Dynamic Sleep Scheduling using Online Experimentation for Wireless Sensor Networks

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***Abstract*— In sensor networks it is critical to conserve energy as replacing batteries is an expensive manual operation. Energy needs to be saved when events are detected as well as when there is no event. Current sleep-scheduling approaches for sensor networks that address energy consumption either only save energy when idling or have high latencies and low channel utilization. Our contribution is an energy efficient sleep-scheduling protocol called BSMac for sensor networks while maintaining high throughput and low latency. BSMac is based on a new architecture called BoostNet in which the base station broadcasts critical scheduling coordination information using large transmission range to reach all sensor nodes in one hop. Nodes assigns colors sequentially to the outgoing links along the traffic path, and nodes not on the data path operate at a low duty-cycle. To accommodate different traffic patterns, the number of colors is critical. To achieve optimal throughput, the base station experiments the network with different maximum number of colors periodically. The performance of BSMac is evaluated using simulations. In comparison to CSMA based approach, BSMac can reduce energy consumption by up to 80% while maintaining similar throughput and latency.**

I. INTRODUCTION

"Touching" a deployed sensor for replacing batteries is an expensive manual operation especially for large deployments. Consequently, power conservation is crucial in designing wireless sensor networks with long network lifetime. One such example is the Glacsweb project [1] where sensors are embedded 60 feet below the surface of the glaciers for studying their movement patterns. Thus, it is critical to design protocols that conserve energy in wireless sensor networks.

Energy conservation is important during periods with no activity and also during occurrence of events. It is critical to reduce traffic overhearing since the transceiver consumes similar energy for idle listening as transmission [2]. The overhearing can be minimized if nodes can determine when they are expected to send and receive packets. To facilitate energy savings during event occurrence, smart sleeping schedule can allow nodes to sleep for short periods when a node is neither transmitting nor receiving.

Although sleep-scheduling in sensor networks has been an active area of research, scheduling to conserve energy for nodes carrying traffic has not received much attention. MAC layer protocols that put nodes to low duty-cycle usually lead to low throughput and high event reporting latency. While for some applications like event tracking, throughput and latency are also important metrics besides energy saving. To save energy on nodes carrying traffic, TDMA based link scheduling is widely studied to put nodes to sleep when they do not transmit or receive packet while they are on the traffic path. In the context of ad-hoc networks, the problem of scheduling has been well modeled as a graph theory problem with solutions based on local coordination and backoffs [3][4]. However, such protocols are not energy-aware and are incapable of determining the periods when the node can go to sleep. In [5], authors have proposed centralized per-packet scheduling based on information gathered from all links. Such global coordination requires excessive messaging and cause delays in link scheduling. To overcome the drawbacks of centralized scheduling, TRAMA [6] proposes distributed scheduling at each node based on information collected within a fixed number of hops. Although TRAMA can conserve energy, the conservative local coordination results in latencies that exceed 100 times the latency of CSMA based approaches. Thus TRAMA is useful only in scenarios where latency and throughput are not critical metrics of performance, which is hardly the case in most sensor networks. **The contribution of this paper is an energy efficient MAC layer sleep-scheduling protocol for sensor networks that maintains high throughput as well as low latency.**

The proposed MAC layer sleep scheduling protocol BSMac is based on a new architecture named BoostNet that leverages the large transmission range capability of the base station to reach all sensor nodes in one hop (Figure 1). Such a large transmission range can be achieved by increasing the transmission power and the antenna height. For large sensor networks, multiple base stations may be deployed to cover the whole network. Alternatively, only nodes close to the single base station use BSMAc protocol since they usually consume more energy than their distant peers. To clearly illustrate the operations of BSMac with the assistance of the base station, in this paper we only focus on the scenario where a single base station can cover the whole network.

The contributions of the paper are as follows:

- We propose BSMac, a energy conserving scheduling approach that conserves energy during event occurrence and does not require any transmissions by the sensors during periods of inactivity.
- We use in-band high transmission power from the base station for network parameters optimization without requiring the second transceiver on sensor nodes.
- We present simulation based comparison of our approach

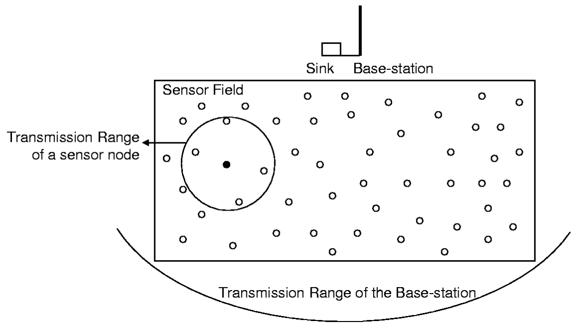

Fig. 1. BoostNet Architecture: The high-power base-station uses the same channel as the sensors and can reach the entire field.

with CSMA based approach. The results show that BS-Mac reduces energy consumption by up to 80% while improving the throughput and maintaining the latency.

