Medium access control with mobility-adaptive mechanisms for wireless sensor networks

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Abstract: Mobility in wireless sensor networks poses unique challenges to the Medium Access Control (MAC) protocol design. Previous MAC protocols for sensor networks assume static sensor nodes and focus on energy-efficiency. In this paper, we present MMAC, a mobility-adaptive, collision-free MAC protocol for mobile sensor networks. MMAC caters for both weak mobility (e.g. topology changes, node joins and node failures) and strong mobility (e.g. concurrent node joins and failures, and physical mobility of nodes). When using MMAC, nodes are allowed to transmit at particular time-slots, based on the traffic information and mobility pattern of the nodes. Allowing transmission at particular time-slots makes MMAC a scheduling-based protocol, thereby guaranteeing collision avoidance. Simulation results indicate that the performance of MMAC is equivalent to that of TRAMA in static sensor network environments. In sensor networks with mobile nodes or high network dynamics, MMAC outperforms existing MAC protocols, including TRAMA and S-MAC, in terms of energy-efficiency, delay and packet delivery.

Keywords: wireless sensor networks; mobility adaptive; energy efficiency.

Reference to this paper should be made as follows: Ali, M. and Uzmi, Z.A. (2006) 'Medium access control with mobility-adaptive mechanisms for wireless sensor networks', *Int. J. Sensor Networks*, Vol. 1, Nos. 3/4, pp.134–142.

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1 Introduction

Wireless sensor networks have emerged as one of the first real applications of ubiquitous computing. Sensor networks play a key role in bridging the gap between the physical and the computational world by providing reliable, scalable, fault tolerant and accurate monitoring of physical phenomena. Sensor network environments, inherently different from the Internet, pose some unique challenges to systems researchers. Energy efficiency has been considered as the single most important design challenge in sensor networks (Akyildiz et al., 2002). Hence, the recent work on Medium Access Control (MAC) protocol for sensor networks focused on energy efficiency instead of, traditional wireless MAC design goals such as fairness, delay, and bandwidth utilisation (Ye and Heidemann, 2004).

Designing a MAC protocol that gives consideration to 'mobility' has been well identified as an open research challenge in sensor networks for quite some time (Akyildiz et al., 2002) and yet even the most recent MAC protocols appearing in the literature, such as ZMAC (Rhee et al., 2005), do not explicitly consider mobility at the MAC-layer. In fact, to the best of our knowledge, we are not familiar with any other work that considers the effects of mobility at the MAC-layer (see a very recent survey of MAC protocols (Langendeon and Halkes, 2005). The research community has not considered mobility at the MAC-layer because sensor networks were originally assumed to be comprising of static nodes but recent works (Dantu et al., 2005; Kansal et al., 2004; Laibowitz and Paradiso, 2005) have enabled mobility in sensor network environments. Furthermore, recent applications of sensor networks in medical health care and emergency disaster-relief (Lorincz et al., 2004; Shnayder et al., 2005) require MAC protocols that can adapt to mobility. This is because the assumption of static sensor nodes, generally made in sensor networks research, is no longer valid in such environments.

In this paper, we show that the current MAC protocols for wireless sensor networks are not suited for mobile sensor network environments. We present a mobility-adaptive, collision-free medium access control (MMAC) protocol for sensor networks. MMAC follows the design principles of TRAMA (Rajendran et al., 2003) a scheduling-based MAC protocol for static multihop wireless sensor networks.

In mobile environments the fixed time frame of current MAC protocols causes performance degradation in a number of ways:

1 the mobile nodes, upon joining a new neighbourhood, need to wait for a long time before they can send data

2 in contention-based MAC protocols, there is a considerable increase in packet collisions and

3 in schedule-based MAC protocols, the two-hop neighbourhood information at each node remains inconsistent for a longer period which could effect the correctness of the protocol.

A dynamic time frame, that is inversely proportional to level of mobility, is required to cope with these problems.

MMAC introduces a mobility-adaptive time frame that enables the protocol to dynamically adapt to changes in mobility patterns, making it suitable for sensor environments with both high and low mobility. MMAC assumes that the sensor nodes are aware of their location. This location information is used to predict the mobility pattern of the nodes according to the AR-1 (Zaidi and Mark, 2004a,b) model. We present a novel mobility-adaptive distributed algorithm that dynamically adjusts the MAC time frame according to mobility. Experimental results indicate that the performance of MMAC is equivalent to that of TRAMA (Rajendran et al., 2003) in static sensor network environments. In sensor networks with mobile nodes or high network dynamics, MMAC outperforms existing MAC protocols, including TRAMA and S-MAC, in terms of energy-efficiency, delay and packet delivery.

MMAC uses a distributed contention based algorithm that imparts transmission rights to nodes at particular time-slots based on the traffic information and mobility pattern of the nodes. MMAC caters for both weak mobility (regular topology changes and node joins or failures exhibited by static sensor networks and slow physical mobility of nodes) and strong mobility (frequent topology changes, concurrent node joins or failures and fast physical mobility of nodes).

