A Light-weight Channel Rendezvous Scheduling for Multi-channel Medium Access in Sensor Networks

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***Abstract*—In this paper, we present an efficient *channel rendezvous* (i.e., sender and receiver communicate on the same channel) scheduling for multi-channel medium access control (MAC) in wireless sensor networks (WSNs). The proposed scheme mainly targets to implement an efficient medium access control that can cope-up and adapt with the mostly available dynamic and diverse traffic environments of WSNs. To do so, the *duty-cycle* (periodic wake-up and sleep under low traffic) and *multi-channel* (at heavy traffic) concepts are applied for the proposed channel rendezvous and medium access design. Unlike earlier works the given approach is asynchronously scheduled and avoids the time-synchronization overhead in maintaining the node's cycles for channel rendezvous as well as the time-slotted medium access in data communication. Finally, the protocol is evaluated through extensive simulations and we have observed the efficiency of the proposed work over few existing schemes.**

***Index Terms*—Wireless sensor network (WSN); Channel Rendezvous; Medium Access Control (MAC); Cycle; Duty-cycle; Multi-channel;**

I. INTRODUCTION

Recently, wireless sensor networks (WSNs) have been applied broadly due to its wide-spread use of different active (e.g. radar and camera) and passive (e.g., seismic, acoustic and temperature) sensor technologies. As a result, multiple classes of applications are evolved for WSNs and most of them are elastic in nature with varying data generation rates. In typical event monitoring environments (e.g., target tracking, intruder detection), very low periodic observation traffic mostly exists for a longer period of time, demanding energy-saving for *energy-efficiency*; whereas, upon event detection a large burst of traffic is generated at high data rate demands *high-throughput*. Additionally, high sampling rate is a pre-requisite for structural health monitoring and multimedia applications. Therefore, it is quite challenging for WSNs to provide energy-efficiency and high-throughput together at this dynamic and diverse (i.e., low and high) traffic environments.

As of now, at low traffic the periodic wake-up and sleep based duty-cycle MAC concept [1][2] has been implemented for energy-saving, and mostly overlooks the consequences of heavy traffic. The existing duty-cycle MAC protocols [1][3][4], mainly target to reduce idle listening (unnecessary channel sensing while there is no transmission/reception) and maximize the energy conservation and network life-time. But, due to the limited capacity of single shared wireless channel (e.g., 250 Kbps in MICAz [5]) at these protocols, the data generated for high-rate applications often overwhelms the network capacity, resulting in congestion collapse [6] and collision losses. Conversely, to ensure optimal capacity utilization and avoid congestion losses, several rate/congestion control protocols [6][7] have been proposed. However, such protocols cannot meet the goal if high-rate is a pre-requisite for the application fidelity. Hence, only capacity enhancement through multi-channel communication is a possible solution to fulfill the high-throughput demand of the mentioned applications. The recent sensor mote MICAz is capable of using the CC2420 radio [8] based on IEEE 802.15.4 standard with multiple channels on 2.4 GHz ISM band.

In many existing multi-channel solutions [9][10], *channel rendezvous* problem is solved using a common channel (CC), and communications are generally occur on time-slot basis at each operational *cycle* (i.e., super-frame). As a result, fine-grained time synchronization is required among the neighbors and often among the two-hop neighbors [9] to maintain the cycles and time-slot. However, in a multi-hop environment, implementation of such neighbor-wide time synchronization is very complex and not a trivial task, and it incurs huge overhead. Furthermore, use of common channel increases the channel switching frequency as well as inter-channel communication cost. As shown in Figure 1, at the beginning of every cycle, a sender and receiver switch their radio to a common

