Towards Higher Throughput and Energy Efficiency in Dense Wireless Ad Hoc and Sensor Networks

Wei Zhou
Department of Computer Science and Engineering
Texas A&M University
zwei@cse.tamu.edu

Radu Stoleru
Department of Computer Science and Engineering
Texas A&M University
stoleru@cse.tamu.edu

ABSTRACT

Traditional single-channel MAC protocols for wireless ad hoc and sensor networks favor energy-efficiency over throughput. More recent multi-channel MAC protocols display higher throughput but less energy efficiency. In this paper we propose NAMAC, a negotiator-based multi-channel MAC protocol in which specially designated nodes maintain the sleeping and communication schedules of nodes. Negotiators facilitate the assignation of channels and coordination of communications windows, thus allowing individual nodes to sleep and save energy. Simulation results show that NAMAC, at high network loads, consumes 36% less energy while providing 25% more throughput than comparable state-of-art multi-channel MAC protocols for ad hoc networks. Additionally, we propose a lightweight version of NAMAC and show that it outperforms (55% higher throughput with 36% less energy) state of art MAC protocols for wireless sensor networks.

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Protocols; D.4.4 [**Operating Systems**]: Communications Management

General Terms

Performance, Design, Measurement, Experimentation

Keywords

wireless sensor networks, ad hoc networks, media access protocols, energy efficient operation, multi-channel allocation

1. INTRODUCTION

Traditional MAC protocols for wireless ad hoc and sensor networks restrict themselves to a single frequency using variety of techniques to optimize throughput. Typically designed to work well under low network load, they also attempt to maximize energy efficiency. Recent research has focused attention on multi-channel MAC protocols designed to work efficiently under higher network loads. Although higher throughput has been achieved, this improvement has come at the cost of decreased energy performance, when compared with single channel MAC protocols. An important factor preventing multi-channel MAC protocols from achieving high energy savings is the synchronization required for communication over multiple channels. Dense wireless networks exacerbate the issue by complicating the schedule of channels on which a node can communicate with its neighbors.

Existing research has proposed several ways to maintain schedule information. Some protocols assign predictable static schedules and channels and propagate this information to all nodes in the network [20]. However, static assignments underutilize bandwidth and prevent the network from achieving high aggregate throughput. Other protocols [19], use a common "contention-based control period" where nodes communicate pairwise on a single channel to coordinate their schedules. This common negotiation period wastes energy when traffic is light, as all nodes must be awake during this period.

To meet the dual, and often opposing, goals of improved throughput and reduced energy consumption, NAMAC does not adopt direct pairwise negotiation. Instead, NAMAC designates a set of negotiators who maintain the schedules of all nodes in the network and assist with channel negotiation. In NAMAC, when a sender has packets for a receiver, it requests assistance from a negotiator. Because the negotiator is aware of all communications schedules in its neighborhood, it can assign a time and a channel for the sender to communicate with the receiver. This minimizes the time a receiver stays awake waiting for potential transmissions, thus resulting in higher energy efficiency. It also reduces non-negotiator storage requirements because schedule information is only exchanged between nodes and their negotiators, and not among all neighbors. The main contributions of our work are:

- A communications negotiator that is responsible for synchronizing senders and receivers on a channel and a time when they can communicate.
- A flexible multi-channel MAC protocol applicable to both wireless ad hoc and sensor networks with minor modifications.
- Extensive simulations evaluating the proposed multi-channel MAC protocol and showing that it outperforms state-of-art multi-channel MAC protocols by achiev-

ing significant energy savings and improved throughput.

The rest of paper is organized as follows. We review related work in Section 2 and present the design of NAMAC in Section 3. A lighter version of NAMAC, Light-NAMAC, with reduced communication overhead is presented in Section 4. Section 5, evaluates the performance of NAMAC and Light-NAMAC in extensive simulations. We finish with conclusions and future work in Section 6.

2. RELATED WORK

A significant number of multi-channel MAC protocols have been proposed for wireless ad hoc networks [11] [16] [10]. Some require special hardware [15], such as the use of multiple radio transceivers to listen to multiple frequencies at the same time. Others, e.g., TMMAC [19] and MMAC [14], are based on the IEEE 802.11 Distributed Coordination Function (DCF) and use control messages for channel negotiations. SSCH [2] uses pseudo random number generators to help with the allocations of frequencies and channel switching. TDMA-based MAC protocols in ad hoc networks have been primarily designed to provide collision-free access to a single channel [3].