The rest of the paper is organised as follows. We discuss related work in Section 2. Section 3 presents the MMAC protocol and Section 4 provides a comparative evaluation of the MMAC protocol, by means of simulations. We draw and summarise the conclusions in Section 5.

2 Related work

MAC protocols for wireless data and voice communication systems could be broadly classified into two categories:

1 scheduled protocols and

2 contention based protocols.

The basic idea of scheduled protocols is to divide the channel into subchannels based on time, frequency or codes respectively. Traditional MAC protocols for wireless networks (LAN MAN standards committee, 1999; Rappaport, 1996) were designed to maximise bandwidth utilisation, promote fair usage of channel by all nodes and to reduce latency. In sensor networks, the typically low data rate relaxes the need for maximum bandwidth utilisation. These sensors generally collaborate with each other to perform a common task, reducing the importance of fair channel usage by each node. Further, the sensor network applications are typically not subsecond delay sensitive. Hence, the recent work on MAC protocol design in sensor networks (Dam and Langendoen, 2003; Rajendran et al., 2003; Ye et al., 2004) focused on energy efficiency and coordination instead of fairness, delay and bandwidth utilisation.

The most widely used MAC protocol for sensor networks is S-MAC (Ye et al., 2002). S-MAC introduced a low-duty-cycle operation in multihop wireless sensor networks, where the nodes spend most of their time in sleep mode to reduce energy consumption (Figure 1). Papers on T-MAC (Dam and Langendoen, 2003) and TRAMA (Rajendran et al., 2003) showed that S-MAC, with fixed sleep and awake periods, does not perform well with variable traffic loads. T-MAC and TRAMA introduced traffic-adaptive dynamic sleep and awake periods for sensor nodes. Traffic-adaptive mechanisms were also later introduced in S-MAC (Ye et al., 2004). The frame time in S-MAC, TRAMA and T-MAC is fixed whereas we introduce mobility-adaptive dynamic time frame in MMAC (Figure 2).

Figure 1 Constant active time (S-MAC) versus Traffic-adaptive dynamic active time (T-MAC)

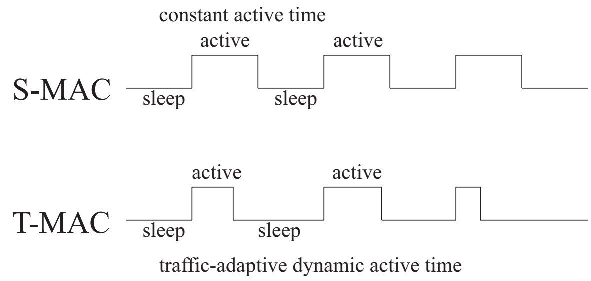
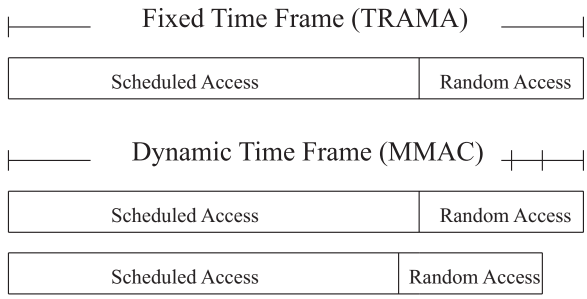


Figure 2 Fixed time frame (TRAMA) versus Mobility-adaptive dynamic time frame (MMAC)



The MAC for wireless sensor networks is an active research area and we refer the readers to Halkes et al. (2005), Langendeon and Halkes (2005) and Ye and Heidemann (2005) for a detailed discussion of recent works on MAC protocols for sensor networks. To the best of our knowledge, none of the existing MAC protocols considers the effect of mobility at the MAC layer which is the focus of our work.

3 MMAC Protocol

We only discuss the issues relevant to mobility and the reader is encouraged to see Rajendran et al. (2003) for a detailed discussion on basic protocol functionality, traffic-adaptivity, schedule maintenance, neighbour discovery and protocol correctness.

3.1 Mobility in sensor networks

Sensor networks have high network dynamics; nodes may fail due to hardware failure or battery consumption, other new nodes may join the network. The network topology is effected by such node joins or failures. We define these regular network topology changes and individual node joins and failures as *weak mobility*. Sensor networks with static nodes can also exhibit weak mobility.

More than one node may concurrently fail or join the network. Such concurrent node joins and failures are, generally, more difficult to handle, by the MAC protocol, than individual ones. Further, the sensor nodes may physically move from their location, either because of motion in the medium (e.g. water, air) or by means of special motion hardware in the mobile sensor nodes. We define concurrent node joins/failures and physical mobility of nodes as *strong mobility*.

