The Multi-Channel Flow-Aware Medium Access Control Protocol for Wireless Sensor Networks

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***Abstract*—We introduce the Multi-Channel Flow-Aware Medium Access Control protocol, or (MFLAMA), an energy-efficient, schedule-based, multi-channel medium-access control (MAC) protocol designed for data gathering applications in wireless sensor networks. MFLAMA improves the channel utilization by establishing collision-free transmission schedules across multiple channels. Energy efficiency is achieved by preventing packet collisions, idle listening, and transmissions to a node that is not ready to receive packets. We evaluate MFLAMA through extensive simulations and quantify the improvement in channel utilization through the use of multiple channels. Our results indicate that as we increase the number of orthogonal channels used for communication, there is significant improvement in channel utilization and queueing delay. However, we notice a "diminishing returns" effect as we increase the number of channels, i.e., the performance improvements observed decrease with the number of channels beyond a certain threshold. This threshold depends on the topology and traffic flow patterns being used.**

I. Introduction

Sensor networks have emerged as an ideal solution to a number of applications with significant scientific and societal relevance. Such applications include environmental monitoring, disaster recovery, emergency rescue, tracking mobile objects, etc. Sensor networks typically refer to a collection of low-cost, small nodes that have processing, (wireless) communication, and sensing capabilities.

Commercial sensor network radios [1] often support multiple orthogonal communication channels. As shown in Figure 1, channel utilization can be improved by scheduling transmissions across multiple channels. This particular example illustrates a data gathering application, in which a sink is collecting data from all the sensors using a data forwarding tree. For the given traffic flow pattern, only one of the flows can be scheduled for transmission without hidden-terminal collisions using a single channel. However, with multiple channels, three flows (i.e., F_d, F_e, and F_f) can be scheduled concurrently without hidden-terminal collisions.

In our previous work we established the importance of application-aware medium access in sensor networks [2]. In this paper, we introduce the Multi-Channel FLow-Aware Medium Access Control protocol, or MFLAMA, a schedule-based MAC protocol that leverages both the traffic predictability in some sensor network applications and also the availability of multiple orthogonal channels. MFLAMA characterizes traffic using directed flows [2] and uses a distributed scheduling algorithm to establish transmission schedules across multiple channels.

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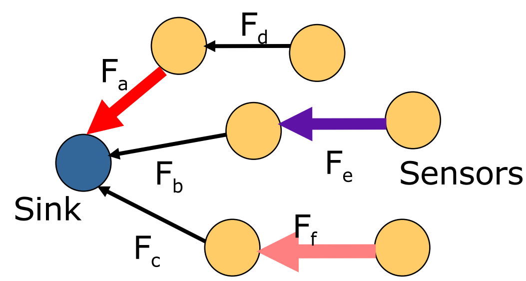

Fig. 1. Multi-channel scheduling in data gathering applications.

The main features of MFLAMA, as described in detail in Section III, are: (a) distributed, energy-efficient, collision-free transmission scheduling based on two-hop neighborhood information and implicit traffic information across multiple communication channels, (b) low transmission delays with limited processing and storage requirements, and (c) robust operation that accommodates topology changes.

We evaluate the performance of MFLAMA through extensive simulations. Section IV presents our simulation results which quantify the benefits of multi-channel scheduling. We observe that as we increase the number of orthogonal channels used for communication, there is significant improvement in channel utilization and queueing delay. However, we notice a "diminishing returns" effect as we increase the number of channels, i.e., the performance improvements observed decrease with the number of channels beyond a certain threshold. This threshold depends on the topology and traffic flow patterns being used.

II. Related Work

Existing MAC protocols can be categorized as contention-, schedule-, or reservation-based. PAMAS [3] is one of the earliest contention-based proposals to address power efficiency in channel access. PAMAS saves energy by attempting to avoid over-hearing among neighboring nodes. To achieve this, PAMAS uses out-of channel signaling. Woo and Culler [4] address variations of CSMA tailored for sensor networks, and propose an adaptive rate control mechanism to achieve fair bandwidth allocation among sensor network nodes. In the power save (PS) mode in IEEE 802.11 DCF, nodes sleep periodically. Tseng *et al.* [5] investigated three sleep modalities in 802.11 DCF in multi-hop networks. The sensor-MAC protocol [6], or S-MAC, exhibits similar functionality to that of PAMAS and the protocol by Tseng *et al.*. Like the other approaches, S-MAC avoids overhearing and nodes periodically sleep. However, unlike PAMAS, S-MAC uses in-line signaling, and unlike modalities of the PS mode in 802.11 DCF, neighboring nodes can synchronize their sleep schedules. T-MAC [7] is an improvement over S-MAC that adapts the duty cycle based on traffic. However, synchronized listen periods increase channel contention significantly and also increases the overall noise floor during transmissions leading to degradation in link quality.

