SA-RI-MAC: Sender-Assisted Receiver-Initiated Asynchronous Duty Cycle MAC Protocol for Dynamic Traffic Loads in Wireless Sensor Networks

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Abstract. Duty cycling is an efficient mechanism to conserve energy in wireless sensor networks. Several existing duty cycling techniques have been proposed to conserve energy, but they are not able to handle the contention under dynamic traffic loads. In this paper we propose a protocol called Sender-Assisted-Receiver-Initiated MAC (SA-RI-MAC) which solves this problem without sacrificing the energy efficiency. SA-RI-MAC employs the receiver initiated transmissions mechanism of RI-MAC with a sender assisted approach to handle the contention at the receiver. Senders tend to cooperate with each other to resolve the contention dynamically based on the contention level at the receiver. A further improvement is achieved by prioritizing the sender transmissions which has been starved long for the channel occupancy. Our simulation results in ns-2 show that SA-RI-MAC achieves significant improvement in conserving energy over RI-MAC. It can handle traffic contention much more efficiently than RI-MAC; thus improving end to end delivery ratio with a reduction in the latency. Under light traffic load, the performance of SA-RI-MAC is comparable with RI-MAC in terms of end to end delivery ratio, latency and energy efficiency.

Keywords: MAC, Duty Cycling, energy efficient wireless sensor networks, asynchronous duty cyling, dynamic traffic loads.

1 Introduction

One of the major limitations considered in wireless sensor networks is scarcity of energy. In order to conserve energy, power efficient protocols are desirable. These protocols tries to mitigate energy consumption by devising different clever mechanisms at different layers of the protocol stack. Among these methods, mechanisms deployed at the Medium Access Layer (MAC) are more power efficient due to its direct access to the wireless medium.

Generally, a wireless Radio has four power levels depending on its state: idle, sleeping, receiving and transmitting. During the active state a node is able to

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transmit and receive data but in sleep state it completely turns its radio off. Idle listening is one of the main reasons of energy consumption as it requires the same amount of energy as to transmit and receive. This consumption can be saved by turning the radio of a sensor off as frequently off as possible. Duty cycling is an efficient mechanism to handle the problem of idle listening [1, 2]. In duty cycling, wireless nodes periodically turn their radios on and off to reduce the idle listening time.

Different approaches to duty cycling MAC can be categorized as synchronous and asynchronous. Synchronous approaches include RMAC [3], T-MAC [4], DW-MAC [5] and S-MAC [6]. In these approaches, neighbouring nodes synchronize their active and sleep schedules by using some synchronizing protocol. These approaches greatly reduce idle listening but are complex and need extra overhead to synchronize different neighbours with different sleep and active schedules. On the other hand, asynchronous approaches such as WiseMAC [7], X-MAC [8], B-MAC [9] and RI-MAC [10] allow nodes to have their own sleep and active schedules independent to any neighbouring nodes. Asynchronous schemes work efficiently for light traffic loads but become less efficient in terms of latency, energy consumption and delivery ratio under high traffic loads.

In some applications of wireless sensor networks such as convergecast [11] and correlated-event workload traffic [12] where sensors are used for event monitoring, communication demand may suddenly increase in a burst. For example, in the event of fire several sensors report this event to some common sink. If contention created by such events is not handled well, the data sent to the sink may experience longer delays or may be lost. Under such dynamic traffic loads, MAC layer protocols should be able to handle the contention at the sink.

In this work, we present a sender-assisted asynchronous duty cycling MAC protocol, called Sender-Assisted-Receiver-Initiated MAC (SA-RI-MAC). SA-RI-MAC attempts to resolve the contention among the senders with a common intended receiver and helps them to find a rendezvous time to communicate with the receiver. SA-RI-MAC differs from RI-MAC and previous asynchronous duty cycling protocols the way different contended senders resolve the contention at the receiver by cooperating with each other. In SA-RI-MAC, a sender waits for an explicit beacon from the receiver to initiate the transmissions. An explicit beacon containing the value of channel access failure is exchanged among the neighbours which have a common intended receiver. This value of channel access failure is used to resolve the contention among the senders for the medium access. Another improvement is achieved by prioritizing the transmissions of the senders which have been starved longer for the channel occupancy.

