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Low-power neighbor discovery for mobility-aware wireless sensor networks

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ABSTRACT

While more and more deployments of Wireless Sensor Networks (WSNs) are successful, very few are actually mobility-aware. Due to their intermittent connectivity, mobile nodes induce certain instabilities, and thus, require to transmit multiple data packets in a short period of time. The nature of mobile nodes can lead to a link quality deterioration or even more to link disconnection. This instability requires frequent link establishments between a mobile and a neighboring static node before initiating data packet transmissions. To do so, the need for an efficient Medium Access Control (MAC) protocol is extremely important and challenging. In this paper, we present MobiDisc, an advanced mobile-supporting scheme for low-power MAC protocols, which allows for efficient neighbor(hood) discovery and low-delay communication. Moreover, we propose a FAN (First Ack Next-hop) mode that accelerates transmissions. Both MobiDisc and MobiDisc-FAN come with a Fast Recovery Mechanism (FRM) that enables seamless handovers in the network. Our thorough performance evaluation, conducted on top of Contiki OS, shows that MobiDisc outperforms a number of state-of-the-art solutions (including MoX-MAC and ME-ContikiMAC), by terms of reducing both delay and energy consumption, while the reliability is kept over 98%.

1. Introduction

Most of current Wireless Sensor Networks (WSNs) applications are oriented to stationary infrastructure, where nodes are deployed statically [1]. Recently, applications such as patient or animal monitoring emerged, with mobility and bulk transmission schemes very often appearing to be essential [2,3]. In such applications, sensor nodes are attached to persons, animals or objects, while under burst transmissions, nodes may transmit n packets in a row once they gain access to the wireless medium [4]. Even though the number of mobile applications keeps growing, most existing Medium Access Control (MAC) protocols focus mainly on static networks, where the topology is considered fixed while the next-hop of each node may change, depending on the physical layer conditions and the status of devices (e.g.,remaining battery, faults) [5,6].

In this paper, we focus on mobile-to-static communications that are subject to frequent link fluctuations and disconnections due to the movement of nodes. We investigate mobile-to-static link management in order to first set up wireless transmissions (i.e., link establishment) and then to allow for next-hop switching upon data offloading (i.e., handover).

We place our work in the context of low power mobile nodes whose prime objective is to dequeue their transmission buffers (in a bursty mode) as soon as any sink-connected neighbor shows up in their vicinity. We here consider that mobile nodes do not participate in the routing structure. Indeed, constructing and maintaining a coherent routing backbone with such dynamics may either endanger network connectivity or induce crippling communication costs. Consequently, as detailed throughout this paper, link establishment and handovers are performed jointly with the MAC layer mechanisms.

In addition, the MAC layer handles all operations related to the main source of energy consumption in WSNs, and in particular packet transmissions [7]. Many MAC protocols have been devised for coordinating access to the wireless medium shared by several nodes [8]. Some of them target mobility-aware WSNs, where mobile nodes aim at establishing communication links with selected

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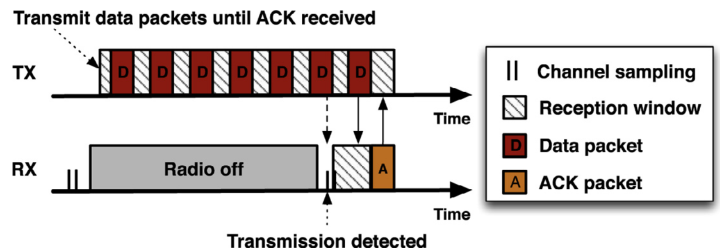


Fig. 1. A representative scheme from preamble-sampling family of MAC protocols. Under unicast transmission mode, nodes sample the medium periodically to detect a transmission. If a carrier is detected, the receiver keeps its radio *ON* to receive the associated data packet.

next-hop static nodes without increasing neither delay nor energy consumption due to potentially longer routing paths.

In this paper, we focus on Low-Power Listening (LPL) MAC protocols, mainly due to the topology dynamics induced by mobile nodes. We discuss to what extent current LPL methods fail to meet those requirements, thus, emphasizing neighbor discovery as a key primitive in mobility-aware WSNs. Consequently, we assume that static neighbors can provide valuable information (e.g.,battery power, number of hops to the sink) that would help surrounding mobile nodes select the best next-hop. We therefore introduce MobiDisc, a mobility-aware scheme that allows an enhanced neighbor(hood) discovery. While the default mode of MobiDisc leads to the discovery of the whole neighborhood, we also propose a FAN (First Ack Next-hop) mode that enables quick and efficient transmissions. Both approaches allow mobile nodes to perform efficient communications, in terms of energy, 1-hop and end-to-end delay. In order to fulfill the mobility-aware application requirements, we further introduce a Fast Recovering Mechanism (FRM) that can be activated in order to enable seamless handovers in the network.

The contributions presented in this paper are as follows:

- After a thorough study of the state-of-the-art MAC layer protocols for mobility-aware WSNs, we first present MobiDisc, an advanced scheme that allows mobile nodes to selectively choose the next hop node while reducing the end-to-end delay.
- We then introduce the FAN mode of MobiDisc that mitigates the tradeoff situation between 1-hop and end-to-end delay. We also implement and integrate a fast recovering mechanism (FRM) in MobiDisc for delay efficient handovers.
- We perform a thorough performance evaluation on top of COOJA (a simulator for Contiki OS). In addition, we compare MobiDisc (by considering default and FAN modes) against state-of-the-art solutions such as ME-ContikiMAC [2] and MoX-MAC [9].

The remainder of our paper is organized as follows. In Section 2 we review the most pertinent related works from the literature. We then detail our problem formulation in Section 3. In Section 4, we present a detailed description of MobiDisc, the FAN mode and the FRM mechanism. We implement our solutions on top of the Contiki OS (Section 5) and then demonstrate the performance of our solutions in Section 6, in terms of latency, energy consumption and reliability. Finally, Section 7 provides the concluding remarks and future perspectives for our work.

2. Background and related work

In the research community, different approaches for MAC layer protocols have been proposed, mainly categorized as scheduled, common active periods, preamble-sampling, hybrid [8] and mobility-aware [10].

Considering the topology dynamics induced by mobile nodes, our work studies the preamble-sampling family of MAC protocols [11]. Under these protocols, nodes sample the wireless medium at regular intervals to detect a transmission for incoming packets. In between, they turn their radio *OFF*, thus reducing energy consumption (i.e., duty cycling). Once transmitting a data packet, a node repeatedly sends the same packet (until a link layer acknowledgment is received), which aims at triggering a transmission detection at the receiver node, which should then forward the packet towards the sink station (see Fig. 1).

In mobility-aware WSNs, many existing solutions require mobile nodes to constantly evaluate link quality, based on the Received Signal Strength Indicator (RSSI) of acknowledgments received from its temporary next-hop (e.g.,MA-MAC [12], MX-MAC [3], MARI-MAC [13]). Hence, if the mobile node evaluates a too low quality of the link between its current next-hop and itself (i.e., persisting deterioration in the link quality), it initiates a neighborhood discovery process which may lead to a handover situation. These schemes are suitable for environments with few mobile nodes and their efficiency strongly depends on the network density. Moreover, to handle mobility by triggering handover procedures, distance thresholds are defined. Therefore, these protocols strongly correlate the RSSI level with the distance. In real-word scenarios using the received signal level as a mobility indication does not provide fair accuracy to evaluate proximity, as reported in [14].