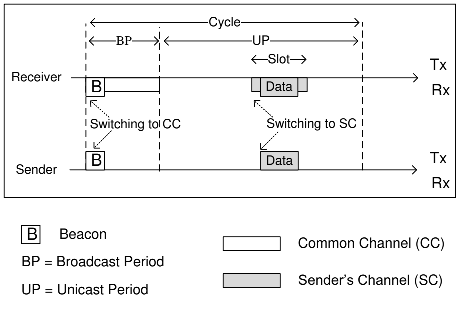


Fig. 1. Channel rendezvous using common channel

channel to negotiate (during broadcast period) about the potential communication on a specific channel (during unicast period). Thereupon, both the sender and receiver switch their radio to the rendezvous channel for data transmission and reception, respectively. Hence, active nodes need to switch their radio at least twice at each cycle for single data transmission, causing more channel switching delay (e.g., for CC2420 radio each switching costs 200μs [8]). The scenario gets worst under heavy traffic, when frequent channel rendezvous negotiations incur *bottleneck* on common channel; and nodes cannot communicate due to heavy contentions, resulting in a whole *cycle delay* for the back-logged data.

In this paper, addressing the above issues, we propose a light-weight channel rendezvous scheduling scheme along with an efficient medium access control (MAC) solution for WSNs. The proposed protocol in one way, aims for energy-saving at low traffic employing the duty-cycle concept; and, in other way, targets to maximize the data throughput at high traffic through multi-channel. The proposed channel rendezvous schedule is derived using a light-weight receiver-driven approach, that creates the scope for an energy-efficient medium access. It is noteworthy that the given approach avoids the neighbor-wide time-synchronization and time-slotted communication; and also optimizes the protocol overhead in terms of incurring minimum channel switching cost.

In rest of the paper, Section II presents related work. Section III, IV and V includes protocol preliminaries, operation and evaluation, respectively. Section VI concludes the paper.

II. RELATED WORK

The medium access design for sensor networks is a prominent research area and over the years, many MAC protocols have been proposed for WSNs; which can be categorized mainly into *synchronous* and *asynchronous* protocols. In case of synchronous protocols, nodes in a common neighborhood maintain fine-grained time synchronization at the cost of huge-overhead. However, synchronous duty-cycle protocols like S-MAC [2] and T-MAC [11] are well known in the literature for their energy-efficiency in handling low rate traffic. On the other hand, synchronous multi-channel protocols MC-LMAC [9] and MMSN [10] are only able to cope up with the heavy traffic scenario of the network using a fixed number of multi-channels, where the channel capacity mostly remains under-utilized when the network possesses low traffic.

To avoid the overhead of synchronous approach, asynchronous protocols has been implemented. Among the well known asynchronous duty cycle protocols, B-MAC [1] and X-MAC [3] are sender-initiated; whereas RI-MAC [4] is receiver-initiated. Note that from the energy point of view, receiver-driven protocol [4] is more effective and efficient than its sender-initiated counterparts [1][3]. Although such protocols are suitable for the low observation traffic of an event monitoring network, are unable to handle the event-triggered traffic burst. Conversely, TMCP [12] is a multi-channel protocol having asynchronous medium access. The main goal of TMCP is to implement sub tree-based clustering in the network and assign distinct channel to each cluster, reducing inter-cluster interference. However, the collision and contention problems of single-channel MAC are still unresolved in TMCP.

Finally, few *hybrid* protocols such as: nW-MAC [13] and SCP-MAC [14] are evolved using the time-scheduled information of the nodes. In our previous work nW-MAC, we have tried to optimize the energy conservation at both low and high traffic through an asynchronously scheduled multiple wake-up provisioned duty-cycle scheme. However, adoption of multi-channel property increases the robustness of nW-MAC against the high-rate applications. Conversely, even though SCP-MAC uses scheduled operation, it requires precise time synchronization due to its dependency on S-MAC [2] operation.

Since the sensor applications possess diverse traffic environments, a dynamic solution is, therefore, required at the MAC layer. To the best of our knowledge, duty-cycle based energy-saving and multi-channel oriented high-throughput requirements are still unrevealed in designing a multi-channel sensor MAC; which our proposed scheduling and MAC have addressed.

III. SYSTEM MODEL

A. Network Model

The proposed rendezvous scheduling and MAC are designed for typical multi-level tree-based WSNs, where multiple unidirectional data flows are converged toward a single point (i.e., sink node). The given topology is a many-to-one routing tree rooted at the sink [7]. The scheme is also applicable for a network with multiple sinks, and multiple routing trees may exist in the network. However, since our protocol operation is independent of the number of sinks, we consider a single sink-rooted routing tree comprising N sensor nodes. Furthermore, the routing tree is considered to be consisted of L levels and each level is identified by l; starting from the sink node with $l = 0$, the level value is increased by one for the nodes at the next level and so on. The parent-child relationship of the nodes in different tree-levels is defined as *downstream-upstream*.

