Reduced-Frame TDMA Protocols for Wireless Sensor Networks

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Abstract:

Time-Division Multiple-Access (TDMA) is a common MAC paradigm in wireless sensor networks. However, in its traditional form, the TDMA-based protocols suffer from low channel utilization and high message delay because of a long frame length needed to provide collision-free transmissions, which is particularly damaging in dense wireless sensor networks. In this paper, we investigate the performance and the energy efficiency of a class of TDMA-based protocols, called reduced-frame TDMA, where every TDMA slot is augmented with a short time period dedicated for CSMA-based contention resolution mechanism. Because of their ability to dynamically resolve collisions caused by conflicting slot assignments, the reduced-frame TDMA protocols can be configured with any frame length, independently of node density. In addition, we present distributed heuristic slot assignment algorithm that minimizes inter-slot interference in the presence of limited number of slots per frame. The simulation results indicate that the reduced-frame TDMA protocols significantly reduce the message delay and increase the maximum throughput without incurring significant penalty in energy efficiency compared to the traditional TDMA scheme.

Key words:

MAC protocols, wireless sensor networks, TDMA protocols, TDMA slots scheduling.

1. Introduction

A wireless sensor networks (WSN) is a distributed system composed of a number of small, low-cost and battery-powered sensor nodes equipped with low-power radio. The common vision is to create a large WSN through *ad-hoc* deployment of hundreds or thousands of such tiny devices able to collect a useful information from a variety of environment, 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][2][3].

From a media access perspective, a WSN is characterized by the fact that all nodes share the same transmission channel. 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) mechanism is a key component to ensure the successful operation of WSNs and it has obtained intensive research attention [4][5][6][7]. A MAC protocol decides when nodes could access the shared medium in order to transmit their data and 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 overall network 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 is also affected by overhearing and idle listening. 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.

In the literature, time division multiple access (TDMA) and contention-based access are two major medium access approaches in WSNs. Contention-based MAC protocols prevent multiple nodes within the interference range from concurrently accessing the medium. In order to achieve low power operation, these protocols incorporate some form of duty cycling mechanism, by turning radio off part of the time. One important approach is to let nodes synchronize their active/sleep periods such that neighboring nodes are awake at the same time. 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 contention period, while others go back to sleep until the next active period. For instance, S-MAC 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 [8]. Although RTS/CTS handshake mechanism can avoid most of potential collisions, it incurs high control overhead because data messages in WSNs usually have a small size compared to those in other networks. Low-power listening (LPL) is another contention-based strategy that fulfills the low-power requirements in contention-based MAC protocols [9][10]. The basic idea of this strategy is that prior to data transmission, a sender transmits a preamble lasting at least as long as the receiver's sleep period. The receiver periodically wakes up for a short time to sample the medium, thereby limiting idle listening. If a preamble is detected, the receiver stays awake to receive the data, otherwise it goes back to sleep. A key advantage of LPL protocols is that the sender and receiver can be completely decoupled in their own duty cycles. However, these protocols suffer from the overhearing problem, since the long preamble also wakes up nodes who are not the intended receivers of a message. The SCP-MAC protocol synchronizes the channel polling times of all neighboring nodes, thus preventing nodes from sending long preambles [11]. In this approach, senders use CSMA to resolve contention before receivers poll the channel. The drawback of SCP-MAC is that communication is grouped at the beginning of active period, increasing the contention and raising the chances on collisions, hence, limiting its dynamic range to low traffic conditions only.

In contrast to the contention-based protocols, TDMA-based solutions establish a schedule where each node is assigned one (or possibly multiple) slots within a network-wide common frame. By letting nodes turn-off their radios alternately, rather than simultaneously, TDMA-based protocols significantly reduce communication grouping. In this way, collisions are reduced and better energy savings is achieved. Pure TDMA protocols, like [12][13][14], assign each node a fixed slot to transmit one message in each frame. Nodes transmit on their assigned slots and wake up to receive in the slots of their neighbors. To prevent that the transmissions 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. This collision-free TDMA scheme is attractive for high data rate WSNs because it is energy efficient and may provide higher throughput than contention-based protocols, especially under heavy traffic load. However, the 2-hop exclusive slot assignment usually requires a frame with a large number of slots. This may lead to a significant message delay and a pour channel utilization, which makes the pure TDMA approach unsuitable for densely-deployed WSNs. Also, overhearing is inevitable in the transmitter-driven TDMA protocols and can be a dominant factor of energy waste when traffic load is heavy and node density is high. In addition, changing the frame length and the slot schedule dynamically according to the unpredictable variations of network topology is usually hard for pure TDMA-based schemes.

In order to cope with the drawbacks of both contention-based and TDMA-based MAC protocols, hybrid TDMA/CSMA solutions have been proposed. Z-MAC [15] is a hybrid TDMA/CSMA protocol where a certain time period at the beginning of every TDMA slot is reserved for contention resolution. In order to improve channel utilization, Z-MAC allows non-owners of a slot to contend for the slot if it is not being used by its owner. This concept is implemented by adjusting the initial contention window size in such a way that the owner is always given chances to transmit earlier than non-owners. In that way, Z-MAC acts like a contention-based protocol under low traffic conditions and a transmitter-driven TDMA-based protocol under high traffic conditions. However, in Z-MAC all the nodes have to constantly perform carrier-sensing in all slots, in order to check the incoming data, which increases energy consumption under low traffic load. Also, overhearing remains a problem of such an approach. Other variations on hybrid TDMA/CSMA scheme are also possible. Rather than scheduling slots for node transmissions, slots may be assigned for reception with CSMA-based contention resolution mechanism within each slot [16][17]. This *receiver-driven* TDMA model can be more energy-efficient under light traffic conditions, because each node samples the medium only in its own receive time slots. Moreover, this setup minimizes overhearing, which makes it suitable for dense networks. However, since the CSMA-based contention resolution scheme is prone to the hidden terminal problem, the receiver-driven TDMA protocols have difficulties in handling bursty traffic.

A common advantage of hybrid TDMA/CSMA approaches stemming from the embedded contention-resolution mechanism is that they can offer flexibility when choosing the frame length and assigning slots to nodes. Unlike pure transmitter-driven TDMA protocols, which do not include any contention resolution mechanism, and thus have to rely on 2-hop exclusive slot assignment, the hybrid TDMA/CSMA protocols can tolerate slot reuse within 2-hop neighborhood, although with some penalty in energy efficiency associated with increased contention level. As a consequence, the frame length is no more determined by the need for 2-hop exclusive slot ownership, but it can be reduced in order to improve some performance metrics, such as message delay and throughput. For instance, Crankshaft [16] simply allocates receivers to slots based on node ID (modulo frame length), that is, practically at random. The frame length is configured at compile time and it is independent on the node density. However, Crankshaft does not suggest how to choose the frame length and it only proposes the use of a random slot assignment scheme.