In wireless sensor networks, the energy efficiency of MAC protocols has received significant research focus. Single-channel protocols [12] [17] [4] [6] use low power listening and sleep schedules to save energy. High traffic loads, due to either application semantics or the sink-oriented topology common in wireless sensor networks, poses additional challenges. To address this issue [13] [1] use a hybrid CSMA/TDMA approach. While single channel MAC protocols have better energy consumption, research has demonstrated that multi-channel protocols can achieve higher throughput. Several multi-channel MAC protocols for wireless sensor networks have been recently proposed. One proposed direction is to have static channel and slot assignments. In [20], a node is assigned a fixed frequency for reception, potentially limiting channel utilization, while [8] proposes that the entire schedule be static. A multi-channel MAC protocol specifically designed for dense sensor networks is proposed in [9]. Although implemented on real hardware, it is not evaluated in a highly dense network. Two multi-channel MAC protocols proposed for wireless sensor networks are related to our work in that they also use special nodes to maintain schedules. PEDAMACS [7] uses special access points to synchronize the nodes and to schedule their communications. Similarly, MCMAC [5] uses cluster heads which require powerful radios. NAMAC is different from these two protocols because it does not require nodes with special capabilities and because the sleep schedules of non-negotiator nodes allow for aggressive energy savings.

3. NAMAC DESIGN

The main idea of our multi-channel MAC protocol is the use of special nodes, called negotiators, that schedule traffic for neighbor nodes. This is fueled by a desire to minimize the principle sources of energy consumption in a wireless network: overhearing, communication, idling and collisions. NAMAC trades off increased energy consumption by the negotiator node for energy savings on all non-negotiators. The energy savings are derived from reduced overhearing and collisions, and reduced duty-cycles allowed by longer sleep states. Figure 1 demonstrates a network using NAMAC. The negotiators, nodes $N1$ and $N2$, are responsible for coordinating packet exchanges between almost all nodes within their communications range. Negotiator $N1$ is responsible for the communication between nodes AB, GH and HJ, while negotiator $N2$ is responsible for the communication between nodes EF, FG, BC and CD. Negotiators stay awake all the time on a default channel and all non negotiator nodes simply listen to its directives. A non-negotiator node can go to sleep after verifying with its negotiator(s) that there is no traffic for it. In the following subsections we present key components of the proposed NAMAC protocol.

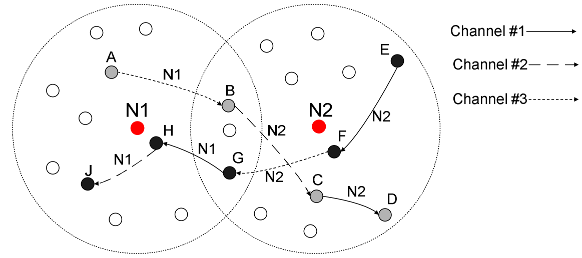

Figure 1: Conceptual design for NAMAC. Nodes N1 and N2 act as negotiators for two data flows in the network: from A to D and from E to J. In this example, all nodes are equipped with radios with three channels. Each link is labeled with the ID of the negotiator responsible for that link. The arrow (i.e., continuous, dashed or dotted) represents the channel, decided by the respective negotiator, to be used by the nodes.

Algorithm 1 Negotiator Election

```
 1: Broadcast HELLO messages. Build Neighbor Table
    (Nbr Tbl) based on HELLO messages heard.
 2: Set MyTimer according to Equation 1
 3: while (MyTimer not expired) do
 4:   if (Received Nbr Tbl from New Negotiator) then
 5:     Adjust MyTimer according to Equation 1
 6:     Set my neighbors (in received Nbr Tbl) as covered
 7:   end if
 8: end while
 9: if (I have uncovered neighbors) then
10:   Declare myself as negotiator
11:   Broadcast my Nbr Tbl
12: end if
```

3.1 Negotiator Election

The negotiator election algorithm, presented in Algorithm 1, is executed by all nodes during network initializations and has two phases. In the first phase, represented by line 1 in Algorithm 1, each node builds a neighbor table. In the second phase, lines 2-12, each node sets a timer, at the end of which, it will declare itself as a negotiator. The timer value is inverse to the number of neighbors uncovered by negotiators and to its residual energy. It is formally given by:

$$T = ((N_{max} - N_{unc}) \times t_c + rand(t)) \times (1 - E/E_{max}) \quad (1)$$

, where N_{max} is a global estimate for the maximum number of neighbors a node can have, N_{unc} is the number of neighbors for which the node does not have a negotiator, t_c is a global time constant, $rand(t)$ is a random number between 0 and t_c, and E and E_{max} are the nodes's current and initial energy levels, respectively.