3.2 Design goals

In this section, we discuss goals and tradeoffs for medium access control protocol design for wireless sensor networks. The primary goal of MAC protocol design in sensor networks is energy conservation with main sources of energy wastage at the MAC layer being collisions, idle listening, overhearing and control packet overhead (Ye and Heidemann, 2004). The MAC protocol should reduce energy consumption by all of the following sources.

- *Collision* occurs when two or more nodes try to transmit at the same time; the packets collide, become corrupted and are discarded. In sensor networks, where *every bit transmitted reduces the life time of the network* (Pottie and Kaiser, 2000), such energy waste is unacceptable. As neighbour information becomes inconsistent at a faster rate in mobile sensor networks, there is more probability of collisions than static sensor networks.
- *Idle listening* happens when nodes keep their radios on to receive possible incoming data. In sensor networks, the idle listening time energy cost is in the same magnitude of receiving and transmitting costs, for example, the idle:receiving:transmission ratio of Mica2 motes (Crossbow Technology©, 2005) is 1:1:1.41. The traffic pattern, in mobile sensor networks, is largely unpredictable and the nodes need to remain in the idle listening state for a longer time.
- *Overhearing* occurs when a node receives packets intended for other nodes. Overhearing generally increases with increase in node density and traffic rate. Mobile sensor nodes are more prone to overhearing unnecessary packets as a node C entering the one-hop neighbourhood of node A may hear the packets that were originally sent by node A for node B.
- *Control packets* transmission, consumes energy without directly delivering data. A more complex MAC protocol, needed to cope with mobility, would increase the number of header bits and reduce the efficiency of the system.

In deciding between schedule-based or contention-based MAC protocol design, we preferred the schedule-based design as different nodes, in schedule-based MAC protocols, are scheduled to communicate in different non-interfering subchannel slots,these protocols are largely collision free. Further, as the receiving nodes need to listen in their own slot alone, a node can turn the radio off for all other slots but the one scheduled to it. This naturally support a low-duty-cycle operation and avoids over-hearing of packets by neighbour nodes.

3.3 Problem definition

Consider a multihop wireless sensor network with homogenous sensor nodes. Let,

$$N_i(\alpha) \rightarrow \{i\text{-hop neighbours of a node } \alpha\}$$
$$PP_i(\alpha, \beta) \rightarrow \text{probability that } \alpha \in N_i(\beta)$$

The network topology could change due to:

1 node joins

2 node failures

3 concurrent node joins/failures and

4 physical mobility of individual nodes.

Let,

$$\alpha \downarrow N_i(\beta) \rightarrow \text{in-mobility transaction, where } \alpha \notin N_i(\beta) \text{ before transaction and } \alpha \in N_i(\beta) \text{ after transaction}$$
$$\alpha \uparrow N_i(\beta) \rightarrow \text{out-mobility transaction, where } \alpha \in N_i(\beta) \text{ before transaction and } \alpha \notin N_i(\beta) \text{ after transaction}$$

In Static Network Model (SNM), the only factor effecting $PP_i(\alpha, \beta)$, when initially $\alpha \in N_i(\beta)$, is node failure. In addition to node failure $PP_i(\alpha, \beta)$, when initially $\alpha \in N_i(\beta)$, is also effected by $\alpha \uparrow N_i(\beta)$ in Mobile Network Model (MNM).

In SNM, node joint can occur if:

1 new static nodes are deployed
2 nodes wake up after a long time and
3 nodes recover from failure and were considered dead before.

In MNM, node joint can occur for the added reason of $\alpha \downarrow N_i(\beta)$. Let,

F_i	$\rightarrow$	a complete frame i, under consideration where, τ = frame time
$\downarrow_i (\alpha)$	$\rightarrow$	{nodes expected to join $N_2(\alpha)$ in F_i}
$\uparrow_i (\alpha)$	$\rightarrow$	{nodes expected to part $N_2(\alpha)$ in F_i}

In MNM, we assume the nodes to be static during F_i. The mobility behaviour of $N_2(\alpha)$ in F_i is predicted during F_{i-1}. If a node β is expected to leave $N_2(\alpha)$ during F_i then $\beta \notin N_2(\alpha)$ from the START of F_i. Similarly, if a node β is expected to join $N_2(\alpha)$ during F_i then $\beta \notin N_2(\alpha)$ from the START of F_i. In other words, $\{\downarrow_i (\alpha) \bigcup \uparrow_i (\alpha)\} \notin N_2(\alpha)$ from the START of F_i.

