Journal of Network and Computer Applications ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at SciVerse ScienceDirect

Journal of Network and Computer Applications

journal homepage: www.elsevier.com/locate/jnca

A medium access control protocol that supports a seamless handover in wireless sensor networks

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ARTICLE INFO

Article history:
Received 31 January 2011
Received in revised form
24 September 2011
Accepted 10 November 2011

Keywords:
Handover
MAC protocol
Mobility
Latency
Neighbour discovery
Packet loss
Wireless sensor networks

ABSTRACT

This paper introduces a mobility-aware medium access control protocol for multi-hop wireless sensor networks (MA-MAC). The protocol evaluates the RSSI values of acknowledgement packets and determines whether a gradual deterioration in the RSSI values eventually leads to a disconnection. If it does, it initiates a handover by switching transmission from a unicast to a broadcast mode and by embedding neighbour discovery requests in the broadcast data packets. While the mobile node continues transmitting data packets via the existing link, the neighbour discovery requests enable it to discover new nodes that can serve as intermediate nodes. Once an intermediate node is found, the mobile node establishes a link with it and switches transmission back to unicast. Conceptually, MA-MAC's handover feature can be implemented by extending any of the existing transmitter initiated, energy-efficient protocols such as XMAC or BMAC. Our present implementation is based on the XMAC protocol. The paper reports how the protocol performs as the speed of mobility, handover threshold, and sending interval vary.

1. Introduction

Wireless sensor networks that accommodate mobile nodes have several applications. For example, they can be useful for monitoring and assisting the activities of patients (Dagtas et al., 2007) and nurses (Cheng et al., 2009) as well as elderly people (Tabar et al., 2006) and children (Dargie and Poellabauer, 2010). Typically, these networks should be able to allow nodes to move freely and interact with nodes they discover on their way.

However, these types of networks require frequent and dynamic reconfigurations to maintain the connection between the individual nodes. Most existing and proposed medium access control protocols support slow changes in the topology of the networks. They can fix a link when it is broken and accommodate when new nodes request to join the network. Protocols that synchronise sleeping schedules, such as SMAC (Ye et al., 2004) and TMAC (van Dam and Langendoen, 2003), enable nodes to exchange sleeping schedules at the beginning of each active period, before they begin with actual data communication. The idea is to enable nodes to update their knowledge about their neighbours. Preamble based protocols, such as XMAC (Buettner et al., 2006), enable newly arrived nodes to employ preamble packets to announce their presence to their neighbours. Receiver-initiated MAC protocols, such as RI-MAC (Sun et al., 2008) and A-MAC (Dutta et al., 2010), enable mobile nodes to listen to broadcast probes to discover potential receivers (relay nodes)—the receivers periodically send out short-duration probes whenever they are ready to receive packets from their neighbours.

Regardless of the way nodes join or leave the networks, the above protocols perceive a change in the surrounding of a node when it first begins an active period,[1] i.e., when it has completed a sleep period. Fig. 1 demonstrates the delay in packet transmission as a result of a slow perception in the change of a topology.

In the figure, a transmitter is communicating with the base station via an intermediate receiver (not shown here), but the link to the intermediate node is broken at time t_x due to the mobility of either the transmitter or the receiver or both. Three nodes, namely, Rx_1, Rx_2, and Rx_3, are located within the transmission range of the transmitter and can forward packets to the base station. The first receiver, which just completed its initial, pre-transmission task (in SMAC clock synchronisation; in RI-MAC and A-MAC, probe transmission) expects neighbours to initiate a communication, by addressing packets to it. Since the transmitter received neither a sleeping schedule nor a probe from Rx_1, it cannot communicate with it. The same is true to the second receiver. As to the third receiver, the transmitter has to wait until the node wakes up and updates it with its schedule or send out a

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[1] Almost all types of contention-based medium access control protocols in wireless sensor networks define a duty cycle ($D = activetime/(activetime + sleeptime)$, which is typically 10%) to enable nodes to sleep periodically, so that they can avoid idle listening and overhearing.

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doi:10.1016/j.jnca.2011.11.011

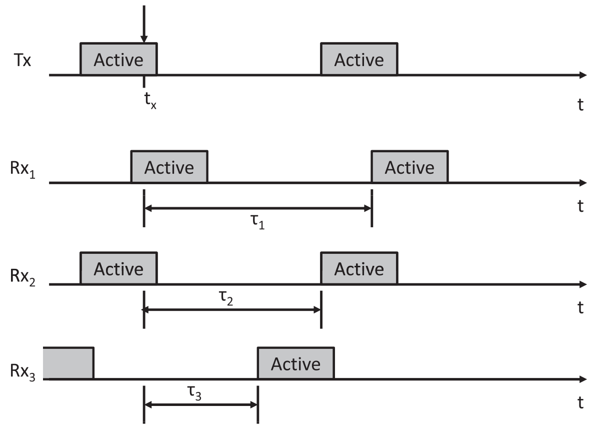

Fig. 1. The delay in packet transmission when a communication link is broken amidst transmission.

probe. In the first two cases, the transmitter can eavesdrop on the neighbours' communication to find out the address of the receivers, but this approach works if the receivers are actively communicating; if they are idle most of the time, it does not work.

A delay due to broken links can be critical for applications which should aggressively collect data for a short duration. The applications mentioned at the beginning of this section are typical examples. For instance, an application that monitors the activity of an elderly person may require to sample the walking pattern of the elderly at a high rate for a short duration without being interrupted. One way to achieve this is by enabling the mobile node to reserve the channel for this duration. Therefore, communication protocols are required that reconcile uninterrupted communications with the freedom of mobility.

