MRMAC: Medium Reservation MAC Protocol for Reducing End-to-End Delay and Energy Consumption in Wireless Sensor Networks

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***Abstract*—This letter proposes a novel medium reservation MAC protocol that reduces both end-to-end delay and energy consumption for wireless sensor networks. MRMAC reduces end-to-end delay by informing the intended receiver of $NPAT$ (next packet arrival time) and MRI (medium reservation information) to reserve the medium in advance. Through this medium reservation phase, following packets can be delivered with reduced delay in multihop streaming phase. A simulation shows that the result of the proposed protocol outperforms previous works.**

***Index Terms*—Wireless sensor networks, medium access control, asynchronous, end-to-end delay, energy consumption.**

I. INTRODUCTION

UNLIKE in other wireless networks, it is generally difficult or impractical to charge or replace exhausted batteries in wireless sensor networks [1]. Therefore, the primary design consideration is how to reduce energy consumption of each sensor node for the network longevity. There have been intensive research efforts on MAC protocols, and we can especially divide contention-based duty cycle MAC protocols into two categories: synchronous and asynchronous. S-MAC [2] and T-MAC [3] are representative synchronous approaches and these approaches require time synchronization in order to align sleep and wake up time of sensor nodes. As a sender and its intended receiver are active at the same time, a sender can send a data packet to its intended receiver as soon as it wakes up. Consequently, these approaches reduce the duration of idle listening. However, the required synchronization leads to extra overhead and complexity.

On the other hand, each sensor node sleeps and wakes up following its own duty cycle independently in asynchronous approach, such as B-MAC [4] and X-MAC [5]. As a result, these approaches reduce energy consumption and complexity due to the removal of synchronization overhead. Recently, the receiver-initiated asynchronous duty cycle based MAC protocol (RI-MAC) is proposed [6]. In this protocol, a sender wakes up and remains active until its intended receiver sends a base beacon. RI-MAC significantly reduces the amount of time which a pair of nodes occupies the medium until reaching a rendezvous time for data exchange compared to the preamble transmission in B-MAC and X-MAC. Previous works have been only improved to reduce energy consumption. However, these works still have the common problem of long end-to-end delay, because each sender should wait to relay a data packet until its intended receiver wakes up in every hop along the routing path. Recently, numerous applications require reduced end-to-end delay. Especially in periodic event applications, such as environmental monitoring and structural health monitoring, a traffic pattern of neighbor nodes can be predictable.[1] In this letter, we propose a medium reservation MAC protocol for reducing both end-to-end delay and energy consumption.[2]

II. MEDIUM RESERVATION MAC PROTOCOL

Basically in MRMAC, a sender transmits a data packet enclosing next packet arrival time ($NPAT$) and medium reservation information (MRI) to its intended receiver to reserve the medium. We explain the operation of MRMAC with a simple chain topology as shown in Fig. 1. We assume that node 1 is a source node that only generates data packets delivered to node 3 through node 2 that is a relay node. First of all, we define structures of $NPAT$ and MRI. $NPAT$ is remaining time until next packet arrival. $NPAT$ is calculated differently whether a node is a source node or a relay node.[3] $NPAT$ of a source node, e.g., node 1 in Fig. 1, can be calculated as follow:

$$NPAT_{source} = t_{interval} - t_{wait} - t_{beacon} \tag{1}$$

where $t_{interval}$ is the inter-arrival time of packets, t_{wait} is the duration of waiting time for receiving a beacon, and t_{beacon} is the duration of time required for receiving a beacon. $NPAT$ of a relay node, e.g., node 2 in Fig. 1, can be calculated as follow:

$$NPAT_{relay} = NPAT_{received} - t_{idle} \tag{2}$$

where $NPAT_{received}$ is $NPAT$ that was notified by a sender of the previous hop, e.g., node 1 in Fig. 1, and t_{idle} is the duration of idle listening time as shown in Fig. 1.

On the other hand, MRI is the set of time points reserved by other nodes and every node maintains its MRI to inform its intended receiver. For example, assume that two reservations are already set by other nodes at t_a and t_b before node 1 sends a data packet to its intended receiver, node 2, as shown in Fig. 1. Therefore, node 1 constructs MRI_{node1} after receiving a beacon from the intended receiver as follow:

$$MRI_{node1} = \{t_a - t_{wait} - t_{beacon}, t_b - t_{wait} - t_{beacon}\} \tag{3}$$

MRI maintains only the starting time of the reserved medium because we define T as the summation of transmitting

Manuscript received October 9, 2009. The associate editor coordinating the review of this letter and approving it for publication was H. Yomo.

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Digital Object Identifier 10.1109/LCOMM.2010.07.091983

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[1] We assume that the packet arrival interval of these applications has to be small enough so that clock drifting at different sensors cannot impact MRMAC.

[2] MRMAC can be easily applied to other asynchronous MAC protocols, but we explain the proposed protocol upon RI-MAC in this letter, because RI-MAC protocol achieves the best performance among them.

[3] We assume that there is no error in the predict packet arrival time.