3.4 Mobility estimation

MMAC uses location information to predict the mobility behaviour of sensor nodes. Localisation is a well studied problem in wireless sensor networks (Bulusu et al., 2000, 2002; He et al., 2006; Römer, 2003; Savvides et al., 2001). Most sensor network applications require that nodes are aware of their physical location, this location information is also used by MMAC. Let,

$\Gamma(\alpha, F_i)$	$\rightarrow$	current mean (x, y) of α in F_i where, $x = x$ coordinate and $y = y$ coordinate
$\Gamma(\alpha, F_{i-1})$	$\rightarrow$	stored mean (x,y) of α in F_{i-1}
$\Gamma(\alpha, F_{i+1})$	$\rightarrow$	expected mean (x,y) of α in F_{i+1}

We use the AR-1 model (Zaidi and Mark, 2004a,b) for mobility estimation. The mobile node's state, at time t, is defined by a column vector.

$$s_t[x_t, \dot{x}_t, \vec{x}_t, y_t, \dot{y}_t, \vec{y}_t]' \quad (1)$$

where s_t is the mobility state, (x_t, y_t) specify position, $\dot{x}_t$ and $\dot{y}_t$ specify velocity, notation $'$ specifies the matrix transpose operator and $\vec{x}_t$ and $\vec{y}_t$ specify the acceleration in the x and y directions. The AR-1 model (Zaidi and Mark, 2004a) gives,

$$s_{t+1} = As_t + \omega_t \quad (2)$$

where A is a 6×6 transformation matrix, the vector ω_t is a 6×1 discrete-time zero mean, white Gaussian process with autocorrelation function $R_\omega(k) = \delta_k Q$, where $\delta_0 = 1$ and $\delta_k = 0$ when $k \neq 0$. The matrix Q is the covariance matrix of ω_t. The values for matrix A and the covariance matrix Q is estimated based on training data using the Yule-Walker equations (Lim and Oppenheim, 1987). See Zaidi and Mark (2004a,b) and Zaidi et al. (2004) for details.

The mobility state information $\hat{s}_t$, at any given time t could be used to predict the mobility state at any time $t + i$. The optimal predicted state $\hat{s}_{t+i}$ of the mobile node in the Minimum Mean-Square Error (MMSE) sense is given by,

$$\hat{s}_{t+i} = A^i \hat{s}_t, \quad (3)$$

More accurate mobility estimation could be obtained if we use AR-3 estimation model instead of the AR-1 model but we believe that using the computationally intensive AR-3 model on memory-constrained sensor nodes is not feasible from a practical point of view (Gadhiok, 2004). The choice of the estimation model, and its effect on different performance metrics in a mobile sensor network environment is an open area for future research.

3.5 Mobility-adaptive algorithm

Basic idea: if a large number of nodes are expected to enter or leave the two-hop neighbourhood of a node β, reduce the time frame and vice versa.

1 $\forall\alpha \in N$, where N = set of all nodes, calculate optimal predicted states $\hat{s}_{t+0}, \hat{s}_{t+1}, \ldots, \hat{s}_{t+j}, \ldots, \hat{s}_{t+\max}$, where max = time frame, and t = starting time of F_{i+1}

2 $\forall\alpha \in N_2(\beta)$, calculate

$$\Gamma(\alpha, F_{i+1})\text{average}(\hat{s}_{t+0}, \hat{s}_{t+1}, \ldots, \hat{s}_{t+j}, \ldots, \hat{s}_{t+\max})$$

3 Using $\Gamma(\beta, F_{i+1})$ and $\forall\alpha, \Gamma(\alpha, F_{i+1})$, populate the sets $\downarrow_{i+1} (\beta)$ and $\uparrow_{i+1} (\beta)$

4 If $\alpha \in \{\downarrow_{i+1} (\beta) \bigcup \uparrow_{i+1} (\beta)\}$ remove α from $N_2(\beta)$

5 If $|\downarrow_{i+1} (\beta) \bigcup \uparrow_{i+1} (\beta)| \geq \lambda_{\max}$,

$$\tau_{\text{new}} = \tau - \left(\tfrac{\eta}{100} \times \tau\right)$$

where τ = time frame, $\lambda_{\max}$ is a threshold value and η is a variable.

6 If $|\downarrow_{i+1} (\beta) \bigcup \uparrow_{i+1} (\beta)| \leq \lambda_{\min}$,

$$\tau_{\text{new}} = \tau + \left(\tfrac{\eta}{100} \times \tau\right)$$

where τ = time frame, $\lambda_{\min}$ is a threshold value and η is a variable.

7 Adjust the number of *scheduled access* and *random access* slots according to τ_{new}.

3.6 Protocol issues

We identify the following main issues with the generic mobility adaptive algorithm described above:

1 *Mobility information*: individual nodes can predict their future mobility state, but in the mobility adaptive algorithm each node requires future mobility state information of *all* the current and potential two-hop neighbour nodes.

2 *Synchronisation*: using the mobility adaptive algorithm, individual nodes could independently calculate time frame different from each other; leading to synchronisation problems in the schedule-based MMAC protocol.

