A New MAC Approach for Mobile Wireless Sensor Networks

Prasad Raviraj, Hamid Sharif and Michael Hempel
Department of CEEN
University of Nebraska-Lincoln
Omaha NE-68182, USA
{praviraj, hsharif, mhempel}@mail.unomaha.edu

Hesham H. Ali and Jon Youn
Department of Computer Science
University of Nebraska at Omaha
Omaha NE-68182, USA
{hesham, jyoun }@mailunomaha.edu

Abstract— **Several MAC protocols have been proposed for Wireless Sensor Networks. These include T-MAC , D-MAC, and the more commonly utilized SMAC. In this paper, we propose a new MAC layer approach to support mobility in WSNs. The proposed technique utilizes an adaptive frame size approach to overcome the effect of frame losses caused by the Doppler shift under mobile scenarios. An Extended Kalman Filter (EKF) is used to predict the frame size for each transmission which it directly enhances the energy efficiency of the system. Mica-2 sensors have been modeled and simulated using MATLAB and implementation in ns-2 to characterize a more accurate wireless sensor networks physical layer. Our results show that based on the adaptive frame size predictor and its comparison with the SMAC protocol, the proposed technique can improve overall system performance and deliver enhanced energy efficiency of 23.8% under mobility. The current implementation of ns-2 does not take into consideration the packet error rate. As another contribution of our work, we have developed a physical layer model for ns-2, which processes the received frame based not only on the fading characteristics of the signal but also the SNR and relative velocity between the nodes.**

***Index Terms*— Wireless Sensors, Mobility, Energy Efficiency, Adaptive Frame Size, Extended Kalman Filter, Physical Layer Model**

I. INTRODUCTION

The field of Wireless Sensor Networks (WSNs) has seen rapid growth due to the remarkable progress in microelectronics and electromechanical systems. WSNs are comprised of numerous wireless sensor nodes that can sense light, temperature, sound, motion, etc. and wirelessly transmit them to a remote base station that aggregates the data and processes it locally or at another location. One of the advantages is that they are self-organizing and are capable of forming ad-hoc networks automatically. Another advantage is that sensors are small and inexpensive which facilitates the deployment of large number of sensors. Although the initial usage was for military applications, recently more and more applications in almost every area have begun to utilize WSNs. Sensors have been implemented in hazard alarms, monitoring, and tracking wildlife, heartbeat monitoring for patients, habitat monitoring and many more applications.

Wireless sensor nodes typically operate with a limited power source such as batteries. In most applications, battery replacement is difficult or impossible. Thus, energy efficient protocols are crucial to obtain maximum network lifetime. The transmission and reception consumes the most energy. By controlling the communication parameters, it is possible to obtain improved energy savings. The SMAC obtains higher energy efficiency by turning the radio on and off based on a periodic listen/sleep cycle. Although the SMAC [1] by itself is not very suitable for mobile scenarios, the MS-MAC [2] details a method to improve energy consumption by using the mobility of the nodes to monitor the wake period of the nodes. As it is reported in [2] and based on our investigation, we do not know any other MAC protocol to support mobility except the MS-MAC. The problem, however with, MS-MAC is that it fails to consider the frame losses due to the bit errors introduced by mobility of the nodes.

The major problem faced by wireless sensor nodes in mobile scenario is that a large number of retransmissions occur due to corrupt frames received at the recipient. This is due to the bit errors resulting from the Doppler shifts. Thus reducing the number of retransmissions will improve the energy efficiency of the system. None of the existing MAC protocols addresses this issue, thus providing a scope for enhancement.

II. APPROACH

This work focuses on two issues in wireless sensor networks

1. The need for a realistic physical layer model considering the quality of the channel and the relative velocity between the nodes

2. An approach to make the MAC protocol energy efficient by addressing the problem of frame losses in cases where the communicating nodes are mobile

The mobility of the nodes and the noise in a channel are the major causes of retransmissions and this in turn impacts the energy depleted by them.

This research project was partially supported by the NSF grant number EPS-0346476 and by a Nebraska Research Initiative Grant

Thus, there is a serious need to develop a realistic physical layer model, to understand the influence of the parameters discussed above on the system performance.