In [15], authors consider that data packets originated from a mobile node are of higher priority compared to those of static ones. Their solution, named X-Machiavel, therefore allows any mobile node to steal the wireless medium from a static node that has gained it earlier. Potential steals are detected by overhearing mobile nodes, which prevents those nodes from low power operations, due to intensive sampling of the medium. In addition, static nodes can postpone their own data transmissions, which may induce some further issues in terms of message buffering, retransmissions and end-to-end delay in the static infrastructure.

In [9], authors present the MoX-MAC protocol. Under MoX-MAC, similarly to X-Machiavel, when a mobile node expects to transmit a data packet, it overhears the wireless medium to detect transmission between two static nodes. It waits until the end of the scheduled transmission, and afterwards, it transmits its own data packet to the transmitter static node (see Fig. 2). If no transmission is detected, then a mobile node acts as in a typical preamble-sampling procedure (i.e., X-MAC [16]: preamble sending, data sending upon ACK). The efficiency of this approach strongly depends on the communication frequency between the static nodes.

Under MOBINET [17], a mobile node, by overhearing the medium, builds a neighborhood table with destination addresses of the static nodes within its transmission range. Later, when it expects to transmit, it unicasts a data packet to one of the destination addresses listed in its neighborhood table. For the next-hop selection, MOBINET comes with two methods, the random and selective respectively.

In [18], authors introduce M-ContikiMAC which extends the statically oriented ContikiMAC [19] protocol to allow for mobile to static node communication. Mobile nodes transmit in anycast

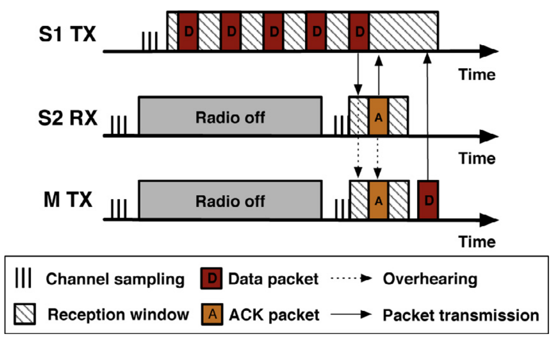


Fig. 2. MoX-MAC implemented on top of ContikiMAC protocol (static transmitting and receiving nodes, referred to as S1 TX and S2 RX respectively, being within the communication range of the mobile transmitter, i.e., M TX).

(the first data packet of total n of burst) meaning that all potential receivers are identified by the same destination address. The first acknowledging node will serve as temporary next-hop, and thus will forward the data packet towards the sink. Meanwhile, within some dense networks, two or more static nodes may sample the medium channel simultaneously, thus, inducing duplicated packets and degraded network performances (i.e., congestions, channel occupancy, collisions, packet retransmissions).

In [2], authors overcome the previously mentioned limitations by proposing ME-ContikiMAC. Mobile nodes expecting to transmit n data packets in burst, will transmit one additional control packet upfront, $n + 1$ packets. More specifically, it will repeatedly transmit a control packet by anycast which will be labeled not to be forwarded. Thus, once the mobile transmitter receives the corresponding ACK for the control packet, it will proceed with the actual data packets to its new temporary next-hop. The principle of ME-ContikiMAC is shown in Fig. 3.

Most of the previously presented protocols may not satisfy our objectives of addressing mobility efficiently under the bursty traffic in a highly proactive manner and by attaining low end-to-end and handover delays and energy consumption. As summarized in Table 1, MA-MAC, MARI-MAC and MX-MAC approaches are highly reactive solutions since link quality estimation (before link establishment) requires a significant number of packet transmissions. Moreover, these solutions strongly depend on the network density and are designed for small-scale networks. On the other hand, even though X-Machiavel being a traffic independent protocol, it strongly depends on features of the X-MAC protocol, such as strobe packets in the preamble. MoX-MAC, MOBINET, M-ContikiMAC and ME-ContikiMAC being proactive protocols, appear as the most relevant to our targeted context. These solutions are independent from the underlying MAC protocol, since they can be implemented both on top of strobe-based (e.g.,X-MAC) and data-based (e.g.,ContikiMAC) MAC protocols. Therefore, we selected MoX-MAC and ME-ContikiMAC as candidates for further comparison during our evaluation campaign.

3. Problem formulation

In this paper, we consider mobile nodes in low power WSNs that aim at discovering neighbors for transmissions towards the sink station. We assume that mobile nodes do not participate in the routing operations as they may either endanger network connectivity or induce crippling communication costs to maintain a coherent routing backbone. Mobile nodes have to perform some neighbor discovery in order to set up a point-to-point communication link towards the sink station. We therefore place our work in the context of low power mobile nodes whose objectives are to dequeue their transmission buffers as soon as some sink-connected neighbors show up in their vicinity. We assume that those neighbors contain up-to-date information at the routing layer. This information can be made available to the MAC layer of potentially surrounding mobile nodes in order to allow them to select the best next-hop without knowing anything about the routing infrastructure.

Mobile nodes often have to switch their static next-hop as their movement may prevent them from offloading all their data to the same one (i.e., handover procedure). Moreover, link fluctuations and disconnections (mobile to any static node) also frequently occur due to the mobility nature. Handover procedures must allow mobile nodes to maintain an uninterrupted communication with the static infrastructure by seamlessly changing the next-hop receiving node. Therefore, we decide to integrate our proposed mechanisms to the link layer, jointly with the preamble-based MAC protocol. Consequently, only mobile nodes are required to implement our solutions while static nodes (which participate in the routing) simply have to undergo minor code modifications at the link layer as well (e.g.,timeout for energy-efficient link establishment).

In most MAC protocols intended to handle mobility, mobile nodes aim at establishing communication links with randomly selected next-hop static nodes (e.g.,ME-ContikiMAC, MoX-MAC, M-ContikiMAC, X-Machiavel). Such approaches can lead to increased end-to-end delay and energy consumption due to potentially longer routing paths.

Fig. 4 illustrates those potential issues. Let us assume that a mobile node has n packets to be transmitted towards a static infrastructure, in order to dequeue its buffer. In the transmission range of the mobile node, appears to be four static nodes, namely

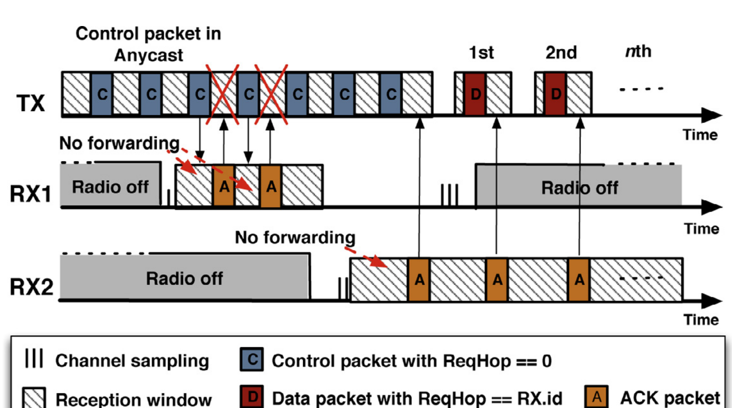


Fig. 3. ME-ContikiMAC: a packet duplication control is introduced (RX1 and RX2 being within the communication range of TX).

Table 1
Summary of state-of-the-art preamble-sampling based MAC layer contributions addressing mobility in WSNs.

