distance of 3 hops between simultaneously active receiver nodes, the T-tones transmitted by intended senders in one transmitter group cannot be heard by the receiver node of another group. Similarly, the R-tone broadcasted by one receiver node cannot be detected by intended senders in another transmission group. In this manner, simultaneously active neighboring transmitter groups are practically isolated one from another.

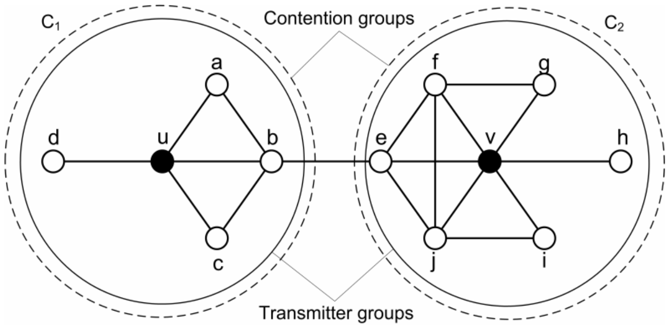


Fig. 6 Transmitter and contention groups in RD-TDMA/TONE

3.2. Group splitting algorithm

At each CG, during the course of a contention session, the group splitting algorithm determines which non-eliminated contenders are included into AC and which into the SC group. Consider the transmitter group formed around receiver node v. For the purpose of group splitting algorithm, each node in this group should know: the competition number, $CN(v)$, the size of the transmitter group, $\delta(v)$, and the length of contention period, M. The

$CN(v)$ is an integer from 0 to $\delta(v) - 1$ and must be unique in the transmitter group. The length of contention period is a fixed parameter and it has the same value for every transmitter group in the network. The group of non-eliminated contenders that participate in a particular CR is represented by the contention interval, i.e., the interval $CI = [C_{min}, C_{max}]$ of competition numbers, where C_{min} is the minimum, and C_{max} is the maximum competition number in the group. The size of contention interval equals $c = C_{max} - C_{min} + 1$. Initially, the contention interval includes all 1-hop neighbors of node v, and therefore $C_{min} = 0$, and $C_{max} = \delta(v) - 1$. At the beginning of each CR, the contention interval is split into two subintervals. The left one represents the group of active contenders, that is $AC = [C_{min}, C_{max} + k - 1]$; the right one represents the group of silent contenders, that is $SC = [C_{min} + k, C_{max}]$. Here, k represents the number of active contenders, i.e. the size of AC group. The size of SC group is $c - k$. At the end of the CR, the contention interval is updated. With no intended senders in AC group, the left subinterval is eliminated, that is $C_{min} = C_{min} + k$; otherwise, the right subinterval is eliminated, that is $C_{max} = C_{min} + k - 1$. The competition terminates when the contention interval shrinks to one competition number, that is, when $C_{min} = C_{max}$. Using the concept of contention interval, the group splitting algorithm needs only to decide on the size of AC group, and 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, each contending node can individually determine to which subgroup it belongs.

The group splitting algorithm impacts both the time- and the energy-efficiency of the tone-based CRM. The time-efficiency relates to the number of CRs needed for the competition, and thus determines the length of the contention period. A group splitting algorithm that requires a large number of CRs may reduce the throughput of the protocol. The energy-efficiency depends on how many channel sampling operations and tone transmissions are needed to complete the competition. Since the energy for transmitting a tone is significantly larger than the energy consumed for sampling the channel, the primary concern is to minimize tone transmissions. As will be demonstrated, there is a tradeoff between time- and energy-efficiency, that is, a group splitting algorithm that is focused on speeding up the competition generates a larger number of tones than one that spreads the competition over a larger number of CRs. In what follows we first describe two straightforward but opposite group splitting strategies, and then we introduce our proposed algorithm for splitting the group of contenders that aims to minimize the number of tones transmitted during the contention resolution process.