We believe this the first attempt which combines the idea of receiver initiated transmissions with the sender assisted contention resolution. This sender assisted coordination adaptively increases the channel utilization which improves the packet delivery ratio, and power efficiency under dynamic traffic loads. We have implemented SA-RI-MAC in ns-2 [15] simulator for evaluation in different network scenarios under dynamic traffic loads.

The rest of the paper is organized as follows. Section 2 discusses related work. Section 3 discusses the contention resolution mechanism in RI-MAC and its weaknesses. Section 4 presents the detailed SA-RI-MAC design. Section 5 reports the performance evaluation of SA-RI-MAC using ns-2 simulation. Finally in section 6, we present our conclusions.

2 Related Work

In wireless sensor networks where energy is a scarce resource, transmissions between sender and receiver can be classified as sender or receiver initiated. The idea of Receiver initiated transmissions in a MAC protocol has been recently introduced in [10]. We make the first attempt to combine the idea of receiver initiated transmissions with the sender assisted contention resolution in ad hoc wireless sensor networks.

Receiver initiated collisions avoidance schemes for general wireless networks have been proposed in [16]. In these approaches collision avoidance is more important than energy efficiency. However under high traffic loads when the degree of contention rises, these approaches lack any coordination among the senders to resolve the contention. Low power probing (LPP) is an asynchronous receiver initiated transmission mechanism used in Koala systems [17]. In koala systems, downloads of the bulk data are initiated by the gateway nodes which allows other nodes to sleep most of the time to conserve energy. In LPP, each node broadcasts a preamble periodically. Other nodes which receive the preamble sends an acknowledgement. After receiving an acknowledgement, a node stays awake and starts acknowledging the probes of other nodes. However LPP approach triggers the false wake ups and sleeps affecting the throughput and energy efficiency.

B-MAC [1] and X-MAC [8] are asynchronous duty cycling MAC protocols in which transmissions are initiated by the senders. Prior to transmissions a sender sends a wake up signal to the receiver by using a long preamble. The length of the preamble is longer than the sleep interval of a node to ensure that the node will wake up at least once during this duration. B-MAC is optimized under light traffic loads for energy consumption. However, an increase in the traffic load may keep a node awake unnecessarily spending a significant amount of time in the active state even if the packets are destined for other nodes. X-MAC solves this problem by sending the preamble as a series of short preambles prior to any transmission and waits for an acknowledgement generated by the receiver which reduces the channel occupancy significantly. X-MAC preamble contains the target address which allows the irrelevant nodes to go to sleep immediately to conserve energy and allows the intended receiver to send an acknowledgement to the sender to stop probing the channel. After receiving the first DATA transmission, a receiver in X-MAC stays awake for a duration equal to maximum back-off window size. This time interval termed as dwell time is used by the sender to send any queued packets.

RI-MAC [10] uses the concept of receiver initiated transmissions. In R-MAC, it is the receiver which initiates the transmissions by sending beacons at regular intervals. Sender wakes up asynchronously at regular intervals to receive an invitation for transmission from the receiver. In response to an invitation from the receiver, sender sends a DATA frame to acknowledge the reception of the beacon. In RI-MAC collisions are handled by receiver dynamically. On detecting the contention, receiver sends an explicit beacon with an increased value of Contention window to the senders to reduce the contention at the receiver. In RI-MAC medium access among senders is controlled by the receiver, however such contention resolution is not very power efficient and reliable under dynamic traffic loads. Senders back off according to the back off value specified by the receiver, however under dynamic traffic loads an increased value of back offs affect the energy efficiency and delivery ratio significantly.

Previous synchronous and asynchronous duty cycling approaches such as X-MAC, B-MAC and RI-MAC achieves greater energy efficiency under light traffic loads. However SA-RI-MAC differs from these approaches by dynamically triggering the coordination among the senders to handle the contention under high traffic loads. Other asynchronous duty cycling approaches give no preference to nodes to transmit which have been starved longer for channel occupancy. SA-RI-MAC on the other hand, prioritizes the transmissions from the starved senders after contention resolution.