In this paper, we focus on analyzing the efficiency of reduced-frame TDMA protocols in terms of the performance and the energy consumption. Rather than presenting a detailed implementation of a full-featured MAC protocol, we explore the benefits of a model for TDMA-based design that exploits the possibility of adjusting the frame length in MAC protocols based on hybrid TDMA/CSMA channel access mechanism. For this purpose, we extend the principle of the reduced-frame receiver-driven TDMA, introduced in Crankshaft, to transmitter-driven TDMA protocols, also. The advantage of having a reduced TDMA frame is clear: a smaller frame length will reduce delay in distributing data because a greater number of messages can be transmitted in a fixed amount of time. On the other hand, a small number of available slots may increase the level of contention during individual slots which in turn may annul the benefits of shorten frame period. Thus, the question is: what is the length of TDMA frame which allows the best network performance and what the price is (in terms of energy overhead). The second problem we are faced with is how to share a limited number of available slots among nodes in a fashion that prevents inter-slot interference as much as possible. In this paper, we present a new distributed heuristic slot assignment algorithm and compare its performance to a random slot-assignment scheme.

The remainder of the paper is organized as follows. In Section 2, we introduce a classification of TDMA-based schemes with respect to the frame length and the type of slot ownership, and present the channel access mechanisms for both pure TDMA and hybrid TDMA/CSMA protocols. Also, we discuss in more detail the general characteristics of full-frame TDMA protocols, that is, TDMA protocols that rely on 2-hop exclusive slot ownership. Section 3 deals with the reduced-frame TDMA model. We give an analysis of various types of conflicts that arise in both the receiver-driven and the transmitter driven reduced-frame TDMA schemes, and present our proposed heuristic algorithm for slot assignment. The performance of reduced-frame TDMA protocols is evaluated in Section 4. Section 5 concludes the paper.

2. TDMA-based MAC Protocols

2.1. System Model

A WSN is composed of a set V of nodes, and each node v in the network is assigned a unique identifier $ID(v) \in \{1,...,n\}$. Nodes are equipped with low-power radios, so each node 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, that is, $u \in N_1(v)\, iff\; v \in N_1(u)$. Two nodes are denoted as *2-hop-neighbors*, if the shortest communication path, by means of shortest hop count, is equal to 2. The set of node *v*'s 2-hop neighbors is denoted as $N_2(v)$. The *1-hop neighborhood* and *2-hop neighborhood* of node *v* are denoted by $N_{\le 1}(v)$ and $N_{\le 2}(v)$, respectively. $N_{\le 1}(v)$ is the set of nodes formed by node *v* and node *v*'s 1-hop neighbors (i.e., $N_{\le 1}(v) = v \cup N_1(v)$). $N_{\le 2}(v)$ is the set of nodes formed by node *v* and *v*'s 1-hop and 2-hop neighbors (i.e., $N_{\le 21}(v) = v \cup N_1(v) \cup N_2(v)$).

A single frequency channel is shared spatially by all nodes in WSN, and communication is half-duplex: node *v* cannot send one message and receive another simultaneously. All node clocks are synchronized to a common global time [18], and time is slotted. Slots of constant duration are grouped into *TDMA frame* (or shortly the frame), of length *L*, and numbered. Each data message requires one slot for transmission. Nodes access the channel according to the predetermined TDMA schedule that specifies in details which nodes are to send and which are to receive in each slot of the frame. Because node's activities within the frame are pre-scheduled, it is possible for node to sleep during slots when it is not expected to transmit or receive any message.

2.2. Classification of TDMA protocols

Two types of TDMA scheduling problems have been investigated in the literature: *node scheduling* and *link scheduling* [19]. 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 $S(v) \in \{1,...,L\}$ in the frame. We said that node *v* owns slot $S(v)$. 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.

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. The spatial reuse of slots creates so called *slot assignment (SA) conflicts* between nodes. We define a *k-hop SA conflict* as one in which a pair of nodes at hop distance of *k* is assigned the same slot. Presence of *k*-hop SA conflicts, where $k \le 2$, causes radio-interference, which may lead to message collisions if not properly handled. Slot assignment is defined to be a 2-hop conflict-free if slot $S(v)$ is not reused in $N_{\le 2}(v)$. We refer to TDMA with 2-hop conflict-free SA as *Full-Frame TDMA* (FF-TDMA), as opposite to *Reduced-Frame TDMA* (RF-TDMA) wherein the 2-hop conflict-free SA is not guaranteed.

Taking into account types of slot ownership (transmitter- vs. receiver-driven) and the 2-hop SA constraint (full- vs. reduced-frame), we classify TDMA-based protocols into four categories

(Figure 1). Protocols in each category are denoted as XX-YY-TDMA, where XX $\in$ {FF, RF}, and YY $\in$ {TD, RD}. FF-TD-TDMA protocol (i.e. the full-frame transmitter-driven TDMA) corresponds to the traditional pure TDMA, which is the only protocol in the family which provides interference-free transmissions. The remaining three protocols are subjected to radio-interference caused by either the receiver-driven slot ownership type or a shortened length of frame, which cannot accommodate 2-hop conflict-free SA. To cope with radio-interference, these three TDMA protocol types need to be augmented with a collision-avoidance mechanism, such as CSMA that senses the medium before starting a transmission. These protocols are usually classified as hybrid TDMA/CSMA protocols.

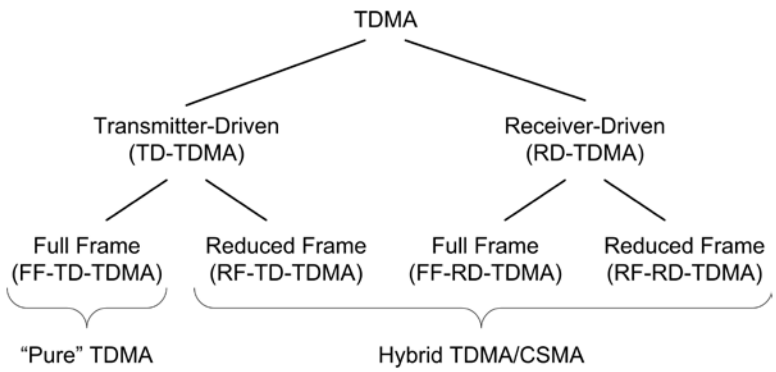

Figure 1 Classification of TDMA-based protocols.

2.3. Channel Access Mechanisms

Pure TDMA and hybrid TDMA/CSMA protocols require different mechanisms to access the channel in the reserved slots. With pure TDMA scheme (i.e. FF-TD-TDMA), the nodes access the channel without having to content for the medium or having to deal with collisions. This greatly simplifies the design of channel access mechanism. To deal with potential collisions, hybrid TDMA/CSMA schemes need a more sophisticated channel access mechanism, which includes contention-resolution procedure at the beginning of each slot. This subsection describes in details both channel access mechanisms.

Channel access for pure TDMA protocol. Figure 2 illustrates the channel access activities for exchanging a data message between a pair of transmitter and receiver nodes utilizing FF-TD-TDMA protocol. In order to avoid unnecessary long idle listening when the slot owner does not have data to send, the receiving nodes briefly sample the channel at the beginning of slot, just long enough to detect a signal above the noise threshold. If there is no message to be sent, receivers will detect a clear channel and go to sleep immediately. Otherwise, if the channel is determined to be busy, receivers stay awake to receive the incoming data message. To avoid unnecessary overhearing of complete data messages, a 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. After successful reception of data message, the destination node may return an optional acknowledgment (ACK) message. To guard against a possible drift in synchronization, the slot owner adds a so called stretched preamble before the data message [20]. The length of preamble, T_p, depends on the tolerance of clock (θ), the periodicity of maintaining synchronization (t_{sync}), and the time needed for channel sampling (T_{cs}):

$$T_p = 4\theta t_{sync} + T_{cs}$$

Note that the computed value of T_p ensures the overlapping of stretched preamble with the channel sampling at the maximum drift between sender and receiver clocks.