The basic operations of the protocol are receiver-driven. The receivers in the routing tree are differentiated by their respective tree levels, and the i-th receiver of the l-th level is denoted by r_i^l, such that $r_i^l \in N$. Moreover, the downstream node (or receiver) of r_i^l at the $(l-1)$-th level is denoted as r_i^{l-1} and the upstream nodes (or senders) of r_i^l at the $(l+1)$-th level are denoted as r_i^{l+1}. Furthermore, a data flow is considered as the traffic from a particular source node. The unicast transmission of a flow is only taken into account, since it supports most sensor application's traffic pattern.

B. Assumptions

We assume that sensor nodes maintain time scheduling operation such a way that each upstream node measures the time difference of the clock with its immediate downstream node; which is also known as *master-slave* approach [13]. Such approach is very simple and light-weight, since it does not require neighbor-wide synchronization and *sync* message.

Additionally, time is divided into active operational period called *cycle* for the receivers placed at each level of the tree. Let, the cycle of receiver r_i^l at the l-th level is denoted by T_c^l.

Sensor nodes communicate using an identical, half-duplex, and low cost wireless radio based on the proposed medium access design. Furthermore, the transceiver of a node can tune to maximum N_{ch} non-overlapping channels of equal capacity. However, at a given time period a subset of the channels are used by the nodes of a particular sub-tree of the network, which is denoted by n_{ch} and $n_{ch} = 2, 3, 4, \ldots, N_{ch}$. The proposed protocol does not rely on any particular routing protocol, and we use a static approach to generate the routing tree rooted at the sink node; where the multi-hop paths between source and sink nodes are bidirectional.

IV. PROTOCOL OPERATION

A. Initialization

The network starts with multiple channels, and each receiver randomly selects and occupies one channel (for data reception) as its *base-channel*. The number of channels may vary and for the simplicity in description, we use $n_{ch} = 4$. Furthermore, in order to initiate a communication based on the IEEE 802.15.4 standard, we use a beacon (given by B) as a control packet transmitted by the receiver [4]; which is acknowledged with either beacon-Ack (in channel rendezvous) or data packet (in data communication) by the upstream sender(s).

The *start-of-cycle* (SoC) of the receiver r_i^l at l-th level begins at a random time offset, given by t_{SoC}^l; hence, the cycles of the nodes are asynchronously scheduled [13]. Furthermore, in a cycle the protocol provisions total K beacon sending/wake-up offsets for a receiver r_i^l, such that $K = n_{ch}$. The k-th beacon is identified by B_k, whose sending offset is originated from the receiver's start-of-cycle (SoC).

$$t_{B_k}^l = t_{SoC}^l + (k \mod n_{ch}) \times \frac{T_c^l}{n_{ch}}; \tag{1}$$

where $k = 0, 1, \ldots, (n_{ch} - 1)$. Hence, in a cycle of r_i^l, the interval between the consecutive beacon sending/wake-up offsets is $\frac{T_c^l}{n_{ch}}$. In contrast, a node r_i^{l+1} at the $(l+1)$-th level is a potential sender for r_i^l and is aware about the cycle length of l-th level (i.e., T_c^l). The node r_i^{l+1} periodically and sequentially maintains a *low-power-listening* (LPL) [1] at each of the n_{ch} channels for a time period of T_{lpl}^{l+1},

$$T_{lpl}^{l+1} = \frac{T_c^l}{n_{ch}} + T_{TO}; \tag{2}$$

where, T_{TO} is used for the time taken by r_i^l for a beacon transmission including the contention back-off period.