3 Contention Resolution Mechanism in RI-MAC

In RI-MAC, a receiver coordinates the DATA transmissions from the contending senders by exchanging an explicit beacon. In the beacon, receiver specifies back off window size(BW) which senders should use to contend the channel. The size of BW is controlled by the receiver depending on the number of collisions. Receiver can know about an incoming packet with the help of Start Frame Delimiter (SFD). Clear channel assessment (CCA) is used to detect any channel activity. If CCA detects any channel activity, receiver assumes a collision and generates another beacon with an increased value of BW. Depending on the network conditions, receiver in RI-MAC adjusts the value of BW by using binary exponential back off (BEB). Receiver turns its radio off if it keeps detecting continuous collisions after consecutive beacon transmissions or if the value of BW exceeds maximum back off window size. Due to high contention, a sender could potentially miss the beacon with the exact value of BW. Sender increments the retry count, if no beacon has been received from the intended receiver for duration equal to three times of the sleep interval. Further, retry count is incremented if no acknowledgement has been received from the receiver for a DATA transmission within the maximum back off window time. If the value of retry count exceeds a predefined value of retry limit, sender cancels the further transmission of the DATA frame.

Contention resolution mechanism used by RI-MAC does not involve the contended senders to resolve the contention at the receiver. RI-MAC tries to handle the contention with the help of a BW value specified by the receiver. We show that by using only BW value specified by the receiver is not sufficiently enough to cope efficiently with the collisions at the receiver. This increased BW value increases back off at the contended senders which decreases throughput and increases latency. Further, increased back offs at the contended senders does not help to conserve any energy even when the sender is not able to access the medium. If the contending senders are not well coordinated , they may deviate from the BW value specified by the receiver and may decide to transmit without any back off. This deviation from the BW value specified by the receiver only can degrade the throughput [18].

Figure 1 shows continuous collisions at the receiver caused by simultaneous transmissions from the contending senders in RI-MAC. RI-MAC tries to handle these collisions by adjusting the size of the BW. However under high traffic loads, the probability of loss of the beacon with the exact BW value by the contending senders increases which makes their transmissions more likely to collide at the receiver.

4 SA-RI-MAC Design Overview

Sender in SA-RI-MAC tracks the number of times it has failed to access the channel when trying to transmit a packet to the receiver. A counter CHANNEL_ACCESS_FAILURE is maintained to record the failure to access the channel. This counter is updated every time retry limit exceeds the maximum retry limit threshold. Contending senders exchange an explicit beacon with each other containing the value of CHANNEL_ACCESS_FAILURE counter at regular intervals. Prior to transmission, sender estimates the contention level at the receiver by using the BW value specified by the receiver. If the value of BW specified by the receiver exceeds the maximum contention window size, sender considers it as an indication of high contention. However, under high traffic loads, possibility to drop the beacon containing the BW value increases. In this case, maximum value of CHANNEL_ACCESS_FAILURE among all the contending senders is compared with the CHANNEL_ACCESS_FAILURE_THRESHOLD. If CHANNEL_ACCESS_FAILURE exceeds CHANNEL_ACCESS_FAILURE_THRESHOLD; this indicates the high contention at the receiver.

If the contention at the receiver is significantly high, the sender node will evaluate if any of its neighbours has the value of CHANNEL_ACCESS_FAILURE higher than its own value. If there is such a contending neighbour which starved longer , it turns its radio off immediately to conserve energy and to minimize further contention at the receiver and wakes up asynchronously. More importantly, this sender assisted contention resolution increases fairness among the senders and gives priority to starved senders. This design choice is more energy efficient to resolve the contention at the receiver.

Figure 2 shows how SA-RI-MAC avoids collisions at the receiver. It shows that contending senders S1 and S2 coordinate with each other under high traffic loads by exchanging their recent CHANNEL_ACCESS_FAILURE values. S1 has CHANNEL_ACCESS_FAILURE value greater than S2; therefore S1 starts transmissions to the receiver R. In order to avoid collisions at the receiver, S2 turns its radio off to conserve energy.