To address these issues we introduce cluster heads in MMAC. Time is divided into rounds with exactly one node as cluster head for a given round, r. The responsibility of being a cluster head is rotated among sensor nodes to conserve energy. We use a variation of the cluster head selection and rotation mechanism of LEACH (Heinzelman et al., 2002) to select cluster heads in MMAC. Each node α determines a random number between 0 and 1. If the number is less than a threshold λ_{head}, the node becomes a cluster-head for the current round. The threshold is set as (Handy et al., 2002),

$$\lambda_{\text{head}} = \frac{P}{1 - P\left(r \bmod \frac{1}{P}\right)} \times \frac{E_{\text{current}}}{E_{\max}} \qquad \forall\alpha \in G$$

$$\lambda_{\text{head}} = 0 \qquad \forall\alpha \notin G$$

where P is the cluster-head probability, r is the number of current rounds, G is the set of nodes that have not been cluster-heads in the last $1/P$ rounds, E_{current} is the current energy of the node and $E_{\max}$ is the initial energy of the node. We define round r as $r = k \times \tau$ where, τ = time frame and k is an integer variable > 1. The number of cluster heads is set as 5% of the total sensor nodes, which is a reasonable number (Heinzelman et al., 2002). Each node α becomes member of a cluster with exactly one node as cluster-head as in the LEACH protocol (Heinzelman et al., 2002).

According to efficient clustering schemes (Heinzelman et al., 2002) around 6% of all nodes in the network become cluster heads and as these heads are evenly distributed in the network (Chan and Perrig, 2004; Younis and Fahmy, 2004) this puts a limit on the number of members per cluster.

3.7 Mobility information

We modify the signal header and the data header of MAC packets to include the predicted mobility state information. At the start of frame F_i each node α independently calculates the expected mean (x, y) of α in frame F_{i+1} as,

$$\Gamma(\alpha, F_{i+1})\text{average}(\hat{s}_{t+0}, \hat{s}_{t+1}, \ldots, \hat{s}_{t+j}, \ldots, \hat{s}_{t+\max})$$

and then sends $\Gamma(\alpha, F_{i+1})$ in the header of every signal and data packet generated by α. The head node always keeps the radio to listen mode and collects $\Gamma(\alpha, F_{i+1})$ for each node that transmitted a data or signal packet during F_i. The last frame slot is reserved for a BROADCAST from the head. This BROADCAST from the head sends all stored $\Gamma(\alpha, F_{i+1})$ to the member nodes. This ensures that each node α has 'best-effort' knowledge of the predicted mobility states of it's current and potential two-hop neighbours. We define this knowledge as best-effort because clearly the head would not have information about a node β that would actually move into the two-hop neighbourhood of α but has yet to transmit anything. The head node would get mobility information of such a node β as soon as it transmits a packet.

3.8 Synchronisation

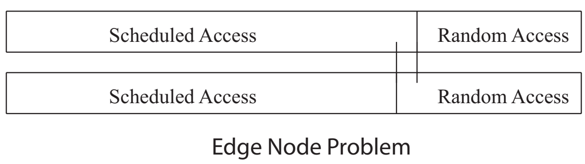
To address the synchronisation problem we change the last step of the generic mobility adaptive algorithm. Each node α independently calculates τ_{new} but instead of adjusting the number of *scheduled access* and *random access* slots, α includes τ_{new} in the data and signal header along with $\Gamma(\alpha, F_{i+1})$. The head node of cluster c collects τ_{new} from the headers of transmitting nodes $\alpha \in$ cluster c. The head calculates τ_{mean} = average (all received τ_{new}) in each frame. We introduce a global synchronisation period (GSP), consisting of p empty slots, that occurs at the end of every round r, where $r = k \times \tau$. At the start of GSP, the latest values of τ_{mean} are collected from all cluster heads and their mean value τ_{GSP} is disseminated in the entire network. All participating nodes of the network adjust the *scheduled access* and *random access* slots according to τ_{GSP}, new cluster heads are elected and the next round begins.

The frame time could ONLY change during a GSP. τ_{GSP} is the new frame for the next round with respective *scheduled access* and *random access* slots. A GSP occurs after k frames (i.e. after one round) and there could be changes in the mobility rate during this time. MMAC dynamically adapts to these changes by altering the division between scheduled access and random access slots after each frame. Each cluster head sends the calculated τ_{mean} in each frame to all member nodes during the BROADCAST message during the last reserved frame slot. If the value of τ_{mean} is less than that of the previous one stored at the nodes, they increase the number of random access slots and decrease the scheduled access slots keeping the total time frame constant and vice versa. Therefore,

- After a GSP, all time frame, schedule access times, and random access times would be the same and they would reflect the mobility of all nodes in the network for example, if recently most of the nodes exhibited greater mobility the time frame would be reduced.
- After each frame before the next GSP, the time frame in the network would remain the same but the random access period of each cluster-members would increase or decrease reflecting the mobility patterns of cluster nodes.
- Times frame would be the same $\forall\alpha \in$ network.
- If all two-hop members of a node $\alpha \in$ a cluster c, then their random access time and scheduled access time would be the same.