The rest of the paper is organized as follows. Section II motivates the problem and our approach. Section III presents the details of our protocol. In Section IV, we present results from simulations comparing our approach to a CSMA based approach. Section V summarizes related work on this topic. Section VI presents discussion on future extensions to the work. Finally, Section VII concludes the paper.

II. Motivation

In this section we present the limitations of fine-grained scheduling and the limitations of apriori parameter assignment. To motivate the design of BSMac, we also outline the advantages of both CSMA and TDMA, and our technique of leveraging the power differential between the base-station and the sensors.

Limitations of fine-grained scheduling: To reduce the energy consumption of overhearing, nodes not involved in current transmission should shut down their transceivers. Ideally, in a sensor network, a scheduling protocol must determine a transmission schedule for each packet to avoids collisions. Such fine-grained scheduling can be performed centrally or distributedly. For central computation like [5], the overhead of control messages and the delay in scheduling is often prohibitive. Although an out-of-band channel and an extra radio could be used to facilitate the scheduling, the additional cost, and the added complexity of managing the power in the second radio makes it a less attractive alternative. Distributed computation of fine-grain scheduling is also faced with problems of extra messaging, conservative channel assignment and thus low channel utilization. In [6], authors designed a local messaging based scheduling approach that may increase latency by a factor exceeding 100. In contrast, some sensor network applications like event tracking require low latency as well as low energy consumption, which makes these approaches are not appropriate.

In this paper, we explore the design of a coarse scheduling approach that consists of long slot (in the order of $100ms$) and uses local coordination with upstream and downstream nodes only. Limiting coordination only with upstream and downstream nodes also allows the coordination information to be piggybacked in the data packets.

Limitations of apriori parameter optimization: Most protocol parameters can be optimized during initial simulations and field tests. However, there is often a set of critical parameters that can not be optimized apriori due to the following four key reasons. First, certain parameters may be a function of the generated traffic pattern, that can not be determined before the occurrence of the event. For example, parameters for a scenario with an event triggering a few sensors may be quite different from an event that triggers a large number of sensors. Second, parameters at different protocol layers often have complex interactions that are hard to predict. Third, the application's prime metric of interest may change dynamically during an event's lifetime. For example, in an event tracking sensor network, the latency may be the primary metric for initial event detection, but throughput may become the primary metric after the initial detection. The critical metric may be application dependent or may even be controlled by a human in the loop. And fourth, changes in the network topology due to node failures, may render apriori optimizations useless.

In this work, we study the optimization of the maximum number of colors used for scheduling links to optimize throughput. We have observed that the optimal value of the number of colors depends on factors such as the number of traffic sources, mobility patterns and node density, which can not be known apriori considering the irregularity of these factors. We optimize the parameter by dynamic exploration with multiple settings during occurrence of the event.

Leveraging the large transmission range capability of the base station: In order to perform parameter tuning during the occurrence of an event, global coordination is required to perform multiple explorations with different parameter settings. A 2-radio solution can be used to coordinate using an out-of-band channel. However, the additional cost of the secondary radio module in each sensor and the added complexity of managing the sleeping cycle of that radio poses questions on the practicality of the 2-radio approach.

In our design, by controlling the parameter exploration from the sink using the base station, critical scheduling broadcast information can reach all sensor nodes immediately, while data traffic communication is carried out with normal transmission power level. However, unlike the complex 2-radio approach outlined above, we assume that the base-station is using the same channel as the sensors. Such a design requires the broadcast of the base station to finish quickly and to be in low frequency so that the data communication throughput and latency is not greatly impaired.

TDMA versus CSMA: Compared to CSMA based protocols popular in WLANs, TDMA based protocols have several advantages in sensor networks. In TDMA, slot assignments can be done in a smart way to allow nodes to sleep for a few packet durations. But coordinating transmission schedules of nodes to avoid collisions is challenging. As discussed above, for TDMA, a centralized approach requires excessive communication, and a distributed approach incurs significant coordination overhead and often leads to channel under-utilization.

Our scheduling approach uses the benefits of both TDMA and CSMA. We use globally coordinated time-slots in the order of $100ms$, that are synchronized with the high power transmissions of the base station. However in each transmission slot, that can handle multiple packet transmissions, nodes use CSMA to compete for the channel. Thus the energy is saved while the throughput metric is also maintained.

An Example: We show a simple example to illustrate the motivation for the problem and our approach. We consider a linear network topology with 12 hops where adjacent nodes are separated by 200 m. The interested reader may see Section IV for other details of the simulation environment. Time is divided into cycles, and each cycle is divided into one DCF and k dedicated colored slots. Figure 2 shows that by choosing the optimal number of colors (four) the throughput can be optimized.

More interestingly, we observe that optimizing the throughput also optimizes the normalized energy consumption (Figure 3). Normalized energy is defined as the total energy consumption divided by the number of received packets. In comparison to CSMA, in our architecture, optimization of the number of colors can reduce the energy consumption by 40% while improving the total throughput.