3.2.1. Bit-map algorithm

With the bit-map (BM) algorithm, the AC group always contains a single contender, i.e. $k = 1$. In every CR of the competition, the only active contender is the one with the smallest competition number in the current contention interval. The BM algorithm is the most energy-efficient group splitting strategy because two tones only are generated during a contention session (i.e., one T-tone and one R-tone) independent of the size of transmitter group. However, the BM algorithm requires at most $\delta(v) - 1$ CRs to elect the winner. Because of the fact that the distribution of node degrees is usually not uniform throughout the network, the length of contention period must be adapted to the largest transmitter group in the network, that is, $M = \delta_{max} - 1$. The linear dependence on the node density of the length of contention period makes BM approach non-scalable and extremely time-inefficient in dense networks.

3.2.2. Binary algorithm

The binary (BIN) algorithm divides the contention interval in two halves, i.e. $k = \lfloor c/2 \rfloor$. In this manner, BIN needs only n CRs to resolve the contention among 2^n contenders, which makes it the most time-efficient group splitting approach. Hence, with BIN, the length of contention period can be as small as $M = \lceil \log_2 \delta_{\max} \rceil$. However, BIN algorithm may generate a large number of tones, especially under high traffic load when most of the nodes in the transmitter group are intended senders. In addition, BIN algorithm is not able to use the surplus of CRs in sparse areas of the network in order to reduce the number of tones transmitted during competition session.

3.2.3. BM-BIN algorithm

Our proposed group splitting algorithm, named BM-BIN, combines bit-map and binary strategies into an adaptive splitting scheme. The main idea of BM-BIN is to start the competition in the bit-map mode and to keep using this mode as long as there is a sufficient number of remaining CRs to finish the competition in the binary mode. If the competition terminates during the bit-map phase, two tones will be transmitted, only. Otherwise, BM-BIN switches to binary mode with aim to speed up and finish the competition before the end of the contention period. Competition during the BIN phase requires more tones, but the total number of generated tones is still smaller than the number of tones that would be generated if the competition was performed in BIN mode from the beginning. In this manner, the contention in sparse areas of the network is mostly carried out in BM or near-BM mode providing a high energy-efficiency. In dense parts of the network, competition is performed in BIN or near-BIN mode, without the need to prolong the contention period. In what follows we present detailed description of BN-BIN group splitting algorithm.

Given the sequence number $r \in \{0,...,M-1\}$ of the current CR, BN-BIN algorithm determines the number of active contenders as:

$$k = \begin{cases} 1 & if \quad c \le 2^{M-r-1} \\ c - 2^{M-r-1} & else \end{cases} \tag{1}$$

At each CR, BM-BIN chooses between two options on how to split the current contention interval based on the size of contention interval and the number of CRs in the remainder part of the contention period. When the number of non-eliminated contenders, c, is small enough so that the contention can be completed without the use of the current CR, the BM-BIN algorithm selects one active contender, only (the first option in (1)). Otherwise, the contention interval is split in the manner in which the size of SC group equals the maximum number of contenders that can be handled by BIN strategy in the remainder part of the contention period (the second option in (1)). Therefore, in contrast to BIN in which the competition is condensed into the minimum number of CRs, BM-BIN algorithm spreads out the competition over all available CRs. In other words, contrary to BIN that always chooses the AC group of maximum size, with BM-BIN the number of nodes in AC group is as small as possible, constrained only by the requirement that the competition must be completed within the fixed-length contention period. By keeping the number of active contenders small, BM-BIN reduces the number of T-tone transmissions and thus save the energy.

To illustrate the efficiency of the proposed group splitting algorithm, let us consider a transmitter group composed of 12 nodes. Suppose that the length of contention period is $M = 4$ CRs, and all nodes in this group are intended senders. With every node being an intended sender, any group splitting algorithm will eliminate SC group in every CR. When BIN algorithm is used, the size of AC group for the next round equals the half of the size of AC group in the current round. Hence, there are 6 active contenders in the first round, 3 in the second, and 1 active contender in the third and last round. The total number of tones transmitted during the competition is 13, that is, it equals the sum of sizes of AC groups (corresponds to the number of emitted T-tones) plus the number of used CRs (corresponds to the number of R-tones).