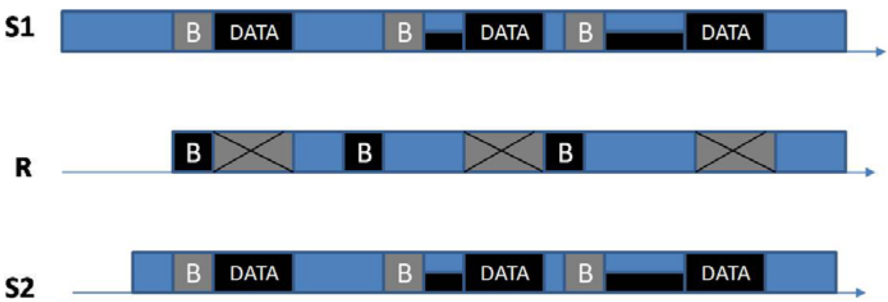

Fig. 1. RI-MAC: DATA frame transmissions from contending senders. Simultaneous transmissions from the contending senders can cause continuous collisions at the Receiver.

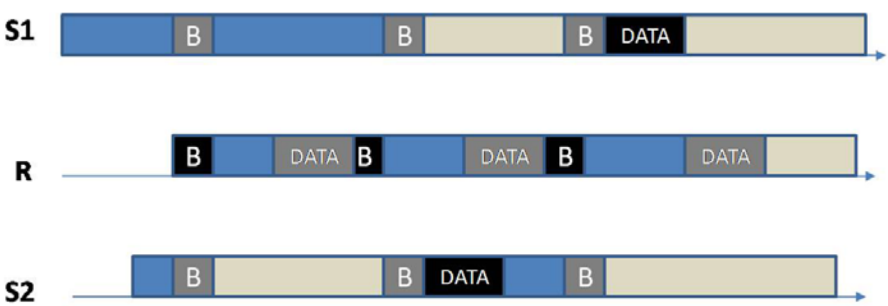

Fig. 2. SA-RI-MAC: DATA frame transmissions from contending senders. Transmissions from the contending senders are well coordinated to avoid continuous collisions at the Receiver.

4.1 Beacon Frame in SA-RI-MAC

When a receiver wakes up it sends a base beacon containing the value of source field. Base beacon can have two optional fields, destination field and BW size. If destination field is set in the base beacon, it means beacon frame is an acknowledgement to the sender with the destination field and other senders can treat this it as a request to send data.

BW value is specified by the receiver according to the contention level at the receiver. In RI-MAC, this BW value is used by the contending senders to back off before transmissions to reduce the chance of collision at the receiver. However, in SA-RI-MAC this value is used as an indication of the contention at the receiver and triggers the coordination among the contending senders prior to further transmissions. It is a better design choice instead of continuous back offs which are not very any energy efficient and does not improve delivery ratio significantly. Further these back offs increase the latency of the transmissions significantly.

After receiving a beacon from the receiver, a sender always makes a Clear Channel Assessment(CCA) before transmission in order to avoid collisions at the receiver. CCA must indicate the medium idle for at least SIFS plus maximum propagation delay time. If no activity is detected during this time, receiver R turns its radio off.

4.2 Collisions in SA-RI-MAC

By coordinating the senders to transmit data at the receiver, SA-RI-MAC reduces collisions significantly at the receiver and thus cuts down unnecessary retransmissions. As data transmissions among contending senders are explicitly controlled and coordinated based on the contention level at the receiver, contending senders know when not to send the data and thus can turn their radio off to conserve energy. In RI-MAC, if the back off value reaches the maximum back off window and receiver keeps detecting collisions, it turns its radio off. On the other hand, SA-RI-MAC tries to reduce the continuous collisions at the receiver and thus prevents any back offs forced by the collisions which affects latency and delivery ratio significantly.

5 Performance Evaluation

We evaluated SA-RI-MAC in ns-2 simulators and compared its performance with the RI-MAC. We simulated SA-RI-MAC under different network scenarios with dynamic traffic loads.