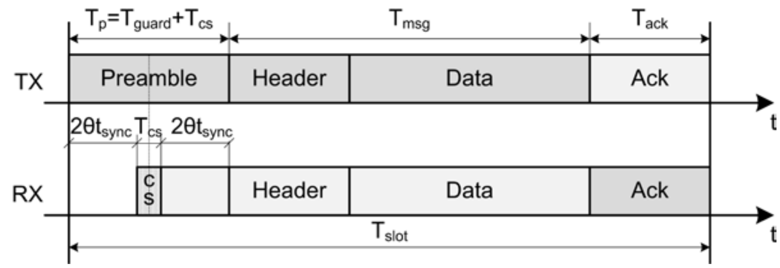

Figure 2. Channel access scheme of full-frame transmitter-driven TDMA protocol.

Channel access for hybrid TDMA/CSMA protocols. With hybrid TDMA/CSMA protocols, a node may receive signals from two or more different senders at the same slot. If at least two of messages are destined to that receiver, this is called a collision. For example, if nodes $a \in N_{\le 1}(v)$ and $b \in N_{\le 1}(v)$ both transmit their messages at the same slot, then v will not correctly receive any of them. In general, there are three types of potential collisions in a multi-hop wireless network (Figure 3) [21]. Type_1 collision occurs when an intended receiver of particular transmission is also within the transmission range of another transmission intended for other nodes. Type_2 collision is due to multiple nodes attempting to send data messages simultaneously to a single node. Type_3 collision happens when an intended receiver of particular transmission simultaneously transmits to another node (half-duplex constraint).

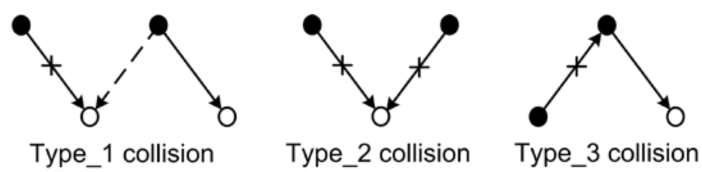

Figure 3. Types of collisions in multi-hop wireless networks.

To deal with potential collision in hybrid TDMA/CSMA protocols, we assume that transmitting nodes perform a simple CSMA-based contention-resolution procedure at the beginning of each slot. As illustrated in Figure 4, every TDMA slot is extended with a contention window (T_{CW}) which is divided into many short contention slots. A node that wants to transmit in a particular TDMA slot randomly selects a slot within the contention window to perform channel sampling. An idle channel allows the node to proceed, by sending the wakeup tone that covers the rest of contention window until the end of time reserved for stretched preamble. Otherwise, if the node detects a busy channel (which happens when another node first started transmitting the wakeup tone), then it gives up its attempt to transmit and switches to the receiving mode in order to avoid a potential Type_3 collision. Therefore, only the contention winner can transmit a message to its destination node, while others postpone their transmissions for some later time. On the other hand, a node that is scheduled to receive in the slot, acts as in the pure TDMA approach. To prevent the idle listening of receiving node in the case of collision, the node stops the reception if it does not receive the message header for timeout period of T_{h_tout} after channel sampling. After the successful reception of a message, the receiver node immediately responds with an acknowledgement (ACK) packet within the same slot. The sender's only indication of a collision is the absence of ACK from the intended receiver.

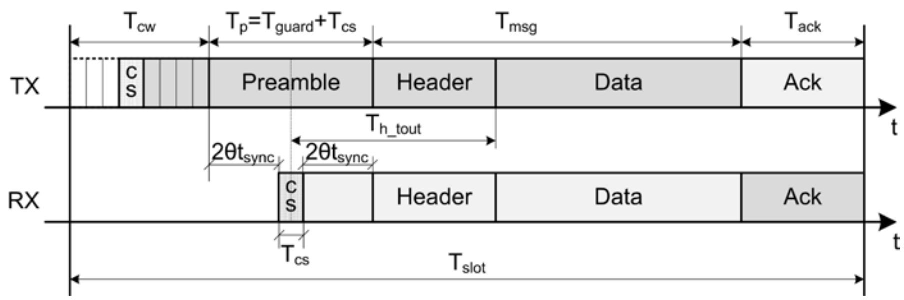

Figure 4. Channel access scheme of hybrid TDMA/CSMA protocols.

The main advantage of CSMA-based contention-resolution method is its simplicity. However, this method suffers from the well-known problem of exposed and hidden terminals, which may lead to inefficient bandwidth utilization. The exposed-terminal problem occurs when a node that loses competition for the medium refrains from transmission even though it would not have interfered with the transmission of winning node. In addition, CSMA is limited only to contention resolution between neighboring sender nodes. As a consequence, it can avoid neither Type_1 nor Type_2 collisions when sender nodes are outside radio range of each other, that is, the hidden terminal effect. Therefore, 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 in the same TDMA slot of frame. Retransmissions are scheduled according to the binary exponential back-off strategy. To each TDMA slot *s*, an integer variable $BI(s) \geq 1$ is associated. Whenever the sender node experiences a collision in slot *s*, it first doubles $BI(s)$ (up to maximum value of BI_{max}) and then chooses the back-off delay, randomly and uniformly, from interval [1, $BI(s)$]. When an ACK packet is received in slot *s*, the sender node removes acknowledged data message from its buffer and resets the back-off interval to $BI(s) = 1$. In general, the back-off scheme reduces the probability of collisions when the traffic load is high, while minimizing message delay when the load is low.

2.4. Full-Frame TDMA

Most existing designs of TDMA-based MAC protocols are founded on 2-hop conflict-free SA. In FF-TD-TDMA scheme, this approach maximizes the network throughput at high traffic load. On the other hand, in FF-RD-TDMA scheme, it minimizes energy usage at low traffic load. Consider a 2-hop conflict-free transmitter-driven SA shown in Figure 5(a). In this figure, the dark dots, *u* and *v*, represent nodes that share the same transmitting slot. Because these nodes do not have common neighbors, the collision in a case of their concurrent transmissions cannot occur. Such a scheme is thus able to reduce energy wasted by contention and collisions. Also, FF-TD-TDMA provides guaranteed throughput for all nodes in the network since each node can utilize its slot for message transmission at any frame, no matter what are the actual traffic conditions. Therefore, FF-TD-TDMA is attractive for high data rate WSNs. However, each node must wake up in every slot owned by one of its neighbors in order not to miss incoming messages. This results in increased energy wastage due to channel sampling, even in the absence of traffic. Additionally, listening to all of slots assigned to neighbors leads to overhearing. Note that this kind of energy overheads is the characteristic of any transmitter-driven TDMA scheme, and is particularly evident in dense networks.