This paper proposes a mobility-aware medium access control protocol (MA-MAC) that supports a seamless handover in wireless sensor networks. The protocol detects a gradual deterioration in a link quality and initiates a handover by switching packet transmission from a unicast to a broadcast and by embedding handover and neighbour discovery requests in the transmitted packets. The paper also reports the prototype implementation of the protocol. The prototype implementation extends the XMAC protocol implementation of the Unified Power Management Architecture (UPMA, Klues et al., 2007) and ports it to the MicaZ sensor platform.

The rest of this paper is organised as follows: in Section 2, related work is briefly summarised; in Section 3, the MA-MAC protocol as a concept is presented. In Section 4, the prototype implementation of the MA-MAC protocol is discussed. In Section 5, the evaluation of the protocol is presented. Finally, in Section 6, concluding remarks are given.

2. Related work

There is a substantial body of work on mobility and distance estimation in wireless sensor networks. Most approaches exploit RSSI or SNR measurements. Zaidi and Mark (2004) propose an autoregressive model to predict the mobility of a node from its past mobility history. It gives the mobility state of a node at the current time in terms of the position, velocity, and acceleration. But the model is computationally intensive. Farkas et al. (2008) apply cross-correlation and a pattern matching algorithm to predict link quality variations. The combined computation cost of correlation and pattern matching makes the technique likewise expensive. Ji (2004) apply multidimensional scaling and coordinate alignment techniques to estimate the position of nodes. However, their approach requires the presence of a large number of anchor (reference) nodes.

At a protocol level, MS-MAC (Pham and Jha, 2004) extends SMAC to support mobility. Each node discovers the presence of mobility within its neighbourhood based on the received signal strength of periodical SYNC messages from its neighbours. A change in signal strength is perceived to be due to the mobility of either the neighbour or the receiving node itself. The level of the change in the received signals is also related to the speed of the mobile node. This information is used to create an active zone around a mobile node when it moves from one cluster to another cluster, so that the mobile node can expedite connection set up with new neighbours before it loses all its neighbours. In the active zone, nodes run the synchronisation periods more often, resulting in higher energy consumption, but the time it takes to create new connections is lower. MS-MAC is not well developed and suffers from the same shortcomings of the SMAC protocol.

MMAC (Ali et al., 2005) is an extension to the TRAMA protocol (Rajendran et al., 2006). TRAMA is a distributed TDMA-based MAC Protocol in which the size of a frame as well as slot distribution takes place dynamically. The protocol divides a time frame into two parts: a random access period and a schedule access period. The random access period is used to collect neighbour information. Each node uses an adaptive election algorithm to determine the slot which can be used to transmit packets. The schedule access period is then used to announce the schedule and perform the actual data transmission. MMAC uses a probabilistic autoregressive model to predicate the mobility of two-hop neighbours. It adjusts the time frame and random access time according to the mobility of nodes. This protocol handles both weak mobility and strong mobility where nodes physically move through the network, however, the algorithm is computation intensive.

Our protocol (MA-MAC) extends the XMAC protocol—a contention based protocol, which divides a long preamble into multiple strobes to reduce the cost of preamble transmission. MA-MAC detects mobility through the received signal strength of ACK packets during communication and switches from a unicast to a broadcast communication to interleave data communication with neighbour discovery requests. Unlike all the protocols discussed above, MA-MAC recognises deterioration in a link quality while communication still takes place and attempts to seamlessly handover a communication to a better link.

3. Concept

Conceptually, when MA-MAC detects mobility while a transmission is not completed, one of the following conditions occurs:

1. The node completes transmitting all the data before a link breaks, and hence, there is no need to deal with mobility.
2. The node negotiates with the receiving node for dynamic rate adaptation, so that it can send all the data at a higher rate and complete transmission before the link breaks.
3. The node initiates and completes a handover before the link breaks.

These decisions require the link layer to rely on information that comes from the application, network, and physical layers. The application/network layer provides information pertaining to the size of the data. With it and additional information about the speed of travel and the transmission rate of the radio, it is possible to estimate the time required to transfer the data ($t_s = D_s/r$ and $t_s \leq \tau$; where D_s is the data size; r is the transmission rate; t_s is the time required to send the data; and τ is the remaining time before a link breaks).

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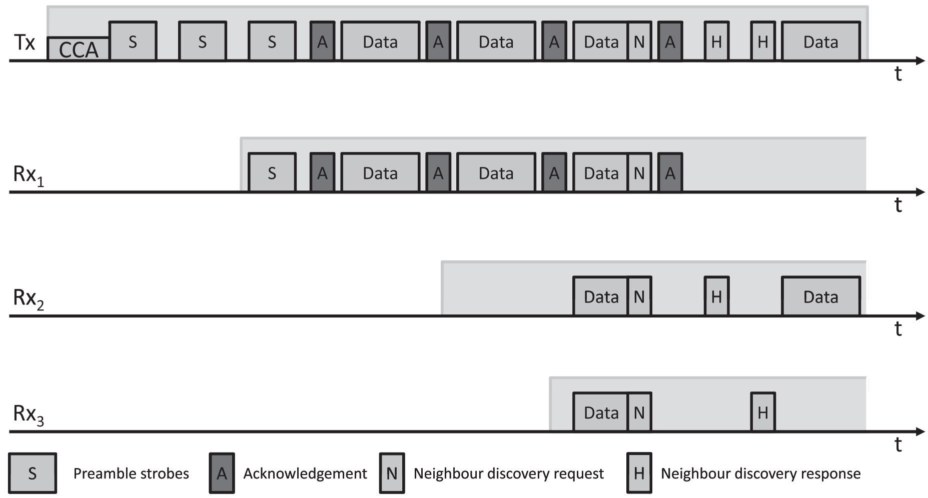

Fig. 2. Mobility mode for data transmission in MA-MAC.

The physical layer provides information about the transmission rates that can be supported by the radio. MA-MAC defines two distance thresholds to support a seamless handover. The first threshold prompts it to initiate a handover while the second threshold sets an upper limit to the distance that should be travelled before the mobile node has established a link with a new intermediate node (i.e., before a handover is completed). A handover process that cannot be completed before the second threshold is reached will be aborted. Between the two thresholds, MA-MAC broadcasts data packets in which handover requests are embedded.

