Performance Analysis of a Handover Mechanism for a Mobile Wireless Sensor Network

Qian Dong and Waltenegus Dargie
Chair of Computer Networks, Faculty of Computer Science, Technical University of Dresden, Germany, 01062
Email: qian.dong, waltenegus.dargie@tu-dresden.de

***Abstract*—Several applications have been proposed for mobile wireless sensor networks. Some of these applications require the transfer of a large amount of data in a short period of time. This is challenging, since the mobile node may be required to repeatedly establish a link with multiple relay nodes which proceed to forward the data to the base station. Apart from the technical difficulty mobility may cause, there is an associated latency to the data transfer. One way to deal with the problem of latency is to timely foresee the deterioration in the quality of a link and to seamlessly transfer the communication to a more stable link. This paper extends the RI-MAC protocol to support a seamless handover. Once a mobile node realizes that its data packets cannot be completely transmitted before an existing link breaks, it will search for a new relay node without interrupting the communication with the current node. The paper sets up a mathematical model to investigate the latency associated with a handover. The analytic model quantifies the handover latency as a function of the network density and the duty cycle.**

***Index Terms*—MAC protocols; wireless sensor networks; mobility; handover; medium access control;**

I. Introduction

Wireless sensor networks that support the mobility of nodes are applied in several applications [3]. For example, they are useful for supervising post-surgery rehabilitation (recovery from a hip or knee replacement) [2]); for diagnosing dyskinesia symptoms of patients in Parkinson Disease (PD) [8]; for monitoring and controlling the behavior of animals (such as grazing pattern and aggressive temperament) [9], and for detecting oil spills and avoiding toxic gases in refieries [1].

These applications consist of nodes attached to mobile persons, animals, or objects as well as static nodes assisting the mobile nodes to deliver the sensed data to the base station over a multi-hop link. Some of the applications are delay sensitive. For example, the wireless sensor network proposed by Sikka et al. [9] monitor the temperament of bulls using GPS, accelerometer, and compass and generate an audio and a vibration feedback to prevent bulls from fighting. Another characteristic of these applications is that they require the transfer of a large amount of sensed data. For example, the healthcare application proposed by Lorincz et al. apply a sampling rate of 50 KHz from 3D accelerometer sensors to detect PD and epileptic symptoms in patients [8]. Kim et al. also emphasize the need for oversampling to compensate for the effect of noise and high packet loss in harsh surroundings [7].

A MAC protocol dealing with mobility is faced with multiple critical requirements. To begin with, it should enable a mobile node to establish a link with a static node as quickly as possible (to reduce the packet transmission latency). Secondly, it should reduce the cost of frequent disconnections and link establishments due to mobility. Thirdly, it should enable the transfer of a large amount of packets once a link is established and before it breaks. Fourthly, it should contribute to the optimization of the overall lifetime of the network. None of the existing or proposed MAC protocols fulfil these requirements in their entirety.

An adaptive handover mechanism can partially overcome these challenges. Ideally, it should enable a transmitter node to predict the change in the quality of a link and to bind to a relay node with a better communication link. In this paper, such a mechanism is proposed. It is implemented by broadcasting a data packet in which a neighbour discovery request is embedded. We have developed a mathematical model to investigate the factors that may affect the success of a handover. The paper makes three contributions: (1) the handover mechanism enables to transmit data packets with a minimum delay, (2) data transmission does not significantly interfere with neighbour discovery and vice versa, and (3) the handover mechanism is triggered only when necessary – hence, it does not influence the performance of the MAC protocol in a static setting.

The remaining part of this paper is organized as follows: in Section II, RI-MAC and its optimization are described. In Sections III and IV, the handover mechanism is presented and its performance is evaluated. In Section V, the result is visualized and the observations are discussed. Finally, in Section VI, concluding remarks are given.

II. Selection of a Hybrid MAC Protocol

A. RI-MAC

We choose the Receiver-Initiated MAC protocol (RI-MAC [10]) to introduce a seamless handover. In RI-MAC, the receiver initiates a communication by broadcasting a beacon whenever it completes its sleep period, thereby avoiding the need for the transmission of long preambles by transmitters. This approach reduces the energy consumption of nodes and simplifies the design complexity of the MAC protocol.

After receiving a beacon, potential transmitters compete for the media. As a result, if two or more transmitters send packets simultaneously, collision will occur, leading to another beacon transmission by the receiver. The second beacon additionally contains a back-off window field (BW) to reduce the collision

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probability of future packets. If a transmitter wins the channel, the receiver will reply with an ACK beacon (DST) serving as the acknowledgement. However, if no packet is received within a specified dwell time after a beacon is transmitted, the receiver will go to sleep. In RI-MAC, the dwell time is proportional to the BW value in beacons. Since the BW value is automatically adjusted according to the contending senders, so is the dwell time.