In FF-RD-TDMA, each node is assigned a 2-hop exclusive slot to receive messages; the neighbors that have messages to deliver to it should use this slot to send (Figure 5(b)). FF-RD-TDMA is more energy efficient then FF-RD-TDMA under light traffic conditions, because each node checks for channel activity only in its own slot, that is, once per frame. Also, 2-hop conflict-free SA completely avoids the overhearing of unrelated messages, because the intended receiver of every transmission is the only active receiver in the transmitter's neighborhood. However, RD-FF-TDMA cannot provide collision-free access to the medium, even with CSMA implemented. Although 2-hop conflict-free SA helps the CSMA to eliminate most collisions (i.e. all collisions of Type_1 and Type_3), it cannot prevent hidden terminal collisions of Type_2. For example, in Figure 5(b), nodes *a* and *c* form a hidden node pair with respect to node *u*. Thus, any simultaneous message transmissions from *a* and *c* will cause the collision of Type_2 at node *u*. Observe that in the FF-RD-TDMA, any two nodes at the distance of 2-hops form a hidden node pair with respect to any common neighbor. The large number of hidden node pairs may lead to frequent message retransmissions, causing significant performance degradation (in terms of throughput and message delay) and increased energy consumption, especially under heavy traffic conditions. In addition to the hidden, CSMA also introduces the exposed node pairs between nodes with 3-hop conflicting SA. For example, in Figure 5(b), CSMA will prevent nodes *c* and *e* from transmitting at the same slot although their transmissions will not collide at their intended receivers *u* and *v*.

Apart from their above-mentioned individual advantages and disadvantage, both full-frame TDMA schemes share a common problem of choosing the optimal frame length. The frame length determines both the channel access delay (as a node has to wait for its own slot in the frame before it is allowed to send/receive), and the throughput (as a node can send/receive once per frame only). From one hand, if we choose to shorten the frame, with an aim to improve the performance, it may happen that some nodes stay out of the network (due to the inability to assign every node with a 2-hop exclusive slot). From the other hand, the higher number of slots per frame we chose, the more nodes will be able to obtain 2-hop exclusive slots. However, a large length of the frame period leads to a long channel access delay and a low throughput. To allow all nodes to participate in the network, the frame length has to be adapted to the densest area of network, which may lead to over-provisioning (wasted slots) in sparse areas. Full-frame TDMA protocols also suffer from utilization problems during periods of light traffic conditions.

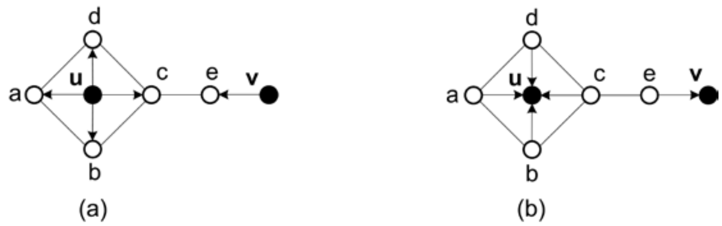

Figure 5. Full-frame TDMA slot assignment: (a) transmitter-driven slot assignment; (b) receiver-driven slot assignment.

3. Reduced-Frame TDMA

In reduced-frame TDMA protocols, there is no constraint on minimum frame length, and nodes are allowed to choose their slots without strictly imposing the 2-hop exclusive slot ownership constraint. Two opposite tendencies affect the performance of reduced-frame TDMA protocols. First, as the frame period is smaller, nodes will have a chance to use their slots more often, leading to a higher throughput and a smaller channel access delay. Second, as the frame length is smaller, slots will be reused within 2-hops more often, leading to a higher level of radio-interference during individual slots. This reduces the throughput and increases the channel access delay. The combined effect determines the overall efficiency of reduced-frame TDMA protocols.

The manifestation of 1-hop and 2-hop SA conflicts in reduced-frame TDMA protocols depends on whether the transmitter-driven or the receiver-driven TDMA model is used. Consider an example of transmitter-driven SA in Figure 6(a), where nodes *u*, *v* and *w* are assigned the same (transmission) slot. There are one 1-hop SA conflict, between *u* and *v*, and one 2-hop SA conflict, between *v* and *w*. Assume $CN(u,v)$ is the set of common neighbors for nodes *u* and *v*, i.e. $CN(u,v) = N_1(u) \cap N_1(v)$, and $EN(u,v)$ is the set of *u*'s exclusive (not shared with *v*) neighbors, i.e. $EN(u,v) = N_1(u) \setminus N_1(v)$. Notice that for nodes *u* and *v* in Figure 6(a) holds: $CN(u,v) = CN(v,u) = \{a,c\}$, $EN(u,v) = \{b\}$, and $EN(v,u) = \{d\}$. If at least one of nodes *u* and *v* intends to transmit to a node $x \in CN(u,v)$, CSMA will prevent collision at *x*. However, if both nodes intend to transmit to their exclusive neighbors (e.g. *u* to *b*, and *v* to *d*), CSMA will cause exposed terminal effect. Thus, in the context of RF-TD-TDMA, the main negative effect of 1-hop SA conflicts is the reduction of node throughput. If a node shares the slot with *n* neighboring nodes, its effective bandwidth will not be 1 transmitted message per frame, as in FF-TD-TDMA, but only $1/(1+n)$ transmitted messages per frame. On the other hand, 2-hop SA conflicts introduce hidden terminal effect between conflicting nodes. For example, concurrent transmissions from nodes v and w in Figure 6(a) will cause collision at node $d \in CN(v,w)$ if at least one of these transmissions is intended for node *d*. Hidden terminals are serious problem in RF-TD-TDMA, because each node condenses all its transmissions within its own slot, which may increase the chance for collisions caused by hidden terminals even under relatively light traffic load.

Figure 6. Reduced-frame TDMA slot assignment: (a) transmitter-driven slot assignment; (b) receiver-driven slot assignment.

As discussed in Section 2.4, the presence of hidden terminals is the main problem in receiver-driven TDMA schemes. The total number of hidden node pairs in a network is determined by the network topology, and does not depend on the length of TDMA frame, that is, it is the same in the full-frame as in the reduced-frame receiver-driven TDMA with any frame length. Therefore, as opposite to RF-TD-TDMA, the SA conflicts in RF-RD-TDMA do not create new hidden node pairs. However, the presence of 1-hop and 2-hop SA conflicts may increase the probability of collision caused by hidden terminals. Specifically, in addition to hidden terminal collisions of Type_2, the presence of 1-hop and 2-hop SA conflicts in RF-RD-TDMA may also cause collisions of Type_1. Moreover, SA conflicts in RF-RD-TDMA create conditions for message overhearing and introduce new exposed node pairs.