The transmission mode of all nodes which participate in a handover process will be on broadcast to enable neighbour discovery and dynamic link establishment. Active neighbours which receive a handover request remain active to participate in the process and the sleeping nodes randomly wake up for a brief amount of time to participate in a handover. This wake up duration is markedly smaller than the active state defined by the duty cycle, and it is a tunable parameter that depends on factors such as delay, network density, and expected network lifetime.

The currently available wireless standards (for example, the IEEE 802.15.4, Karapistoli and Pavlidou, 2010) and their implementation (de Paz Alberola and Pesch, 2008) do not support rate adaptation in wireless sensor networks. Therefore, the main focus of the remaining part of this paper will be on the third aspect.

3.1. Data transmission

MA-MAC is a transmitter-initiated MAC protocol, i.e., a transmitter initiates a handover request. In a normal mode, it is similar to preamble-based LPL protocols. Our own implementation extends the X-MAC protocol, but one can also extend either B-MAC or WiseMAC (El-Hoiydi and Decotignie, 2004). The main difference between MA-MAC and the others is how a handover is supported. MA-MAC evaluates the RSSI of received acknowledgement packets during transmission and when it realises that a communication link is gradually deteriorating and the mean RSSI is below a set threshold, it undertakes the following tasks:

1. reminds the receiver that it is switching communication from a unicast communication to a broadcast communication;
2. embeds a neighbour discovery request in the broadcast packet; and
3. selects a new intermediate node and switches back to a unicast communication to resume transmission with it.

Neighbours which receive broadcast packets first check if it embeds a neighbour discovery request and whether they should participate in a handover process. Fig. 2 illustrates the mobility mode of MA-MAC during data transmission. After a clear channel assessment (CCA), the sender, *S1*, transmits a series of short preamble strobes until the receiver Rx_1 replies an acknowledgement (ACK). At this moment, *Tx* does not have enough mobility information to carry out mobility estimation. Therefore, it transmits data packets to Rx_1. Meanwhile, the mobility estimation scheme at the background evaluates the RSSI values of incoming ACK packets to estimate the mean RSSI. This value depends on the size of the queue, which in turn depends on the sampling rate, the speed of mobility, and the minimum distance that should be reached to initiate a handover. The protocol then decides whether or not a handover should be initiated.

In case a handover is necessary, the protocol enters into a handover state. In this state, *Tx* embeds handover requests in the outgoing data packets and transmit the packets in a broadcast mode. Upon receiving the first broadcast packet, Rx_1 as well as all the neighbouring nodes which receive the broadcast packets randomly back off before sending acknowledgement or discovery response packets to avoid collision. If there is no active node at the time, *Tx* resumes sending out handover requests until the second threshold is crossed. Following the first handover request (assuming the request is intercepted), Rx_2 and Rx_3 will send back handover response at a random. *Tx* picks up the first relay node (Rx_2 in Fig. 2) and communicate with it in a unicast mode. After a while, Rx_3 will realise that it has not been selected as a relay node since it has not received a unicast packet from the mobile transmitter. Therefore, it does not participate in the handover process any longer.

3.2. A finite state model

Fig. 3 illustrates the state of a mobile transmitter with a finite state machine having five states: sleep, receive, send, discover or handover.

Initially, the transmitter is found in a `sleep` state, after having successfully booted. It may wake up at any time if it has data to send, in which case it enters into a `send` state. It remains in this state until it has transmitted all pending data.[2] Another condition

[2] Not shown in the figure is the periodic transitions between send and receive states during the entire period of data transmission and the reception of acknowledgement packets.

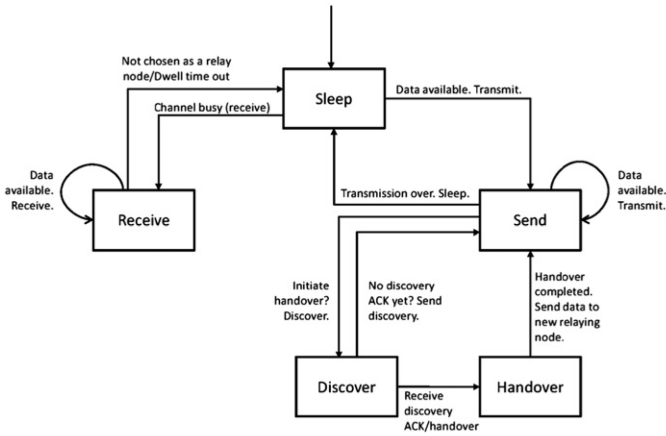

Fig. 3. The finite state machine of MA-MAC.

for leaving the sleep state is when the node either randomly wakes up to participate in a handover process or begins the normal active period. Both conditions cause it to transit into a `receive` state—the former only for a brief amount of time. If a transmitting node detects that either the receiver or itself has crossed the first mobility threshold, it enters into a `Discovery` state in which the transmitting node searches for an alternative neighbour before the actual link breaks. If it receives ACK packets from a neighbour before it reaches the second mobility threshold, it enters into the `Handover` state to establish a link with the newly discovered node and to update its routing configuration. If the node cannot discover any neighbouring node, it sends out discovery packets until the second mobility threshold is crossed. If the handover attempt is unsuccessful by then, it enters into a sleep state (this is not shown in the figure). Otherwise, it enters into a send state to resume unicast transmission via the new intermediate node.

3.3. Mobility model

Our mobility model takes human activities and movements into account. The movement of people in most places can be characterised as an intermittent and slow movement (approximately 1.5 m/s). In rehabilitation centres and hospitals the movement of people is slower (0.5 m/s). Physical surroundings and the presence of other people around constrain mobility. Hence, the model we consider makes the following assumptions:

1. The deterioration of a link quality due to mobility is a gradual but a steady process; and
2. Mobile nodes are surrounded by some quasi-static nodes.