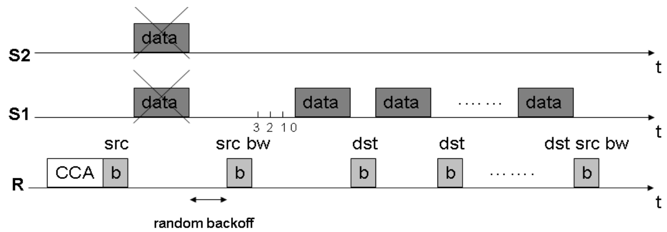

Fig. 1. Optimization on top of RI-MAC

Even though RI-MAC achieves efficient channel utilization and high packet delivery ratio, it has some demerits. Firstly, in a round of transmission, the BW size in beacons never decreases. Instead, it either remains unchanged or keeps increasing whenever a collision is detected. This may lead to a large back-off window. Therefore, a sender has to remain idle for a long period of time before it can transmit data packets. Secondly, a receiver is unable to receive any data packet during a dwell time may also because of an unsuccessfully transmitted beacon instead of an idle channel. Consequently, it may happen that a receiver has to go to sleep although there are transmitters wishing to communicate with it.

B. Optimization of RI-MAC

To slow down the monotonous increment of BW size and to reduce the probability of a dwell time, we propose to use a burst transmission pattern of data packets. Thus, instead of competing for a media to send just a single packet, a node transmits a pre-defined number of packets in burst. The beacon between two data packets is only set as acknowledgement, as shown in Figure 1. By intercepting the ACK beacons, competing neighboring will realize that the medium is currently occupied and will refrain from attempting to seize the channel. The burst transmission may be unfair, but it is efficient in terms of latency and energy consumption.

III. The Handover Mechanism

Handover, as the process of transferring data communication from one sensor node to another without breaking the original link [6], is necessary to be triggered when an existing link deteriorates in the middle of data transmission. In order to justify a handover, the duration of data communication should be comparatively long and the probability of link disconnection should be reasonably high. RI-MAC in its optimized condition meets both requirements.

A. Working Mechanism

In our approach, a pre-defined distance threshold d is used to begin a handover. Figure 2 summarizes a handover process. Once a transmitter, $S1$, seizes the medium, it will transmit a burst of data packets. Based on the first w ACK beacons received from the intended receiver, $R1$, $S1$ can deduce the relative distance between $R1$ and itself. The distance can be evaluated via multiple location estimation techniques (such as RSSI, GPS and accelerometer based approaches) [5]. If the distance is calculated to be larger than d, $S1$ will learn that its remaining data packets cannot be completely transmitted before the link breaks. As a result, it will search for a new relay node without interrupting the communication with the current one. This is implemented by broadcasting a data packet in which a handover request is embedded.

$R1$ will learn that $S1$ is searching for a new relay node after it receives the handover request. Although $R1$ is the original receiver, it is necessary for it to reply with an ACK beacon. This ACK beacon acknowledges the correct data receipt regardless of the handover success. However, not all of the other neighbors of $S1$ will send back handover replies. Instead, only those waking nodes whose distance with respect to $S1$ does not exceed d are qualified. This ensures that once the transmitter transfers the communication to a newly discovered receiver, its remaining data packets can be completely transmitted before the new link breaks. In other words, handover will be triggered at most once during a node's data transmission.

If the neighbors of $S1$ are active, they will definitely receive the handover request. This is because $S1$ will broadcast a beacon as soon as it wakes up and detects a free medium. But in case of a busy medium, the node has to keep listening to the channel during which it will overhear the handover request. This characteristic directly determines the number of handover replies that may be transmitted simultaneously. In order to avoid collision, a node will do a back-off by randomly choosing a value ranging from 0 to BW slots. Unlike the back-off field in beacons whose value is variable, the size of BW is the same in all the handover requests. The node which chooses the smallest value will win the medium and will be regarded as the new receiver. However, if $S1$ does not receive any handover reply until BW expires, it will initiate another handover attempt. As soon as a new link is established, $S1$ will resume its data transmission with the newly found receiver, $R2$, in a unicast way. By overhearing the data packet between $S1$ and $R2$, the original receiver, $R1$, will enter into a sleep state.