B. Light-Weight Channel Rendezvous Scheduling

In protocol operation, a light-weight receiver-driven scheme deduces the sender-receiver rendezvous schedule at one of the K beacon sending offsets of the receiver (on its base-channel). Basically, a successful rendezvous on a channel shows the sender-receiver pair the way to make the potential communication at that stored schedule in every cycle of the receiver. Theorem 1 portrays the proposed scheduling concept and Figure 2 delineates a snapshot of the scheduling.

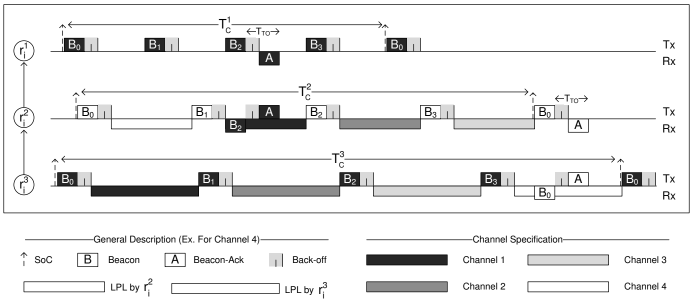


Fig. 2. Receiver-driven channel rendezvous snapshot (here, $K = n_{ch} = 4$)

Theorem 1: *Let, a receiver r_i^l at l-th level successfully sends $K = n_{ch}$ beacons (on its base-channel), each at the equally spaced K beacon sending offsets during the cycle T_c^l. Conversely, at every $\frac{T_c^l}{n_{ch}}$ interval a potential upstream sender at $(l+1)$-th level maintains low-power-listening (LPL) for at least T_{lpl}^{l+1} period on each of the n_{ch} channels. Thus, without any collision originated loss it is guaranteed that the sender-receiver pair can meet (communicate) with each other on any of the K offsets and would have at least one rendezvous schedule (offset) on receiver's base channel during the cycle period T_c^l.*

Proof: *The sender's low-power-listening (LPL) period satisfies $T_{lpl}^{l+1} \geq (\frac{T_c^l}{n_{ch}} + T_{TO})$ for each of the n_{ch} channels through sequential switching. Hence, according to the overlapping principle [15], the sender-receiver pair would have at least one rendezvous offset on receiver's base-channel during T_c^l; and that would be at any of the K beacon sending offsets of the receiver.*

In reply to the receiver's beacon, a beacon-Ack is expected from one of the potential upstream senders as a rendezvous confirmation message. As shown in Figure 2, node r_i^2 and r_i^3 receive the beacons B_2 and B_0, respectively from r_i^1 (on its base-channel 1) and r_i^2 (on its base-channel 4); and in reply r_i^2 and r_i^3 send a beacon-Ack after performing a contention back-off. Thereupon, both the sender and receiver store the beacon offset as a rendezvous schedule in every cycle of the receiver. Additionally, to implement the Theorem 1, we need to adjust the cycle length of $(l+1)$-th level nodes as,

$$T_c^{l+1} = T_c^l + n_{ch} \times T_{TO}; \tag{3}$$

To do so, we simply add the time requires for the time-out periods (i.e., n_{ch} times) with the cycle length of l-th level. This approach generates a constraint as, $T_c^{l+1} > T_c^l$; meaning that nodes closer to the sink have more reception opportunity (beacon offset) than that of the distant nodes. Hence, practically, in achieving energy-efficiency the given constraint lies within the typical WSN characteristics, allowing distant nodes to wake-up less frequently and thereupon conserve more energy.

The proposed scheduling is called light-weight, since no common channel and neighbor-wide time synchronization are required for channel rendezvous. Moreover, the receiver-driven rendezvous scheme seems very effective in terms of reducing channel switching frequency during data communication. Although the initial sequential channel switching for channel rendezvous by the sender causes few overhead to some extent, it takes a small number of cycles to make the rendezvous schedule with the receiver. However, we believe such idea is worthy in comparison to tolerate much more channel switching cost (i.e., delay) at the whole network life-time.

C. Medium Access Design

The proposed medium access design is very simple and solely depends upon the derived rendezvous schedule between each sender-receiver pair. At a scheduled rendezvous, a receiver wakes-up or tune to the base-channel to initiate a communication, and thereupon collects data from its senders. Apart from medium access, a receiver also maintains the regular scheduling operation (Section IV-B) to ensure scalability; that is joining of new nodes in the network.