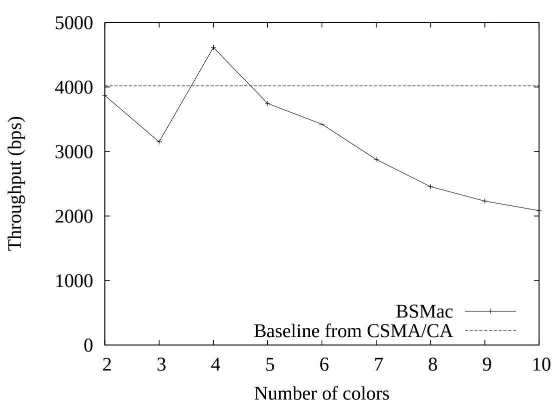

Fig. 2. Throughput for the 12-hop chain topology.

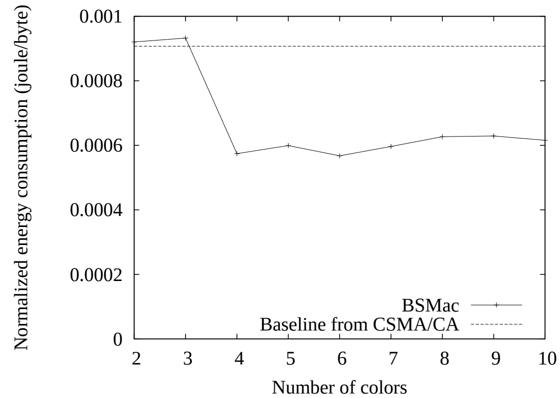

Fig. 3. Normalized energy consumption for the 12-hop chain topology.

III. Protocol Description

In this section, we first briefly state the design ideas of BSMac derived from Section II followed by its detailed description.

Basic design ideas: As the Section II suggests, BSMac protocol is a hybrid TDMA/CSMA protocol that uses in-band signaling assistance from the base station. There are four main considerations for the design of BSMac:

1) **Frequency of in-band signaling:** In order not to conflict with the data traffic since the link between the base station and sensor nodes are asymmetric, the in-band signaling frequency should be kept low, and only the critical global sleep scheduling information can be broadcast from the base station. In BSMac protocol, only the time synchronization information and current experimental maximum number of colors are broadcast.
2) **Length of colored time slot:** The transceivers of sensor nodes needs some time to switch between their working and sleeping states, and the switching operation consumes more energy than normal operation. Thus the slot in each TDMA cycle is relatively large (of the order of $100ms$ currently).
3) **Maximum number of colors:** This number is a network-wide parameter which needs to be chosen carefully. Using too many colors leads to channel under-utilization, and using too few colors leads to high channel contention. As throughput is one of the design goals, we prefer color collision over channel under-utilization. Thus the maximum number of colors is limited to a small number (no more than 6 in our simulations). This number is further optimized through the online parameter experiment conducted by the base station.
4) **Coloring style that achieves low latency:** Our observation is that, when the links along the data path are colored sequentially, the latency is usually the lowest. Thus we adopt such a sequential coloring style in BSMac.

In BSMac, time is divided into cycles. Each cycle is divided into equal sized slots. The default value of number of colors is four. Initially the nodes wakeup only during the DCF periods. Thus initially the duty cycle is 20%. Each slot can accommodate several packet transmissions (our simulations were based on a value of 5).

If an event happens during a non-DCF slot, the event reporting is delayed to the next DCF slot. Since multiple packets can fit in a single DCF slot, the first packet travels a few hops before it encounters a cycle-long delay . The traffic source picks up a color that is least used in its neighborhood. It can be learned by the color information contained in other nodes' packets transmitted in the DCF period. This requires snooping packets in the DCF slot. To optimize the end-to-end delay, and to avoid color coordination messages with all the neighbors, the sequential coloring scheme is used. The colors are assigned to links on the route to the sink in an increasing order, repeating the colors from the beginning if needed. Thus, each node learns of the colored slots in which it will receive data and the colored slot in which it will transmit. Nodes wake up in the DCF, transmission, and reception slots, and sleep in the remaining slots.

When two flows merge, the coloring beyond the merging point depends on the first flow that colors it. The reason to do this is to avoid the frequent recoloring until the first passing flow ends. As the color on the first link of the two flows are chosen independently, there is a chance that the links to the branching point are assigned the same color. We do not try to reversely recolor upstream links because such operation can cause high path recoloring latency. Figure 4 shows two merging flows where flow A-B-C-D-E was colored first. Subsequently, traffic source F started coloring with the least used color in its neighborhood which happened to be color 4. Figure 5 shows the periods in which nodes A, F, and B remain awake.