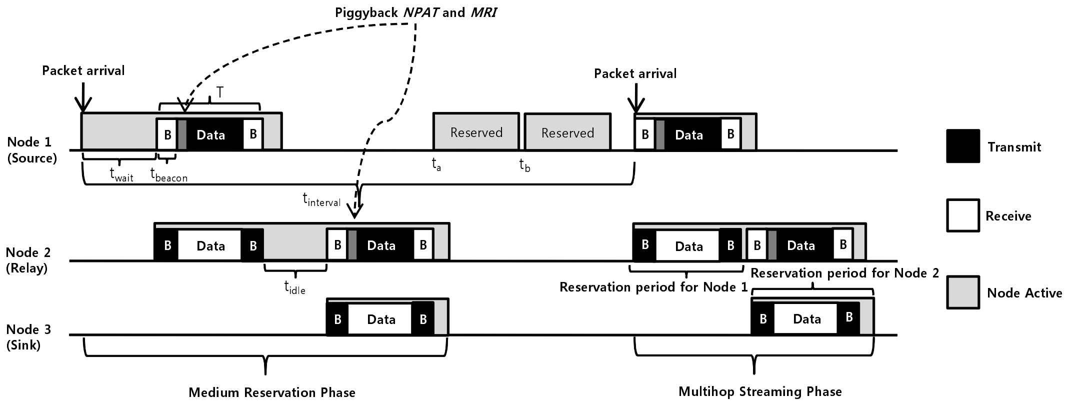

Fig. 1. The basic operation of MRMAC.

time of two beacons and a longest data packet depicted in Fig. 1. Consequently, T is always fixed with the maximum data size. This increases end-to-end delay a little bit due to longer transmitting time, but makes MRMAC less dependent on the size of data. Each sensor node maintains $NPAT$ and MRI by itself, and piggybacks $NPAT$ and MRI into a data packet when transmitting to its intended receiver. After receiving a data packet, the intended receiver can reserve the medium at proper time based on $NPAT$ and MRI notified by the sender, and MRI of itself. At this point, we describe how the intended receiver reserves the medium. Assume that we have following MRI_i as MRI of the sender and MRI_j as MRI of its intended receiver. In other words, MRI_i indicates node 1 (sender)'s MRI, and MRI_j indicates node 2 (intended receiver)'s MRI at the 1-hop communication between node 1 and node 2 in the example of Fig. 1.

$$MRI_i = \{S_i^1, S_s^i, ..., S_i^N\} \tag{4}$$

$$MRI_j = \{S_j^1, S_j^2, ..., S_j^N\} \tag{5}$$

where S_i^k and S_j^k are the medium reservation schedules of the sender and its intended receiver, respectively, N is the maximum reservation size, and $1 \leq k \leq N$. We define a reservation function $R(a)$ as follow:

$$R(a) = \{x | a \leq x \leq a + T\} \tag{6}$$

This function defines the duration of time that is required to send two beacons and one data packet. The intended receiver needs to reserve this duration for data packets generated in the near future. The starting time of this duration is determined by finding minimum x satisfying following condition:

$$R(x) \cap [\bigcup_{k=1}^{N} \{R(S_i^k) \cup R(S_j^k)\}] = \varnothing \ \&\& \ x > NPAT_{received} \tag{7}$$

After the intended receiver determines minimum x, it adds x into its MRI. It means the intended receiver will be able to send an invitation beacon which is a new type of beacon and has the invitation field to the sender at the next packet arrival time whenever the sender contains data. In other words, after the sensor node also wakes up at the scheduled time that is determined through medium reservation phase based on the next packet arrival time in multihop streaming phase, it sends an invitation beacon to the specific 1-hop neighbor that is expected to have a data packet. If a base beacon is used instead of an invitation beacon, medium reservation phase is wasted, because all 1-hop neighbors that have data can simultaneously send data packets, and it always leads to collision. As each sensor node along the routing path can reserve the medium for data packets generated in the near future through medium reservation phase[4], data packets can be delivered to the sink node with reduced delay in MRMAC. We denote it multihop streaming phase.

When multiple senders want to transmit data to an identical receiver simultaneously, collision may occur at the receiver. In addition, if the senders want to send data periodically, collision can occur repeatedly, and it leads to serious performance degradation. To resolve this situation, MRMAC basically follows the collision resolving mechanism of RI-MAC. Additionally in MRMAC, $NPAT$ and MRI of the senders are delivered to its intended receiver in order to reserve the medium for future-generated data packets without overlapping the medium among the multiple senders. Consequently, repeated collision does not happen again.

III. PERFORMANCE EVALUATION

We have performed numbers of simulations by using the ns-2 network simulator. Receiving, listening, transmitting, and sleep modes consume 13.5mW, 13.5mW, 24.75mW, and 15μW, respectively [7]. We deploy 50 sensor nodes randomly in 1000m by 1000m target area and pick one sink node randomly. Transmission range is set to 250m and channel model is two-ray ground model. As we assume that an event generation follows a Poisson distribution, all sensor nodes except the sink detect an event exponentially in the target area. After detecting an event, a sensor node periodically generates packets with a fixed interval during the period of time selected exponentially. The data packet size is set to 50 bytes, and the size of a base beacon is 6 bytes both in RI-MAC and MRMAC. However, MRMAC introduces a new

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[4] Each sensor node along the routing path sends a data packet just same as RI-MAC (using base beacon) and also concurrently reserves the medium for data packets generated in the near future through piggybacking $NPAT$ and MRI into the data packet. So, only one data packet is required between two nodes for the reservation in medium reservation phase.