As shown in Figure 3, to access the medium, a *receiver* first contends with a random back-off for a beacon (data request message) transmission at its scheduled offset $t^l_{B_k}$. If the medium is found BUSY while attempting beacon transmission, the receiver waits until the mentioned T_{TO} period; otherwise, would go to sleep. However, in reply to the beacon if any sender transmits a data packet, the receiver accepts it and acknowledges with a data-Ack beacon. In this case, the later beacon acts as another request for data as well. Note that posterior to a data-request beacon transmission, the receiver also waits for T_{TO} period to receive the data. Therefore, during medium access, the beacon from a receiver actually serves three purposes; *firstly*, it acts as a data request message; *secondly*, it is used for data acknowledgment, and *finally*, it helps new nodes to find channel rendezvous with the receiver, ensuring scalability of the network.

In contrast, a *sender* waits in sleep mode till its scheduled rendezvous time on receiver's base-channel. A sender might also remains busy in collecting data (i.e., while acting as a receiver) from its upstream nodes on its base-channel. The nodes store the rendezvous scheduling information; therefore, as given in Figure 3, the sender can estimate the residual time (given by T_r), from the current time to the forthcoming scheduled beacon sending offset (t_{B_k}) of the receiver,

$$T_r = \{T^l_c - (t_c - t^l_{B_k}) \bmod T^l_c\} - T_g; \qquad (4)$$

where, t_c is the current time, and T_g is used as a guard time to adjust the potential clock drifts [13]. Prior to the rendezvous schedule, the sender tunes its transceiver to the receiver's base-channel and waits for ($T_g + T_{TO}$) period to have potential data-request beacon from the receiver; otherwise it goes to sleep or does the scheduled tasks. Upon receiving the beacon, sender(s) performs a random back-off to avoid collision with other potential senders. A node with early back-off expiration sends a data packet and waits for a *short intra-frame space* (SIFS) to have a data-Ack from the receiver (see Figure 3). However, if any sender looses the contention, it pauses the back-off and updates the *network allocation vector* (NAV) till the ongoing data transmission. Another data-request beacon (i.e., data-Ack for previous sender) from the receiver resumes the back-off for such sender(s).

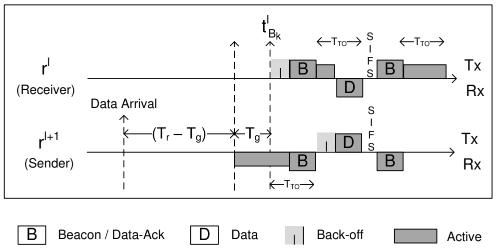


Fig. 3. Proposed medium access design

A *new node* or *node having link failure* in the network is also able make channel rendezvous with any of the potential neighborhood receivers. To do so, the node needs to perform the same low power listening (mentioned in Section IV-B) at different channels to get the rendezvous beacon from the receiver. Therefore, at the cost of at most K beacons at each cycle of the receiver, such strategy makes the protocol adaptive and scalable to any topology changes in WSNs.

D. Choice of First-level Cycle (T^1_c)

The cycle lengths of different tree-levels are derived using the first-level cycle (T^1_c) as the base-value. Hence, the choice of T^1_c carries an importance as a parameter value, and we choose the length of T^1_c based on the measured expected worst-case end-to-end delay (D_{worst}). Because, in order to ensure a proper and stable adjustment of the cycles and schedules of the nodes at different levels of the routing tree, the D_{worst} acts as a more suitable and stable parameter. Here, the end-to-end delay of a data packet largely depends upon the cycle durations at different levels of the routing tree. Thus, in delay analysis we measure D_{worst} according to the cycle durations at different depths (L) of the routing tree,

$$D_{worst} = \frac{1}{2}\{L \times T^1_c + \sum_{l=1}^{L}(L-l) \times n_{ch} \times T_{TO}\}; \qquad (5)$$

Thus, from Equation 5 we derive the value of T^1_c as,

$$T^1_c = \frac{1}{L}\{2 \times D_{worst} - \sum_{l=1}^{L}(L-l) \times n_{ch} \times T_{TO}\}; \qquad (6)$$

In order to ensure more stability and avoid rapid changes, we have further deduced the expected value of T^1_c using the *exponential weighted moving average* (EWMA) formula,

$$T^1_c = (1-w) \times T^1_c + w \times T^1_c(inst); \qquad (7)$$

where, the instantaneous T^1_c is given by $T^1_c(inst)$, and w is the tuning parameter (we use, $0 < w \leq 1$). In determining the value of w, we have given more emphasis to avoid the overestimation of T^1_c, hence, we set a small value as, $w = 0.1$.