D-MAC [8] is a contention-based medium access protocol optimized for data gathering applications over unidirectional trees. It schedules transmissions at each hop so that the latency in data collection is reduced. However, D-MAC assumes fixed topology and does not allow multiple data gathering trees. It cannot adapt to other sensor network applications. All of the above mentioned protocols improve energy efficiency by avoiding idle listening. However, they waste energy in (1) collisions due to hidden terminals and (2) carrier-sensing.

In scheduled-access MACs, all nodes are time synchronized and access the medium using well-defined transmission schedules. Scheduled-access MACs [9]–[14] have become an attractive approach to medium access in MANETs due to their potential for improving channel efficiency and increasing energy savings.

The Traffic-Adaptive Medium Access (TRAMA) protocol [15] was the first proposal to implement energy-aware schedule-based medium access. TRAMA addresses energy efficiency by having nodes going into sleep mode if they are not selected to transmit and are not the intended receivers of traffic during a particular time slot. Besides its energy efficiency benefits, TRAMA's use of traffic information also makes it adaptive to the application at hand. However, TRAMA's adaptiveness comes at a price, namely the complexity of its election algorithm and scheduling overhead for announcing traffic information. It should be noted that schedule-based protocols exhibit inherently higher delivery delays when compared to contention-based approaches. In TRAMA, this is exacerbated by the need to propagate schedule information.

Unlike TRAMA [15]), FLAMA [2] does not require explicit schedule announcements during scheduled access periods. Alternatively, application-specific traffic information is exchanged among nodes during random access to reflect the driving application's specific traffic patterns, or *flows*. This allows FLAMA to still adapt to changes in traffic behavior and topology (e.g., node failure).

All previously mentioned protocols are designed to work with a single channel. The work by So and Vaidya describes a multi-channel MAC for ad hoc networks (MMAC) using a single transceiver [16]. It is a contention-based medium access protocol similar to IEEE 802.11 and it uses the ATIM window in IEEE 802.11 PSM for announcing channel switching information. In MMAC, every node must listen in a default channel during the ATIM window. Nodes negotiate channels to transmit or receive by exchanging Preferred Channel Lists (PCLs). Another recent example of a multi-channel MAC is the Slotted Seeded Channel Hopping (SSCH) [17] protocol. SSCH is an improvement over SEEDEX [14] for scheduling across multiple channels. However, both the approaches are based on the assumption that nodes can continuously listen to the selected channel and does not consider energy efficiency.

III. MFLAMA

MFLAMA uses a distributed algorithm to establish transmission schedules across multiple channels. We assume that (a) all nodes are equipped with a single radio that can be tuned to transmit/receive in different orthogonal channels and (b) channel access is time-slotted. MFLAMA extends the FLAMA [2] approach to support scheduling across multiple channels. While the neighbor discovery, traffic characterization, and time structure organization of MFLAMA is similar to that of FLAMA, MFLAMA uses a novel distributed algorithm to schedule transmissions across multiple channels that guarantees collision freedom as well as no transmissions to sleeping nodes. For that reason, MFLAMA also requires additional signaling information as will be described in detail below.

MFLAMA requires consistent two-hop neighborhood and flow information to establish data transmission schedules. Similar to FLAMA, time is organized in periods of random- and scheduled-access intervals. Channel access is contention-based during random-access and time-slotted during scheduled-access periods. During random access all the nodes listen in the same channel (control channel). Neighbor discovery, time synchronization, and implicit traffic information exchange are performed during this period. Data transmissions are scheduled across multiple channels during scheduled access.