We define an *edge node e* as a node who has two-hop neighbours belonging to more than one virtual cluster. In the two-hop neighbourhood of e the frame size of two-hop nodes α would be the same but the random access time could be different (Figure 3). Such a node e should use the shortest data transmission time and the shortest random access time out of the different access times in-use that is, according to Figure 3(e) should NOT transmit anything between the overlapping region.

Figure 3 A node α receiving random access slot numbers from more than one head node



3.9 Localisation

Localisation is the *natural* first step towards handling mobility. Most sensor network applications, for static or mobile sensor networks, assume that location information is available to the application. MMAC makes use of location information for mobility estimation. Accuracy of mobility estimation depends on the accuracy of the underlying localisation mechanism. Localisation is a well-studied problem in wireless sensor networks (Bulusu et al., 2002; He et al., 2006; Lorincz and Welsh, 2005) and studies have shown that many multihop localisation algorithms have yielded extremely accurate results in simulation and there are works going on to bridge the gap between simulation and real world performance of localisation algorithms (Whitehouse et al., 2005). There have also been some recent works on localisation for mobile sensor networks (Hu and Evans, 2004). A detailed discussion of localisation algorithms is beyond the scope of this paper.

3.10 Energy costs

Communication costs in sensor networks are much higher than computation costs (Raghunathan et al., 2002) and it is actually desirable to have more computation done at each node (in-network processing) if that could reduce on communication (Silva et al., 2004). Furthermore, with advances in hardware technologies, specially low-power computing chips, the energy costs of computations are reducing as directed by Moore's law but the energy consumption of wireless radios is largely determined by laws of physics which puts a limit on reducing energy used for communication (Clark et al., 2005). Thus, in the coming years the wireless interface will be the *primary consumer* of energy in any device that combines computation and radios (this is true to a certain extent even today) (Clark et al., 2005). Based on these current and future trends in hardware energy-consumption we primarily focus on communication energy costs while evaluating the energy costs of MMAC.

In the AR-1 model, *self mobility* could be estimated without any communication. However, for the mobility information to be useful to MMAC, any node, say α, would also need information on all neighbour nodes' mobility estimation. Every node performs local processing and instead of sending out raw location values each node transmits only the final locally calculated predicted future location information but even such predicted future location would need to be communicated at *regular intervals*. In Section 4, we present a cost-benefit evaluation, in terms of energy efficiency, to determine if it is worth expending energy on such mobility information.

4 Protocol evaluation

We performed a comparative study of MMAC with TRAMA (Rajendran et al., 2003), SMAC (Ye et al., 2002), and CSMA. The study was carried out by doing extensive simulation in NS2.

4.1 Protocol comparison set

MAC research for sensor networks has been an active research area and there are a lot of proposed MAC protocols in the literature. A recent survey of MAC protocols (Langendoen and Halkes, 2005) lists twenty worth mentioning MAC protocols for the area. It is not possible to have a comparison with each and every one of these MAC protocols proposed in the literature. Therefore, in our work we carefully choose a comparison protocol set from the available choices. CSMA is included in the set as a worst-case protocol as it has no energy saving mechanisms. The performance of contention-based protocols falls back to that of CSMA in high contention environments or high data rates (Rhee et al., 2005) but does not go below that. Therefore, CSMA becomes a good choice for a worst-case protocol. TRAMA embodies schedule-based MAC protocols for wireless sensor networks, whereas SMAC represents contention-based MAC protocols.

When referring to SMAC researchers generally mean the originally proposed SMAC (Ye et al., 2002) and not the later version with some traffic-adaptive mechanisms, called *adaptive listening*, (Ye et al., 2004). SMAC with adaptive listening (Ye et al., 2004) would behave like the traffic-adaptive protocols TMAC (Dam and Langendoen, 2003) and TRAMA (Rajendran et al., 2003). Hence, when choosing protocols for our protocol comparison set we include SMAC (Ye et al., 2002) as representative of low-duty-cycle protocols *without* traffic-adaptive mechanisms and from the category of MAC protocols *with* traffic-adaptive mechanisms we choose TRAMA as the representative protocol of this category.

4.2 Simulation environment

The underlying physical model, in all our experiments, is based on TR1000 (1999). For SMAC, the `SYNC-INTERVAL` is 10 sec and the duty cycle is varied as either 10% or 50%. For TRAMA and MMAC, `SCHEDULE-INTERVAL` is 100 transmission slots. Random access period is 72 transmission slots and is repeated every 10,000 transmission slots. MMAC dynamically changes the number of random access period slots and the respective repeat rate. Nodes have transmission range of 100 m and they are randomly deployed on a 500 m × 500 m plane. Traffic is generated, at a variable rate, on the sensor nodes. All sinks are corner-sinks. In order to route a packet to the sink, at each hop the node simply forwards the packet to the node closer to the sink. The simulation is allowed to run for 500 seconds and the results are averaged over several hundred simulation runs.