V. PERFORMANCE EVALUATION

A. Simulation Setup and Performance Metrics

The performance of this work is evaluated through extensive simulations in ns-2. A network of 100 x 100 m^2 area is used, where 80 sensor nodes are deployed in a uniform random distribution. A sink-rooted routing tree is pre-established using the deployed nodes. The transmission and interference range of the nodes are set as 30m and 67m, respectively. The radio capacity is set as 250 Kbps. Table I summarizes the simulation parameters.

In this study, we compare the performance of the proposed scheme with MC-LMAC [9] and MMSN [10], since both of these have the common channel and fine-grained time synchronization properties in the protocol operation. Although the CC2420 radio [8] supports 16 channels in 2.4 GHz band, maximum 8 non-overlapping channels are used in simulation to reduce the effect of inter-channel interference. To achieve more stable results, an average of ten simulation executions is performed, each of that is 200 seconds long.

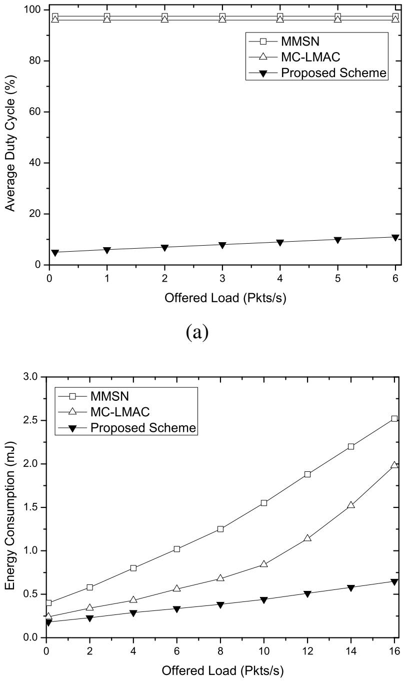
To analyze the performance, we have used these metrics: (i) *Average duty cycle* - The ratio between per cycle average active time to the entire cycle time, expressed in percentage; (ii) *Energy consumption* - The per packet average energy cost, expressed in milli-Joule (mJ); (iii) *Aggregate throughput* - The sum of the sizes of the total received packets by the sink in per unit time; (iii) *Delivery ratio* - The ratio between total received packets at sink to the total generated packets at the sources; and (iv) *End-to-end delay* - The interval between a packet generated at source and received at the sink node.

B. Simulation Results

In simulation, 50 randomly selected nodes are acted as sources. To create diverse traffic environment (low and high), we vary the data rates in between 0.25 to 16 Pkts/s. In Figure 4, we have shown the energy-efficiency of the protocols as a function of offered load. As shown in Fig. 4(a), the duty-cycles of the protocols are measured with the data rates till 6 Pkts/s. Beyond this data rate, we have hardly found the necessity of duty-cycle, since the overall traffic load actually saturates the network capacity. However, for our protocol the duty cycle rises marginally (only up to 11%) till 6 Pkts/s, due to the use of receiver-driven multiple wake-up approach. Conversely, as both the MMSN and MC-LMAC do not have any duty-cycle concept in implementation, their behavior is like the 'always on' protocol having almost 99.9% duty-cycle.