The implementation of MFLAMA we showcase in this paper is customized for data gathering scenarios, an important class of sensor network applications. When performing data gathering, the information sink(s) sends out a query for a given sensor reading. When relevant sensors reply, a tree rooted at the sink is established. MFLAMA uses this tree to define the corresponding flows and flow weights [1].

A. Random-Access Period

During random access, all nodes contend for access to the control channel and exchange signaling information. Also during random access, a number of tasks necessary to MFLAMA's operation are performed, namely: (1) local time synchronization, (2) data forwarding tree formation, (3) traffic flow

[1]Refer to FLAMA [2] for more information on traffic characterization.

TABLE I
MFLAMA SIGNALING INFORMATION

Size (bytes)	Field	Description
1	len	physical layer length
1	type	packet type, SYNC or SYNC_REQ
2	dst	destination node address
2	src	source node address
4	st	start time (Sched Access)
4	ts	time stamp of this packet
2	parent	parent of src node
1	weight	cumulative weight
1	nn	numNodes, num of one hop neighbors
1	seq	seq num of this update
2 * nn	oh	one hop node ids.
2 * nn	oh_p	one hop parent ids
4 * nn	oh_ts	time stamp last heard from
1 * nn	oh_wt	node weights
1 * nn	oh_seq	last seen seq num

information exchange and weight computation for traffic-adaptive election, and (4) two-hop neighborhood information and corresponding node weight exchange.

Signaling information exchange is initiated by the sink of the data gathering application who sends out a query for relevant sensed data. As the query propagates, sensor nodes establish their parent which they will use to forward sensed data to the sink. Data gathering tree formation, time synchronization and signaling packet exchange mechanisms are similar to FLAMA [2].

One notable difference when compared to FLAMA is that MFLAMA requires additional signaling information to accommodate collision-free, multi-channel scheduling. Table I presents the signaling information that is exchanged during MFLAMA's random-access period. Unlike FLAMA, MFLAMA requires the parent identifiers for all its one-hop neighbors. This information is used by the distributed scheduling algorithm for ensuring collision freedom and protocol correctness.

During random access periods, signaling packets may be lost due to collisions. Hence, random access intervals should be long enough to accommodate signaling retransmissions. In general, the length of the random access period is $NUM\_RETX \times SYNC\_INTERVAL \times NETWORK\_RADIUS$, where NUM_RETX is the desired number of retransmissions and $NETWORK\_RADIUS$ is the network radius. NUM_RETX is computed to guarantee a given probability of successful signaling transmissions [12], [15] and is dependent on the one-hop neighbor density of the network.

B. Scheduled-Access Period

During scheduled access, time is slotted and the slot interval is fixed based on the maximum physical layer frame size. In our implementation we used a packet size of 128 bytes which is the maximum physical layer packet size for TinyOS's CC1000 physical radio module. A guard interval is added to the time slot duration to account for synchronization errors (due to clock drifts) and radio mode switching. The number of slots in the scheduled-access period is dependent on the length of the scheduled access period. For a static network with limited topology changes, the scheduled access period can be very long with occasional random-access periods.

Distributed Election Algorithm: MFLAMA uses a distributed election algorithm to schedule collision-free transmissions. All the nodes use this algorithm to decide the radio mode, (*transmit, receive, or sleep*), and operational channel. The algorithm ensures that there is only one transmitter in the two-hop neighborhood per channel and thus avoids hidden-terminal collisions. It also ensures that if a transmitter is elected to transmit in a particular channel, then the intended receiver listens in the same channel without any inconsistency.

Each node computes a priority value for all the nodes in its two-hop neighborhood, using a pseudo-random function as shown below:

$$prio(n,t,weight) = pseudorandom(n+t) + weight \times C$$

where C is a constant multiplier, n is the node identifier, t is the time-slot identifier, and *weight* is the weight assigned to the node based on its throughput requirements. Node weights are computed during the random access period and are incorporated to provide more channel access for nodes with higher traffic rates. This makes MFLAMA traffic-adaptive while maintaining the simplicity of the election algorithm. The pseudo-random function could be implemented using linear shift registers and $(n+t)$ determines the initial state of the register. The transmission channel for a node is a pseudo-random function of the node identifier n.

Nodes are sorted based on the computed priority value and radio modes are allocated starting from the highest priority nodes. A node can transmit to its *parent*, if: (i) it has the highest two-hop priority for the given time slot t, (ii) the transmission channel is not alloted to any other higher priority neighbor, and (iii) the receiver (*parent*) is not scheduled to receive from a higher priority neighbor.