MAC protocol	Advantages	Drawbacks
MA-MAC [12], MARI-MAC [13], MX-MAC [3]	• Traffic independent • Handover mechanism integrated	• Reactive protocols • Inaccurate proximity estimation • Network density dependency • Designed for very small networks
X-Machiavel [15]	• Traffic independent • Hybrid protocol (reactive and proactive) • Overhead minimization (preamble-less)	• Underlying protocol dependency • Proportion of mobile to static nodes dependency • Non-fair contention-based protocol
MoX-MAC [9]	• Proactive protocol • Overhead minimization (preamble-less)	• Traffic dependent (passive protocol) • Unnecessarily consume energy (for static nodes)
MOBINET [17]	• Proactive protocol • Optimal next-hop selection	• Traffic dependent (passive protocol) • Increase of idle listening (energy consumption)
M-ContikiMAC [18], ME-ContikiMAC [2]	• Proactive protocol • Traffic independent • Independency from underlying protocol • Overhead minimization	• Inefficient under intermittent link connections • Inefficient handover and recovery procedures

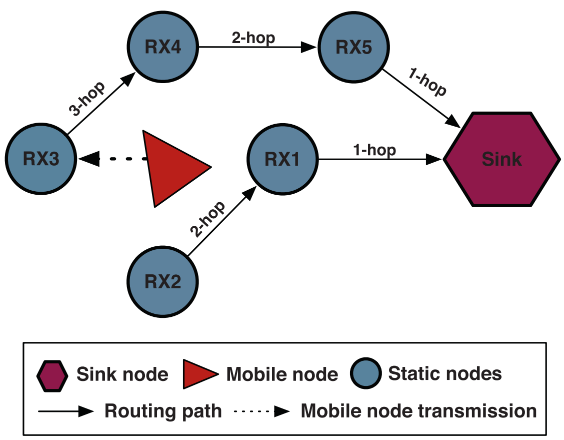


Fig. 4. A random next-hop selection (RX1, RX2, RX3 and RX4 are neighbors of the mobile node).

RX1, RX2, RX3 and RX4 that are 1, 2, 3, and 2 hops away from the sink respectively. The mobile node may connect to any of those neighboring static nodes (e.g.,the first acknowledging its request). Thus, if RX3, which is 3-hops away from the sink, may wake-up and respond first to the request. It would then receive and forward the n data packets to the sink. Consequently, the end-to-end delay would increase and traffic in the network would enlarge as well, when compared to another neighboring node, e.g.,RX1. As a result, by employing such opportunistic schemes, there is no guarantee that the mobile node will select its temporary next-hop based on certain qualitative criteria.

Moreover, during data transmissions to a selected next-hop, a mobile node should be allowed to discover other potential forwarders, which would help using the best qualitative next-hop. This requires a fast and efficient neighbor discovery at the mobile and regular updates from surrounding nodes.

Finally, with nodes moving throughout the network, by updating next-hop either due to mobility or to discovery of new forwarders, mobile devices should be able to perform seamless handovers in order not to interrupt a (burst) transmission upon next-hop changes.

4. Design of MobiDisc

The current section starts by introducing the underlying protocol and corresponding subsections provide detailed description of the proposed schemes.

MobiDisc includes information exchange during the neighborhood discovery phase, which allows for efficient end-to-end delay performance. This information exchange may adapt to the application layer requirements, such as remaining energy in order to prioritize the relay node accordingly to the energy level [20]. MobiDisc is compliant with the preamble-sampling family of MAC protocols. We therefore embed MobiDisc into ContikiMAC [19], the leading preamble-sampling MAC protocol and default MAC layer protocol in the commonly used Contiki OS[1], rather than leveraging a simple proof-of-concept implementation. This allows us to evaluate MobiDisc over a realistic emulator where we verify MobiDisc's efficiency in dense and mobile network scenarios.

4.1. Selection of the underlying protocol

Our core mechanisms are general enough to be applied to any preamble-sampling oriented MAC protocols. In this study, we assume ContikiMAC as the underlying protocol for our MobiDisc proposition.

Even though ContikiMAC embeds most of the innovative features of existing preamble-sampling protocols (e.g.,periodic wake-ups, phase-lock optimization and use of data packet copies as a wake-up strobe), it lacks in scenarios where static and mobile nodes co-exist. In fact, since mobile nodes do not participate in the routing construction, they are unable to communicate with static nodes in an efficient manner (e.g.,energy, delay) [18].

Still, it comes with a burst handling mechanism to anticipate high traffic loads in the network [4]. To do so, the sender sets a flag at each data packet of the queue (except the last one) in order to notify the receiver that another packet will follow. On the other side, the receiver turns its radio *ON* and switches into Carrier Sense Multiple Access (CSMA) mode, in order to handle the high traffic load during this bursty period. The principles of the ContikiMAC's burst mode are illustrated in Fig. 5.

In this study, we consider scenarios where mobile nodes transmit in burst, and, thus, the burst notification flag of ContikiMAC is activated.

4.2. Neighborhood discovery with MobiDisc

Let us assume a mobile node that expects to transmit n-packets in row. Due to its mobility nature, the node is not aware of the static nodes that are (or will be) located in its transmission range, and even more about their distance (i.e., in terms of hops) to the sink. To overcome this barrier, we propose a MAC layer scheme,

[1] http://www.contiki-os.org/.

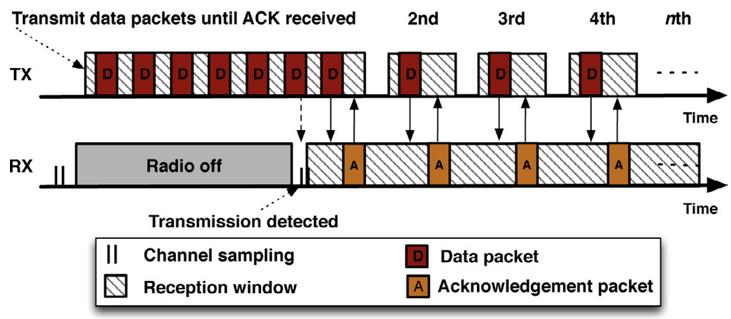


Fig. 5. ContikiMAC in burst mode: the receiver switches to CSMA mode to handle high traffic.

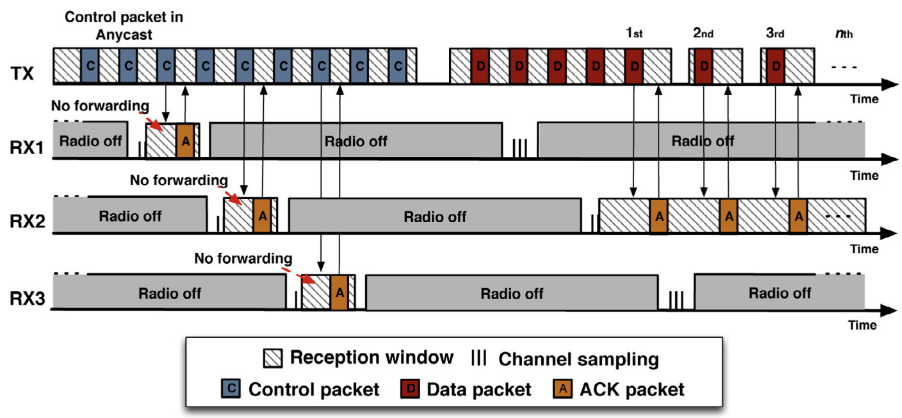


Fig. 6. MobiDisc (default mode): after a neighborhood discovery with anycasted control packets, TX chooses RX2 and starts sending data packets right after its next sampling period.

namely MobiDisc, that aims at allowing neighborhood discovery with anycasted control packets. More specifically, by employing MobiDisc, a mobile node will search for the best (according to a given metric) next-hop static node.