The current implementation of ns-2 [3] does not take into consideration the packet error rate and assumes that all frames sent at the transmitter are received correctly at the receiver when the signal level is above a certain threshold. This is truly not the case in any communication systems as it excludes the possibility of bit errors. The Bit Error Rate (BER) of any system depends mainly on the modulation scheme and the Signal to Noise Ratio (SNR). The Doppler shift caused by the relative movement between the transmitter and the receiver. To make a comprehensive study we simulated the physical layer of the mica-2[4] sensors from Crossbow technologies in Matlab [5]. The results of the simulation were used as data for the physical layer in ns-2.

In order to deal with the frame losses in mobile scenarios, we propose an algorithm that will significantly reduce the energy consumption without losing fairness at the MAC. When the nodes are mobile, the signal experiences a Doppler shift that results in bit errors. Noise, which is most common in wireless channels, is also a major contributor. This in turn results in retransmissions leading to needless expenditure of energy. We use an Extended Kalman Filter as detailed in [6] to predict an optimal frame size for each transmission based on the current and previous channel characteristics, previous frame length, and protocol overhead. A prediction technique is used to deal with the time-varying nature of wireless channel and the dependency of the system performance on frame size. A smaller frame size is predicted when the signal characteristics are poor and larger frame sizes are predicted when the quality of the channel improves. By having a small frame size in a bad channel there are two advantages (1) smaller frames need lower transmission power compared to larger frames so their loss is less costly, and (2) the probability of occurrence of bit error in a smaller frame is less than that for a large frame. In the case of the nodes being stationary, when the channel is clear larger frame sizes are predicted which results in higher throughput.

A. Physical layer modeling for Wireless Sensor Networks

The generic physical layer model in ns-2 for wireless channels considers only the fading effects of the signal based on the propagation models. This is employed to decide if it is possible to successfully receive a frame but fails to consider the possibility of bit errors. The physical layer model that we have implemented takes also into consideration the noise in the channel and the relative velocity between communicating nodes to arrive at a bit error rate. This is crucial to decide if a frame is received correctly or if a retransmission request has to be made.

We have modeled the physical layer characteristics based on the mica-2 sensors, which uses the Chipcon CC1000 [7] for its radio module. The radio operates at 433.3 MHz and uses a NC-FSK modulation with a chip rate of 40K chips per second. It uses Manchester coding and has a data rate of 20 Kbytes per second. The sampling frequency is 230.4 KSamples/second. The Doppler shift which is one of the parameters in the simulation is calculated using the radio frequency and the relative velocity as

$$f_d = \frac{v}{\lambda} \quad \text{and} \quad \lambda = \frac{c}{f_c} \tag{1}$$

Where

v = Relative velocity in (meters/second) and
f_c = Carrier frequency of the radio in Hz

The system is simulated using Matlab based on the mica-2 parameters. This yields the BER of the system at different SNR and various relative velocities. This is used as the data for the physical layer model in ns-2.

The physical layer at the receiver calculates the relative velocity and the noise in the channel from the simulator and uses it to arrive at the BER for the corresponding values. This BER is used in the calculation of the Packet Error Rate (PER) as shown below.

Probability of error free reception of the frame as given in [8] when using Manchester coding is

$$P_{efr} = (1 - BER)^{8f} (1 - BER)^{8(f-l)2.0} \tag{2}$$

where f equals the length of the frame. Thus the probability of erroneous frame is

$$P_e = 1 - p_{efr} \tag{3}$$

B. A Mobility based MAC protocol

Where the nodes are mobile, the signal undergoes a Doppler shift which leads to bit errors in addition to those caused due to noise in the channel. This leads to frame errors causing the frame to be dropped at the receiver. Thus, a suitable solution would be to adaptively vary the size of the frame based on the signal characteristics. Transmitting smaller frames results in lower probability for frame errors. Moreover, the energy consumed in losing a smaller frame is less than losing a larger frame. Nevertheless, this leads to reduced bandwidth, which is undesirable for time critical applications thus the system must be able to adaptively vary frame size based on mobility. An Extended Kalman Filter is used to predict the size of the frame for each transmission.

The Kalman Filter can be used to estimate the past, present and future states even without precise knowledge of the modeled system. The Kalman filter has limitations in nonlinear and non-Gaussian systems. Extended Kalman Filter (EKF) was proposed to overcome these limitations and is considered one of the most efficient estimating schemes for nonlinear systems [9]. It is a Minimum Mean-Square Error (MMSE) estimator based on the principle of linearizing the measurements and evolution models.