5.1 Simulation Evaluation

we used two-ray ground reflection radio propagation model for all the scenarios. Different simulation parameters used are shown in Table 1. These parameters are similar to CC2420 radio [18] used in MICAz motes. CCA check is performed by sampling RSSI delay as reported by Ye et al [14]. This check is performed every 20ms longer than the interval between two short preambles. The transmission and sensing range are modelled according to 914 MHz lucent WaveLAN radio, as similar ranges have been observed in some sensor nodes [20]. In both RI-MAC and SA-RI-MAC, BW value is adjusted based on BEB which takes value of 0,31,63,127 and 255. We used Initial value back off window size of 32 and congestion window of size 8 which are default values used in UPMA package distributed as TinyOS [21]. Dwell time for both RI-MAC and SA-RI-MAC is dynamically adjusted based on the BW specified by the receiver plus propagation delay and SIFS. Initial wake up for both the protocols is randomized and a value of 1 second is used for the sleep interval.

We compared the performance of SA-RI-MAC with RI-MAC in random networks, clique networks and a 49 node (7×7) grid network.

Table 1. Simulation parameters for Radio

Tx range	250 m
Slot time	320 us
SIFS	192 us
Bandwidth	250 Kbps
CCA check Delay	128 us
Carrier Sensing Range	550 m
Duty Cycle	1 %
CHANNEL_ACCESS_FAILURE_THRESHOLD	5
Tx Power	31.2 mW
Rx Power	22.2 mW
idle Power	22.2 mW
Contention Window (CW)	32 ms

Clique Networks. We compare the performance of SA-RI-MAC and RI-MAC in clique networks. In a clique network all the nodes are within the transmission range of each other. We varied the number of flows in the network to vary the traffic load in the network. We allow flows to share the same destination to cause contention.

For clique network, number of nodes in the network are twice the number of flows. Each source node generates packets 10 seconds after the start of the simulation. The interval between two packets is uniformly distributed between 0.5 and 1.5 seconds. Next wakeup time for each node in the network is randomly chosen between 0 and 10 seconds. A packet is not considered delivered if it is in the queue. Each simulation runs for 100 seconds. We have taken an average on three random clique network scenarios.

Figure 3 shows the delivery ratio of SA-RI-MAC for a clique network with an increase in the number of contending flows. Both RI-MAC and SA-RI-MAC achieves delivery ratio close to 100 when the number of flows are fewer than 15. However, as the number of flows exceed 15, the delivery ratio of RI-MAC drops significantly due to an increase in the contention level at the receiver. The delivery ratio of SA-RI-MAC does not drop significantly as an immediate coordination will be triggered among the contending senders to resolve the contention at the receiver.