The main idea of MobiDisc consists of two concrete phases, first the neighborhood discovery and then the transmission of n packets in burst. The principles of MobiDisc are depicted in Fig. 6. During the neighborhood discovery phase, the mobile node sends control packets in anycast transmission mode. This control packet, similarly to broadcast transmission, is repeatedly transmitted during the whole preamble period (e.g.,125 *ms*) in order to assure that all neighbors in its transmission range will successfully receive the control packet. The potential receivers (e.g.,RX1, RX2, RX3), of the control packet, will respond with an acknowledgment by including their identifier (which is assumed to be unique) and an associated metric (e.g.,remaining battery power, number of hops to the sink station, value of some link quality indicators). Once, the static nodes will acknowledge the control packet of TX, they will turn their radio *OFF*, for energy saving purposes. On the other side, the transmitter node continues transmitting the control packets of the scheduled preamble while receiving acknowledgments.

Once the neighborhood discovery phase is completed, TX determines the best next-hop node, by utilizing the retrieved information (e.g.,number of hops from the sink for all surrounding static nodes). Thus, during the second phase of MobiDisc, the mobile node transmits the n packets in burst to the previously identified static node.

4.3. First ACK next-hop (FAN) mode

We now introduce the FAN mode under which MobiDisc can work. The neighborhood discovery remains unchanged (i.e., control packets sent in anycast), except that a mobile node sets up a

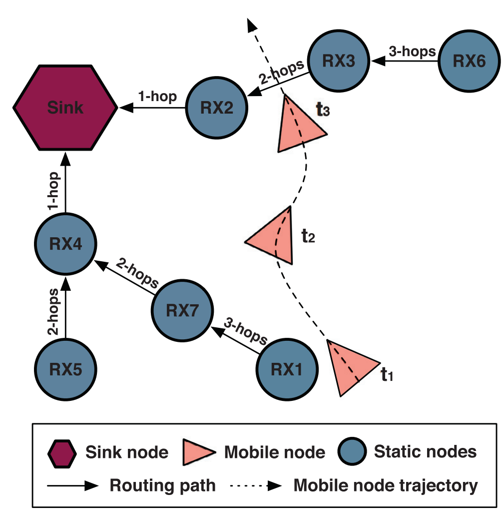


Fig. 7. Use case of FAN mode. Upon reception of notification packets, a mobile may change next-hop.

link with the neighboring sensor node, that first acknowledges its control packet (e.g.,RX1 on Fig. 7). Once the link between the mobile and a static node is established, the transmission of n packets initiates. We should take into account that during this burst transmission, the mobile node is moving constantly, and thus, it may approach a static node that is more appropriate (e.g.,according to a min-hop metric to the sink or a node with higher remaining energy level). As observed on Fig. 7), the mobile node moves from a neighbor 3-hop away from the sink (i.e., RX1) to another one only 1-hop away from the sink (i.e., RX2). As a result, under such a scenario, multiple handovers may occur. To efficiently handle the potential of handovers, we here introduce the FAN mode.

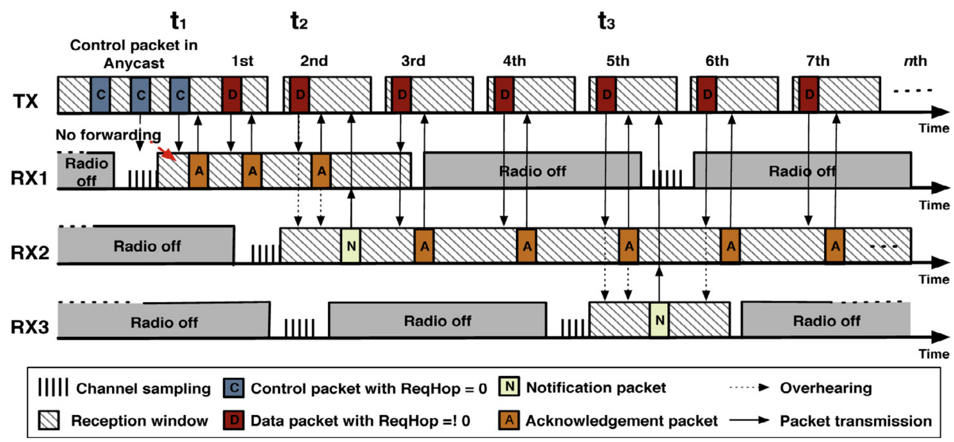


Fig. 8. FAN mode: static nodes here announce a min-hop metric value to mobile node TX, thus allowing it to switch its next-hop (RX1, RX2 and RX3 are located as depicted on Fig. 7).

By using MobiDisc with the FAN mode, if another static node (e.g.,RX2, RX3) samples the medium during the burst transmission, then it will notify its metric value to the mobile by transmitting a notification packet. Later, the mobile node, upon a local calculation will assess the “best” candidate and potentially perform a handover, if switching its temporary next-hop. If TX will rate the RX2 as the optimal next-hop among RX1, RX2 and RX3, it will then perform the handover by switching from RX1 to RX2, and thus, TX will transmit the following data packet to RX2. It is important to mention that in this case RX1 (and RX3) after expiration of default timeout (i.e., between 20 to 30 ms) will turn its radio *OFF* to save energy, like with any other preamble-sampling MAC protocol. The functionality of our FAN mode is depicted in Fig. 8. In this study we implemented the FAN mode based on the min-hop metric.

Furthermore, after each data packet transmission of n, the mobile node keeps its radio *ON* longer than in typical LPL MAC protocols (e.g.,ContikiMAC, X-MAC), to be able to receive the “notification” packets from the surrounding static nodes. On the other hand, for the static nodes, we increased the Clear Channel Assessment (CCA) checks to six in order to handle the extended packet interval time gap (see Fig. 8). It should be mentioned that the efficiency of the FAN mode comes at the cost of energy consumption. Indeed, the FAN mode strongly depends on additional “notification” packets and on increase of the number of CCA checks (i.e., from two to six), which in turn increase the energy consumption both at the mobile and static nodes.

To evaluate the additional cost in terms of energy consumption, we performed a set of simulations on top of Contiki OS, with different CCA numbers to estimate the Radio Duty Cycle (RDC) level. Note that no transmission occurred, thus, the RDC calculation comes explicitly from channel sampling (i.e., sampling frequency at 4 Hz). As can be observed, from Fig. 9, the RDC essentially increases with growth of CCA checks per channel sampling.

Note that, throughout the remaining of this paper, for the sake of clarity, MobiDisc under default and FAN modes will be referred to as MobiDisc and MobiDisc-FAN respectively.

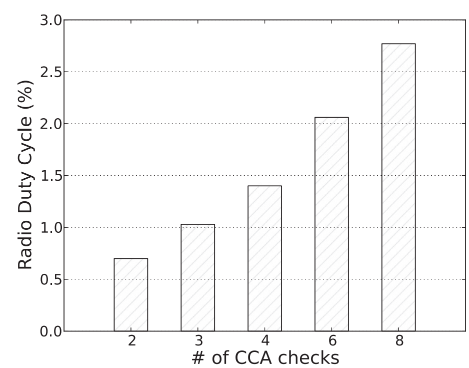


Fig. 9. Impact of number of CCA checks on the overall radio duty-cycle (with 125 ms sampling period).