Similar to all low duty cycle MAC protocols, MA-MAC enables a node to sleep most of the time and periodically switch on the radio to listen to incoming packets. It has two operational modes: static and mobile. In the static mode, MA-MAC performs similar to XMAC. When it operates in a mobile mode, however, the RSSI values of the incoming ACK packets are evaluated to assess the quality of a link. If a mobile node crosses the first threshold, the transmitter begins to embed handover requests into the MAC protocol data unit (MPDU), sets the address to broadcast mode and sends the data packets in this fashion until an acknowledgement is received from a neighbour node.

3.4. Mobility estimation

Even though precise information concerning the mobility of a node is not required to support a handover, a transmitter should make a credible estimation of the deterioration in the quality of a link and where this deterioration eventually leads. Like most decisions in wireless sensor networks, this requires a trade-off between delay, energy consumption, and the required level of processing. Complex mobility estimation techniques usually do not provide satisfying results in a short period of time. On the other hand, simple estimation techniques are quite inaccurate and unreliable, often leading to unnecessary oscillations. An example of such a model is the one proposed by Texas Instruments for the Chipcon CC2420 radio (de Paz Alberola and Pesch, 2008)

$$RSSI = -(10\gamma \cdot \log_{10} d + A) \quad (1)$$

where γ is the signal's propagation constant; d is the distance between the transmitter and the receiver; and A is the received signal strength of a line-of-sight link at a 1 m distance. The main problem with this model is its disregard of the impact of multipath scattering and non-uniform propagation. This is particularly the case in indoor environments. Furthermore, repeated experiment shows that even though the surrounding setting does not change, the placement of nodes in the mobile objects (body) significantly affects the propagation patters of electromagnetic signals.

Fig. 4 displays two sets of measurements and their corresponding cumulative distribution functions taken from an ankle and a waist during a slow movement of a person. In both cases, the receiver was placed on a table which had a height of 1 m from the floor. Both measurements were taken on a corridor in which a significant portion of the propagated signal has a line-of-site (LOS) communication link (a Reighlay channel). The user approaches the receiver from a distance of 27 m up to a distance of 5 m with an approximate velocity of 1.5 m/s. In the case of the measurements from the ankle, both the fluctuation rate and magnitude of the RSSI values were low, but the average RSSI value was low as well (modelling the variation of the RSSI values as a random variable X yields: $P(X \geq -80\ \text{dB m}) = 1 - P(X \leq -80\ \text{dB m}) = 0.3$ for $27\ \text{m} \leq d \leq 10\ \text{m}$). This is shown by the CDF in Fig. 4. In contrast, a high fluctuation was observed when the transmitter was placed at the waist, but the average RSSI value was comparatively high ($P(X \geq -80\ \text{dB m}) = 1 - P(X \leq -80\ \text{dB m}) = 0.8$ for $27\ \text{m} \leq d \leq 10\ \text{m}$). This knowledge is useful to define the two handover thresholds.

Fortunately, MA-MAC does not need precise distance information to initiate a handover. It suffices to estimate whether a gradual deterioration of a link's quality eventually leads to a disconnection. Therefore, instead of applying existing or proposed models, we concentrated on finding out the mean received signal strength (RSSI) below which the communication link becomes poor. Repeated experiment confirms that for the CC2420 radio, the packet arrival rate dramatically falls below −85 dB m. A similar study at Stanford University (Srinivasan et al., 2008) set this threshold at −80 dB m. Latter in the Evaluation section (Section 5), it will be shown how the packet arrival rate is affected for two handover thresholds, namely, −30 dB m and −40 dB m. These two thresholds were selected so that the transmitter could complete a handover before the link quality reached −80 dB m.

4. Implementation

As mentioned before, MA-MAC extends the Unified Power Management Architecture (UPMA) implementation of the XMAC protocol (Klues et al., 2007). Thus, it inherits several features of the TinyOS message header – frame length, frame control field, data link sequence number, and address – and introduces additional control headers to support a handover. A higher-level

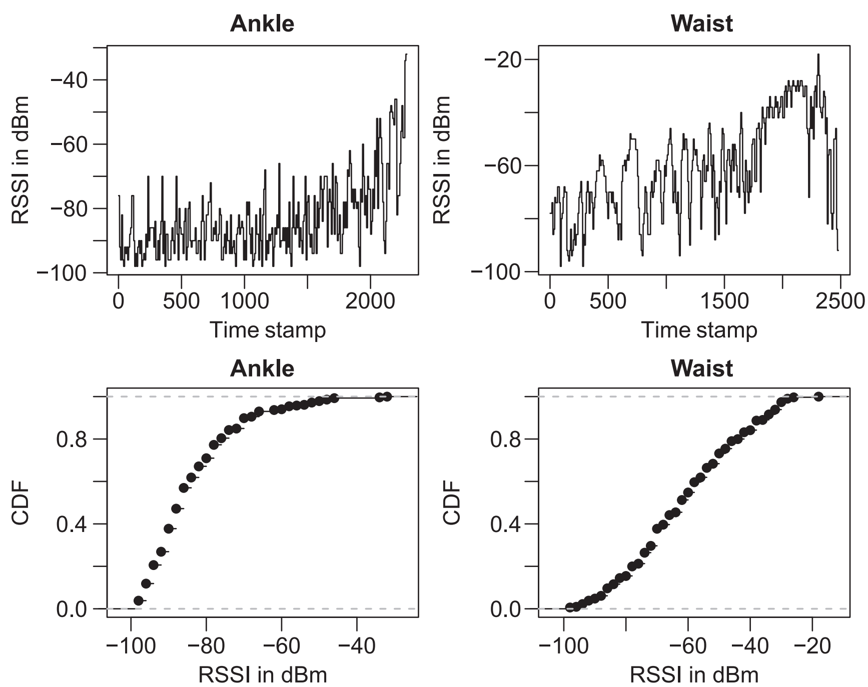

Fig. 4. The impact of position on the fluctuations of the RSSI values obtained from acknowledgement packets during mobility. The figures above display the raw measurements while the ones below display the cumulative distribution functions (CDF) of the raw measurements.