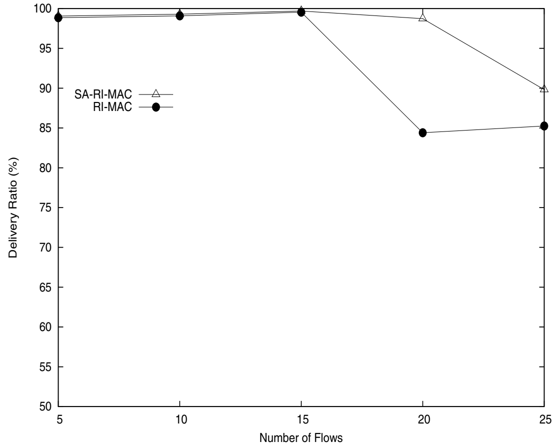

Fig. 3. Delivery Ratio vs. number of Flows

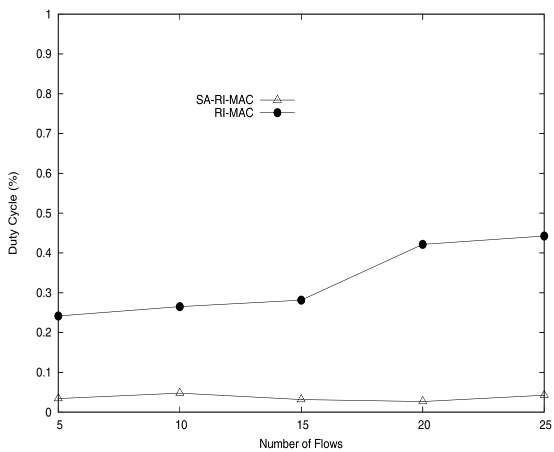

Fig. 4. Duty Cycle vs. Number of Flows

The overall duty cycle of the nodes is shown in figure 4. In addition to a gradual drop in the delivery ratio, SA-RI-MAC conserves much more energy than RI-MAC. It can be observed from the figure that for all contending flows the energy consumption of SA-RI-MAC is less than RI-MAC. For all flows, SA-RI-MAC saves more than 75% energy compared to RI-MAC. SA-RI-MAC conserves much more energy during high traffic loads by triggering coordination among the senders giving them a chance to conserve energy by turning their radio off compared to back off mechanism used by RI-MAC.

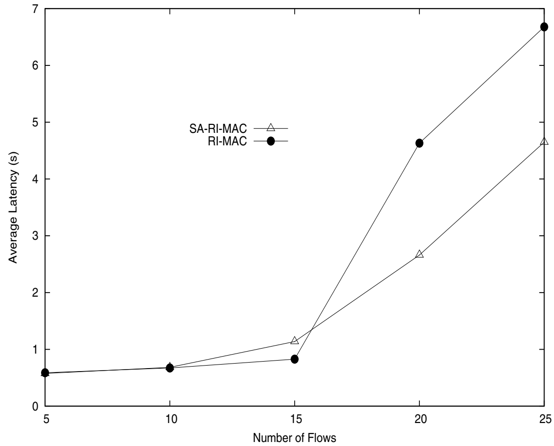

Fig. 5. Avergae Latency vs. Number of Flows

In addition to high duty cycle, RI-MAC also has higher latency compared to SA-RI-MAC as shown in figure 5. This increase in latency is due to an increased value of back off by the receiver to handle the contention. However, SA-RI-MAC avoid collisions at the receiver by prioritizing a starved node among the contending senders to transmit during high traffic loads which reduces unnecessary back offs and helps to conserve the energy.

Grid Network under Correlated Event Workload. We compare the performance of SA-RI-MAC with RI-MAC in a grid network with 49 nodes. Maximum distance between two neighbouring nodes is 200 meters. Target sink node to receive event notifications is at the centre of the grid. We used a Random Correlated-Event (RCE) model to generate traffic in the grid network [13]. RCE is based on the correlated-event workload which simulates spatially-correlated events in a sensor networks. This model simulates a synchronized triggered traffic load in the network which is a common case for tracking and detection applications. In RCE, an event is generated on some randomly selected location (x,y) in the network. A node in the network can sense and report an event if it is in the radius R centred at (x,y). We generated a new event once every 200 seconds. Each node with in radius R senses the event and reports it to the sink. In a 7×7 grid network, path traversed by each packet varies from 1 to 6 hops and on average 3.05 hops. We perform each simulation for 3 random runs for a series of 48 events triggered from random locations. Unicast packets are transmitted by the nodes within the radius R to notify the sink. Each simulation run lasts for 10,000 seconds.