On the other hand, when BM-BIN algorithm is used, the competition terminates as early as the second round with total of 7 tone transmissions. To see how BM-BIN succeeds to beat the BIN algorithm, consider the equation (1). At the first CR, BM-BIN cannot apply the first option in (1) ($k = 1$) because the size of initial contention interval ($c = 12$) is too big to be handled in remaining 3 CRs even if BIN strategy is used. Therefore, BM-BIN applies the second option in (1) and chooses $k = 4$. The rationale is simple: $k = 4$ is the minimum size of AC group that, in case of AC group elimination, ensures that the contention among nodes in SC group ($c - k = 8$ nodes) can be resolved in 3 remaining rounds by using BIN strategy. Because in this example all nodes are intended senders, the first CR survive 4 nodes in AC group. In the second round, with 4 non-eliminated contenders and 3 CRs left (including the current CR), BM-BIN is able to apply the first option in (1) and to include only one node in the AC group. Being the only member of the AC group, the selected node wins the competition in this round. During this short competition there was the total of 7 tone transmissions: 5 in the first and 2 in the second round.

Consider now what happens if we extend the contention period for one CR. Having $M = 5$ CRs at disposal, BM-BIN algorithm starts the competition among 12 nodes with an AC group containing a single contender. Assuming that the selected active contender is an intended sender, the first round of the competition will be the last. In this case, only two tones are needed to select the winner. Otherwise, the competition enters the second round with AC group of size 3, and then continues in pure BIN mode. If we extend the contention period to $M = 6$, the AC groups for the first two CRs will be of size 1, and the AC group for the third CR will be of size 2. It is easy to see that the number of beginning CRs with single-contender AC groups will increase by one with every CR added to the contention period. In this manner, the chance for competition to end with only two tone transmissions increases. When the length of contention period reaches 11 CRs, BM-BIN reduces to BM strategy. Note that BIN algorithm is insensitive to the length of contention period. Increasing the length of contention period is simply a waste of time because BIN will proceed in the same way, independent of the number of available CRs.

Finally, assume that each of 12 contending node independently decides with the probability p whether to participate or not in the contention session. Fig. 7 shows the average number of tones transmitted during contention session versus p for different lengths of contention period. As can be seen from Fig. 7, BM-BIN is more energy-efficient group splitting strategy than BIN even with the minimum-length contention period ($M = 4$ CRs). As the length of contention period increases, the energy-efficiency of BM-BIN improves and gradually approaches that of BM strategy. However, it should be noted that any increase of the number of CRs comes at the expense of increased message delay and reduced throughput due to prolonged duration of TDMA slots.

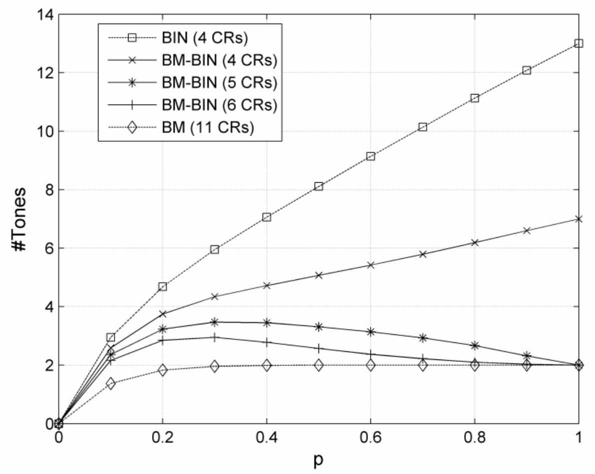


Fig. 7 The average number of generated tones per contention session in transmitter group of size 12 versus transmission probability for different group splitting algorithms

In a network with maximum node degree of δ_{max}, the BM-BIN algorithm can be configured with the contention period of length in the range from $\lceil \log_2 \delta_{max} \rceil$ up to $\delta_{max} - 1$. The ability of BM-BIN to utilize the full length of contention period is important due to following two reasons. First, it allows to tradeoff communication performances for energy-efficiency. Second, it is beneficial in networks with non-uniform node deployment. Even if the contention period is configured with the minimum length of $\lceil \log_2 \delta_{max} \rceil$, a substantial saving in contention energy can be achieved in sparse areas of the network. In these areas, BM-BIN will operate in BM or near-BM mode due to small size of transmitter groups, consuming much less energy than in the dense areas where it must work in near-BIN mode.