The optimal frame size predictor reduces the size of the frame if the communicating nodes are moving relatively fast, if there is high noise in the channel, or in case where there is involvement of both. The EKF predicts larger frame sizes in cases where there is very little or no mobility and the channel is close to noise free.

The aim would be to maximize the throughput while maintaining improved energy savings. Thus the throughput at time K is

$$\begin{aligned}\rho_k = {} & L_k R_k /((L_k + H)((1 - Pb_k)^{-(L_k+H)} + N_k) \\ & + (B + D + h + o)((1 - Pb_k)^{-(L_k+H)} + N_k)R_k \\ & + ACK(1 - Pb_k)^{-ACK} + O((1 - Pb_k)^{-ACK} * R_k + N_k * Coll_k))\end{aligned} \tag{4}$$

Thus the throughput at time K+1 is

$$\begin{aligned}\rho_{k+1} = {} & L_{k+1} R_{k+1} /((L_{k+1} + H)((1 - Pb_k)^{-(L_{k+1}+H)} + N_{k+1}) \\ & + (B + D + h + o)((1 - Pb_{k+1})^{-(L_{k+1}+H)} + N_{k+1})R_{k+1} \\ & + ACK(1 - Pb_{k+1})^{-ACK} + O((1 - Pb_{k+1})^{-ACK} * R_{k+1} + N_{k+1} * Coll_{k+1}))\end{aligned} \tag{5}$$

Where L is the frame payload, R is the data rate, H is the MAC header, N is the average number of collisions, B is the average backoff time, D is the DIFS used by MAC, h is the PLCP header, P_b is the bit error rate experienced by a frame, ACK is the length of an ACK frame, o is the overhead of PHY layer, O is the overhead of ACK and Coll is the average length of collisions.

In order to maximize the channel throughput ρ, the optimal frame size at K+1 needs to be predicted for each transmission based on past signal characteristics and the length of the frame. The following equation can be derived from combining the above two equations. Thus, the optimal length can be obtained by solving the following equation for

$$L_k Pb_{k+1} = L^2{}_{k+1} + uL_{k+1} + v = 0 \tag{6}$$

$$L_{k+1} = \frac{(-u \pm \sqrt{u^2 - 4L_k Pb_{k+1} v}))}{(2L_k Pb_{k+1})} \tag{7}$$

where u and v are

$$\begin{aligned}u = {} & 2L_k Pb_{k+1} H + L_k SR_k Pb_{k+1} - Pb_k L_k{}^2 - 2L_k Pb_k H - H \\ & - Pb_k H^2 - HN_k - SR_k - SR_k Pb_k L_k - SR_k Pb_k H - SR_k N_k \\ & - ACK(1 - Pb_k)^{-ACK} - OR_k(1 - Pb_k)^{-ACK} - N_k Collk\end{aligned} \tag{8}$$

$$\begin{aligned}v = {} & L_k H + L_k Pb_{k+1} H^2 + L_k HN_k + L_k SR_k + L_k SR_k Pb_{k+1} H \\ & + L_k SR_k N_k + L_k ACK(1 - Pb_{k+1})^{-ACK} + L_k OR_k(1 - Pb_{k+1})^{-ACK} \\ & + L_k N_k Collk\end{aligned} \tag{9}$$

The following equations are then developed as the state transition model of the frame size predictor. The process model is

$$L_{k+1} = \begin{cases} L_{\max} & L_{K+1} > L_{\max} \\ K & L_{\min} < L_{k+1} < L_{\max} \\ L_{\min} & L_{k+1} < L_{\min} \end{cases} \tag{10}$$

Where

$$k = \frac{(-u \pm \sqrt{u^2 - 4L_k Pb_{k+1} v}))}{(2L_k Pb_{k+1})}. \tag{11}$$

The frame length is predicted for each transmission based on the condition given in equation (10).

III. SIMULATION AND RESULTS

We used ns-2, a popular open source simulator to run our simulations. Our physical layer model based on the mica2 sensors is implemented in ns-2. The parameters used for our Matlab simulation model were obtained from the CC1000 datasheet and by correspondence with Chipcon who are the makers of the radio modules. The EKF algorithm was incorporated in to the SMAC.