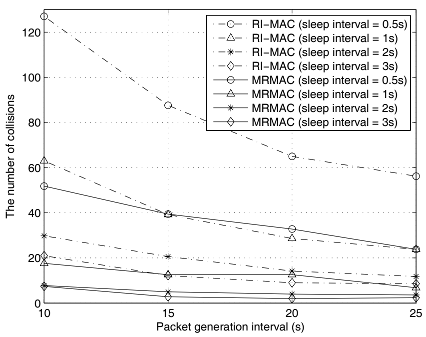

Fig. 2. A comparison of the number of collisions.

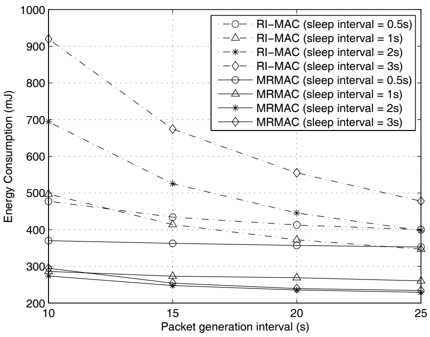

Fig. 3. A comparison of energy consumption.

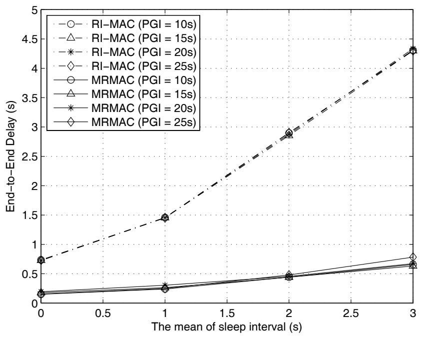

Fig. 4. A comparison of end-to-end delay.

type of a beacon defined as an invitation beacon which has the invitation field represented by 1 byte. To piggyback $NPAT$ and MRI into a data packet, 8 bytes are required additionally. A simulation time is set to 10000 seconds and we obtain the average of the number of collisions, energy consumption, and end-to-end delay from simulation results of 20 independent scenarios. In simulations, the packet generation interval is set to 10, 15, 20, and 25 seconds, and the sleep interval is set to 0.5, 1, 2, and 3 seconds.

The number of collisions of both RI-MAC and MRMAC increases as the packet generation interval and the sleep interval decrease as shown in Fig. 2. However, the number of collisions of RI-MAC is at least twice larger than that of MRMAC in all cases. As collision always leads to retransmission, the performance of RI-MAC compared to MRMAC is expected to be degraded with respect to end-to-end delay and energy consumption.

Figure 3 shows that energy consumption of both RI-MAC and MRMAC decreases approximately linearly with increasing the packet generation interval, which means how often packets are generated periodically. The difference in energy consumption reflects that MRMAC reduces idle listening significantly and consumes less energy than RI-MAC due to multihop streaming phase. We can see that energy consumption of RI-MAC increases as the packet generation interval decreases. However, the packet generation interval hardly affects energy consumption in MRMAC because the idle listening of the nodes along the routing path is reduced significantly with medium reservation information exchange and wake up time synchronization. When the sleep interval is small, sensor nodes wake up more frequently and overhear many beacons destined to other nodes. This is the reason why energy consumption increases slightly in both RI-MAC and MRMAC when sleeping for a short time (i.e. 0.5s and 1s).

Figure 4 shows end-to-end delay according to the sleep interval and the packet generation interval. End-to-end delay of RI-MAC is nearly 7 times longer than MRMAC's. As the mean of the sleep interval increases, end-to-end delay of both RI-MAC and MRMAC increases whichever a packet generation interval is selected. However, an increasing rate of RI-MAC is much higher than MRMAC because relay nodes know the next packet arrival time of the periodic traffic and are able to transmit packets to next hop without waiting in MRMAC. It means that MRMAC can transmit much more end-to-end packets with low latency than RI-MAC for a certain period of time.

IV. CONCLUSIONS

In this letter, we have proposed a medium reservation MAC protocol that reduces end-to-end delay and energy consumption. We observe that numerous applications generate a periodic traffic during a certain period of time. Based on this feature, we can design a new MAC protocol that reserves the medium for data packets generated in the near future in advance. Simulation results show MRMAC significantly reduces both end-to-end delay and energy consumption compared to previous works. For the future work, we plan to investigate MRMAC for event-driven applications.

ACKNOWLEDGEMENT

This work was supported by the Mid-Career Researcher Program through a National Research Foundation grant funded by the Ministry of Education, Science and Technology (No. 2009-008364).

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