3.2.4. Fairness

It is clear from the previous section that the nodes in a transmitter group assigned with small competition number have the higher priority to access the channel. Hence, in order to maintain the fairness in channel access, the assignment of CNs within each transmitter group in the network is shifted at the beginning of each frame. In other words, if a node $u \in N_1(v)$ is assigned a competition number of value i for slot $S(v)$ in the current frame, the node u will be assigned competition number of value $(i + 1) \bmod \delta(v)$ for the same slot in the next frame.

3.2.5. Optimization

The active participation of receiver nodes in the tone-based contention resolution process opens up the possibility to avoid the transmission/detection of stretched preamble during data transfer period. As explained in section 2.3.1, the purpose of stretched preamble is to prevent a long idle listening of the receiver node when there is no data message transmission. However, if the receiver node has already detected an announcement-tone during the contention period, it does not need to detect the presence of stretched preamble because it already knows to expect a transmission during the data transfer period. Also, the transmitter node that wins the competition does not need to transmit a stretched preamble if it has already transmitted an announcement-tone. The only transmitter node that can win the competition without any tone transmission is the node with the highest competition number in the transmitter group. Having the highest competition number, this node will always be included into SC group, and thus it will not transmit announcement-tone in any CR. Of course, to win the competition, this node must be the only intended sender in the transmitter group. Therefore, the rules for transmitting/detecting stretched preamble are: (a) the transmitter node that wins the competition transmits stretched preamble if it is assigned the highest competition number in the transmitter group; (b) the receiver node detects the presence of stretched preamble if it had not detected any announcement-tone during the contention period.

4. SIMULATIONS

In this section, we analyze the performance of RD-TDMA/TONE protocol by simulation in a custom event-driven simulator. The performance of RD-TDMA/TONE is compared with two other TDMA-based schemes, i.e. TD-TDMA and RD-TDMA/CSMA, which were discussed in section 2. Our evaluations are based on the simulation of a network topology composed of 200 nodes uniformly and randomly distributed within a circular area of radius 100 m. In all simulations, the transmission range of all nodes is set to 12.8 m which results in a network topology with the distribution of node degrees as shown in Fig. 8. As can be seen, the network is characterized by the minimum and the maximum node degrees of $\delta_{min} = 4$ and $\delta_{max} = 16$, respectively. The average node degree of the network is $\delta_{avr} = 10.3$. With such node degree distribution, a TDMA frame of at least 25 slots is required to accomplish a 2-hop exclusive slot assignment, and the contention period of RD-TDMA/TONE protocol can be configured with the length in the range from $M = 4$ up to $M = 16$.

We assume that the transmission channel is error-free and a reception failure is only due to message collisions. The values of parameters used for simulations are as shown in Table 1. For radio parameters, we used CC1100 radio transceiver as the hardware reference [1]. The channel sampling adopts a low-power listening approach, and the energy consumption of a single channel sampling operation is 17.3 μJ [4, 7]. In this study, we investigate the performance of TDMA-based protocols in terms of throughput and energy-efficiency under varying traffic load. It has been assumed that nodes generate data messages following a Poisson distribution.

Table 1 Parameters used in simulations

Radio parameters:	
Data rate	19.2 kbps
Power in transmitting	50.7 mW
Power in receiving	49.2 mW
Energy per channel sampling	17.4 μJ
Time to sample channel (T_{CS})	0.3 ms
MAC parameters:	
Preamble length	6 bytes
Message overhead (header + CRC)	10 bytes
ACK packet size (CSMA)	16 bytes
Contention period (CSMA)	8 (contention slots)
Contention slot duration (CSMA)	0.62 ms
Maximum back-off interval (CSMA)	16 frames
Clock drift (Θ)	1 ms