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Channel data rate	250 Kbps	No. of channels	8
Packet size	40 Bytes	Slot time	320 μs
Beacon size	11 Bytes	SIFS	192 μs
Back-off window	16	CCA check delay	128 μs
Retry limit	4	Simulation time	200 Seconds



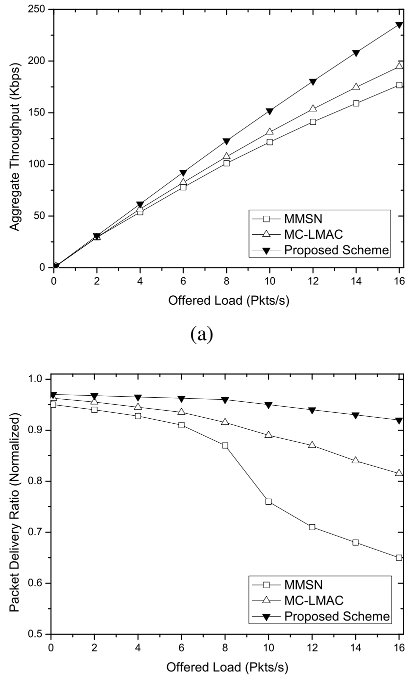
(a)

(b)

Fig. 4. Energy-efficiency: (a) Average duty cycle, and (b) Per-packet energy cost

The per-packet energy expenditure is shown in Fig. 4(b). The energy cost for proposed scheme is significantly lower than those of other protocols. It is because at both low and high rates, our protocol is able to maximize energy-utilization avoiding the collision and contention oriented energy-waste. Note that due to the random and distributed medium access at multiple beacon offsets on receiver's base-channel, the contention and collisions are reduced significantly. Conversely, the time-slotted MC-LMAC restricts itself to a lower energy cost, but, at high rates, channel conflict oriented collisions on common channel cause more energy waste for MC-LMAC. Finally, as expected, MMSN has the worst energy performance, since it always experiences comparatively more channel sensing, switching and collisions at different rates.

In Figure 5, data fidelity in terms of throughput and delivery ratio is observed. As in Fig. 5(a), the aggregate throughput of the protocols increases with the data rates. At lower rates (up to 6 Pkts/s) the performance of the protocols remains almost identical, though at higher rates it varies significantly. The per cycle multiple packet reception at different offsets helps our protocol to achieve a maximum throughput of 14.7 Pkts/s (235 Kbps). In contrast, MC-LMAC and MMSN achieve a maximum throughput of 12.16 Pkts/s (195 Kbps) and 11.04 Pkts/s (176 Kbps), respectively. Furthermore, the achieved delivery ratio as delineated in Fig. 5(b) also proves the fidelity effectiveness of the proposed protocol. The delivery ratio of MMSN suffers mostly, since in this protocol lack of coordination in channel allocation results in more collision-oriented packet drops.



(a)

(b)

Fig. 5. Data fidelity: (a) Aggregate throughput, and (b) Packet delivery ratio

Figure 6 represents that our proposed work surpasses the other protocols in terms of delay, especially when the traffic load is comparatively high. Because the per cycle multi-beacon and minimal channel switching of the nodes (receivers) in data communication ensure in-time and fastest delivery of the packets; which is very important for timely and effective actions. However, both MC-LMAC and MMSN experience longer delay, especially due to the heavy contention oriented cycle delay at high traffic rates. In the graph, the vertical line shows the max-min delay variation in simulation runs.

VI. CONCLUSION

In this paper, we propose a light-weight channel rendezvous scheduling for multi-channel medium access in WSNs. It takes the advantageous properties of duty-cycle and multi-channel concepts. According to the simulation results, the proposed scheme performs better than the existing multi-channel protocols in terms of average duty-cycle, energy consumption, throughput, delivery ratio, and delay. As a future work, we would like to extend this work for a complete load-adaptive multi-channel MAC solution, which would include load balancing and channel allocation/de-allocation techniques.

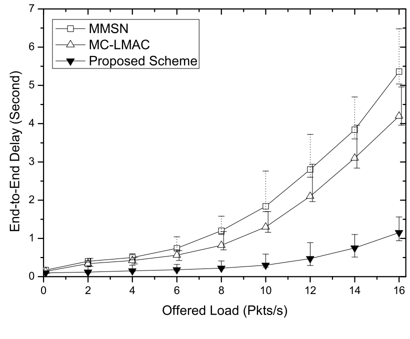


Fig. 6. End-to-end delay

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REFERENCES

[1] J. Polastre, J. Hill, and D. Culler, “Versatile low power media access for wireless sensor networks,” in *SenSys ’04: Proceedings of the 2nd international conference on Embedded networked sensor systems*. Baltimore, MD, USA: ACM, 2004, pp. 95–107.