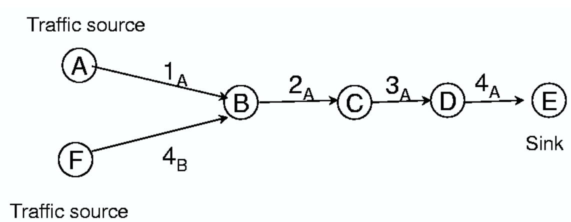

Fig. 4. Color assignment for converging flows. The subscripts represent the corresponding source of the flow.

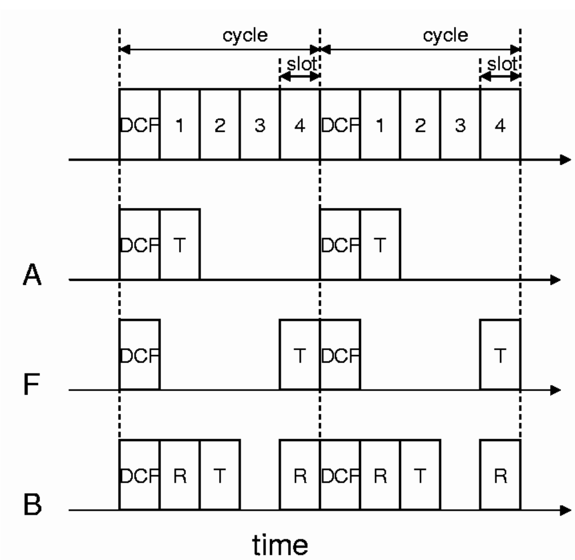

Fig. 5. Slots to wakeup. T is a transmitting slot and R is a receiving slot. All nodes can transmit in the DCF slot.

If a source has no more traffic to send, the slot assignment along the flow path from the source to the sink will timeout. Thus nodes can adjust their sleep schedules according to the change of traffic patterns, which is important for energy conservation in the case of moving events. If some other flows converge with this one later, then after the slot assignment timeout for the first flow, other flows can color the common path according to some specific criteria. In our simulations, the nodes at the converging points will select the slot assignment of the most heavily loaded upstream node to re-color the downstream common path.

At the outset, each sensor node operates using default number of colors (k). However, for a new event the default k may be suboptimal. The base-station evaluates the throughput (other metrics could also be used) by experimenting with a value of k for one epoch, which consists of several cycles. In simulations, we have observed that 10 sec is enough for evaluating an assignment of the parameter. A small epoch may not be sufficient to evaluate the performance for that assignment of the parameter, and a large epoch will require long time to converge to an optimal value. In different experiments depending on the number of active sources, we have observed that the number of optimal colors could be anywhere between 2 and 5. BSMac experiments with these four values of k before converging to the optimal value.

IV. Performance Evaluation

In this section, we evaluate the performance of BSMac in various scenarios. The three main performance metrics are throughput, latency and normalized energy consumption. Normalized Energy is defined as the energy consumed to deliver one byte to the sink. As energy consumption is critical in sensor nodes, this metric is of utmost importance.

The simulations are conducted in ns2 [7]. Our approach is implemented over the IEEE 802.11 code of ns2, where the corresponding backoff timer is paused when the transmission slot or DCF slot ends, and is resumed when one of these two slots occurs again. In addition, nodes are put to sleep when they are not in their transmission, reception or DCF slots. The choice of the colored transmission slot of each node is carried in the packet header, and it introduces 2 bits of extra overhead compared to IEEE 802.11. However, since IEEE 802.11 is designed for WLANs (Wireless LANs), some fields are redundant for wireless sensor networks, which means these 2-bit overhead can use the reserved fields in the MAC header.

The transmission range and interference range are left at the default values of 250 m and 550 m respectively, which are similar to the best results of the Mica2 [2] radio. But our approach does not rely on the specific values. Thus it can be easily applied to wireless sensor networks with smaller or larger transmission interference ranges.

For BSMac, the length of each time slot is set to 110 ms, which can accommodate the transmission of 5 packets, and the default number of colored slots is set to four. The other significant parameters are summarized in Table I.

To validate the BSMac protocol, we conduct performance measurement under three network topology configurations: the simple chain topology, a randomly generated large topology with multiple simultaneous traffic sources and a grid topology with one moving event. We compare the performance of BSMac with IEEE 802.11 (without RTS/CTS). The highlights of our simulation based evaluation is as follows:

TABLE I
SIMULATION SETTINGS

Parameter	Value
DATA packet size	62 bytes
ACK packet size	40 bytes
IEEE 802.11 DATA packet size	60 bytes
IEEE 802.11 ACK size	38 bytes
Transmission range	250m
Carrier sense range	550m
Bandwidth	38.4 Kbps
Data rate	50 packets/sec.
Transmission Power	0.075W
Receiving/idle Power	0.025W
Interface Queue length	50
Routing protocol	GPSR
Slot time length	110ms
Default number of slots	4

- Our approach saves the normalized energy consumption by 40-45% and improves throughput by about 20% for the chain topology.
- BSMac saves 50-80% normalized energy, while achieving about 80% throughput of IEEE 802.11 DCF mode in case of multiple events. For small number of events (one or two), BSMac obtains higher throughput that 802.11. In addition, latency in BSMac is also comparable to that of IEEE 802.11.
- For the scenario with one moving event, BSMac saves normalized energy up to 60%, and can achieve more than 80% throughput of CSMA/CA when the moving speed is less than 10m/s, and 75% when the speed is between 15m/s and 20m/s.
- We observe that a probing interval (epoch) of 10 seconds suffices for determining the best value of a parameter.