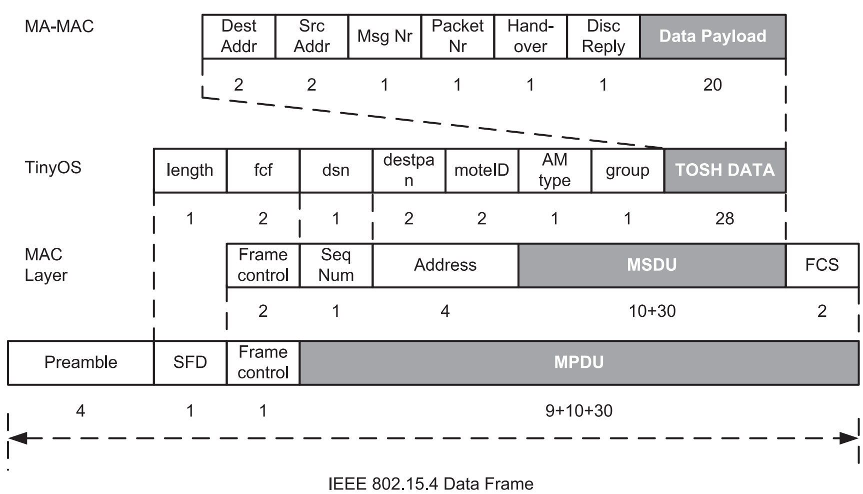

Fig. 5. Placement of the MA-MAC header in the TinyOS radio stack.

protocol implementation is shown in Fig. 5. Even though the IEEE 802.15.4 frame specification permits 4–20 bytes of the address field, this is fixed at 4 bytes in the TinyOS implementation. Since the `moteID` in a TinyOS message refers to the destination address, in MA-MAC, the source node's address is embedded in the `TOSH_DATA` field. Moreover, TinyOS defines the default size of a message payload to be 28 bytes. During a handover, seven of these bytes are used to embed a handover request, i.e., the handover control fields.

We ported the UPMA implementation onto the Micaz platform, as the presently available UMPA implementation runs on the TelosB platform. This includes porting the code that runs on the MTS Serial Microcontroller to ATmega128 Serial Microcontroller.

`Dest addr` and `Src addr` are used to identify the message which may be split into several packets. The `MsgNr` field is used to re-construct individual received packets into a complete message. The `PacektNr` indicates the order of the packets. The Boolean field `Handover` is useful for an implicit neighbour discovery request. If the `Handover` field is TRUE and the destination address is not the same as the local node which receives the data packet, this local node would reply to the discovery request and keep its radio on until a confirmation packet from the handover initiating node arrives. Once a handover is completed, the `Handover` field is set back to FALSE. The `Disc_Reply` field is a Boolean field and serves as a response to a handover (neighbour discovery) request. When a nearby neighbour replies to the handover request, it sets this field as TRUE and leaves all the other bytes empty.

The Micaz platform integrates an IEEE 802.15.4 compatible radio that employs a digital direct sequence spread spectrum baseband modem and provides a spreading gain of 9 dB and an effective data rate of 250 kbps (de Paz Alberola and Pesch, 2008). A TinyOS implementation of this hardware consists of many layers that reside between the application and the radio hardware. The

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higher-level components in the radio stack modify the data and control headers in each packet as it progresses towards the low level components.

The link layer relies on `Active Messages`, which are packets that specify a handler ID in their header. They are called so because they trigger the invocation of a named handler upon receipt, pre-empting any ongoing computation. The active messages provide an unreliable single-hop datagram service. We keep this layer as the highest layer in our implementation. The `CSMA (Carrier Sense Multiple Access)` layer is responsible for defining IEEE 802.15.4 FCF (Frame control Field) byte information in outgoing packets. It provides a default back-off time when the radio detects a channel in use and defines the power-up/power-down procedure for the radio. We keep this as the lowest layer in our implementation to connect to the radio hardware via the `ReceiveP` and `TransmitP` components.

Between the `Active Message` layer and the `CSMA` layer, we inserted the `MA-MAC` layer. This layer consists of the modules which are responsible for low power listening, mobility estimation, work mode adaptation and data link handover.

5. Evaluation

The main aim of a seamless handover is to avoid interruption during packet transmission. The achievement of this aim depends on factors such as mobility, transmission rate, and the handover thresholds. Apparently, the extent to which these factors affect successful handover in turn depends on other factors such as node density, the energy constraint of individual nodes (since this affects the duty cycle of nodes), and the matching in sleeping schedules of the cooperating nodes. A comprehensive evaluation of the protocol with respect to all these factors is out of the scope of the paper.

Therefore, the initial evaluation focuses on examining the effect of mobility, sending interval and handover thresholds on packet loss and delay for a fixed network set up. Six Micaz sensor nodes were used in the experiment. One of these nodes was connected to a laptop computer and served as a base station. Three of the nodes were placed along a straight line (L1) that was about 20 m away from the base station. Two mobile nodes moved beyond a straight line (L2) which was either 20 or 40 m away from L1. The length of L2 was about 60 m. Fig. 6 shows the experiment setting.

The nodes establish a 2-hop network in which intermediate nodes were chosen based on the quality of links they establish with the mobile nodes. We carried out the experiment first without a handover mechanism and then with the handover mechanism. We consider the following parameters: sending interval = 30 ms and 250 ms; speed of mobility = fast and slow movements; and distance of communication, when L2 was 40 m away from L1 and when L2 was 20 m away from L1. The relationship of each parameter with the average RSSI was examined by keeping all the other parameters constant. The experiment parameters are summarised in Table 1.