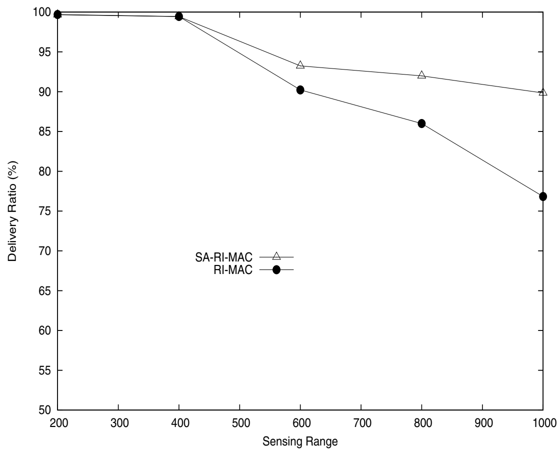

Fig. 6. Delivery Ratio vs. number of Flows

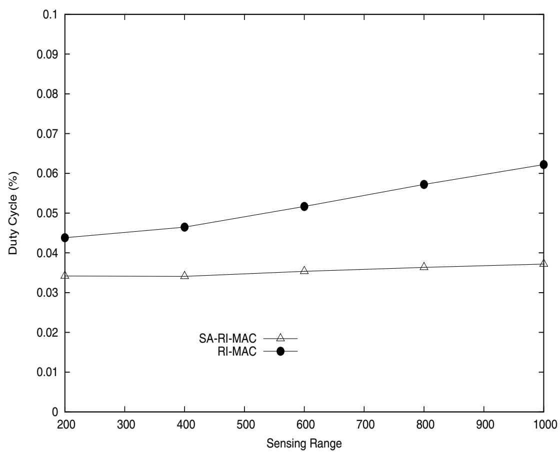

Fig. 7. Duty Cycle vs. Number of Flows

Performance comparison of RI-MAC and SA-RI-MAC is shown in figure 6. Figure 6 shows the packet delivery ratio. When the traffic load in the network is not very high RI-MAC and SA-RI-MAC maintains packet delivery ratio upto 100%. However, with an increase in sensing range high contention is caused for medium access so the performance of RI-MAC and SA-RI-MAC drops. However, SA-RI-MAC is augmented with sender assisted coordination which maintains its delivery ratio higher than RI-MAC in high traffic loads. SA-RI-MAC as shown in figure 7 in addition to achieving the better delivery ratio than RI-MAC also

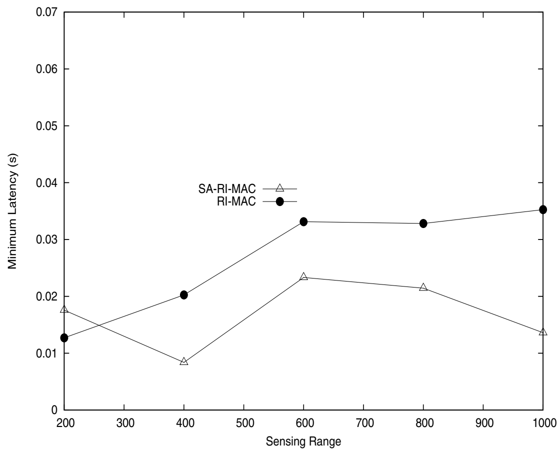

Fig. 8. Minimum Latency vs. Number of Flows

achieves lower duty cycles. In RI-MAC, contention is handled at the receiver end only which increases the value of back off for senders. This unnecessary back off does not conserve any energy. On the other hand, in SA-RI-MAC, sender coordination allows contended sender to turn off their radio to conserve energy and reduce contention at the receiver. For all sensing ranges, the duty cycle for SA-RI-MAC is significantly lower than RI-MAC. For example, for a sensing range of 1000 m, SA-RI-MAC duty cycle is better than RI-MAC duty cycle at 200m. Figure 8 show the minimum end to end latency for packets reported to a sink for RCE model as the sensing range increases in the grid network. It is apparent from the figure that, in SA-RI-MAC an event notification is received earlier than the RI-MAC. This event reporting is faster than RI-MAC for all the sensing ranges. Sender coordinated contention resolution conserve energy and at the same time allows contended senders to deliver packets without collisions at the receiver. For the RCE model, how quickly an even has been notified to a sink is more important than average and maximum latency of all the packets received at the receiver.

Random Networks. We compare the performance of SA-RI-MAC and RI-MAC in 3 random networks with 40 nodes randomly located in 1000m × 1000m simulation area. Flows are generated between a random source and a randomly selected sink node. The interval between two consecutive packets is 1 second. Each simulation run lasts for 100 seconds. Figure 9 shows the delivery ratio achieved by SA-RI-MAC and RI-MAC. For random network scenario, with flows between random source and destination pairs, SA-RI-MAC outperforms RI-MAC. SA-RI-MAC shows a substantial improvement over RI-MAC in terms of delivery ratio as the traffic load in the network increases. SA-RI-MAC