Due to limited neighborhood information and the distributed nature of the algorithm, special care should be taken to prevent a node from sleeping or listening to another channel when it is the intended receiver of a neighbor's transmission. To ensure this, for a given *parent* (receiver node), only the highest priority one-hop *child* is allowed to transmit. Hence, a node always listens to its highest priority one-hop child (if it is not a transmitter) on the channel chosen by the transmitting child.

A node can turn off its radio, i.e., go to sleep, if (a) it is an elected transmitter and does not have data to send, or (b) it is an elected transmitter with receiver conflict. While in receive mode waiting for data, the node can switch to sleep mode if it does not start receiving data for $PREAMBLE\_INTERVAL$.

The pseudo-code of the election algorithm is presented in Figure 2.

IV. PERFORMANCE EVALUATION

MFLAMA's performance is evaluated through extensive simulation experiments using Qualnet [18]. The goal of the simulation study is to quantify the performance improvements that can be gained by using multi-channel when compared to single channel scheduling (FLAMA). A physical layer model based on Mica2 motes' Chipcon CC1000 radio is implemented

```
Compute SortedOneHop(u,t) based on descending order of node priorities.
Initialize parentAvailable = TRUE; UsedChannelList = ∅; u.state = UNKNOWN;
foreach (node ∈ SortedOneHop(u,t))
  if (node == u) then : Out-going flow to parent
    foreach (twoHop ∈ TwoHopList(u))
        if PriorityHigh(twoHop, u) then : TwoHop higher priority
            if (TXCHANNEL(u) == TXCHANNEL(twoHop) || u.parent == twoHop.parent)
                  let u.state = SLEEP; break ;
            endif
        endif
    end
        if (u.state == UNKNOWN && parentAvailable && TXCHANNEL(u) ∋ UsedChannelList) then
        let u.state = TX; u.txchan = TXCHANNEL(u); u.rx = parent;
    else let u.state = SLEEP; break ;
  end
  if (node == CHILD(u)) then : Incoming flow from child
    let u.state = RX; u.rxchan = TXCHANNEL(node); u.tx = node;
  else
    let UsedChannelList = {UsedChannelList, TXCHANNEL(node)};
    if (node == u.parent) then let parentAvailable = FALSE endif
end
if (u.state == UNKNOWN) let u.state = SLEEP endif
```

Fig. 2. MFLAMA election algorithm pseudo-code

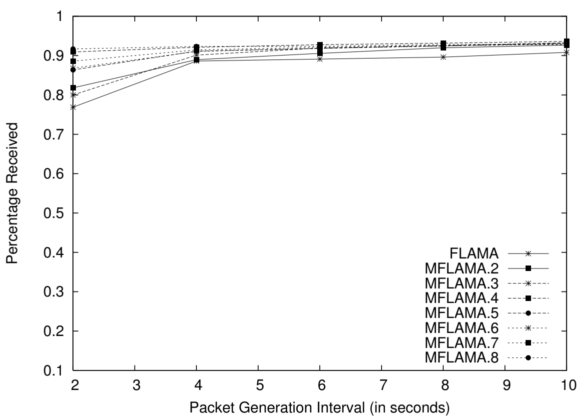

Fig. 3. Average Delivery Ratio

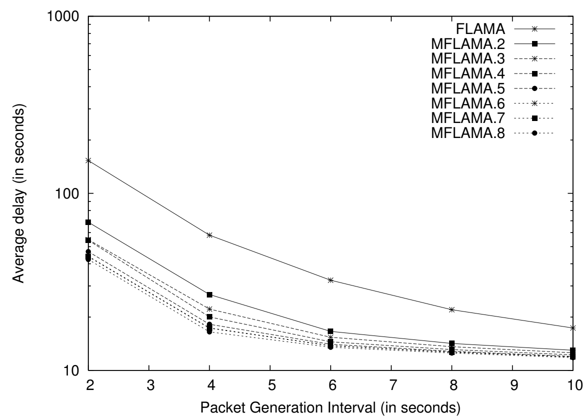

Fig. 4. Average Queueing Delay

to accurately model the operating environment. The radio's data rate is $19.2Kbps$ and its range is around 300 feet (90m).