The mobile nodes moved in and out of the communication range of the static nodes while sending and receiving data packets. When the received signal strength was below the set thresholds, the mobile nodes initiated a handover. In order to focus on the handover strategy, we disabled some of the features of the MA-MAC protocol, such as periodic sleeping. Moreover, we separated data transmission into sending and receiving features. The intermediate nodes and the base station were deployed with both features enabled, i.e., they could send and receive data packets whereas the mobile nodes were deployed with only the sending feature enabled, i.e., their purpose was to generate and transmit data packets only (though this is done with an acknowledgement). Lost packets were not retransmitted.

Table 2 shows the memory footprint of the application code, according to the features that were enabled. Because the intermediate

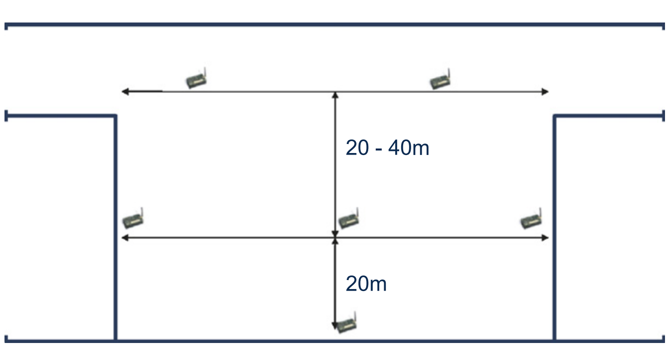

Fig. 6. Experiment setting.

Table 1
Experiment parameters.

Parameter	Values
Distance (m)	20, 40
Sending interval (ms)	30, 250
Mobility (m/s)	0.5 (slow), 1.5 (fast)

Table 2
The memory footprint of the motes in the experiment.

Role	ROM (Bytes)	RAM (Bytes)
Base station	15 244	1726
Relay station	12 178	956
Mobile node	12 368	314

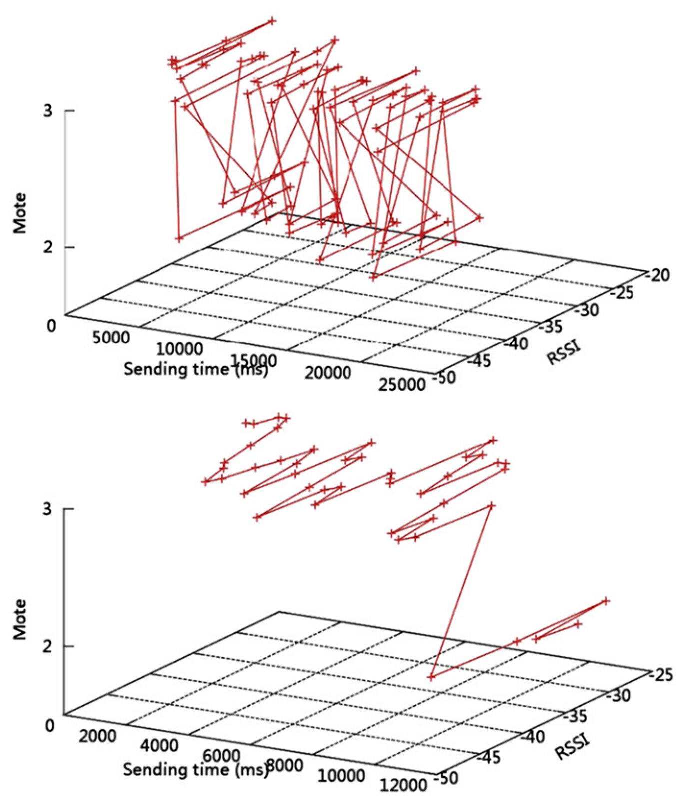

Fig. 7. Handover without the oscillation avoidance mechanism implemented (top) and when the oscillation avoidance mechanism was implemented (bottom).

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nodes managed a queue, their RAM usage was larger than the mobile nodes. The base station had the largest RAM usage, because it managed two queues: one for the wireless link and the other for the serial port.

5.1. Oscillation

One of the problems of relying on a simple handover model, such as the one discussed in Section 3, is that the handover oscillation is high. From Fig. 4, it is evident that the RSSI values fluctuate quite often, leading to frequent false positives. In fact, the RSSI values oscillate even when there was no actual mobility taking place. Therefore, we take advantage of knowledge of human mobility to deal with false positives. By assuming that a minimum distance of 1 m should be travelled before a change in a link quality warrants a handover, we managed to reduce false positive significantly. Hence, for a fast movement (1.5 m/s), the mean RSSI values of the last 0.6 s were considered, whereas for a slow movement (0.5 m/s), the mean RSSI values of the last 2 s were considered. Note, however, that the number of samples in these time windows depend on the sending intervals. Fig. 7 shows the difference between handover oscillations without and with the oscillation avoidance mechanism, respectively.