A. Chain Topology

In this section, we considered a linear topology of 13 nodes. Simulations are run for 1000 second to obtain a stable performance measurement. In addition, we also study the impact of different node densities.

From Figure 6 we can see that after finding the optimal parameter of number of slots, the throughput can be improved by about 20%, and the latency is only 30% higher than CSMA/CA protocols (Figure 7) although packet transmission is confined to specific time slots. As for the energy consumption, the BSMac protocol consumes less than 60% of CSMA/CA (Figure 8), which can be anticipated since nodes sleep in some slots. Taking optimal number of slots for 200 m hop distance as an example, the optimal number is 4, thus a cycle is composed of 5 slots, and each node is awake in the DCF, one transmission slot and one reception slot, which leads to about $\frac{3}{5}$ energy consumption compared to CSMA/CA. In addition, since the optimal number of colors can alleviate the contention, BSMac can use less than 60% energy to deliver more packets.

Actually, in the chain topology, each node participates in the packet transmission and reception, which is not the case for a large sensor networks where only nodes along the path from the source to the sink will wake up in their transmission and reception slots, while other nodes will only wake up in the DCF slots. Thus BSMac can save more energy for more complex network scenarios (Section IV-B).

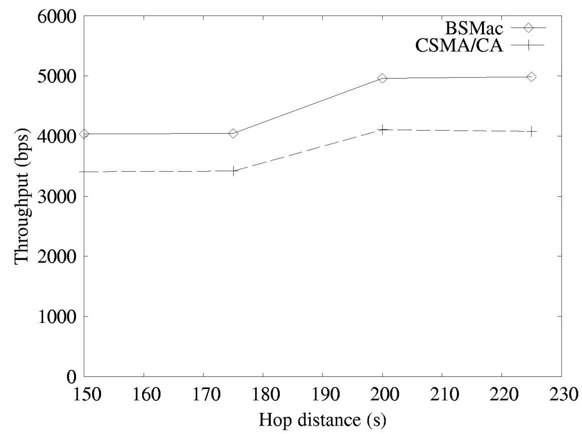

Fig. 6. Throughput for the 12-hop chain topology in 1000s

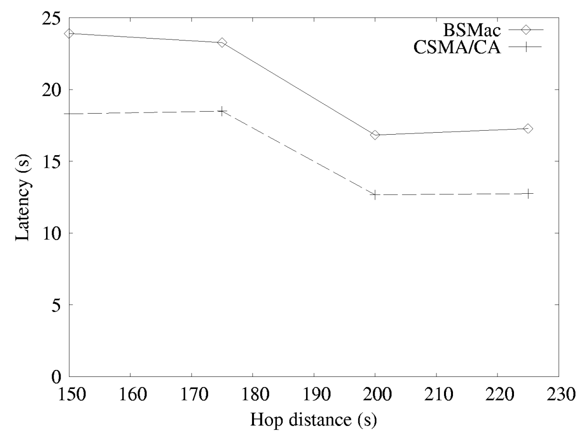

Fig. 7. Latency for the 12-hop chain topology in 1000s

B. Randomly Generated Network with Multiple Simultaneous Events

To test the performance of BSMac in a large deployed network, we generate a network topology by placing 400 nodes uniformly randomly in a $2000m \times 2000m$ area, and randomly select some places to trigger events. One to ten flows are simulated to show the efficiency of the BSMac protocol.

All simulations are run for 1000 seconds to achieve stable results. Figure 9 exhibits the normalized energy consumption of the BSMac and CSMA/CA. We observe that when there are only 1 or 2 flows, the normalized energy consumption is reduced by more than 82%. Even in the case of more than 2 flows, the energy consumption per byte is in the range of 20-45% compared to CSMA/CA. Figure 10 summarizes the throughput of BSMac together with that of IEEE 802.11 DCF node. It can be seen that if the number of flows is very small (1 or 2), the BSMac protocol improves the throughput by 5-10%. If the number of flows is more than 2, the BSMac protocol can achieve more than 85% throughput of CSMA/CA.