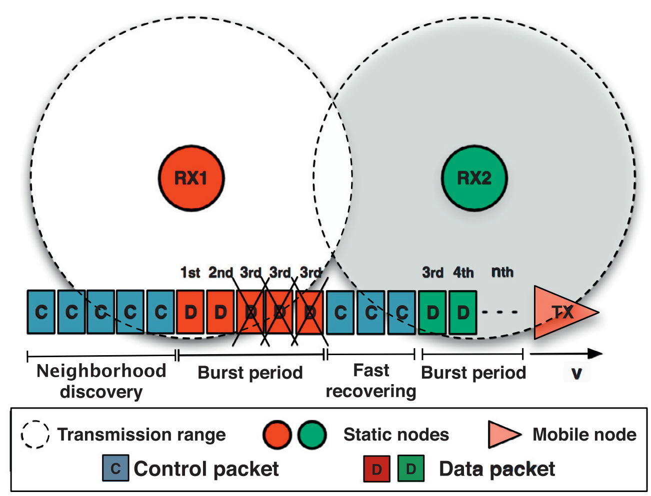
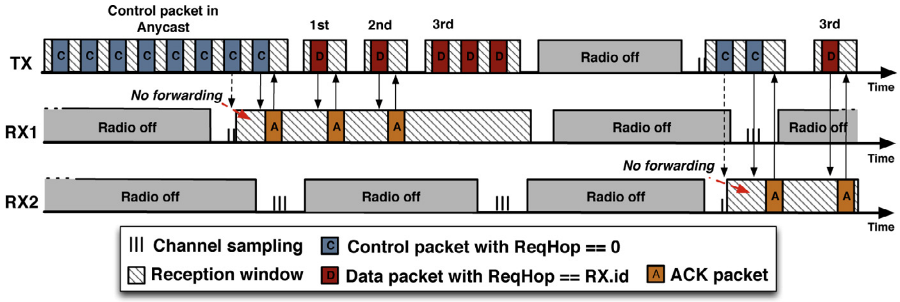


Fig. 10. A recovery use case integrated in MobiDisc (default mode).

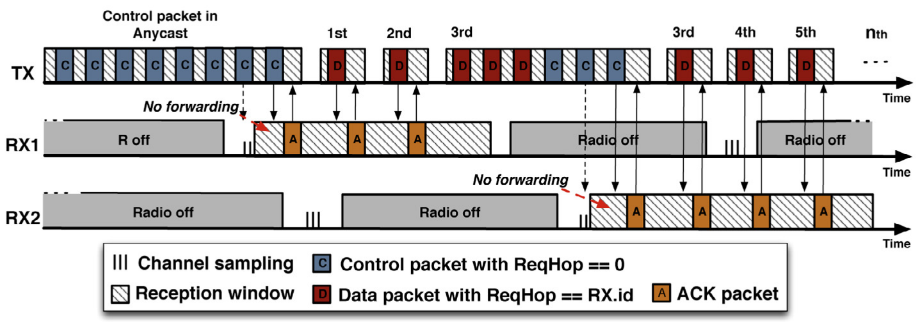
4.4. Integration of a fast recovering scheme

In applications such as patient or animal monitoring, connections and disconnections between mobile nodes and the static infrastructure are frequent and typical use cases. Fig. 10 illustrates a mobile node which has to switch its next-hop from RX1 to RX2, as imposed by its trajectory. That requires TX to detect the disconnection with RX1 as soon as possible, while starting to look for a new next-hop. We therefore introduce a fast recovering mechanism to perform seamless handovers in the network, in order to fulfill the mobility-aware application requirements.

Even though employing MobiDisc, link disconnection (due to the mobility) may occur during the transmission of n packets in burst. As can be observed from Fig. 11a, the 3rd data packet from mobile node TX is never acknowledged by its temporary receiver RX1. After the default three tentatives, TX cancels its transmissions, and postpones them for the following preamble round.



(a) Handover delay due to the default setup of MobiDisc: upon link disconnection with its temporary receiver (RX1), mobile node (TX) postpones its transmission for the following preamble round.



(b) Enhanced version of the handover mechanism of MobiDisc: mobile node (TX) continues transmitting control packets without turning its radio OFF.

Fig. 11. MobiDisc (default mode) in handover enhanced illustration: Mobile node in "'aggressive" behavior mode.

Hence, it will waste time for at least one complete sampling period (e.g.,125 ms) before initiating the new-neighborhood discovery process. As a result, MobiDisc induces high handover delays, especially when the nodes are configured with long preamble-sampling frequencies such as 500 ms.

In order to improve the previously discussed handover and reconnection delay issues, we here introduce the concept of the Fast Recovering Mechanism (FRM) integrated in MobiDisc. By employing the FRM, mobile nodes have priority to the medium access over static ones. In particular, once a mobile node detects the network disconnection (after transmitting repeatedly the data packet for a predefined time), it immediately initiates the next-hop discovery procedure (by repeatedly transmitting control packets) without the involvement of the CSMA layer, during the same preamble cycle [21]. By this way, we aim at reducing the 1-hop delay from mobile to static node. The concept of fast recovering mechanism integrated in MobiDisc is depicted in Fig. 11b.

5. Implementation aspects

In order to evaluate the performances of our proposition and to compare against state-of-the-art contributions, we decided to use COOJA[2], a simulator allowing real hardware platforms to be emulated. We therefore implemented MobiDisc in the Contiki OS with Tmote-Sky platform[3] (i.e., CC2420 radio chip at 2.4 *GHz*) and used the simulator to configure the network topology.

To generate mobility, we utilized the BonnMotion tool [22]. For the sake of clarity, nodes have different implementations according to their role in the network (mobile or static). We therefore have a static topology and some additional nodes moving inside. Those have a specific MAC layer that includes the solutions described in this paper. Note that if static nodes could become mobile and conversely, mobility detection could be made with some dedicated hardware (e.g. accelerometer, GPS receiver) or software (e.g. RSSI-based triangulation).

Furthermore, we employed the Contiki `energest` module to log the radio on-time for energy estimation. This module monitors in real-time the radio and Central Processing Unit (CPU) usage by saving the duration spent in each state (i.e., transmitting, receiving, awaken, sleeping).

Hereafter, we will detail the modifications performed on Contiki OS, in order to implement our MobiDisc scheme.

Software acknowledgments: We disabled the hardware acknowledgments (i.e., "autoack") from the default functionality of Contiki OS, in order to implement the anycast transmission mode. Note that with hardware acknowledgments enabled, when a packet is being transmitted in unicast, then CC2420 radio immediately acknowledges and receives the packet. If it is transmitted in broadcast (i.e., 0.0 in RIME stack), then the receiver receives the packet without acknowledging it. In any other case, the receiver rejects the packet. By disabling hardware auto-acknowledgments, the interrupt will be triggered at the MAC layer (i.e., radio driver), and thus, the receiver will check the destination RIME address and will decide to acknowledge it or not.

CCA: However, when reconfiguring software acknowledgments, certain timing issues arise. More specifically, the time interval from the packet reception to its acknowledgment is increased from 0.192 ms (i.e., hardware ACK) to 1.3 ms with software acknowledgments. As a result, collisions between transmitter's consecutive

[2] http://www.contiki-os.org/start.html.
[3] http://contiki.sourceforge.net/docs/2.6/a01784.html.

Table 2
Timing configuration for ContikiMAC and MobiDisc respectively. The new timing of MobiDisc fulfills the requirements of Eq. (1).

Timing	ContikiMAC	MobiDisc
t_a	0.192 ms	1.3 ms
t_r	0.192 ms	0.192 ms
t_d	0.16 ms	0.16 ms
t_i	0.4 ms	1.5 ms
t_c	0.5 ms	0.8 ms
t_s	0.884 ms	1.2 ms

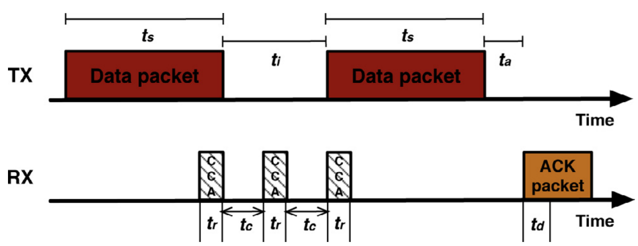


Fig. 12. A detailed representation of a packet transmission and CCA timings.