The objective of the simulation is to show that

1. More frames will be lost with a realistic physical layer model when compared to the current wireless PHY implementation. This will lead to more retransmissions resulting in high energy consumption.
2. In mobile scenarios and in noisy channels, an adaptive frame size approach, using an EKF to predict the size of the frame, will show improved energy efficiency compared to the SMAC.

A. Comparison of SMAC performance with and without a realistic physical layer implementation

We use five stationary nodes running SMAC at the MAC layer. One of which is the base station. The base station and the nodes can communicate directly. The reason for using five nodes is that WSNs usually operate in clusters and that this would be a good size to test the performance of the MAC protocol. We use the “Wireless PHY” in ns-2 as the physical layer for the first scenario and the “MICA2PHY” that we have implemented as the physical layer for the second scenario.

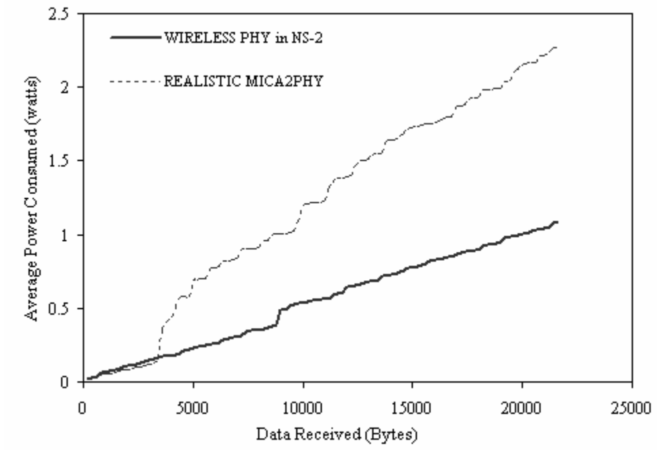

Figure1 . SMAC performance at low receiver signal strength

It can be seen from the above results that when using the realistic physical layer model, the energy consumed is more. This is due to the frame losses resulting from bit errors. The current wireless PHY implementation in ns-2 does not take this in to consideration so no frame losses are seen. This shows that the wireless PHY implementation in ns-2 does not resemble that of real world communication systems.

B. Comparison of SMAC performance at various speeds

We use five nodes running SMAC at the MAC layer. Four of which are mobile and the other is the stationary base station. We use the "Wireless PHY" in Ns-2 as the physical layer for the first scenario. For scenarios 2 and 3, we use the "MICA2-PHY" that we have implemented as the physical layer at different speeds.

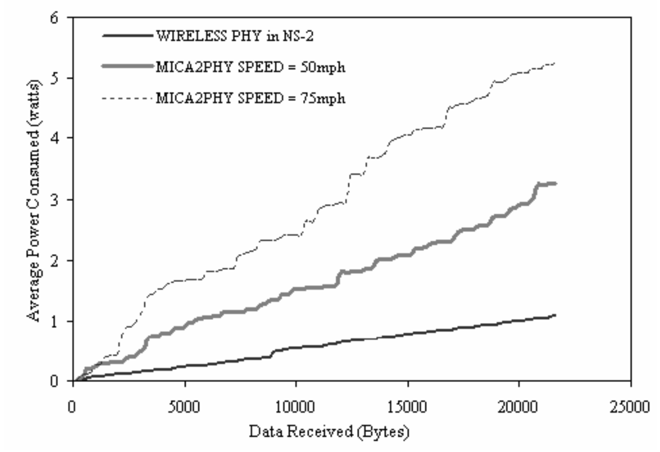

Figure 2. SMAC performance at various speeds

It can be seen from the above results that when the nodes are mobile, the average power consumption increases due to retransmissions. The wireless PHY in ns-2 does not consider these frame losses so the average power consumed is the same when the speed is 50mph and 75mph. Thus, simulations using the wireless PHY implementation in ns-2 for mobile scenarios will show less frame losses than what would actually occur.

C. Comparison of SMAC performance with and without EKF at low receiver signal strength

We use five stationary nodes running "MICA2-PHY" at the physical layer. We use the SMAC as the MAC for the first scenario. For scenario 2, we use the SMAC with the EKF as the MAC.