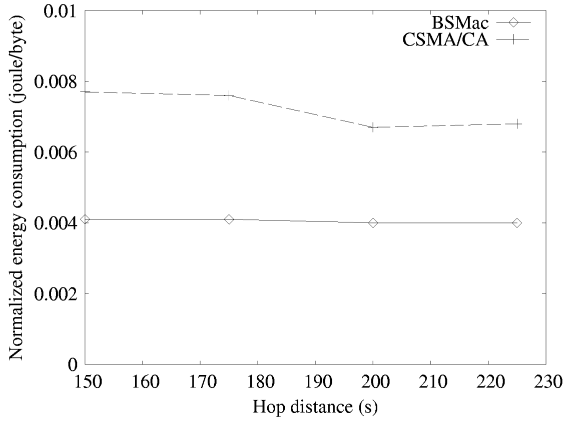

Fig. 8. Normalized energy consumption for the 12-hop chain topology in 1000s

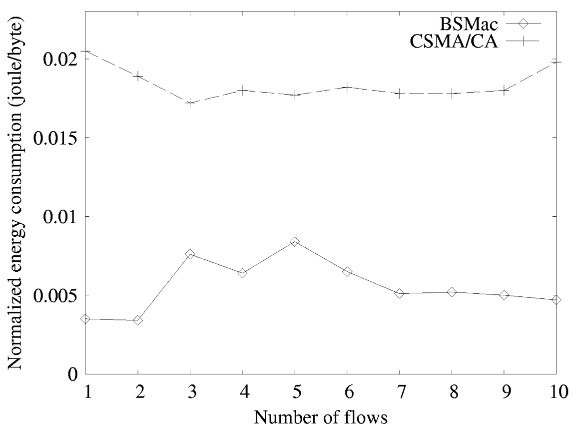

Fig. 9. Normalized energy consumption for the randomly generated topology with multiple events in 1000s

Figure 11 shows that the latency of BSMac with slotted time is comparable with the that of CSMA/CA. The three metrics together validate that the BSMac protocol is suitable for the energy-constrained wireless sensor networks.

C. Grid Network with One Moving Event

In this section, we constructed a 10x10 grid network in a $2000m \times 2000m$ area. We study the performance of BS-Mac together with CSMA/CA under different moving speeds. Figure 12 shows that BSMac impairs the throughput by less than 20% when the moving speed is slower than 10 m/s. Although the throughput degradations are about 25% when the moving speed is increased to 20 m/s, we observe from Figure 13 that BSMac saves 60% normalized energy. In addition, Figure 14 shows that BSMac has almost the same latency performance as CSMA/CA. Therefore, BSMac may not be better for monitoring fast moving events with high data rate, it still exhibits its significant advantage in energy savings. For such dynamic scenarios, it may be better to wakeup all nodes on the route with a 100% duty cycle. We plan to explore this limitation of our protocol further.

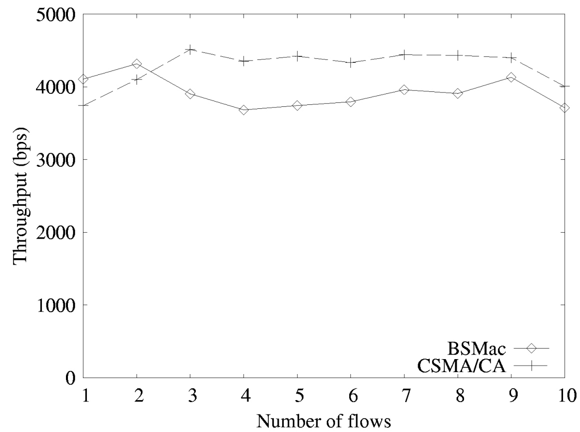

Fig. 10. Throughput for the randomly generated topology with multiple events in 1000s

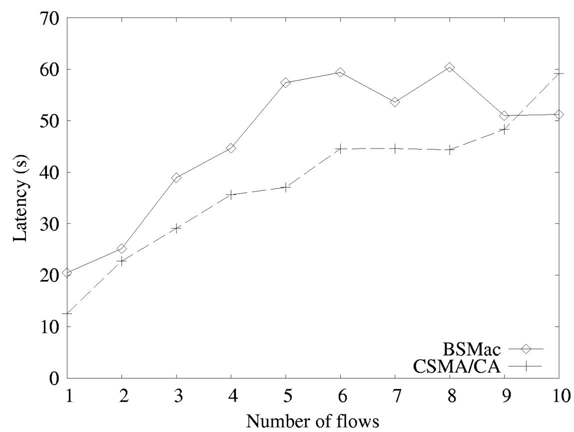

Fig. 11. Latency for the randomly generated topology with multiple events in 1000s