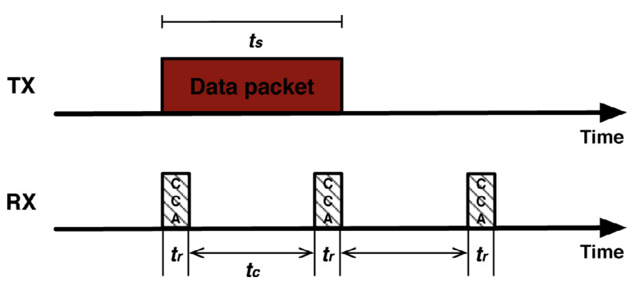


Fig. 13. The duration of a packet transmission should be longer than the time interval of two consecutive CCAs.

packets in burst and the receiver's acknowledgments may appear, which in turn leads to transmission interruption.

The default timing setup of ContikiMAC is presented in Table 2, as well as the one of MobiDisc in order to fulfill the requirements of Eq. (1):

$$t_a + t_d < t_i < t_c < t_c + 2t_r < t_s \quad (1)$$

where the timing requirements from the equation are:

- t_i: the time interval between consecutive transmissions
- t_r: the time needed for a stable CCA indication
- t_c: the time interval between two consecutive CCAs
- t_a: the time between receiving a packet and sending its acknowledgment
- t_d: the time for detecting an acknowledgment
- t_s: the time to transmit a data packet

To overcome with the previously presented issue, we increased the time interval (i.e., t_i) between two consecutive data packets. Consecutively, in order to reliably detect a transmission, we increased from two to three the ContikiMAC's default inexpensive CCA, while the time interval between each CCA (i.e., t_c) remains unchanged.

In order to be robust, three CCA checks are required. The reconfigured timers must be compliant with Eqs. (2) and (3). The new values are illustrated in Figs. 12 and 13, while the updated values are detailed in Table 2.

$$t_a + t_d < t_i < 2t_c + t_r \quad (2)$$

$$t_c + 2t_r < t_s \quad (3)$$

Gradient: In this study, we based on RIME communication stack [23], and thus, for data collection we rely on a low overheaded and scalable under realistic conditions Gradient protocol [24] which generates and maintains a tree-based routing topology, rooted at the sink, by employing the number of hops from the sink as the cost metric.

6. Performance evaluation

6.1. Simulation setup

In the previous Sections, we have presented the design of MobiDisc, the implementation aspects, and discussed to what extent our proposition may improve the mobility-handling when compared to major contributions in the related literature. Hereafter, we present a thorough performance evaluation of MobiDisc, when employing both default and FAN modes, while using a min-hop metric. For comparison purposes, we also implemented and compared MobiDisc against state-of-the-art solutions such as ME-ContikiMAC and MoX-MAC.

Our simulation scenario involves 40 fixed nodes (including the sink) that are uniformly (i.e., grid) or randomly distributed in an area of 50 × 40 m, with network degree 6.15 in average, similarly to dense wireless lighting control networks [25].

Moreover, there are 8 mobile nodes that move, inside the area covered by the fixed nodes. We opted for the random waypoint mobility model mainly because of its simplicity and wide availability. Even though the literature about such models is very dense ([26,27]), we believe that the utilization of alternative patterns would not impact much the comparison of our solution with other state-of-the-art contributions, as long as tests are performed with different velocities (i.e., three in this evaluation campaign).

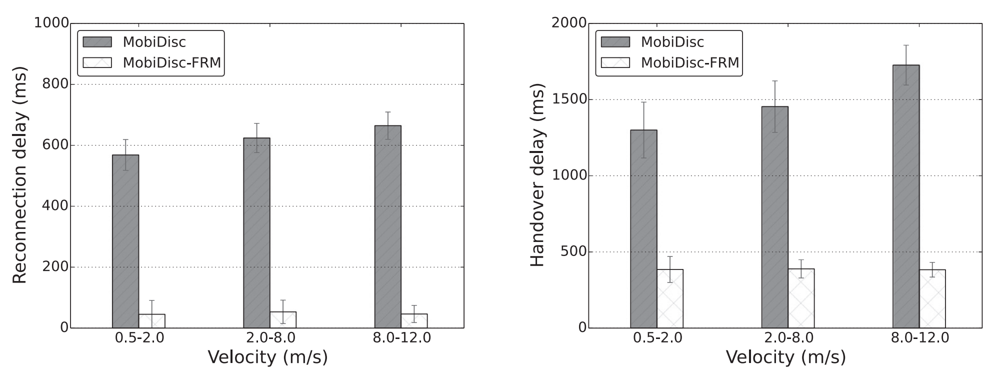
More specifically, we used a low speed (i.e., from 0.5 to 2 m/s, which represents a human walk), a medium speed (i.e., from 2 to 8 m/s, which represents a typical jogging speed) and a high speed (i.e., from 8 to 12 m/s, which represents cycling speed). We here present application-dependent (i.e., time-driven) results where mobile nodes employ a bulk transmission scheme of 32 packets every 120 s while the static nodes transmit by utilizing a Constant Bit Rate (CBR) of 1 *pkt* per 30 s. As far as it concerns the MAC layer, we have set a maximum of three retransmissions and the sampling frequency to 125 ms. We chose the packet size to be equal to 33 bytes that corresponds to all necessary information for MAC, routing and application operations (e.g., node ID, packet sequence, burst and ReqHop flags, sensed values). Even though MobiDisc is generic enough to employ various (routing) layer metrics (e.g., battery power, link quality, end-to-end delay, distance to the sink station), we here present results obtained from schemes utilizing a min-hop metric. Furthermore, we used a radio model based on disks for the sake of clarity, where each node emits at −12 dBm transmission power, imposing thus, multi-hop communications among the mobile nodes and the sink (up to six hops).

To evaluate the efficiency of the MobiDisc and MobiDisc-FAN (along with FRM extension), we run a set of simulations with COOJA by using emulated Tmote-Sky nodes with Contiki OS embedded. Finally, each simulation lasted 68 *min*. The details of the simulation setup are exposed in Table 3.

The results hereinafter show the performance of the studied schemes in terms of efficiency of our FRM option, delay (i.e., both 1-hop and end-to-end), energy consumption, congestion and reliability. In fact, we demonstrate that two different MAC configurations (i.e., statically oriented and mobile oriented) can cooperate with each other, so that the mobile nodes can smoothly coexist

Table 3
Simulation setup.

Topology parameters	Value
Topology	Grid and Random (50 × 40)
Number of nodes	40 fixed and 8 mobile sensors
Number of sources	47
Node spacing	$x = 6$ m / $y = 8$ m
Network degree	Grid 10.05 - Random 9.24 (with Confidence Interval 0.45)
Mobility parameters	**Value**
Mobility model	Random waypoint
Velocity	Low speed: from 0.5 m/s to 2 m/s
	Medium speed: from 2 m/s to 8 m/s
	High speed: from 8 m/s to 12 m/s
Simulation parameters	**Value**
Duration	68 min
Data collection scheme	Mobile nodes: Burst: 32 pkts /120 s
	Static nodes: CBR: 1 pkt / 30 s
Number of events	Mobile nodes: 8192 pkts
	Static nodes: 5108 pkts
Payload size	38 *Bytes*
Routing model	Static network: Gradient [24]
	Mobile nodes: Opportunistic
Number of hops	Multihop (see Table 4)
MAC model	Mobile nodes:
	MobiDisc, ME-ContikiMAC
	Static nodes: ContikiMAC
Sampling frequency	125 ms
Maximum retries	3
Hardware parameters	**Value**
Antenna model	Omnidirectional CC2420
Radio propagation	2.4 GHz
Modulation model	O-QPSK
Transmission power	−12 dBm



(a) Average reconnection delay, from mobile to any static node.