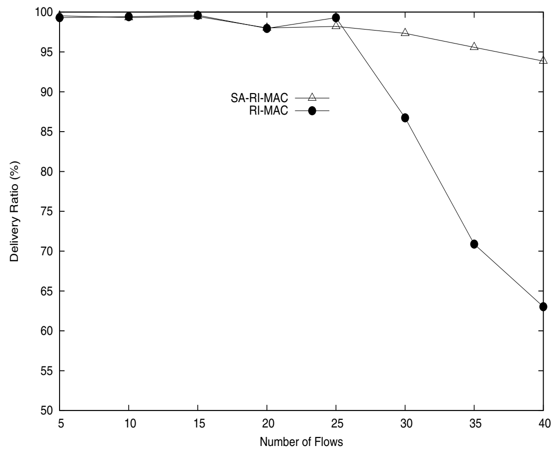

Fig. 9. Delivery Ratio vs. number of Flows

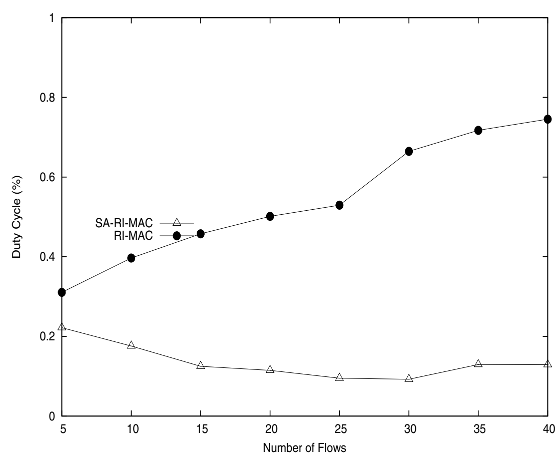

Fig. 10. Duty Cycle vs. Number of Flows

maintains delivery ratio above 90% for all the traffic loads. SA-RI-MAC conserves much more energy than RI-MAC by turning off the radio of a contended sender under high traffic loads as shown in figure 10. Figure 11 shows that for light traffic loads, RI-MAC has lower latency than SA-RI-MAC. However, as the contention in the network increases, RI-MAC triggers increased back offs at the senders which causes an increase in the latency. On the other hand, SA-RI-MAC triggers sender assisted coordination among the contended senders to avoid collisions at the receiver which reduces its latency significantly.

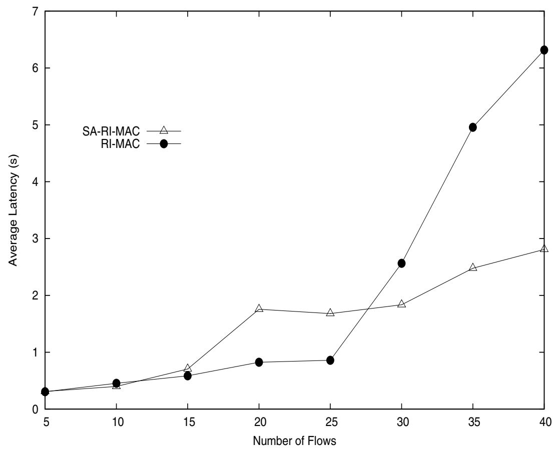

Fig. 11. Avergae Latency vs. Number of Flows

6 Conclusion

In this paper, we have presented a sender assisted receiver initiated asynchronous duty cycling MAC protocol for wireless sensor networks. SA-RI-MAC adaptively resolve the contention at the senders as traffic load increases, allowing SA-RI-MAC to achieve higher delivery ratio, lower delivery latency and less energy consumption under dynamic traffic loads. To achieve this, SA-RI-MAC turns off the radio of the contending senders to minimize the collisions at the intended receiver while still decoupling sender and receiver clocks. SA-RI-MAC significantly improves fairness among the contending senders by prioritizing the transmissions from the most starved senders.

We compared SA-RI-MAC with RI-MAC through extensive simulations. We found through evaluation that SA-RI-MAC significantly outperforms RI-MAC, with higher delivery ratio, lower delivery latency and higher power efficiency under high traffic loads. For example, under high traffic loads in clique networks, SA-RI-MAC conserve more than 75% energy than RI-MAC. In addition, SA-RI-MAC improves delivery ratio and latency under all scenarios in our simulations.

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