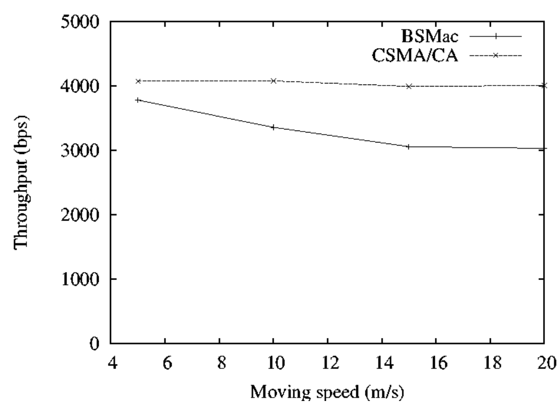

Fig. 12. Throughput for the scenario of moving event in 1000s

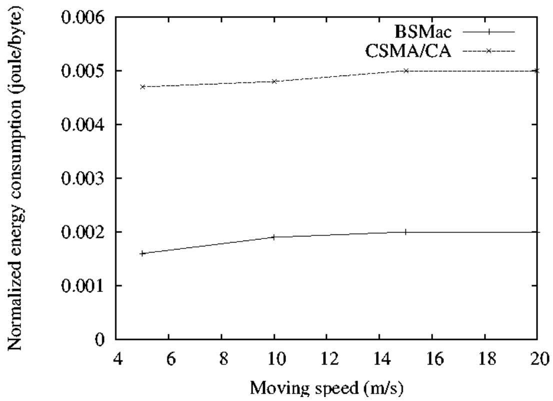

Fig. 13. Normalized energy consumption for the scenario of moving event in 1000s

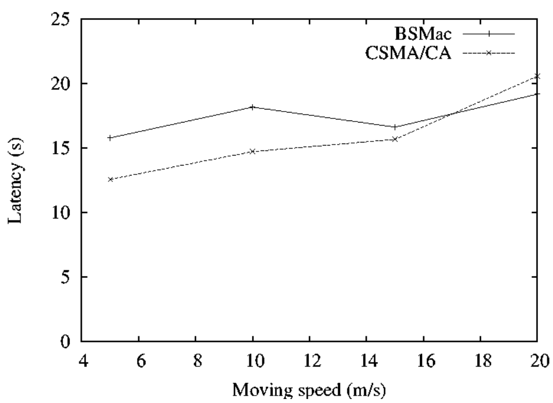

Fig. 14. Latency for the the scenario of moving event in 1000s

D. Parameter Probing Interval

To probe the optimal parameter, namely the number of colors for the network, parameter probing messages are broadcast by the sink to the whole network. To quickly get the optimal value, the probing interval should be small. But with a very small interval, it is hard to gather sufficient evidence to discard one value or adapting to another. In addition, frequent probing will surely impair the throughput of data traffic because of the asymmetric links between each sensor node and the sink.

To find an appropriate value for the probing interval (also referred to as epoch interval), we conduct a simple simulation with the chain topology used in Section II. The throughput observed by the sink is shown in Figure 15. From the figure we can see that after 10 s, using 4 time slots leads to the best performance, and the throughput observed by the sink is stable. In our simulations, we have cautiously used a larger probing interval of 20 s for stability. It also means less overhead and collisions with on-going data-traffic since the link between a common sensor node and the sink is asymmetric. We have given a higher priority to the broadcasts from the base-station in order to reduce collisions with ongoing data transmissions in the DCF slot. The higher priority has been implemented as a lower value of DIFS and no backoff if the channel is found to be available. Although the probing interval, can itself be optimized by utilizing the BoostNet architecture, it has not been studied in this paper.

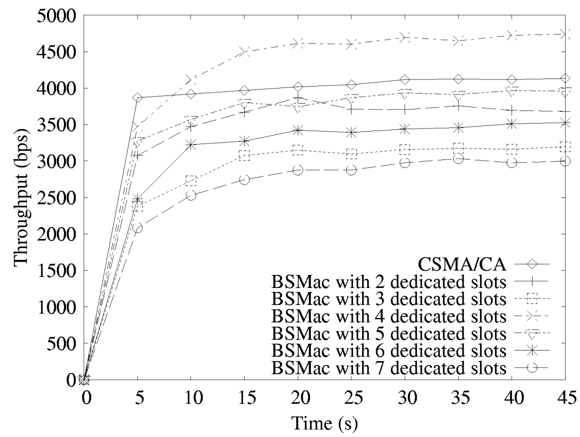

Fig. 15. Throughput observed by the sink vs. runtime

V. Related Work

By introducing the concept of duty cycles, CSMA/CA has been extended to allow nodes to sleep for short durations. S-MAC [8] is a CSMA/CA based approach that requires nodes to be synchronized and enables energy savings by using the concept of periodic sleeping. Woo and Culler [9] have proposed a CSMA/CA based approach that uses adaptive rate control to achieve fair bandwidth allocation while being energy-efficient at low as well as high duty cycles. As opposed to BSMac, these mechanisms require a predefined global duty cycle and periodic messaging by the sensors for time synchronization.

Centralized coordination mechanisms can produce conflict-free schedules at the cost of high overheads for fine-grained information collection from all nodes. In [5], authors propose three link coloring schemes to solve the optimal parallel communication scheduling problem: minimal weight color heuristic, random color selection heuristic, and least used color heuristic. The central coordinator needs to learn the exact topology, interference range, and complete traffic information of all nodes. The message overhead is prohibitive for large sensor networks.