(b) Average handover delay, from mobile to any static node.

Fig. 14. Reconnection and handover delays of MobiDisc in grid scenario (default mode, with and without integration of fast recovering mechanism).

within a static network, without causing inefficiencies in the network.

6.2. Efficiency of the FRM option

Figs. 14a and b illustrate the average reconnection (i.e., time to establish a new link since the disconnection) and handover delays respectively, per packet transmission from any mobile to any static node. As can be observed, both reconnection and handover delays essentially are improved for all considered velocities by more than 90% and 70% respectively. These performances are mainly due to the “aggressive” behavior of mobile nodes (i.e., to continue transmitting control packets during the same preamble cycle, without switching to CSMA mode) under FRM. As a result, utilizing FRM helps improving communications for mobile WSNs significantly.

6.3. Number of hops

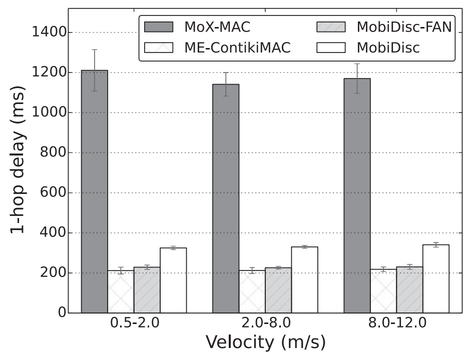
By employing MobiDisc, mobile nodes select the neighboring static node with shortest distance (in terms of hops) to the sink, as temporary next-hop. Indeed, as can be observed from the Table 4, MobiDisc chooses its next-hop node by at least 1-hop closer in average (i.e., in all considered velocities and topologies) when compared to the randomly-based neighbor discovery schemes such as MoX-MAC and ME-ContikiMAC.

6.4. 1-hop and end-to-end delays

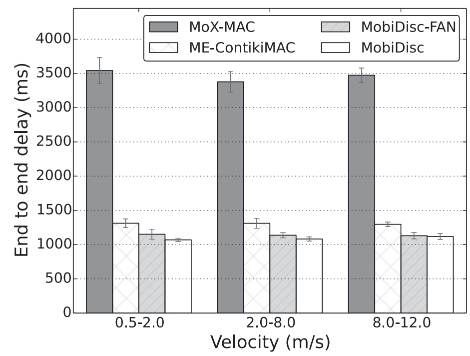
Figs. 15a, 15b, 16a and 16b illustrate the average 1-hop (from any mobile to any static node) and end-to-end (from any mobile to sink node) delay per data packet transmission. Both 1-hop and end-to-end delay include the channel sampling period, initial

Table 4
Average (along with confidence interval) number of hops, from mobile to sink.

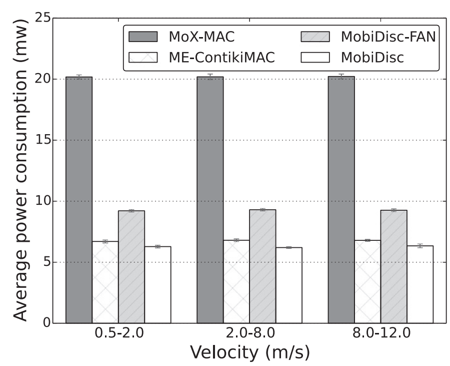
Scenario	MoX-MAC	ME-ContikiMAC	MobiDisc-FAN	MobiDisc
Grid: 0.5 – 2.0 (m/s)	3.64 (0.05)	3.60 (0.06)	2.88 (0.05)	2.74 (0.05)
Grid: 2.0 – 8.0 (m/s)	3.59 (0.05)	3.55 (0.11)	2.88 (0.03)	2.73 (0.05)
Grid: 8.0 – 12.0 (m/s)	3.61 (0.07)	3.54 (0.06)	2.82 (0.02)	2.79 (0.05)
Random: 0.5 – 2.0 (m/s)	4.47 (0.26)	4.34 (0.26)	3.92 (0.23)	3.50 (0.18)
Random: 2.0 – 8.0 (m/s)	4.52 (0.22)	4.43 (0.20)	4.05 (0.35)	3.58 (0.46)
Random: 8.0 – 12.0 (m/s)	4.62 (0.30)	4.51 (0.14)	3.82 (0.24)	3.77 (0.19)



(a) Average 1-hop delay, from mobile to any static node.



(b) Average end-to-end delay, from mobile to sink station.



(c) Average energy consumption.

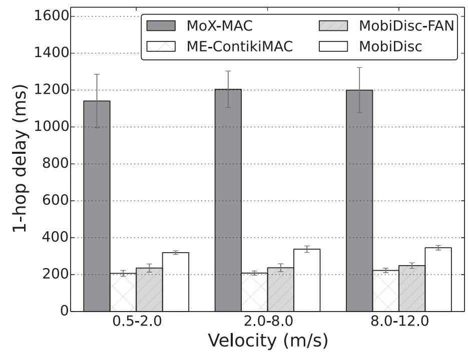
Fig. 15. Evaluation of MobiDisc (default and FAN modes) in terms of 1-hop and end-to-end delays, and energy consumption, when compared against MoX-MAC and ME-ContikiMAC when used in grid topology.

back-off, potential congestion back-off, potential retransmission delay and the transmission time of the preamble.

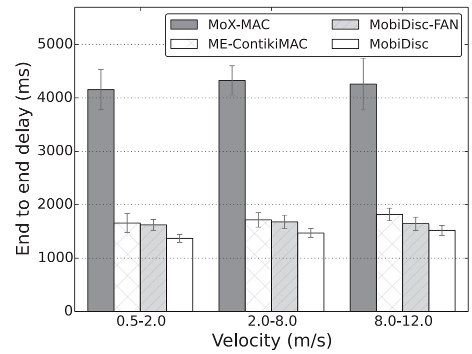
Overall, all schemes within high velocity scenarios perform worse than in the low ones, mainly due to the difficulties of a link establishment between the mobile and static node (i.e., frequent connections and disconnections). Moreover, the protocols perform worse in random topologies when compared to grid (e.g.,end-to-end delay performance). This phenomenon takes place due to the potential bottleneck links that are more prone to appear in random topologies, having as a result nodes to handle heavy traffic.

Our simulation campaign shows that MobiDisc-FAN and ME-ContikiMAC attain the best performance regarding 1-hop delay (i.e., transmission from any mobile node to any static node in the network), since these schemes opportunistically initiate the neighborhood discovery, to the first static node that acknowledges the corresponding anycast control packet. On the other hand, MobiDisc and MoX-MAC present the worst results. This could be explained by the fact that under MobiDisc scheme (during the neighborhood discovery procedure), mobile nodes repeatedly transmit control packets during the whole preamble period (e.g.,125 ms), in order to assure that all neighbors in the transmission range will receive the control packet.