5.2. Packet loss

We investigated the packet loss due to a handover by varying the experiment parameters listed in Table 1. We realised that the packet loss was not much affected by the speed of mobility as it was affected by the sending interval and the handover threshold. Moreover, packet loss was relatively insensitive to both the speed of travel and the sending interval when the handover threshold was −30 dB m, but when the handover threshold was −40 dB m, both parameters affected the packet loss. Fig. 8 shows the packet loss when packets were sent at 250 ms interval; the first RSSI threshold was −40 dB m and the speed of travel was

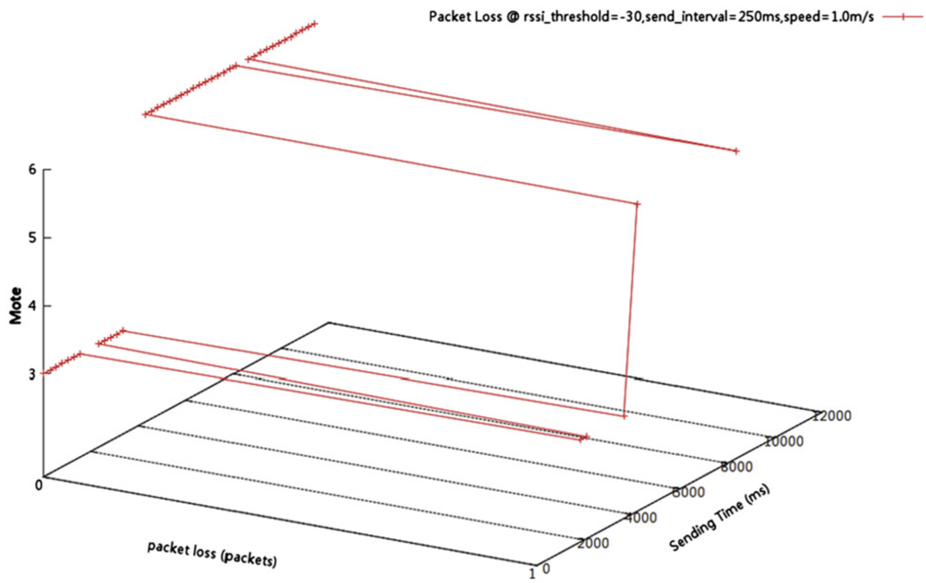

Fig. 8. Packet loss with the sending interval = 250 ms; the RSSI threshold = −40 dB m; speed = 0.74 m/s; and distance = 20 m.

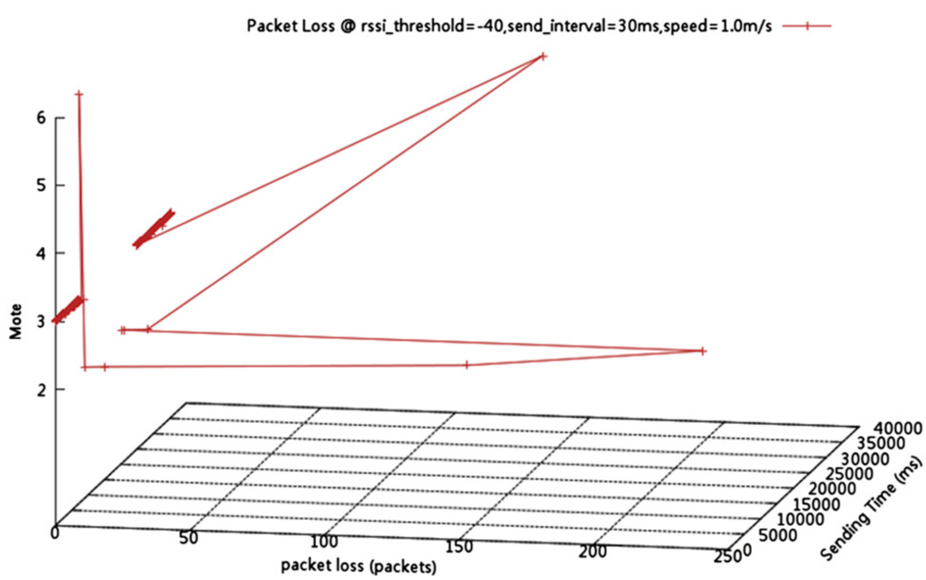

Fig. 9. Packet loss with the sending interval = 250 ms; the RSSI threshold = −30 dB m; speed = 1.62 m/s; and distance = 20 m.

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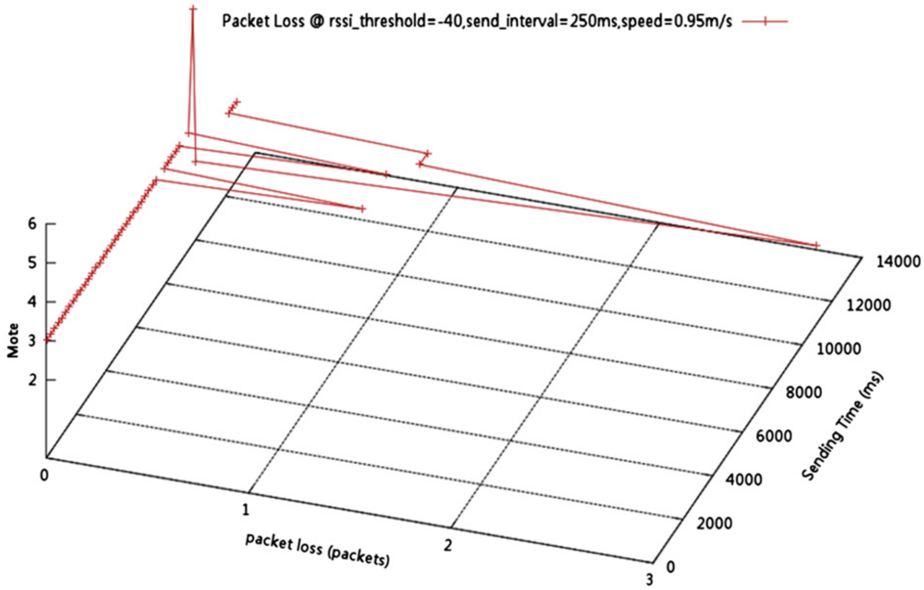

Fig. 10. Packet loss with the ending interval = 30 ms; the RSSI threshold = −40 dB m; speed = 1.76 m/s; and distance = 40 m.