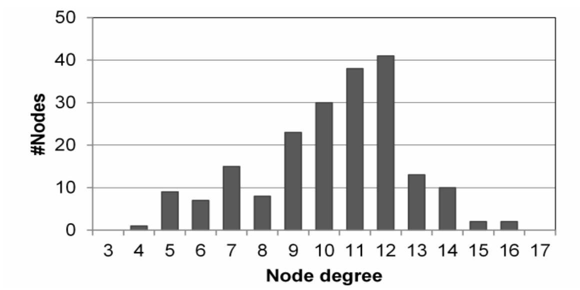


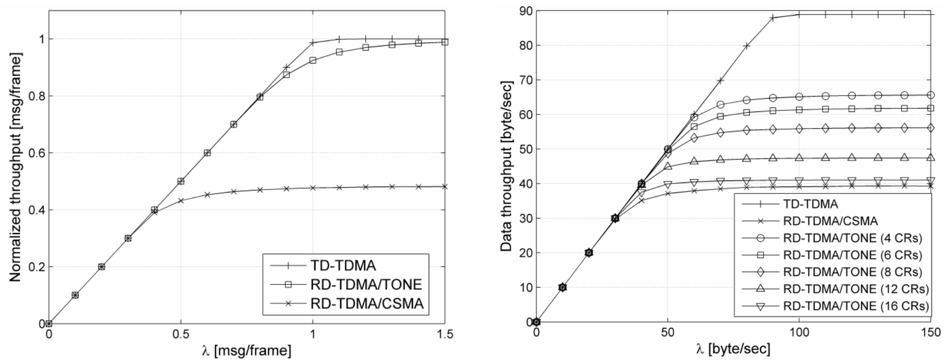
Fig. 8 Distribution of node degree in simulated network with transmission range of 12.8m

4.1. Throughput

The throughput is evaluated in terms of the following two metrics: the normalized throughput, and the data throughput. We now explain these metrics. Suppose the simulation last for N_{fr} TDMA frames of duration T_{fr} seconds, and the network is composed of N_{nodes} nodes. Suppose also that the total number of successfully received data messages is N_{msg}, and each message contains L_{msg} bytes of payload data. The *normalized throughput* (NT) is defined as: N_{msg} / ($N_{nodes}\,N_{fr}$). The NT is expressed in units of messages per frame, and it shows the average number of data messages received by a node during one frame. The *data throughput* (DT) is defined as: ($N_{msg}\,L_{msg}$) / ($N_{nodes}\,N_{fr}\,T_{fr}$). The DT is expressed in units of bytes per second, and it signifies the average number of data bytes received by a node in one second.

Fig. 9(a) depicts the normalized throughput versus message arrival rate for different TDMA schemes. Note that the NT suggests how efficiently nodes can use allocated bandwidth depending on traffic load and it is independent of the duration of frame. In the analyzed class of TDMA-based protocols, the maximum NT is limited to 1 *msg* /*frame* due to restriction that every node can own exactly one slot in the frame. Having a property of being collision-free, both TD-TDMA and RD-TDMA/TONE protocol demonstrates almost-ideal throughput characteristics, that is, when the traffic load increases, the NT increases linearly and finally saturates at the level of 1 *msg /frame*. On the other hand, the NT of RD-TDMA/CSMA saturates at 0.481 *msg /frame* due to combined effect of hidden and exposed terminals, even with back-off mechanism implemented. This results show that replacing CSMA-based contention resolution mechanism with TONE leads to the significant improvements of RD-TDMA protocol's performances in terms of NT.

Fig. 9(b) shows the data throughput of TDMA-based protocols. In contrast to NT, the DT takes into account both the duration of frame and the length of data messages. Therefore, this metric additionally capture the influence of time overhead due to contention and message acknowledgement. In this simulation, we assume that the data messages are of length of 256 bytes. The TD-TDMA has the highest DT among all other protocol variants due to the shortest slot, which consists of data transfer period, only. The DT of the RD-TDMA/TONE protocol with the contention period of minimum length (i.e. 4 CRs) is lower for about 35% with respect to that of TD-TDMA protocol. The DT of RD-TDMA/TONE protocol further decreases with increasing the number of CRs, and drops to the level of DT of RD-TDMA/CSMA protocol when it is configured with the maximum-length contention period (i.e. 16 CRs).