[2] W. Ye, J. Heidemann, and D. Estrin, “Medium access control with coordinated adaptive sleeping for wireless sensor networks,” *IEEE/ACM Trans. Netw.*, vol. 12, no. 3, pp. 493–506, 2004.

[3] M. Buettner, G. V. Yee, E. Anderson, and R. Han, “X-mac: a short preamble mac protocol for duty-cycled wireless sensor networks,” in *SenSys ’06: Proceedings of the 4th international conference on Embedded networked sensor systems*. Boulder, Colorado, USA: ACM, 2006, pp. 307–320.

[4] Y. Sun, O. Gurewitz, and D. B. Johnson, “Ri-mac: a receiver-initiated asynchronous duty cycle mac protocol for dynamic traffic loads in wireless sensor networks,” in *SenSys ’08: Proceedings of the 6th ACM conference on Embedded network sensor systems*. New York, NY, USA: ACM, 2008, pp. 1–14.

[5] “Xbow mica2 mote specifications.” Available online: http://www.xbow.com (2011).

[6] S. Rangwala, R. Gummadi, R. Govindan, and K. Psounis, “Interference-aware fair rate control in wireless sensor networks,” *SIGCOMM Comput. Commun. Rev.*, vol. 36, no. 4, pp. 63–74, 2006.

[7] C. T. Ee and R. Bajcsy, “Congestion control and fairness for many-to-one routing in sensor networks,” in *SenSys ’04: Proceedings of the 2nd international conference on Embedded networked sensor systems*. New York, NY, USA: ACM, 2004, pp. 148–161.

[8] “Cc2420 2.4 ghz ieee 802.15.4 / zigbee-ready rf transceiver.” Available online: http://www.chipcon.com (2011).

[9] O. D. Incel, L. van Hoesel, P. Jansen, and P. Havinga, “Mc-lmac: A multi-channel mac protocol for wireless sensor networks,” *Ad Hoc Network*, vol. 9, pp. 73–94, January 2011. [Online]. Available: http://dx.doi.org/10.1016/j.adhoc.2010.05.003

[10] G. Zhou, C. Huang, T. Yan, T. He, J. A. Stankovic, and T. F. Abdelzaher, “Mmsn: Multi-frequency media access control for wireless sensor networks,” in *INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings*, april 2006, pp. 1 –13.

[11] T. van Dam and K. Langendoen, “An adaptive energy-efficient mac protocol for wireless sensor networks,” in *SenSys ’03: Proceedings of the 1st international conference on Embedded networked sensor systems*. New York, NY, USA: ACM, 2003, pp. 171–180.

[12] Y. Wu, J. Stankovic, T. He, and S. Lin, “Realistic and efficient multi-channel communications in wireless sensor networks,” in *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, april 2008, pp. 1193 –1201.

[13] M. Rahman, M. Alam, M. Monowar, C. Hong, and S. Lee, “nw-mac: multiple wake-up provisioning in asynchronously scheduled duty cycle mac protocol for wireless sensor networks,” *Annals of Telecommunications*, pp. 1–16, 2010, 10.1007/s12243-010-0226-7. [Online]. Available: http://dx.doi.org/10.1007/s12243-010-0226-7

[14] W. Ye, F. Silva, and J. Heidemann, “Ultra-low duty cycle mac with scheduled channel polling,” in *SenSys ’06: Proceedings of the 4th international conference on Embedded networked sensor systems*. New York, NY, USA: ACM, 2006, pp. 321–334.

[15] S. Thakur, S. Nandi, R. Bhattacharjee, and D. Goswami, “An asynchronous wakeup power-saving protocol for multi-hop ad hoc networks,” *Int. J. High Perform. Comput. Appl.*, vol. 21, no. 4, pp. 429–442, 2007.