Sensor network deployments for data gathering are often hierarchical, where there are some more capable data gathering nodes, each of which collect data from a subset of sensor nodes. We try to mimic this kind of deployment by using a grid topology with 16 nodes with the sink in the corner periodically issuing queries to the network to gather requested information. Nodes in the grid are separated by a distance of $75m$. All sensor nodes participating in the network report to the sink sending the requested information at the rate specified in the query. In our simulations, sensor nodes generate periodic 128-byte packets after an initial warmup time. This initial warmup period is needed to allow for neighbor discovery and is fixed at 50 seconds. The data generation rate is one of the parameters we varied in the simulation experiments we conducted. We also varied the number of available orthogonal channels.

A. Performance Metrics

The following metrics are used to assess the performance of the protocols:

- **Average Packet Delivery Ratio** is the ratio of the number of packets received at the sink to the number of packets sent by all sensor nodes.
- **Percentage Sleep Time** is the ratio of the time spent in low-power sleep mode to the total experiment run time.
- **Average Queueing Delay** is computed as the average per-hop queueing delay for the network.

V. Simulation Results

Figure 3 shows the average packet delivery ratio at the sink and Figure 4 presents the average per-hop queueing delay for different traffic generation intervals for FLAMA and MFLAMA (with different number of total available channels). The delivery ratio of the scheduling-based protocols are mainly

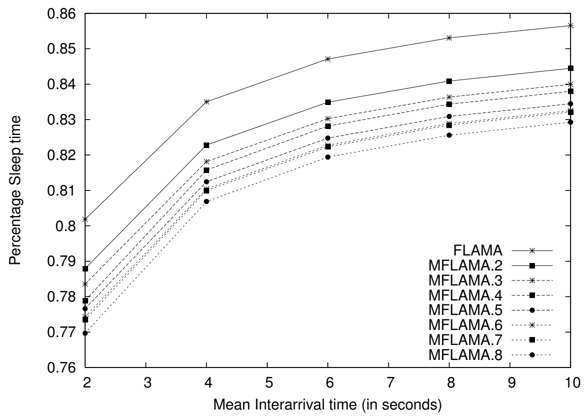

Fig. 5. Percentage sleep time

affected due to packet losses due to buffer overflow as we increase the offered load. When the number of orthogonal channels available for communication increases, the delivery ratio improves at higher offered load due to the reduced per-hop queueing delay.

This is due to the fact that with multiple channels available for communication, simultaneous transmissions can be scheduled without collisions. However, the improvement in channel utilization is limited by the availability of the simultaneous transmitter(s) and receiver(s) in the two-hop neighborhood. This depends on the node density and the traffic flow pattern of the application. For example, in a data-gathering application, near the data collection node (sink), the main bottle-neck for channel utilization is the availability of the sink rather than the availability of orthogonal communication channels.

Figure 5 shows how MFLAMA's energy efficiency compares to FLAMA. We observe that there is a slight decrease in percentage sleep time as the number of communication channels increase. When more channels are available for communication, nodes spend more time listening to the medium. This is due to the simple election algorithm employed in the MFLAMA approach that forces a node to listen to its child, if it has the highest one-hop priority without channel or transmit conflicts. As the offered load increases, nodes also spend more time on transmitting frames due to the increase in channel access probability due to multiple channels.

VI. Conclusion and Future Work

This paper introduced MFLAMA, a multi-channel, energy-aware medium access control protocol for wireless sensor networks. MFLAMA improves channel utilization and queueing delay by scheduling transmissions across multiple channels, while maintaining energy efficiency. MFLAMA's performance is evaluated by simulations using data gathering scenarios, an important sensor network application domain. Our results indicate that an increase in the number of orthogonal channels results in a significant improvement in channel utilization and queueing delay. However, the benefits of using multiple channels are limited by the topology and traffic flow patterns. In the specific scenarios we used in our simulations, the number of channels threshold beyond which performance improvements start to decrease is two channels.

In future work, our multi-channel scheduling framework will be extended to support any general application. We are also developing a Mica2 Mote based test-bed with an implementation of MFLAMA on TinyOS. We will run test-bed experiments as proof of concept as well as to validate our simulation results.

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