(a) (b)

Fig. 9 Data throughput of TDMA-based protocols under varying traffic load: (a) normalized throughput and (b) data throughput

4.2. Energy efficiency

The energy efficiency of TDMA-based protocols is evaluated by using the metric of *energy overhead per message* (EOM), which measures the total energy overhead averaged over all successfully received messages: $(E_{tot} - N_{msg}E_{msg}) / N_{msg}$. The total overhead energy includes the energy spent on collisions, overhearing, contention, channel sampling and idle listening. It is calculated as a difference between the total energy consumed by all nodes during simulation (E_{tot}) and the amount of energy needed to transfer one data message between a pair of transmitter and receiver nodes under the interference-free medium condition and the perfect time synchronization (E_{msg}) multiplied by N_{msg}. The value of E_{msg} is estimated on the basis of radio parameters given in Table 1 by assuming the format of data message presented in Fig. 2.

Fig. 10 shows the EOM versus message arrival rate for different TDMA-based schemes. Due to the possibility of collisions, the EOM of RD-TDMA/CSMA depends on the length of data messages. In this simulation, we assume that the data messages are of length of 64 bytes. The EOM of both TD-TDMA and RD-TDMA/TONE protocol is independent of message length since both protocols provide a collision-free message transmission.

The EOM of different protocols is influences by different sets of energy overhead sources. Dominant sources of energy wastage are: overhearing (in TD-TDMA), collisions (in RD-TDMA/CSMA), and contention, that is, tone transmissions (in RD-TDMA/TONE). Among the secondary overhead sources, the most important is the channel sampling, which is used in all protocol variants for tone (and/or stretched preamble) detection. In fact, the shape of each plot in Fig. 10 is determined by relative contribution to the EOM of the channel sampling and the source of energy overhead that is dominant in particular protocol. The channel sampling dominates at low traffic load, while the main overhead sources dominate at medium and high traffic loads.

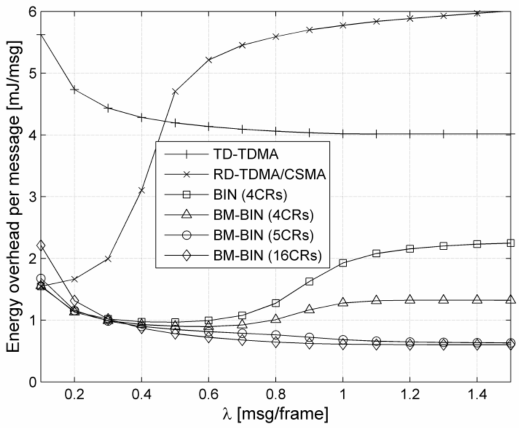


Fig. 10 Energy overhead per message of TDMA-based protocols under varying traffic load

Even though individual channel sampling operations require a small amount of energy (order of few tents of micro joules), their joint contribution to the EOM is not negligible, especially at low traffic load. In fact, the channel sampling is the only source of energy loss in the absence of traffic. In TD-TDMA protocol, a node v must sample the channel in all of slots assigned to its neighbors, that is, $\delta(v)$ times per frame. In RD-TDMA/TONE, a receiver node must sample the channel in every CR of the contention period plus once more in the data transfer period, that is, $M + 1$ times per frame. The RD-TDMA/CSMA provides the lowest possible power consumption in the absence of traffic since every node samples the channel only once per frame. In TD-TDMA, the number of channel sampling operations per frame is independent of traffic load. In RD-TDMA protocols, the number of channel samplings increases with the increase of traffic load because not only the receiver node but also intended senders sample the channel. However, with the gradual increase of traffic load, the cost of channel sampling is first amortized by the increasing number of transferred messages, and then it is overwhelmed with other sources of energy wastage.

In TD-TDMA protocol, there is no energy wasted on contention resolution and collisions. However, in this approach, a significant amount of energy is wasted due to message overhearing. A receiver node can recognize whether it is an intended receiver of a message only after it receives the message header. Hence, every message transferred from node u to node v is partially received by all nodes in $N_1(u) \setminus \{v\}$. Note that, the part of EOM attributed to overhearing is independent of traffic load. As can be seen in Fig. 10, although the EOM of TD-TDMA protocol improves as traffic load increases due to the increased number of transferred messages, its retains relatively high value of 4 mJ/*msg* at maximum load.