The complex interplay of hidden and exposed terminals in RF-RD-TDMA protocols produces various types of radio-interference in the surrounding of nodes subjected to 1- and 2-hop SA conflicts. Consider an example of receiver-driven SA in Figure 6 (b). Again, dark dots represent nodes that share the same (receiving) slot. Node *a*, which is a common neighbor of 1-hop SA conflicting nodes *u* and *v*, now has to use the same slot to send messages to both of them. Node *v* will overhear every message that node *a* send to node *u*, and vice versa. Also, node *b*, which is an exclusive neighbor of *u*, will have to contend for the medium with node *a* more often, that is, not only when *a* intends to send a message to *u*, but also when *a* intend to send a message to *v* (exposed terminal effect). The increased transmission activity of node *a* will also increase the probability of collision with node *c* at node *u* because the messages concurrently sent by *a* and *c* will collide at node *u* not only when *a* transmits to *u* (hidden terminal collision of Type_2), but also when *a* transmits to *v* (hidden terminal collision of Type_1). In addition, exclusive neighbors of nodes *u* and *v*, which are neighbors of each other (e.g. nodes *c* and *d*), will have to contend for the medium in this slot, although their transmissions will never have the same destination (exposed terminal effect). Although the existence of exposed node pairs generally reduces the throughput, it may be beneficial in some circumstances. For example, in a case when nodes *c*, *d* and *e* intend to transmits in the same slot (e.g. *d* and *e* to *v*, and *c* to *u*), and node *c* wins in CSMA contention over its exposed terminal pair *d*, the hidden terminal collision between *d* and *e* at node *u* will be prevented.

The same types of radio-interferences also occur as a result of 2-hop SA conflicts (e.g. between nodes *v* and *w*). However, because the number of common neighbors of two nodes at 2-hop distance is typically smaller then between 1-hop neighbors, the level of additional radio-interference caused by a 2-hop SA conflict is usually less significant than with a 1-hop SA conflict. Therefore, as opposite to RF-TD-TDMA, in the context of RF-RD-TDMA, 1-hop SA conflicts are more undesirable then 2-hop SA conflicts.

3.1. Slot Assignment Algorithm

As opposite to the full-frame TDMA, where SA has to satisfy 2-hop constraint, in the reduced-frame TDMA any SA is correct. No matter how nodes chose their slots, there will never be a node in the network that is permanently hinder to use the medium due to a lack of free slot. The simplest approach to SA problem in the reduced-frame TDMA protocols is therefore to let each node randomly chooses its slot. This significantly simplifies the network set up as well as the procedure to join new nodes to the network [16]. However, assigning slots to nodes without paying attention on how many SA conflicts are created may lead to a significant performance loss. In this section, we present a simple heuristic approach for minimizing the number of 1- and 2-hop SA conflicts generated during slot assignment process.

As in many slot assignment algorithms for wireless TDMA networks [22][12], the idea of our algorithm is that nodes are assigned slots sequentially with the slots chosen in response to slots already assigned in the node's 2-hop neighborhood. At the beginning of our algorithm, the nodes are sorted in terms of non-increasing order of their 2-hop neighborhood size, since nodes with bigger 2-hop neighborhood are more likely to create additional SA conflicts if assigned late. The algorithm then assigns slots to nodes in a way that minimizes the number of SA conflicts with already assigned nodes in 2-hop neighborhood. Based on the analysis of SA conflicts in reduced-frame TDMA protocols, presented in Section 3, we formulate different slot selection heuristics for transmitter- and receiver-driven TDMA variants. In RF-TD-TDMA slot assignment, the primary criterion for selecting a slot for a given node is the minimization of additional 2-hop SA conflicts that will be created between the node and already assigned nodes. The secondary criterion is the reduction of additional 1-hop SA conflicts. The same two criteria, but in the opposite order, are used for RF-RD-TDMA slot assignment.

For the distributed implementation of the SA algorithm, we assume that at the beginning of slot assignment process each node *u* knows the following information about each node $v \in N_{\leq 2}(u)$: *ID*(*v*), and the size of *v*'s 2-hop neighborhood, i.e. $|N_{\leq 2}(v)|$. Node *u* uses this information to compute *priorities* of all nodes in $N_{\leq 2}(u)$. Note that node *u* considers itself as a member of $N_{\leq 2}(u)$. The priority of node *v*, denoted as *h*(*v*), is an integer defined as:

$$h(v) = |N_{\leq 2}(u)| \oplus ID(v),$$

where sign $\oplus$ denotes concatenation operation. Note that the node's ID is included to provide uniqueness of priority values. Thus, for two nodes with equal-sized 2-hop neighborhoods, the node with a larger value of ID will be granted a higher priority. Moreover, during the slot assignment process, each node *u* keeps track on slots usage. Two counters $C_1(s)$, and $C_2(s)$ are associated with each slot $s \in \{1,...,L\}$. $C_1(s)$ and $C_2(s)$ count how many times the slot *s* is assigned to nodes in $N_1(u)$ and $N_2(u)$, respectively. Slot counters are used to compute current *ranks* of slots. For RF-TD-TDMA, the rank of slot *s* is defined as:

$$r_{TD}(s) = (C_2(s) \oplus C_1(s)) \oplus P(s) \quad (1)$$

For RF-RD-TDMA, the rank of slot *s*, is defined as:

$$r_{RD}(s) = (C_1(s) \oplus C_2(s)) \oplus P(s), \quad (2)$$

where ***P*** is a vector containing a random permutation of the integers from 1 to *L*, and it is identical in every node. Note that with *P*(s) included in (1) and (2), the uniqueness of slot ranking is guaranteed.

During the slot-assignment phase, nodes within two hops make slot decisions in the decreasing order of their priorities. Nodes that have the largest priorities among their two hops choose their slots first. If a node's priority is not the largest one among two hops, it waits for slot decisions from other nodes within two hops that have larger priorities. Once a node becomes the highest priority non-assigned node in its 2-hop neighborhood, it is allowed to choose a slot. When a node chooses a slot, it picks the slot with the smallest rank.

4. Simulation results

In this section, we analyze the performance of TDMA-based protocols by simulation in a custom event-driven simulator build in C++. 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. The node density, which is defined as the average size of 1-hop neighborhood in the network, was varied indirectly, by varying radio transmission range. In all simulations, the transmission range of all nodes is set to 10 m which results in node density of 6. At this node density, the full-frame TDMA schemes require a frame of at least $L_{\min}^{FF} = 16$ slots to accomplish a conflict-free SA. We assume that the transmission channel is error-free and a reception failure is due only to message collisions. The values of parameters used for simulations are as shown in Table I. For radio parameters, we used CC1100 radio transceiver as the hardware reference [23].

The channel sampling adopts a low-power listening approach, and the energy consumption of a single channel sampling operation is $17.3\mu J$ [5].

Performance is evaluated in terms of the following metrics: the normalized throughput, the average message delay, and the energy overhead ratio. We now explain these metrics. Suppose the length of simulation time is T_{sim}, and the network is composed of N_{nodes} nodes. Suppose also that the energy consumed by all nodes during simulation is E_{tot}, and the total number of successfully received data messages is M. The *normalized throughput* is defined as $\frac{M}{N_{nodes} \cdot T_{sim}}$. The *average message delay* (AMD) is defined as the average time for a data message to be received by the destination node after it was queued in a source node's buffer. The *energy overhead ratio* (EOR) is defined as: $1 - \frac{E_{tot}}{M \cdot E_{msg}}$, where E_{msg} is the 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. The value of E_{msg} is estimated according to timing diagrams of channel access mechanisms for pure and hybrid TDMA/CSMA schemes given in Section 2.3 assuming radio parameters presented in Table I. We study the performance according to local gossiping traffic model, where all data flows consist of only one hop. Two different traffic load scenarios are considered: the maximum traffic load and the variable traffic load. All graphs presented the following subsections plot the average values over 10000 frame periods and over all sensor nodes in WSN.