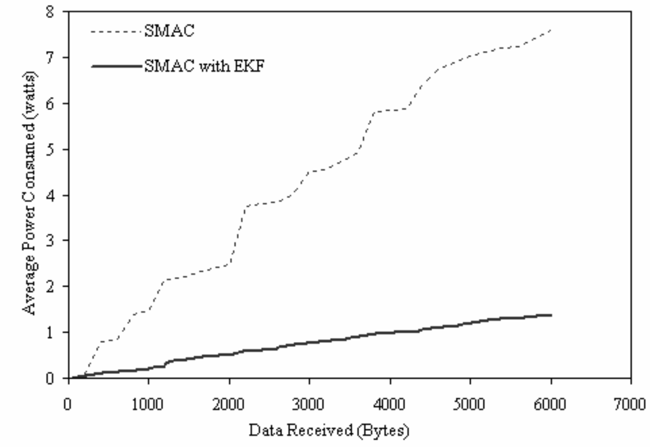

Figure 3. SMAC performance with and without EKF at low receiver signal strength

From the results, it can be seen that in the case of SMAC, there are more frame losses, which results in more energy consumed for a finite volume of data. In comparison, the Extended Kalman Filter demonstrates relatively less energy consumption compared to the SMAC when the signal strength at the receiver is low.

D. Comparison of SMAC performance with and without EKF at different speeds

We use five mobile nodes running "MICA2-PHY" at the physical layer. Four of which are mobile and the other is the stationary base station. The energy consumption of the SMAC is compared for the cases with and without EKF at 50mph and 75 mph

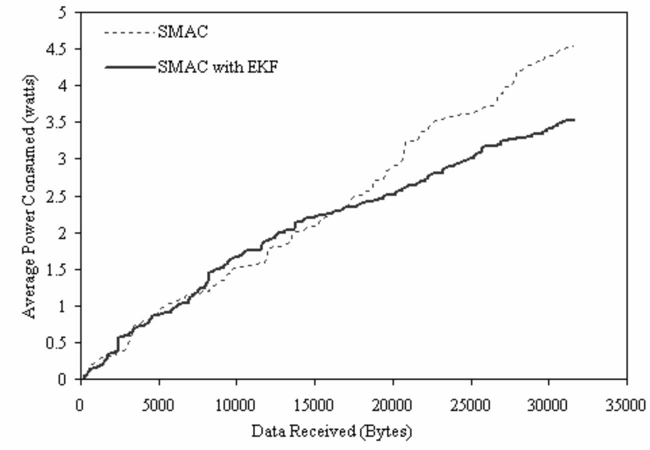

Figure 4. SMAC performance with and without EKF at 50mph

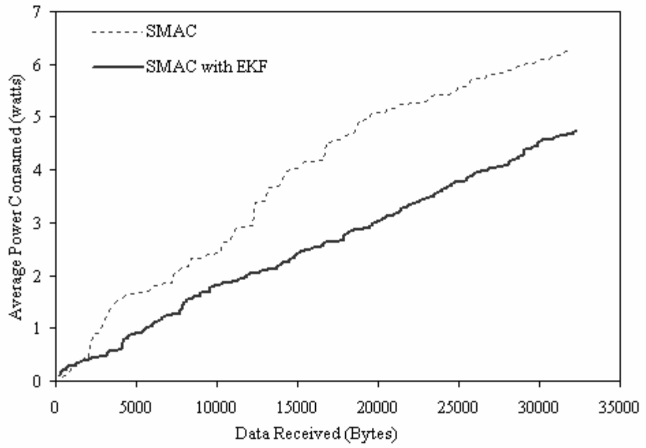

Figure 5. SMAC performance with and without EKF at 75mph

The above results clearly show that SMAC when used with the EKF consumes less energy when compared to using only SMAC in the case of mobile scenarios.

IV. CONCLUSION

The mica-2 physical layer implementation shows the effects of mobility and noise on the performance of the system. The presence of frame losses when the nodes are mobile, channel is noisy indicates the similarity of the implemented physical layer with real world wireless system. The EKF based SMAC proved that it could yield an improvement in energy efficiency of about 24% when compared to the SMAC without EKF in mobile scenarios. In stationary scenarios with low noise level the performance of EKF based SMAC will be similar to that of SMAC.

We demonstrated that our new MAC layer approach, which utilizes an adaptive frame size, supports mobility in WSNs and it minimizes frame losses caused by the Doppler shift.

We also presented our developed ns-2 based physical layer model to include the SNR and relative velocity between the nodes.

Future work will be to evaluate the performance of the enhanced SMAC on multi hop networks by using a suitable routing protocol.

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