The main benefit of RD-TDMA schemes is that nodes only wake up during their own slots to check if there is any incoming message for them. Compared to TD-TDMA scheme, the receiver-driven approach completely eliminates the energy-waste due to overhearing. In addition, when coupled with the CSMA-based contention resolution mechanism, the RD-TDMA scheme provides ultra-low power consumption in the absence of traffic (one channel sampling per frame). However, in RD-TDMA/CSMA protocol, with an increase in traffic load, message collisions become a serious problem. At the receiver side, a collision of data messages leads to idle listening of the receiver node since it cannot distinguish a collision from background noise. At the transmitter side, the cost of collision is much higher since the transmitter node can only detect collision after transmitting entire data message and not receiving ACK. Also, ACK packets are considered as energy overhead since they are related to collision avoidance scheme. At low traffic load, the chance for a collision is small, which allows the CSMA to keep relatively low EOM, as can be seen in Fig. 10. However, as the traffic load approaches the maximum throughput of CSMA, collisions become more often, and EOM rises sharply. When the load exceeds the maximum throughput, EOM saturates at the level of about 6 mJ/*msg*. The high EOM and low throughput makes CSMA not suitable for high traffic load conditions.

From Fig. 10 we can see that the RD-TDMA/TONE shows by far the best EOM performance. This observation holds even when TONE is configured with the minimum-length contention period when it consumes the most energy. For example, at the maximum traffic load, RD-TDMA/TONE with BM-BIN group splitting algorithm and the length of contention period of $M = 4$ CRs has the EOM of 1.3 mJ/*msg*, which is 3 times lower than TD-TDMA, and 4.5 times lower than RD-TDMA/CSMA. In addition, at high traffic load, the EOM of RD-TDMA/TONE with BM-BIN is 42% lower than that of RD-TDMA/TONE with the BIN group splitting algorithm. In Fig. 10 we can also see how the extension of contention period further improves the energy-efficiency of BM-BIN group splitting strategy. With only one CR added to the contention period, the EOM of RD-TDMA/TONE at maximum load is halved. However, any further increase of the convention period has less significant effect on EOM. With $M = 8$ CRs, the EOM at maximum traffic load drops to 0.6 mJ/*msg*, and then it practically keeps this value up to $M = 16$ (correspond to BM group splitting algorithm).

The simulation results presented in Fig. 10 suggest that in the context of TDMA-based protocols, it is more energy-efficient to use the receiver-driven scheme and to transmit a few tones in every slot to resolve contentions in a collision-free manner (as in RD-TDMA/TONE), than to eliminate contention statically, i.e. via conflict-free slot assignment, but constantly losing the energy on message overhearing (as in TD-TDMA). Also, according to Fig. 10, it is wise to spend some more energy in contention and prevent the collisions completely (as in RD-TDMA/TONE), than to relay on a simple contention resolution mechanism but waste the energy (and bandwidth) on collisions and message retransmissions (as in RD-TDMA/CSMA).

5. Conclusions

In this paper, we have presented a collision-free contention resolution mechanism, that we named TONE, specifically designed for receiver-driven TDMA-based WSNs, where each node is assigned one reception slot in TDMA frame unique within 2-hop range. We have presented a detailed design of the contention resolution procedure, which relies on a new group splitting algorithm that enables contention to be resolved in a fixed number of elimination rounds with minimal energy. The key feature of TONE, that is collision-freedom, is achieved by means of a two-phase tone-based signaling scheme which is used as a means of interaction among contending nodes. Our simulation results show that the performances of receiver-driven TDMA protocol significantly improve when the commonly used CSMA-based contention resolution mechanism is replaced with TONE. The performance advantage of TONE is particularly evident under high traffic load conditions, when CSMA has to deal with collisions and message retransmissions. Another important result of our simulation study is that the receiver-driven TDMA scheme with TONE contention resolution mechanism outperforms the transmitter-driven TDMA scheme in terms of energy-efficiency independently of traffic load. For the future work we plan to extend and adapt TONE for use in conjunction with other MAC schemes, such as MAC protocols with common active period.

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