Table I. Parameters used in simulations.

Radio parameters:	
Data rate	19.2 kbps
Power in transmitting	93 mW
Power in receiving	46.8 mW
Energy per channel sampling	17.4 μJ
Time to sample channel	0.3 ms
MAC parameters:	
Message payload	64 bytes
Minimal preamble length	6 bytes
Message overhead (header + CRC)	10 bytes
Total data packet size	74 bytes
Total ACK packet size	16 bytes
"Pure" TDMA slot duration	44.3 ms
Hybrid TDMA/CSMA slot duration	49.1 ms
Contention window	8 (contention slots)
Contention slot duration	0.62 ms
Maximum back-off interval	16 frames
Clock drift	1 ms

The analysis includes transmitter-driven and receiver-driven protocols, in both variants: full-frame and reduced-frame. Also, we considered random and heuristic SA for reduced-frame protocols. Note that the reduced-frame receiver-driven TDMA (i.e. RF-RD-TDMA) scheme with random SA is employed in existing protocol Crankshaft, and FF-TD-TDMA is classical TDMA scheme. To best of our knowledge, up to now all other considered TDMA variants have not been used in MAC protocols for WSN.

4.1. Performance under maximum traffic load

In this section, we show results regarding the efficiency of TDMA-based protocols in the case of saturated traffic condition where each node sends a separate continuous stream of data messages to each neighbor. At the beginning of the simulation, buffers of all nodes are initialized with one data message for each neighbor. After a data message is successfully transferred between two adjacent nodes, the source node immediately generates a new data message for the same destination node. The normalized throughput achieved under such traffic pattern is referred to as the *maximum normalized throughput* (MNT).

Figure 7 shows MNT and EOR of transmitter- and receiver-driven TDMA protocols versus frame length for both random and our proposed heuristic SA. Consider first the performance of full-frame TDMA schemes. Note that MNT and EOR achieved with the full-frame TDMA are shown as dashed lines in Figure 7. At maximum traffic load, the available bandwidth of one transferred message per node per frame can be fully utilized only with the FF-TD-TDMA protocol. On the other hand, in FF-RD-TDMA, the presence of hidden node pairs significantly affects the throughput and the energy efficiency, especially at high traffic load. As a consequence, when compared with FF-RD-TDMA, the FF-TD-TDMA scheme achieves almost 100% higher MNT and 20% lower EOR.

Reducing the number of slots per frame below $L_{\min}^{FF}$ leads to an increase of the bandwidth available to nodes. At the same time, the occurrence of SA conflicts generates inter-slot radio-interference, which reduces MNT within individual slots and increases the energy consumption. When the number of slots is close to $L_{\min}^{FF}$, the SA conflicts are rare, and the resulting MNT increases with a decrease of the frame length. On the other hand, when the number of slots is small, the loss of bandwidth due to significantly increased level of radio-interference can no longer be compensated by reducing the frame period. Consequently, a decrease of frame length is associated with both the decrease of MNT and a sharp increase of EOR. As can be seen in Figure 7(a), the RF-TD-TDMA scheme with heuristic SA reaches the maximum MNT of 1.81 *msg*/*s* with $L_{opt}^{RF} = 9$ slots. This result represents a 33.2% improvement in MNT over FF-TD-TDMA with the frame length of $L_{\min}^{FF} = 16$ slots. More importantly, the highest MNT of RF-TD-TDMA is achieved with an increase of the EOR of only 2% with respect to FF-TD-TDMA (see Figure 7(c)). The similar effects of reducing the frame length of transmitter-driven TDMA can also be observed with receiver-driven TDMA protocols, apart from their generally lower MNT and higher EOR (see Figure 7(b)). The maximum MNT achieved in RF-RD-TDMA with heuristic SA requires $L_{opt}^{RF} = 5$ slots. With this frame length, the RF-RD-TDMA achieves 90% higher MNT at the cost of only 2.2% in energy overhead with respect to FF-RD-TDMA (Figure 7(d)).

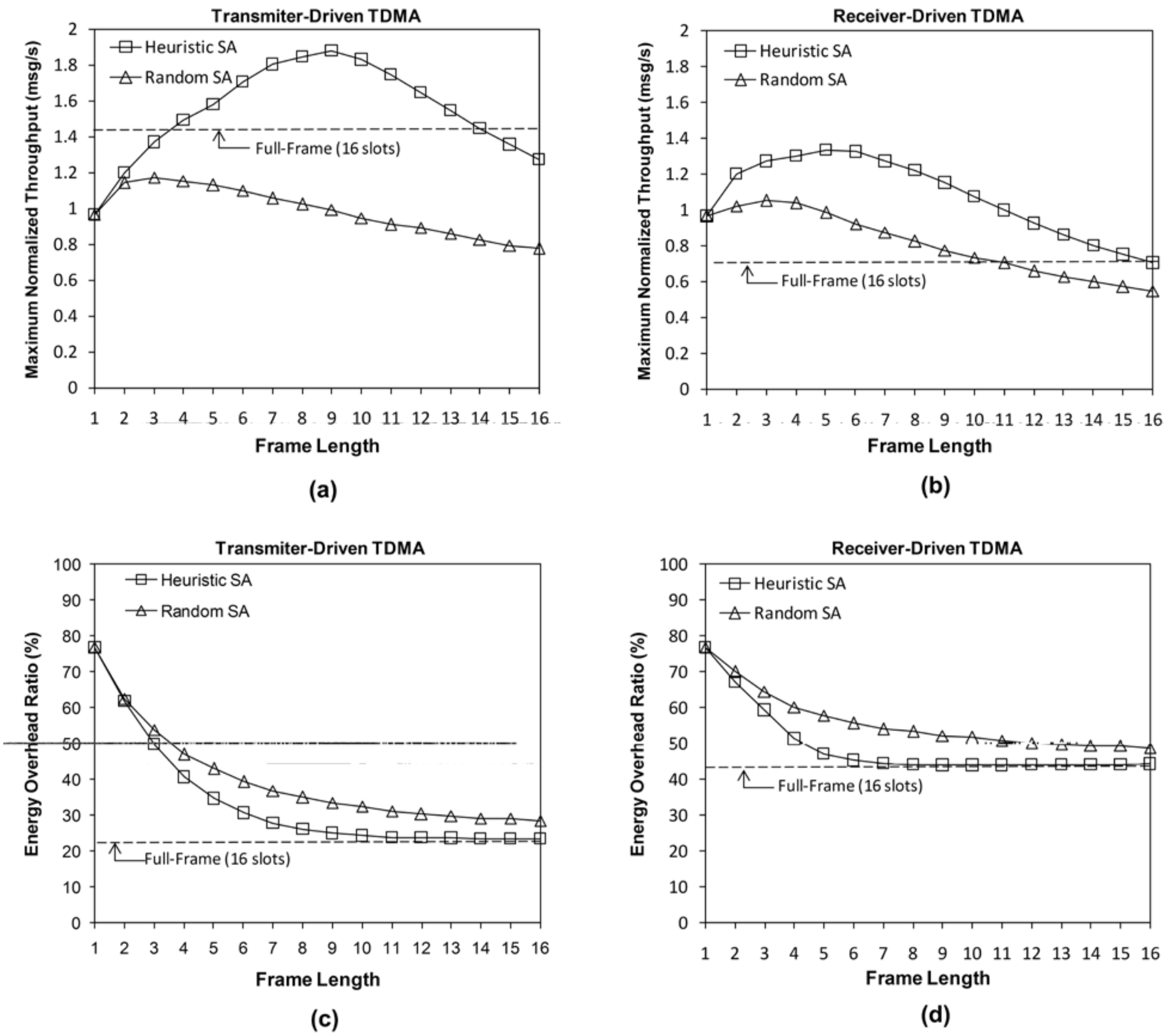

Figure 7. Performancemetrics of TDMA-based protocols undermaximum traffic load: (a) and (b) maximum normalized throughput; (c) and (d) energy overhead ratio.