4.3 Energy calculations

The energy consumption in simulation is calculated using the simple first order radio model (Heinzelman et al., 2002) for wireless communications in NS2. Let E_{electric} be the energy dissipated by the transmitter-receiver and $E_{\text{amplifier}}$ be the energy dissipated by the transmit amplifier. Then,

$$E_{\text{Transmit}}(k, d) = E_{\text{electric}} \times k + E_{\text{amplifier}} \times k \times d^2 \quad (4)$$

$$E_{\text{Receive}}(k) = E_{\text{electric}} \times k \quad (5)$$

Where $E_{electric}$ and $E_{amplifier}$ have values 50 nJ/bit and 100 pJ/bit/m^2 respectively, k is the data rate in bits per packet and d is the distance. The nodes in the simulator are initialised at different energy levels and then after each packet transmission, depending upon the size of the packet in bits and the distance that the packet is sent over, the energy consumed by communication of the packet is respectively deducted from the energy of the respective nodes involved in the communication.

4.4 Simulation results

Figure 4 gives average packet delay for the network. The average mobility of the nodes is set at 0.5 m per second. Nodes generate traffic at variable rates. Average delay values of contention-based protocols CSMA and SMAC, are much less than that of schedule-based protocols. This is because of the latency introduced by random scheduling in TRAMA and MMAC.

Figure 4 Average packet delay (variable traffic)

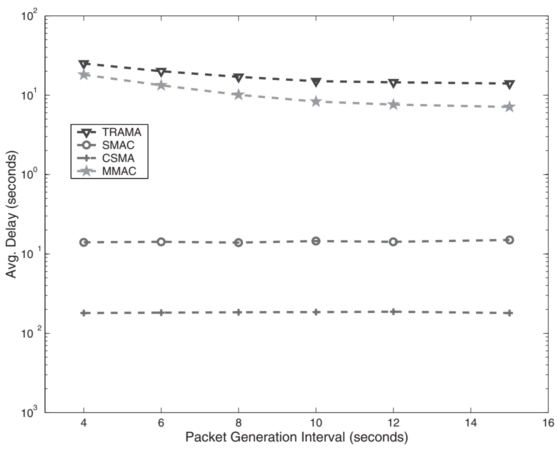


Figure 5 shows the change in average packet delay as we increase the average mobility of the participating nodes in the network. As, MMAC adapts it's time frame, number of data-transfer frames, and number of random-access frames, the average delay remains, almost, constant with increase in mobility rate. However, CSMA, SMAC and TRAMA exhibit degrading average delay with increase in mobility rate.

Figure 5 Average packet delay (increasing mobility)

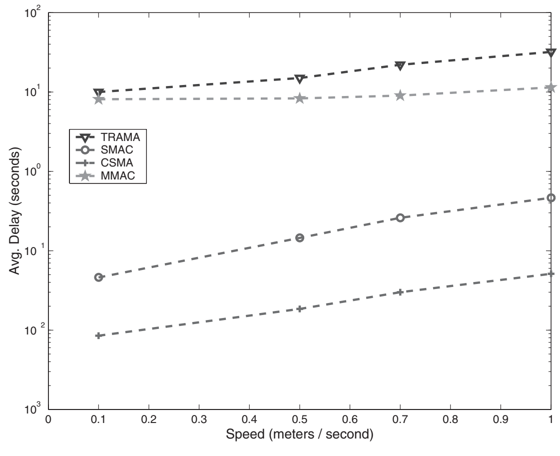


Figure 6 shows the average percentage of variable-traffic packets successfully delivered to sink nodes. As, MMAC and TRAMA are collision-free MAC protocols they outperform SMAC and CSMA in this experiment. When we increase the mobility rate (Figure 7), the number of successfully delivered packets for CSMA, SMAC and TRAMA decrease significantly, whereas MMAC exhibits a minimal decrease.

Figure 6 Percentage of packets received (variable traffic)

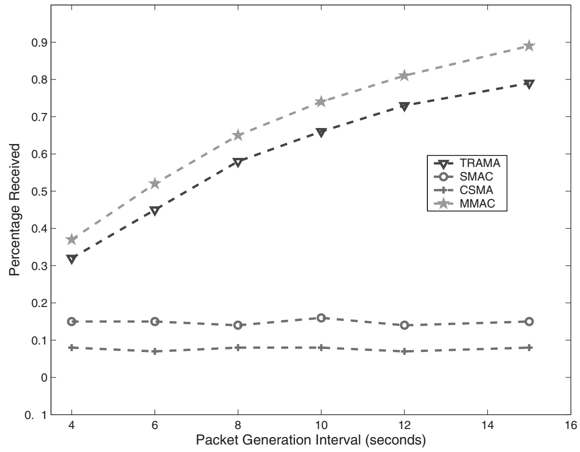
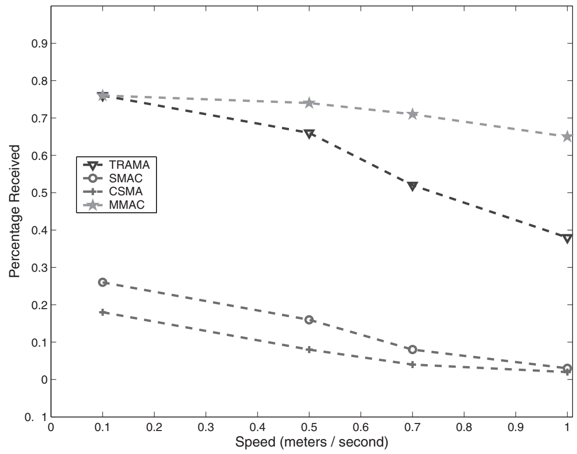