Several distributed scheduling protocols have been proposed in the context of ad-hoc networks [3][4][10] for saving energy by reducing the number of collisions. In [4], authors use the concept of cliques to represent conditions for collision-free transmissions. A backoff adjustment mechanism is devised according to the general framework to ensure proportional fairness in wireless shared channel. But the performance analysis in [4] considered only some special topologies, and the backoff adjustment based approach can not put nodes to sleep because they have to observe the transmission failure ratio to adjust the backoff. [3] analyzes the contention problem in the same manner, but its purpose is to achieve maximum allocation of the shared wireless channel while assuring minimum throughput and delay bounds for each flow. Since the approach in [3] is also backoff-based, it is not suited for conserving idle energy of sensors. NAMA [10] divides time into cycles, where each cycle consists of several hundred slots. Nodes communicate with their 2-hop neighbor nodes to coordinate their slot selection. The authors designed a hash function and an explicit local negotiation mechanism to decide which node has the highest priority to transmit. However NAMA is also not suited for conserving idle energy in nodes.

The idea of power conservation by turning off nodes in a distributed way, has been explored for ad-hoc networks. PAMAS [11] uses out-of-band signaling to avoid over-hearing among neighboring nodes. But adding the second interface to a node may not be cost-efficient and may lead to the complexity of power management across the two radios.

Distributed scheduling protocols have also been proposed for conserving energy in sensor networks [6][12]. TRAMA [6] is an extension of NAMA designed for sensor networks. In TRAMA, nodes sleep in slots in which they do not transmit or receive packets. TRAMA assumes that only the nodes within 2-hops of the transmitting node may collide with it, which may not hold for all node densities. Moreover, the latency of TRAMA may exceed 100 times the latency of CSMA/CA, which may not be desirable if latency is an important performance metric for the application. In [12], the authors propose another TDMA-based MAC scheduling protocol. There are two kinds of slots, one is for transmission and the other is for reception, and nodes negotiate their slot selection locally. Although there are some similarities with BSMac, the authors have explicitly assumed low data rate traffic in the design of the protocol. In contrast, BSMac is designed to handle high data rates.

VI. Future work and Discussions

In this section we discuss some ongoing research issues and future work, that have not been addressed in this paper.

- **Towards a Scalable Design:** By using long antenna and high power, the base-station's range can be made much larger than the sensors range. However, for very large deployments a more scalable approach is needed. We are investigating a hierarchical design with multiple base-stations scattered across the network in such a way that they cover the entire sensor field. These high power base-stations also need an out-of-band channel using which they communicate and coordinate with the base-station. Through coordination, collisions between transmissions of base-stations can be eliminated. As the set of all base-stations cover the entire sensor field, the parameter probing can proceed in a manner similar to that outlined in this paper. This scalable architecture is also suited for fault tolerance that is currently lacking in the single base-station approach.
- **A Multi-channel Alternative:** In Section II we discussed an alternate architecture requiring an additional receiver radio module in each sensor node. Although we did not consider that architecture in this paper, it has some advantages over the proposed architecture. Using a frequency that is more suited for long range such as FM or AM, we can create very large sensor networks by using only a single base-station. However, as mentioned before, the energy consumption on that radio must be optimized as well with smart coordination between the two channels.
- **Leveraging BoostNet for Optimizing Parameters in other Protocols:** We proposed a simple sequential scheduling approach that does not require coordination with nodes other than the immediate upstream and downstream nodes. However, other scheduling algorithms can also leverage the architecture to optimize their performance. In fact, other network protocols can also leverage the BoostNet architecture to statically or dynamically optimize parameters and improve performance.

VII. Conclusion

This paper proposes an energy conserving scheduling protocol, called BSMac. It uses a new architecture called BoostNet, to dynamically adjust the network parameters and improve performance. BSMac divides time into cycles, where each cycle consists of a DCF slot and k scheduled colored slots. Nodes can only transmit packets in DCF or their scheduled transmission slots. During periods with no activity, nodes wakeup only during DCF slots. During occurrence of events, nodes wakeup during transmission, reception, and DCF slots, thus conserving energy. The BoostNet architecture allows the base station with large transmission range capability to command all sensors to change the maximum number of colors and to probe for its optimal value. By dynamically adjusting the parameter, BSMac can improve the throughput and maintain low latency while saving up to 80% energy compared to traditional CSMA protocols. Using BoostNet has two advantages. First the base station can send messages to synchronize sensors obviating the need for the sensors to transmit any messages for time synchronization. The second advantage is that the sink can measure the runtime network performance, and the attached base-station can update the network parameters to quickly adapt to different traffic patterns. Based on the simulation results, we conclude that BSMac is highly suited for networks that require high throughput, low latency, and long network lifetime.

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