The results presented in Figure 7 also clearly demonstrate the superior performance of heuristic over random SA. Benefits of employing heuristic instead of random SA in RF-TD-TDMA with $L_{opt}^{RF} = 9$ slots are 88% higher MNT and 8.5% lower EOR. Similarly, in RF-RD-TDMA with $L_{opt}^{RF} = 5$ slots, heuristic SA improves random SA for 36% in MNT and 18.5% in EOR. This result indicates that without careful SA, the reduced-frame TDMA protocols cannot take the full advantage of higher available bandwidth provided by smaller frame period.

4.2. Performance under varying traffic load

In this simulation, we investigate the performance of TDMA-based protocols under varying traffic load. It has been assumed that nodes generate data messages following a Poisson distribution with an arrival rate of λ *msg/s* and the constant message length of 64 bytes. The results obtained are shown in Figure 8.

The main potential advantage of reduced- over full-frame TDMA schemes is that they can provide a lower message delay. The reduced-frame TDMA protocol configured with a small frame length will allow significantly decreasing the message delay under light traffic condition, but at the cost of reducing the throughput and increasing the energy consumption at high traffic load. As a compromise, in this set of simulations we assume that the reduced-frame TDMA protocols are configured with the frame length that maximizes their MNT, i.e. with $L_{opt}^{RF} = 9$ slots for RF-TD-TDMA, and with $L_{opt}^{RF} = 5$ slots for RF-RD-TDMA. With this frame length, the network will be able to survive periods of traffic congestion in less time and with less energy wasted while providing a reasonably large reduction of message delay during periods of light traffic conditions.

Figure 8 (a) and (b) depict the normalized throughput versus message arrival rate for different TDMA schemes. We observe that when the traffic load increases, the normalized throughput increases linearly and finally saturates at the level of MNT. As expected, because of a higher MNT, the throughput of transmitter-driven TDMA protocols saturates at higher traffic loads than the throughput of receiver-driven TDMA. Notice the sudden transition from linear to saturated regime in the FF-TD-TDMA protocol (Figure 8(a)). This effect appears as a result of the fact that FF-TD-TDMA provides absolute fairness among nodes, regarding throughput, and therefore individual nodes saturate at about the same value of λ. In the RF-TD-TDMA, the throughput saturates not only because of the limited available bandwidth but also due to radio-interference caused by SA conflicts. Although nodes are allocated the same bandwidth (i.e. one slot per frame), the SA conflicts are not equally distributed among nodes. The nodes subjected to a larger number of SA conflicts will saturate at lower traffic load. As traffic load increases, the percentage of saturated nodes increases, too. Finally, the normalized throughput saturates when all nodes enter saturated regime. For example, the transition from linear to saturated regime in RF-TD-TDMA with heuristic SA starts at $\lambda = 0.9 msg/s$ and finishes at $\lambda = 2.1 msg/s$.

Next, we examine the delay characteristics of TDMA-based protocols under varying traffic loads. The results are shown in Figure 8(c) and (d). At very low traffic load, the AMD equals to the half of the frame period, because each message is sent during the same frame when it is generated. Under this traffic condition, a reduced-frame TDMA protocol with the frame length of L^{RF} provides L^{FF}/L^{RF} times smaller AMD than the corresponding full-frame TDMA protocol with the frame length of L^{FF}. With increasing traffic load, the AMD goes up for all protocols by reason of increased queuing delay. In FF-TD-TDMA protocol, the queuing delay comes from the limited available bandwidth only, since a node can transmit at most one message per frame. In hybrid TDMA/CSMA variants, the queuing delay is prolonged as a result of: a) CSMA contention, when a node refrains from its attempt to transmit after it loses competition for the medium, and b) message retransmissions after collision, i.e. back-off delay.