B. Determination of the Distance Threshold

We suppose n data packets are transmitted in burst. Among them, the first w packets are used to obtain the first w ACK beacons to estimate the distance. Then $(n-w)$ data packets are left for the transmission. The distance a node travels during this time can be variable depending on different moving styles. However, most of the mobility models which generalize the movement characteristic from real applications verify that a node usually changes its direction and speed once the time

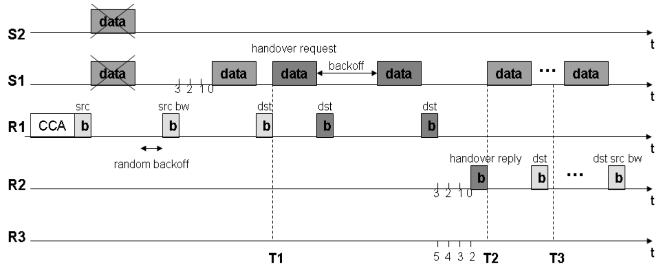

Fig. 2. Working principle of the handover mechanism

TABLE I
DESCRIPTION OF PARAMETERS

i	The maximum handover attempt
p_j^f	The probability that the node is unable to transmit a handover reply in the first j attempts
p^s	The probability that the node is able to transmit a handover reply
t_j^f	The time consumed in the j_{th} handover attempt that fails
t_j^s	The time consumed in the j_{th} handover attempt that succeeds
j	The index of a handover attempt ($j \in (0, i)$)

expires or the maximum permitted distance is reached [5]. Therefore, by assuming a node moves at a uniform speed v along the radius of the radio transmission range, R, of its partner, the distance threshold d can be defined as:

$$d = R - (n - w)\left(\frac{N_{data}}{R_t} + \frac{N_b}{R_t} + 2T_{SIFS}\right) v \qquad (1)$$

Here, the parameters N_{data}, N_b, R_t and T_{SIFS} denote, in respective order, the data packet size, the ACK beacon size, the transmission rate, and the time to switch the radio from transmitting to receiving mode or the other way around.

IV. PERFORMANCE ANALYSIS OF THE HANDOVER MECHANISM

Suppose the number of neighbours[1] of the transmitter excluding the original receiver is N. Among the N neighbors, only those which have already been active and whose distance with respect to the transmitter does not exceed d can attempt to send back a handover reply. If the number of these nodes is greater than one, a collision may occur on the handover replies. In order to obtain an accurate expression, the handover latency should be analyzed differently for different values of N. If only a single neighbor is present, collision will not occur on the handover replies. However, a handover may still fail because (a) the node has not entered into a listen period yet, or (b) the distance the node estimates is larger than d. If the transmitter does not receive any reply during the BW interval, it will immediately broadcast another handover request. This attempt continues until a handover reply is eventually received by the transmitter. The average duration of the handover process for a single neighbor, $\overline{t_{N=1}}$, can be expressed as:

$$\overline{t_{N=1}} = \frac{p^s t_1^s + \sum_{j=1}^{i-1}\left(p^s p_j^f (t_1^f + \cdots + t_j^f) + t_{j+1}^s\right)}{p^s(1 + \sum_{j=1}^{i-1} p_j^f)} \qquad (2)$$

The explanation for all the parameters in Equation 2 is explained in Table I. Since the value of p^s is the product of the probability that a node is awake ($p_a = D$ where D is the duty cycle) and the probability that the estimated distance does not exceed the threshold ($p_d = \frac{\pi d^2}{\pi R^2}$), p^s can be quantified as: $p^s = D\frac{d^2}{R^2}$. The duration of a handover process (with a success or a failure) has nothing to do with the number of attempts, thus t_j^f and t_j^s can be replaced by t^f and t^s, respectively. As illustrated in Figure 2, these two variables can be expressed as:

$$t^f = \frac{N_{request}}{R_t} + t_{SIFS} + \frac{N_b}{R_t} + BW\sigma \qquad (3)$$

$$t^s = \frac{N_{request}}{R_t} + t_{SIFS} + \frac{N_b}{R_t} + \frac{N_{reply}}{R_t} + t_l^{backoff} \qquad (4)$$

The parameters $N_{request}$, N_{reply}, σ and $t_l^{backoff}$ denote, in respective order, the size of a handover request and a handover reply, a slot duration, and the average backoff interval determined by l nodes. Here l is the number of active neighbours whose distance to the transmitter does not exceed d. Since the back-off time has different values when a collision occurs and when it does not occur, $t_l^{backoff}$ should be evaluated separately for $N = 1$ and $N \geq 2$. As only one neighbour exists in this situation, $l = N = 1$. Therefore, $t_l^{backoff}$ should be evaluated as:

$$t_{l=1}^{backoff} = \frac{\sum_{m=1}^{BW}(m\sigma)}{BW} \qquad (5)$$

In Equation (2), the coefficient p_1^f, as the weight for calculating the duration of the handover process which fails in the first attempt, can be expressed as $(1 - p_a p_d)^1$. However, p_j^f cannot be described as $(1 - p_a p_d)^j$ when $j \in (1, i)$. This is because the term $(1 - p_a p_d)^j$ implies that in each of the first j attempts, the failure of the handover is a result of either one or both of the reasons discussed above (see the second paragraph of this section). Therefore, one of the reasons that can lead to a handover failure is that the node is in a sleep state in the first handover attempt, wakes up in the second attempt, and enters into a sleep state again in the third attempt, etc. This, however, does not make sense. Since the duration of a handover process is much shorter than the listen and the sleep phases, transition from an active to a sleep state or the other way around can only occur once during the handover operation. As a result, all the impossible cases that cause the handover failure in the first j attempts should be excluded.

Given that the node is already active, the reason of a handover failure can only be that its relative distance is

[1] In the subsequent analysis, we do not consider the original receiver as one of the contending neighbors. The use of "neighbors" should be clear from the context.

larger than d. But the condition that the node is in a sleep state can sufficiently lead to a handover failure regardless of the estimated distance. Based on this argument, the equation expressing the probability that a handover fails in the first j attempts, p_j^f, can be given for all j, $j \in (1, i)$. Since all these equations are found to meet Pascal's triangle rule, after transformation and generalization, p_j^f can be expressed as:

$$p_j^f = \sum_{m=0}^{j} p_a^{j-m}(1-p_d)^{j-m}(1-p_a)^m \qquad (6)$$

By inserting Equations (3)-(6) into Equation (2) and after simplification, the average handover latency for $N = 1$ can be expressed as:

$$\overline{t_{N=1}} = \frac{t^s + \sum_{j=1}^{i-1}\left(p_j^f(jt^f + t^s)\right)}{1 + \sum_{j=1}^{i-1} p_j^f} \qquad (7)$$

When the number of neighbours of the transmitter is larger than one, a handover failure can also be caused by a collision on the handover replies. The latency introduced with the handover mechanism when $N > 2$ is evaluated elsewhere [4].

V. Result and Discussion

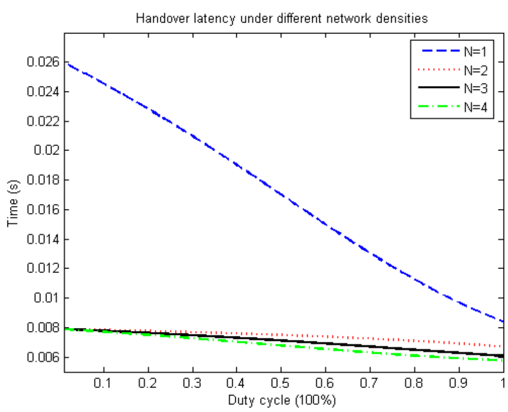

Fig. 3. Overall handover latency under different network densities

We employ Matlab version 7.0.1 to visualize the effect of the duty cycle and the network density on the handover latency. The parameters we used for our analysis are summarised in detail in [4].

As shown in Figure 3, the handover latency is inversely proportional to both the duty cycle and the network density. For $N = 1$, as collision does not occur, the handover latency depends only on whether the node is awake and weather its relative distance is smaller than d. When the duty cycle becomes zero, the handover latency is equal to $0.026s$. This is because in order to justify handover, at least one relay node should be discovered before the original link breaks. When the duty cycle increases to 1, the handover latency decreases to $0.008s$. This $0.008s$ is entirely contributed by the distance estimated to be larger than the threshold.

For $N \geq 2$, as the network density grows, the number of nodes whose distance to the transmitter is less than d increases. Meanwhile, the probability that a collision occurs among the handover replies increases. But the first (which decreases the handover latency) increases faster, since it is only one of the parameters that determines the second (which increases the handover latency). Therefore, the handover latency becomes smaller as the network density grows for a fixed duty cycle. There is a big disparity between the results of $N = 1$ and $N \geq 2$. This appears because different methods are adopted to evaluate the handover latency for the two cases. Multiple cases that can lead to a handover failure are not taken into account when $N \geq 2$, leading to a much less handover latency compared to the case when $N = 1$.

VI. Conclusion

In this paper, we introduced a seamless mechanism and analytically evaluated its performance. We showed that the handover latency increased from $0.006s$ to $0.026s$ as the duty cycle changed from 0 to 1 under different network densities. In the future, we plan to compare this latency with the situation in which no handover mechanism is applied. By doing so, whether and how much the performance can be improved if the handover mechanism is applied can be evaluated.

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