Figure 7 Percentage of packets received (increasing mobility)



Energy-efficiency is the single most important performance metric for wireless sensor networks (Akyildiz et al., 2002). We average the energy consumption values for SMAC for all the active and sleep intervals and compare them with those of CSMA, TRAMA and MMAC. Results (Figure 8) show that, as expected, CSMA is the least energy-efficient protocol. TRAMA nodes consume less energy than SMAC because TRAMA adapts better to variable traffic. MMAC performs slightly better than TRAMA in the first part of the energy consumption experiment.

Figure 9 shows that apart from CSMA, all protocols are energy efficient when the mobility of nodes is minimal or almost zero. As the nodes become more mobile there are more packet collisions and respective packet retransmissions in CSMA and SMAC. Data packets in TRAMA, sent to a node β moving out of the two-hop neighbourhood of node α, are lost and cause retransmissions. MMAC however, adapts to the mobility pattern of the nodes; resulting in, on average, less energy consumption by nodes when compared to TRAMA.

Figure 8 Average energy consumed per node (variable traffic)

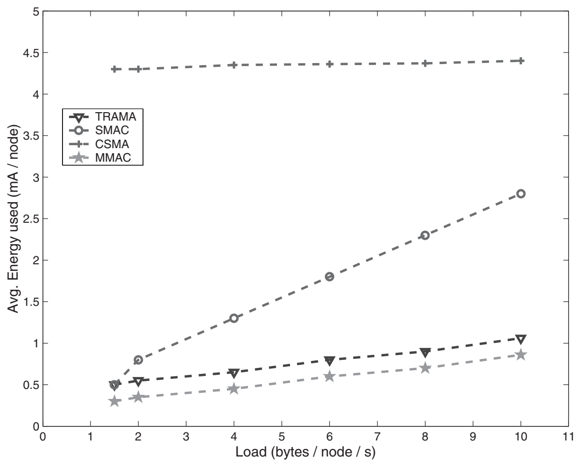
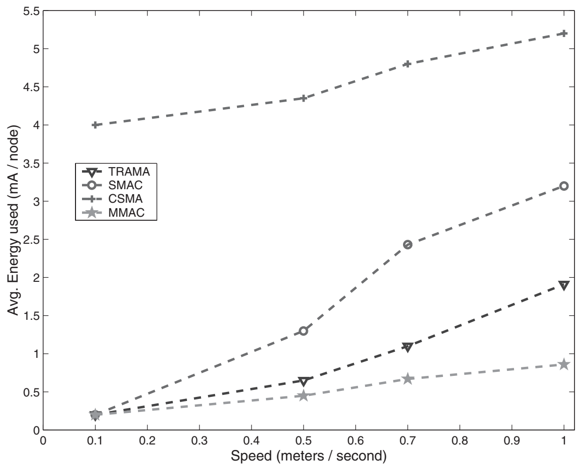


Figure 9 Average energy consumed per node (increasing mobility)



4.5 Implementation

We are currently implementing MMAC, as described in this paper, on the Contiki (Dunkels et al., 2004) operating system for embedded sensor networks using the Protothreads (Dunkels et al., 2005) library. From prior experience we have found Protothreads to be extremely useful in reducing the complexity of event-based programming of wireless sensor networks (Dunkels et al., 2005). We plan to include our implementation of MMAC, presented in this paper, in the Contiki (Dunkels et al., 2004) CVS which would be available from: *http://www.sics.se/˜adam/contiki*.

5 Conclusions

In future ubiquitous environments the individual tiny wireless sensors may be mobile in nature. We showed that the current MAC protocols for sensor networks are not suited for mobile environments and presented a new scheduled-based MAC protocol (MMAC) that adapts the time frame, transmission slots, and random-access slots according to mobility. Our simulation results indicate that MMAC performs parallel to current MAC protocols when there is little or no mobility in the environment. However, in sensor networks with mobile nodes or high network dynamics, MMAC outperforms existing MAC protocols in terms of energy-efficiency, delay and packet delivery.

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