When the timer expires, a node announces itself as a negotiator and broadcasts its neighbor table. The neighbors that receive this announcement, update their negotiator information, recalculate the number of neighbors uncovered (i.e., nodes that are not neighbors of the negotiator) and adjust their timers accordingly.

Because the negotiator needs to be available on the default channel at all times, a design decision we made was that a negotiator does not route traffic (routing traffic would entail switching channels). Consequently, the network connectivity is affected. To better understand the impact of our design decision, in the remaining part of this section we provide the analysis for the effect negotiators have on the degree of network connectivity.

Assuming that n nodes are uniformly distributed within one radio range and that N negotiators are being elected, the total number of connected links is given by:

$$\frac{(n-N)(n-N-1)}{2}$$

Hence, the number of lost links L_l (from a total of $n(n-1)/2$) due to the negotiator election is:

$$L_l = \frac{(2n-1-N)N}{2} \quad (2)$$

If $p_n = N/n$ is the percentage of negotiators in the network, the total number of lost links becomes:

$$L_l = \frac{np_n(2n-1-np_n)}{2} \quad (3)$$

Consequently, the percentage of lost links in the network is:

$$PL_l = \frac{p_n(2n-1-np_n)}{n-1} \quad (4)$$

$$\approx 2p_n - p_n^2 \text{ since } n \gg 1 \quad (5)$$

This result indicates that a small decrease in the percentage of negotiators (p_n) has a significant impact on the number of links that can be used for routing traffic. Consequently, one goal of our negotiator election algorithm is to produce as small a set of negotiators, as possible. The performance of our negotiator election algorithm is further investigated in Section 5. It is important to mention that the negotiator election algorithm runs periodically to enable negotiator rotation, and better distribution of energy consumption.

3.2 Frame Architecture

NAMAC is a TDMA-based multi-channel MAC protocol, thus we assume the presence of a time synchronization scheme. The frame structure, as well as the messages exchanged, is depicted in Figure 2. Time is divided into Beacon Intervals which are further divided into time slots. A set of three time slots forms a Group. Intuitively, the grouping of three slots is due to the distinct types of messages that need to be exchanged: the request from a sender to the negotiator (done only in the first slot of a group), the request from the negotiator to the receiver (done in the second slot of a group) and the acknowledgement from the negotiator to the sender (done in the third slot of a group). All of these messages are sent over the default channel in a contention-based manner. Each node keeps a schedule of its projected activity for each time slot, sleeping or communicating, and the channel to use. A negotiator maintains a copy the schedules for every node it covers.

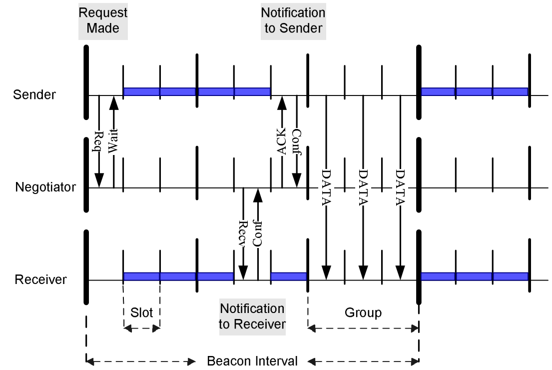

Figure 2: Time slot and channel negotiation in NAMAC. Protocol signaling and data communication are indicated by vertical arrows among Sender, Negotiator and Receiver. In this example, the Beacon Interval contains 3 Groups. Horizontal blue lines indicate time slots when a node sleeps.

NAMAC supports both broadcast and unicast. Broadcast can only be sent in the first slot of a Beacon Interval, a time when all nodes are on the default channel. For unicast, communication is only possible after negotiation. An explanation of the negotiation process in NAMAC follows.

3.3 Negotiation for Unicast

When a sender has unicast packets, a three step process is followed.