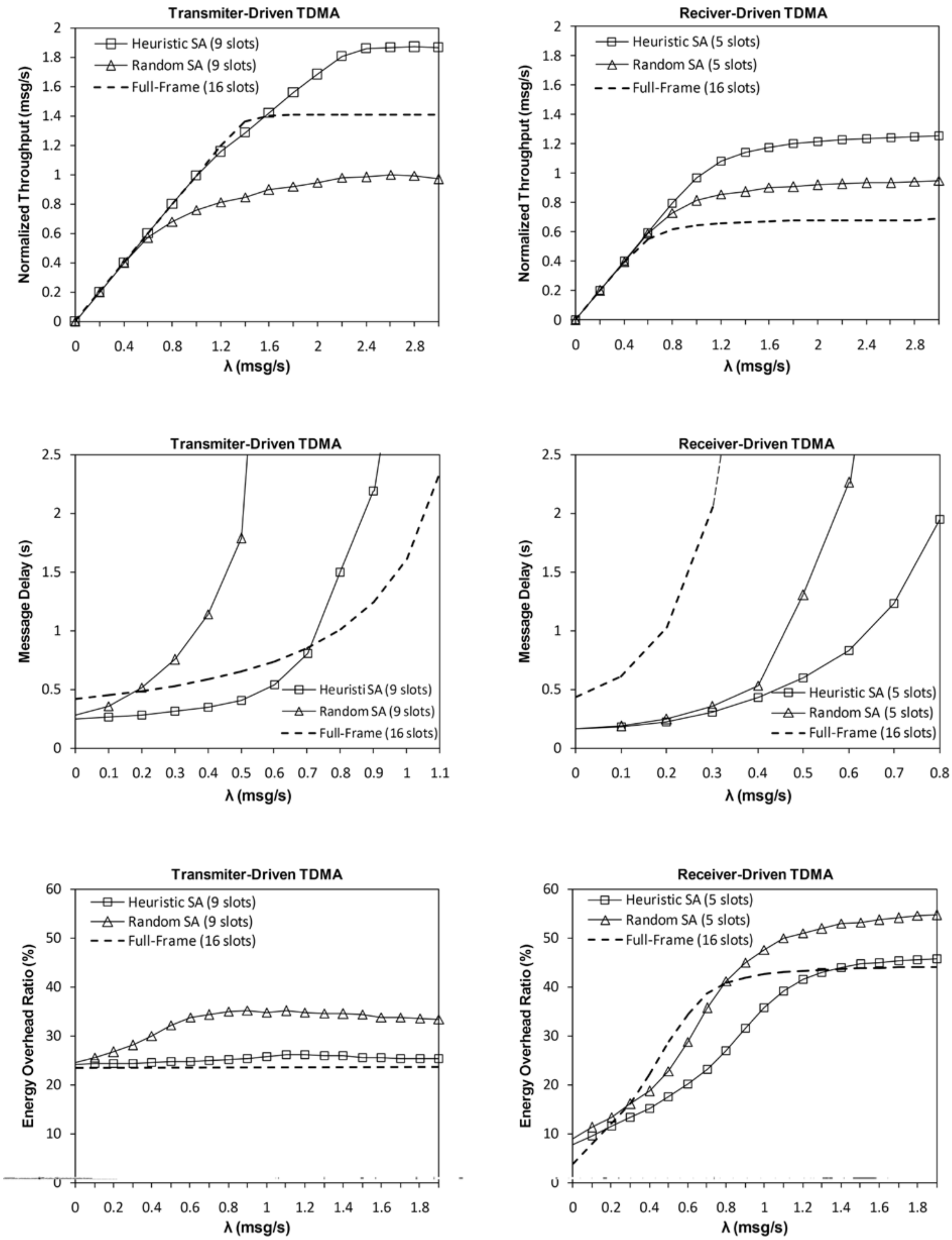

Figure 8. Performancemetrics of TDMA-based protocols undermaximum traffic load: (a) and (b) maximum normalized throughput; (c) and (d) energy overhead ratio.

As can be seen in Figure 8(c), the initial delay difference between FF-TD-TDMA and RF-TD-TDMA with heuristic SA is preserved up to $\lambda = 0.5 msg / s$. However, after this point, the AMD of RF-TD-TDMA with heuristic SA increases at a much faster rate due to collisions, retransmissions and contentions, and finally exceeds the AMD of collision-free FF-TD-TDMA at $\lambda = 0.7 msg / s$. Figure 8 (c) also shows that RF-TD-TDMA with random SA is able to retain the lower delay advantage over FF-TD-TDMA only up to $\lambda = 0.2 msg / s$.

As can be seen in Figure 8 (d), the FF-RD-TDMA provides an acceptable message delay only under very light traffic conditions, because of its long frame period (16 slots) and the presence of a large number of hidden node pairs. Observe that a small frame period of RF-RD-TDMA (5 slots) results in a significant reduction of the AMD, despite the presence of 1-hop and 2-hop SA conflicts. Moreover, when heuristic SA is used, the delay performance of RF-RD-TDMA protocol is further improved and becomes comparable with those of RF-TD-TDMA.

Finally, we present the results concerning energy efficiency of TDMA-based protocols under varying traffic load. Figure 8(e) shows the energy overhead ratio (EOR) of transmitter-driven TDMA protocols. At very low traffic load, both full- and reduced-frame transmitter-driven TDMA protocols have about the same EOR, which is mostly caused by message overhearing. The EOR of FF-TD-TDMA does not change with traffic load. This happens because the message overhearing is the only source of significant energy waste in the FF-TD-TDMA protocol, and each message transferred from node u to node v is overheard by all nodes in $N_1(u)\setminus\{v\}$, regardless of traffic load. In RF-TD-TDMA, beside the message overhearing, there is an additional amount of energy wasted due to collisions, message retransmissions and CSMA contention. Consequently, as traffic load increases, the EOR of RF-TD-TDMA protocols initially increases, and then saturates as the value of λ approaches the MNT of the protocol. Observe that the EOR of RF-TD-TDMA with heuristic SA and 9 slots per frame exceeds the EOR of FF-TD-TDMA for less than 2%. The small increase in EOR indicates that 2-hop SA conflicts, which cause the hidden terminal collisions, are rare in RF-TD-TDMA with heuristic SA. In contrast, when the random SA is used, the EOR of RF-TD-TDMA is significantly higher because of a more frequent collisions caused by a larger number of hidden terminal pairs.

The receiver-driven TDMA protocols have a quite different EOR profile than transmitter-driven TDMA protocols (Figure 8 (f)). If compared with the transmitter-driven TDMA, the EOR of receiver-driven TDMA is significantly lower at low traffic load, but significantly higher at high traffic load. This is because of hidden terminal collisions of Type_2, which are the main source of energy waste in the receiver-driven TDMA, in contrast to message overhearing, which causes great deal of energy overhead in the transmitter-driven TDMA. The rate of collisions increases as traffic load increases, as opposite to overhearing which goes along with every message transmission. Notice also that the EOR of RF-RD-TDMA is higher than that of FF-RD-TDMA at very low traffic load. This is because of sporadic message overhearing, which happens in RF-RD-TDMA due to 1-hop SA conflicts, as opposite to FF-RD-TDMA where the overhearing is completely eliminated via conflict-free SA. Interestingly, in spite of SA conflicts, the EOR of

RF-RD-TDMA increases slower than that of FF-RD-TDMA. This effect can be contributed to the exposed terminals, which suppress some of hidden terminal collisions in RF-RD-TDMA.

5. Conclusions

In this paper we have studied the performance and energy efficiency of reduced-frame TDMA protocols, that is, a class of hybrid TDMA/CSMA protocols in which each TDMA slot is extended with a short time period reserved for CSMA-based contention resolution mechanism. In contrast to traditional TDMA-based protocols, where collisions are fully resolved statically through conflict-free slot assignment, in the reduced-frame approach, only a part of potential collisions are eliminated via slot assignment while the remaining are resolved dynamically, by means of CSMA-based contention-resolution mechanism. This allows configuring the length of TDMA frame independently of node density. Our analysis included studying two common TDMA slot assignment schemes: transmitter-driven and receiver-driven. To increase the performances of reduced-frame TDMA protocols, we presented two strategies. The first consists in tuning the length of TDMA frame, while the second consists in reducing the number of conflicting slot assignments via heuristic slot assignment algorithm. Our evaluations through intensive simulation confirmed the benefits of these approaches. The results show that the network throughput is maximized when the frame is reduced approximately to $\frac{1}{2}L_{\min}^{FF}$, for transmitter-driven, and to $\frac{1}{3}L_{\min}^{FF}$, for receiver-driven TDMA scheme, where $L_{\min}^{FF}$ stands for the length of shortest conflict-free TDMA frame. We also found out that an effective slot-assignment scheme is crucial to take full performance benefits of reduced-frame TDMA approach. In fact, simulation results show that our proposed heuristic slot-assignment algorithm improves the maximum throughput of reduced-frame TDMA protocols over random slot-assignment scheme up to 90% for transmitter-driven, and up to 35% for receiver-driven scheme, while keeping energy consumption at low level. Further work should be conducted to evaluate reduced-frame TDMA protocols in terms of scalability to network density and performance under different traffic scenarios. Another direction for future study is to investigate self-organizing and adaptive reduced-frame TDMA schemes in which nodes will be allowed to select multiple slots in the frame, based on their traffic demands and current conditions of the medium. It would be also interesting to extend this study to multichannel TDMA protocols. Besides, it should be a good idea to verify the simulation results trough field testing coupled with statistical analysis of the obtained data.

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