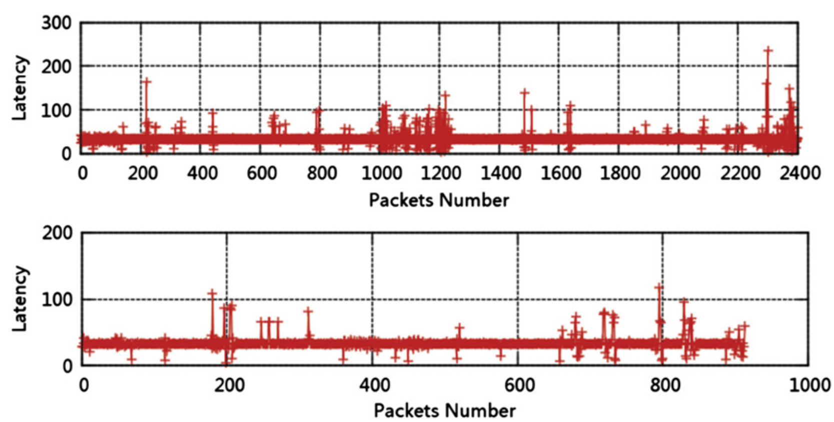

Fig. 11. Latency (in ms) in packet delivery for a handover threshold = −30 dB m. Above: slow movement (app. 0.5 m/s). Below: fast movement (app. 1.5 m/s).

approximately 0.74 m/s. The *x*-axis shows the number of unaccounted packets while the *y*-axis shows the ID of the nodes between which a handover took place, and the *z*-axis shows the sending interval in ms. Fig. 9 demonstrates how the packet loss was not much affected by the speed of mobility as much as it was affected by the sending interval. The worst case was observed when the two significant factors (the handover threshold and the sending interval) were set to −40 dB m and 30 ms, respectively. This is shown in Fig. 10. From this observation, it can be concluded that the packet loss can be reduced by lowering the sending interval for a lower handover threshold. One can alternatively increase the sending interval for a higher handover threshold.

5.3. Latency

Figs. 11 and 12 display the delay in packet arrival for different scenarios, namely, when the initial handover threshold was −30 dB m and −40 dB m; and when the mobility was slow and fast. We obtained the packet arrival time by subtracting the packet received time from the packet transmission time. When the sending interval was 30 ms, the average end-to-end delay between two successive packets was approximately 30 ms without a handover. Remarkably, slow movements experience the worst delay. About 0.05% of the packets transmitted had an end-to-end delay greater than 50 ms for the slow movements when the handover threshold was −30 dB m; 0.007% of them had a delay greater than 100 ms. This figure reduced to 0.024% and 0.002%, respectively, when the handover threshold was −40 dB m. Understandably, the mobile nodes began a handover initiation early and made repeated attempts to discover neighbours when the handover threshold was −30 dB m and the movement was slow. For the fast movements, 0.03% of the packets had a latency greater than −50 ms and 0.002% had a latency greater than 100 ms when the handover threshold was −30 dB m; only 0.04% of the packets had a delay greater than 50 ms and none of the packets had a latency greater than 100 ms when the handover threshold was −40 dB m.

6. Conclusion

In this paper, a mobility-aware MAC protocol (MA-MAC) is introduced to support a seamless handover in a multi-hop communication in wireless sensor networks. The protocol estimates mobility by examining the deterioration in the received signal strength of acknowledgement packets.

Through an exhaustive experiment, it has been realised that a link quality often deteriorates drastically for a mean RSSI value

Please cite this article as: Dargie W. A medium access control protocol that supports a seamless handover in wireless sensor networks. Journal of Network and Computer Applications (2011), doi:10.1016/j.jnca.2011.11.011

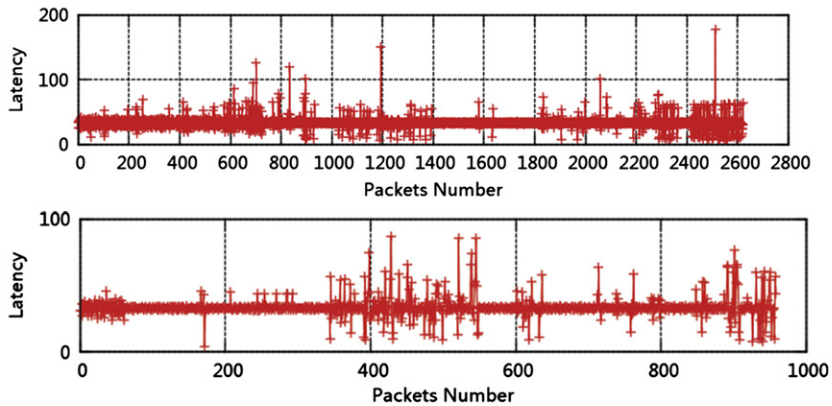

Fig. 12. Latency (in ms) in packet delivery for a handover threshold = −40 dB m. Above: slow movement (app. 0.5 m/s). Below: fast movement (app. 1.5 m/s).

that was below −85 dB m. Therefore, a handover request was initiated before this value was reached. We experimented with two initial thresholds, namely, −30 dB m and −40 dB m. When the handover thresholds are crossed, MA-MAC changes packet transmission from unicast to broadcast and embeds a neighbour discovery request into the broadcast packet. The broadcast packet is received by the existing intermediate node (with the deteriorating link) as well as by the new nodes on the way, which can provide relay support to the mobile node. This way, MA-MAC maintains uninterrupted packet transmission. The implementation of MA-MAC extends UPMA's implementation of the XMAC protocol (developed by Klues et al., 2007). The performance of the MA-MAC protocol was evaluated by varying the speed of mobility, the handover threshold, and the sending interval. High delay was observed when the handover threshold was −30 dB m, the sending interval was 30 ms, and the movement was slow.

Acknowledgement

The author wishes to acknowledge the contribution of Mr. Tang Zhiyong for the partial implementation and testing of the protocol.

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Please cite this article as: Dargie W. A medium access control protocol that supports a seamless handover in wireless sensor networks. Journal of Network and Computer Applications (2011), doi:10.1016/j.jnca.2011.11.011