First, the sender sends a request ("*Request Made*" in Figure 2) to the negotiator in charge of the link between it and the receiver. This request can only be made on the default channel during the first slot of a group. The request from the sender contains the number of packets and the destination. The negotiator examines the schedule of the receiver and replies to the sender with an acknowledgement ("*Wait*" in Figure 2), containing the time slot when the sender should expect a confirmation/decision ("*Notification to Sender*" in Figure 2). After the transmission of the request packet, the sender starts a timer to wait for the acknowledgement. If the timer expires before receiving a reply, the sender reschedules the request packet.

Second, the negotiator examines the schedules of the sender, receiver, and nodes within one hop of either and assigns time slots and channels for the potential communication. The negotiator finds available slots of the receiver and chooses a random channel from all available channels (we use a greedy solution here to find the maximum contiguous number of available slots). This decision (slots labeled as "*Recv*" in Figure 2 and channel) is sent to the receiver as a notification packet ("*Notification to Receiver*" in Figure 2). The

"*Recv*" request is sent by the negotiator during a time slot when the receiver is awake using the receiver's frequency. Upon receiving this notification, the receiver checks its own schedule to see if there are conflicts between the requested tuple (slots and channel) and its own schedule. If there are no conflicts, the receiver sends a confirmation packet to the negotiator ("*Conf*" paired with "*Recv*" in Figure 2). Other negotiators in the neighborhood overhear this confirmation and use it to update their schedules for the receiver.

Third, the negotiator notifies the sender of this decision (in the slot already scheduled with the sender in step 1) as depicted in "*Notification to Sender*" in Figure 2. The sender updates its schedule according to this decision and sends a confirmation to the negotiator as well. All other negotiators in the neighborhood overhear this confirmation and update their schedules for the sender.

3.4 Sleeping Schedule

One key issue that NAMAC addresses is energy consumption. This is accomplished by having non-negotiator nodes operate in a duty-cycle that varies depending on the traffic in the network. Nodes are only awake in four different cases: a) a node is awake during the first time slot of a Beacon Interval. This accommodates broadcast communication; b) a node is awake during the first slot of a group (including the first slot of a Beacon Interval) if it has a request to send to a negotiator, or it has data to send/receive; c) a node is awake during the third slot of a group if it expects an acknowledgement from a negotiator for a previous request or if it sends/receives data; d) a node is awake during the second slot of a group if it has data to send/receive or, or if it expects notification from a negotiator. A receiver infers its potential traffic load based on recent historical data. If the load is heavy, it stays awake during every second slot of a group to wait for notification; if the load is light, it wakes up occasionally (based on the degree of the load) during the second slot of a group and the negotiator has the knowledge of its schedule.

As an example, Figure 2 depicts with horizontal bars the time slots when different nodes are asleep. As shown, negotiators do not duty-cycle. In the example shown, the sender informs the negotiator during slot 1 of its desire to send three packets to the receiver. The negotiator tells the sender to be awake at slot 6 to possibly receive an acknowledgement. In this example, the sender does not expect packets from other nodes, so it can safely sleep for the duration between slots 2-5. Since the negotiation is successful (i.e., it is ACKed in slot 6), the sender is awake during slots 7-9 to send the data packets. As shown, the receiver is awake during slot 1 for a possible broadcast. The receiver does not have packets to send so it can sleep during slots 2-4. Based on the traffic during the previous beacon interval, it expects a "*Recv*" notification during slot 5 and awakes at that time (note, the negotiator is aware of this awake slot). If there is no traffic in the network, ordinary nodes are only awake two slots per beacon interval (out of 48 slots) which means the minimum duty cycle of ordinary nodes is ~4%.

4. OPTIMIZATION - DESIGN OF LIGHT-NAMAC

The negotiation process for NAMAC requires multiple control messages. At high network loads, this negotiation overhead amortizes with the number of packets negotiated in one single request. Thus the overhead is not significant when compared to the energy savings. At lower networks loads, common in wireless sensor networks, the overhead of NAMAC may be significant and the negotiation process too heavy. To address this problem, we propose a lightweight version of NAMAC, called Light-NAMAC.