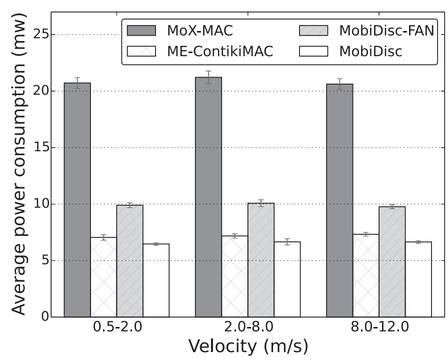
Regarding the case of end-to-end delay (i.e., from any mobile node to the sink station), the default operation of MobiDisc significantly improves the delay for all considered scenarios (i.e., velocities and topologies). Indeed, it reduces significantly the delay performance in high speed for both grid and random topologies. These results are logical, regarding the efficient next hop selection method that we presented in previous section, i.e., choosing a static node closer to the sink station. By doing so, we achieve to reduce the unnecessary transmissions in the network (i.e., traffic), and consequently to decrease the channel occupancy, the competition for medium access and the congestion, which in turn decreases the probability of packet retransmissions (that have a major impact on the delay performance) due to potential collisions. As a result, under MobiDisc scheme we achieve an essential improved communication in mobile WSNs.



(a) Average 1-hop delay, from mobile to any static node.



(b) Average end-to-end delay, from mobile to sink station.



(c) Average energy consumption.

Fig. 16. A thorough performance evaluation of MobiDisc (default and FAN modes) in terms of 1-hop and end-to-end delays, energy consumption and reliability, when compared against MoX-MAC and ME-ContikiMAC when used in random topology.

Table 5
Traffic analysis: total transmissions and collisions in grid scenario(values are in average).

Scenario	MoX-MAC	ME-ContikiMAC	MobiDisc-FAN	MobiDisc
Transmis.: 0.5 – 2.0 (m/s)	58258.40	44741.80	38528.78	37761.90
Transmis.: 2.0 – 8.0 (m/s)	57886.30	44473.90	38392.90	37583.20
Transmis.: 8.0 – 12.0 (m/s)	58165.50	44390.60	37978.22	38234.70
Collisions: 0.5 – 2.0 (m/s)	48156.50	2530.90	3430.33	1997.20
Collisions: 2.0 – 8.0 (m/s)	48054.40	2593.30	3305.30	2040.60
Collisions: 8.0 – 12.0 (m/s)	48054.40	2590.40	3331.44	2249.30

6.5. Energy consumption

In Figs. 15c and 16c the average energy consumption per second for the whole network is depicted. The results confirm that transmissions and receptions of packets have a straightforward impact on energy consumption. As can observed, MobiDisc consumes less energy network-wide when compared to ME-ContikiMAC, MobiDisc-FAN and MoX-MAC. Indeed, it reduces by up to 6%, 31% and 47.1% respectively.

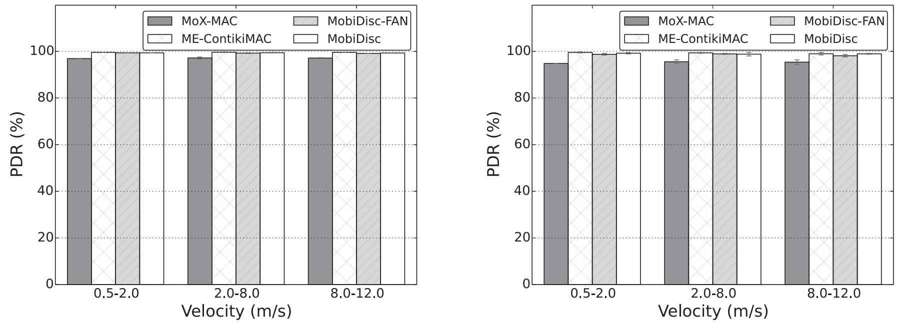
These results can be explained as follows. On the one hand, MobiDisc reduces the average number of hops toward sink Table 4, and thus, the total packet transmissions in the network (see Table 5) while, on the other hand, MobiDisc-FAN comes with high energy consumption due to its multiple CCA checks (i.e., five). Furthermore, MoX-MAC induce large number of collisions in the network, which increase the contention to the medium access, and thus, the retransmissions and congestion, see Table 5. Finally, we should take into account the fact that schemes such as MoX-MAC and MobiDisc-FAN are based on overhearing technique, which actually means the radio remains active for more time.

6.6. Reliability

Finally, Figs. 17a and 17b present the Packet Delivery Ratio (PDR) for both topologies. The results demonstrate that the optimization introduced by MobiDisc, along with MobiDisc-FAN version, does not impact the network reliability. As can be observed, both schemes present similar PDR performance when compared against ME-ContikiMAC.

6.7. Summary of evaluation

In this section, we evaluated to what extent the presented MAC layer schemes can enhance the management of versatile traffic in mobility-aware WSNs. We went over a thorough simulation campaign and observed a typical tradeoff situation between network performance and energy consumption, where depending the employed solution we may obtain either low energy consumption along with low end-to-end delay (i.e., MobiDisc) or low 1-hop delay (i.e., MobiDisc-FAN, ME-ContikiMAC) performance.



(a) Grid topology. (b) Random topology.

Fig. 17. Packet delivery ratio of MobiDisc (default and FAN modes), when compared against MoX-MAC and ME-ContikiMAC.

7. Conclusion and future work

In this paper, we investigated mobile-to-static link establishment and handover procedures which are imposed by link fluctuations and disconnections that frequently occur due to the movement of nodes in mobility-aware wireless sensor networks. We have studied some MAC protocols whose objectives are to coordinate the access to the wireless medium shared by several nodes. For mobile devices, the selection of next-hop static node should neither increase end-to-end delay nor energy consumption.

We have therefore proposed an enhanced neighbor discovery mechanism, MobiDisc. The default mode of MobiDisc leads to the discovery of the whole neighborhood while the FAN (First Ack Next-hop) mode allows quick and efficient transmissions. We have also introduced a Fast Recovering Mechanism (FRM) that can be activated in order to enable seamless handovers in the network. MobiDisc is compliant with any preamble-sampling family of MAC protocols. Our approach is generic enough to employ metrics from other layers of the communication stack (e.g.,number of hops to the sink obtained from the routing layer).

We have shown that both modes of MobiDisc (i.e., default and FAN) could help mobile nodes to perform efficient communications, in terms of energy, 1-hop and end-to-end delay. We compared MobiDisc (again with both default and FAN modes) against state-of-the-art solutions such as ME-ContikiMAC [2] and MoX-MAC [9]. Our performance evaluation over the COOJA simulator highlighted a fundamental trade-off between latency and energy consumption. On the one hand, low delays can be achieved by MobiDisc-FAN which discovers the full neighborhood before next-hop selection. On the other hand, this mechanism consumes more energy than the default mode of MobiDisc. In the same time, we show that MobiDisc does not impact network reliability or handover delay.

Our ongoing work consists of further investigating innovative handover schemes for mobile sensor networks. We also envision co-existing WSNs whose main operator would allow for handovers other than those imposed by node mobility. For instance, technology handover (e.g.,in case of multi-antenna devices), rescue handover (e.g.,upon failure of next-hop node), confinement handover (in case of congestion handling at upper layers) or traffic handover would require similar mechanisms to be proposed at the MAC layer in order to optimize reconnections and handover delays. We also plan to test our solutions under other mobility models that would be either more realistic or more adapted to some specific application scenarios.

Furthermore, our current works over the FIT IoT-LAB testbed[4] should allow for repeatable experiments that involve mobile nodes. Evaluating our performance over a real testbed that enables mobility is therefore a mid-term target for us. For these future investigations we plan to further assess MobiDisc by performing a set of experimental studies over the FIT IoT-LAB testbed [28].

[4] https://www.iot-lab.info/.

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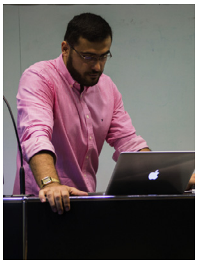

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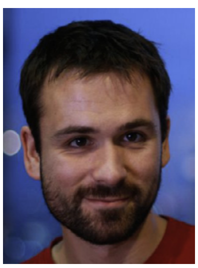

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