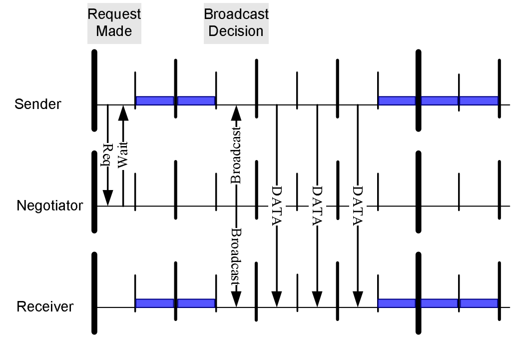

Figure 3: Time slot and channel negotiation in Light-NAMAC. Protocol signaling and data communication are indicated by vertical arrows among Sender, Negotiator and Receiver. In this example, the Beacon Interval contains 3 Groups. Horizontal blue lines indicate time slots when a node sleeps.

The negotiation process in Light-NAMAC is depicted in Figure 3. Each group has only two time slots, since a negotiation takes two steps. If a node wants to transmit, it sends its request to the negotiator and stays awake for the reply. When the negotiator receives the request, it waits until the receiver is available and broadcasts its decision to both the sender and the receiver. Other negotiators overhear this decision. This simplification decreases the number of control messages exchanged for negotiation and is more suitable in situations when the network traffic is light. The time slots when senders and receivers are asleep in Light-NAMAC are depicted with horizontal bars in Figure 3.

5. PERFORMANCE EVALUATION

In this section, we compare the performance of our proposed MAC protocols, NAMAC and Light-NAMAC with existing state of art multi-channel protocols in wireless ad hoc and sensor networks: TMMAC [19], MMAC [14] and MMSN [20], respectively. Our performance evaluation results are obtained through simulations in GloMoSim [18] and investigate both single-hop (30 nodes deployed in one radio range) and multi-hop networks (200 nodes deployed within $1000 \times 1000 m^2$). The radio range was fixed at 250m and we considered radio transceivers with 4 and 6 channels. We use Geographic Forwarding as the routing protocol and the two-ray radio propagation model. The traffic is CBR with a packet size of 512B. For the single-hop and multi-hop scenarios we generated 15 and 20 pairwise random data flows, respectively. The network load was varied through the packet arrival rate in each flow, which ranged from 1-1000 packets/second. Each evaluation point is an average of 20 runs using different seeds. The simulation scenario for the evaluation of Light-NAMAC is similar with that of NAMAC, except the packet size being 64 bytes.

We use two metrics to evaluate performance: the aggre-

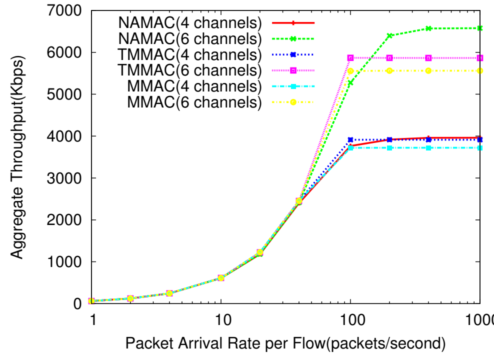

Figure 4: Aggregate Throughput vs. PAR in a single-hop Ad Hoc network

gate throughput (total number of packets received at the end nodes divided by the time) and energy consumed by all nodes in the network (including the negotiators) in a given time, including energy spent for communication or when a node is awake.

5.1 Negotiator Election

In the aforementioned multi-hop experimental setup the negotiator election algorithm elects 21 negotiators, 10% of all nodes. We evaluated the relationship between the percentage of negotiators and the density of the network by gradually changing the number of nodes in the network. The results are summarized in Table 1.

Table 1: Percentage of Negotiators for different Network Densities

Density (Nodes/R)	10	20	40	60	80	90	100
Negotiators (%)	24	19	11	9	7	6	6

As shown in Table 1, and confirming our intuition, as the density of the network increases, the percentage of negotiators decreases to a threshold of ∼6%.

5.2 Evaluation of NAMAC

We first present the performance evaluation of our NAMAC protocol and compare it with TMMAC and MMAC.

5.2.1 Aggregate Throughput

Simulation results for the single-hop network are presented in Figure 4. For single-hop communication, the throughput of the three protocols at low network loads are similar as the traffic is still within each protocol's limit. When traffic is high (packet rates greater than 100 packets/second), NAMAC outperforms TMMAC and MMAC protocols because it can assign more packets per negotiation. Also, NAMAC does not have a fixed negotiation window that takes a large portion of the total time. Once the negotiation is done, all time slots can be used for communication. We also see that as the number of channels increases, the throughput for the three protocols increases as well.

In the simulation results for the multi-hop network (Figure 5), the throughput of the three protocols at low network loads is similar. In high network traffic, the throughput of NAMAC is 25% higher than TMMAC and 94% higher than MMAC, similar to the single hop scenario.

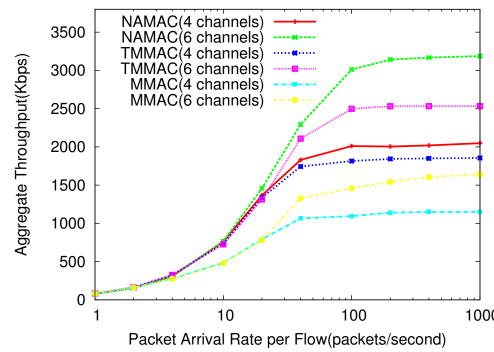

Figure 5: Aggregate Throughput vs. PAR in a multi-hop Ad Hoc network

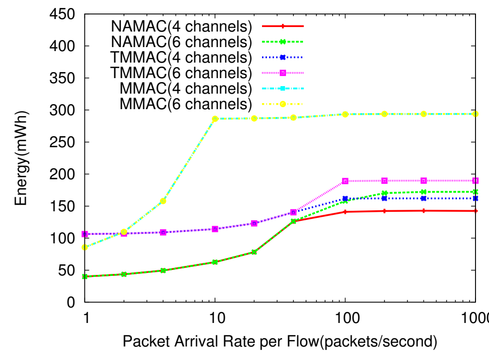

Figure 6: Energy consumption vs. PAR for a single-hop Ad Hoc network

5.2.2 Energy Consumption

Remarkably, in the single hop communication scenario, as shown in Figure 6, NAMAC is the most energy efficient protocol at low and high network loads. NAMAC works especially well at low network loads where it consumes ∼60% less energy than TMMAC and 50% less energy than MMAC. At high loads, when nodes are awake most of the time, the energy consumption of NAMAC is ∼10% less than TMMAC and 40% less than MMAC. The energy consumed by TMMAC is higher than MMAC when the packet arrival rate is below 2 packets/second as the energy is mainly consumed during the negotiation window (TMMAC has a negotiation window takes a larger portion of total time than MMAC). When the network load increases, the energy consumption of MMAC is more than TMMAC. This is due to the fact that nodes in TMMAC can sleep during individual time slots, while MMAC can only sleep if there is no communication within a beacon interval. When the number of channels increases, each protocol's capability to communicate also increases. The energy consumed, however, increases as well. For MMAC, however, the energy consumption for different number of channels remains the same.

In a multi-hop network scenario, as shown in Figure 7, NAMAC still consumes the least energy. TMMAC consumes more energy because the nodes in the network that do not

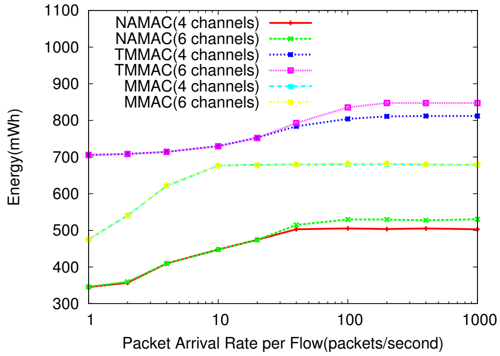

Figure 7: Energy consumption vs. PAR for a multi-hop Ad Hoc network

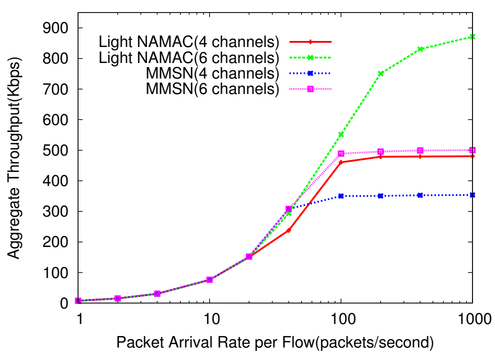

Figure 8: Aggregate Throughput vs. PAR in a single-hop Sensor Network

participate in routing still need to stay awake during the contention-based interval for potential channel/slot negotiations.

5.3 Evaluation of Light-NAMAC

We evaluate the performance of Light-NAMAC and MMSN in both single-hop communication and multi-hop scenarios.

5.3.1 Aggregate Throughput

The throughput of Light-NAMAC, shown in Figure 8 and Figure 9, is similar to that of MMSN when the network load is low. When the packet arrival rate reaches 100 packets/second, Light-NAMAC has better throughput than MMSN for both single hop and multi-hop. This difference in throughput increases when the number of channels increases. This is because Light-NAMAC always uses the default channel for negotiation. As an example, if the radio has 4 channels, Light-NAMAC uses 3 channels for data communication compared with 4 by MMSN. If 6 channels are available, Light-NAMAC uses 5 channels for communication and MMSN uses 6. As shown in Figure 8 and Figure 9 Light-NAMAC achieves 70% higher throughput in single-hop and 55% higher throughput in multi-hop scenarios over MMSN.

5.3.2 Energy Consumption

The energy consumed by Light-NAMAC, as shown in Figure 10 and Figure 11, is smaller than MMSN in both single-hop and multi-hop scenarios. This is because MMSN does not have an energy saving scheme. Nodes using MMSN are

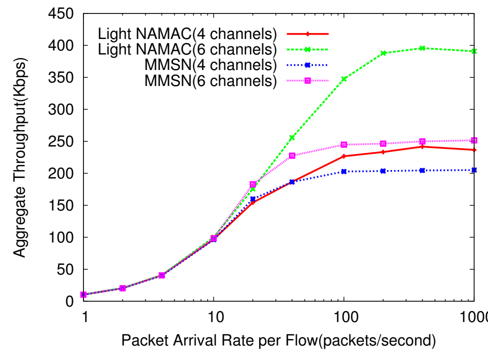

Figure 9: Aggregate Throughput vs. PAR in a multi-hop Sensor Network

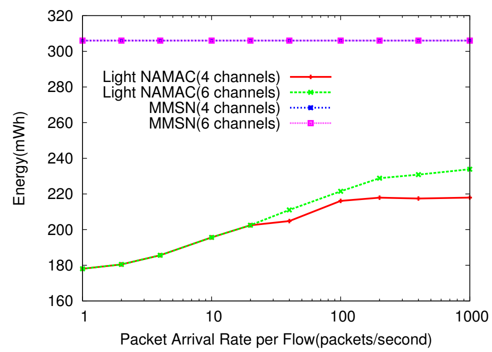

Figure 10: Energy consumption vs. PAR for a single-hop Sensor Network

awake all the time, monitoring traffic. Energy consumption for MMSN is approximately a straight line for both light and heavy traffic. For Light-NAMAC, when the traffic increases the nodes sleep less. In single-hop, Light-NAMAC consumes ∼30% less energy than MMSN at low network loads and ∼24% less energy at high loads. In multi-hop, Light-NAMAC also consumes 36%-40% less energy than MMSN. As the number of channels increases, the energy consumed by Light-NAMAC also increases as a result of higher throughput and less time spent in sleep mode.

6. CONCLUSIONS AND FUTURE WORK

In this paper, we presented NAMAC - a negotiator based multi-channel MAC protocol, in which specially designated nodes maintain sleeping and communication schedules of nodes. Simulation results show that NAMAC, at high network loads, consumes 36% less energy while providing 25% more throughput than state of art multi-channel MAC protocols for ad hoc networks. Additionally, we propose a lighter version of NAMAC and show that it outperforms (55% higher throughput with 36% less energy) state of art MAC protocols for wireless sensor networks. We leave for future work the implementation of Light-NAMAC on real mote hardware. We plan to add redundancy through additional/backup negotiators which can aid in case of negotiator failures. An optimization of our scheme can address the scenario of data streams present in the network. In this scenario, nodes do not need to negotiate frequently.

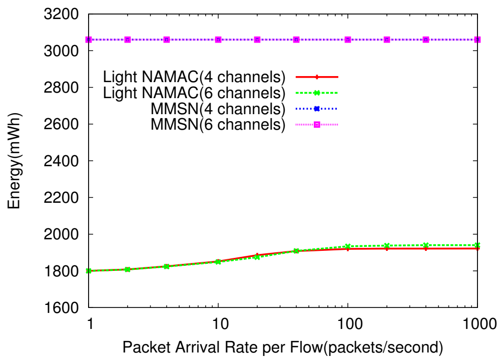

Figure 11: Energy consumption vs. PAR for a multi-hop Sensor Network

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