A Dual-Radio Framework for MAC Protocol Implementation in Wireless Sensor Networks

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***Abstract*—In this paper, we present a dual-radio framework for implementing MAC protocols in wireless sensor networks. The framework is based on the observation that MAC operations can be categorized into bandwidth-independent and bandwidth-dependent. Unlike existing dual-radio systems, we do not propose a new MAC protocol. Instead, we show how a given MAC protocol can be re-implemented using a dual-radio framework resulting in substantial energy savings. Our framework is generic, different categories of MAC protocols can be re-implemented based on dual radios. This includes synchronous (e.g., SMAC), asynchronous (e.g., BMAC) and hybrid (e.g., SCP-MAC). Moreover, recent and promising asynchronous but receiver-initiated protocols like LPP and A-MAC can also be benefited.**

The proposed framework is simple and easy-to-implement. We have been able to re-implement SMAC, BMAC and SCP-MAC in TinyOS to dual-radio implementations using a combination of mica2 and micaZ motes. Extensive evaluation shows that a reduction in energy consumption by up to a factor of 5 can be attained.

I. INTRODUCTION

Recently, multi-radio systems [2, 4, 5, 7, 8, 11] have drawn the attention of WSN community. In most of these work, a MAC protocol using a low power secondary radio is proposed to reduce energy consumption. Unlike these systems, we do not propose a new MAC protocol. Instead, we show that significant power savings can be achieved by distributing a given MAC protocol's operations over dual radios. Our work is based on the observation that in typical WSN MAC protocols, there are two categories of operations:

- **Bandwidth-independent**: despite of several efforts to reduce idle-listening, current MAC protocols still continue to wait and idle listen over specific time spans. Such listening periods are part of the MAC functionality and cannot be easily removed or reduced without adversely affecting the behavior. Duration of such idle listening is independent of the channel bandwidth (data rate). Moreover, energy saving techniques often involve operations like preamble transmission and reception whose time spans are also bandwidth-independent.
- **Bandwidth-dependent**: these operations mainly include transmission and reception of both data packets and certain control packets such as RTS/CTS. The duration of such operations is a function of the channel bandwidth.

Such a categorization is generic in that it applies to common WSN MAC protocols, including scheduled (e.g., SMAC [12]), preamble sampling (e.g., BMAC [9]), and hybrids of these two categories (e.g., SCP-MAC [6]). Moreover, the categorization also applies to recent and promising receiver-initiated protocols like LPP [3] and A-MAC [1]. In scheduled protocols, nodes spend significant time in idle listening while waiting to receive potential synchronization schedules and data traffic. In preamble sampling, nodes transmit and receive preambles spanning long time durations. The hybrid protocols require both preambles but of much shorter length and synchronization. In receiver-initiated protocols, senders are designed to idle listen looking for probes from receivers. Duration of all these operations are bandwidth-independent. On the other hand, the operations of data transmission and reception are bandwidth-dependent.

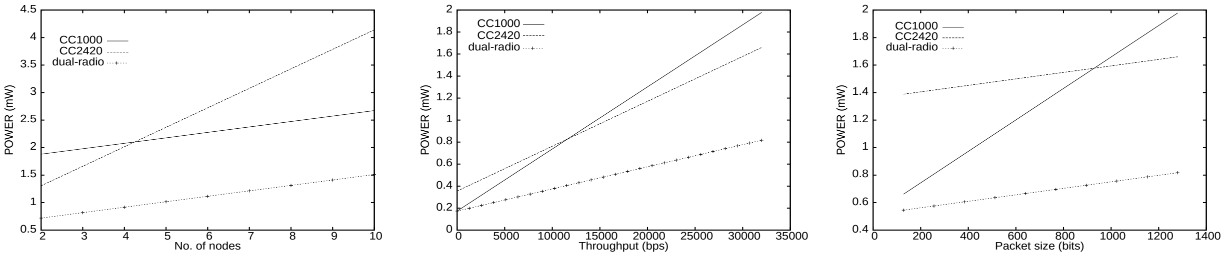
parameter	CC1000	CC2420
data rate	19.2 Kbps	250 Kbps
frequency	433 MHz	2.4 GHz
Tx power (at 0 dBm)	31.2 mW	52.2 mW
Rx power	22.2 mW	56.4 mW
idle power	22.2 mW	56.4 mW
wake-up power	7.4 mW	12.3 mW
sleep power	3 μW	3 μW
Tx energy per bit	1625 nJ	208 nJ
Rx energy per bit	1156 nJ	225 nJ

TABLE I: Characteristics of CC1000 and CC2420 transceivers.

Looking at existing popular WSN transceivers available, we can observe that low-bandwidth radio transceivers operating in lower frequency band (for instance, CC1000 operating in the 433/915 MHz) are more energy efficient than the high-bandwidth transceivers (e.g., CC2420 operating in 2.4GHz), measured in energy consumed per second. However, in terms of energy per bit transmitted, high-bandwidth transceivers operating in higher frequency range are more energy efficient. Table I depicts power consumption values of CC1000 and CC2420 as noted in [6].

Inspired by the above-discussed observations, we propose to use two types of network interfaces to implement a MAC protocol. A high-bandwidth interface running on higher frequency range (primary radio/channel) and a low-bandwidth interface running on a lower frequency range (secondary radio/channel). The high-bandwidth primary radio is used to serve bandwidth-dependent operations and bandwidth-independent operations are served on the low-bandwidth secondary radio.

Our framework is simple and easy to implement. We have re-implemented dual-radio versions of SMAC, BMAC and SCP-MAC by modifying their single radio implementations on TinyOS. We provide detail experimental measurement and analysis of the improvements that can be achieved in all the



(a) No. of neighbors (b) Throughput (c) Packet size

Fig. 1: Analytical demonstration of the advantages of using dual radios

three MAC protocols. Evaluation results in a realistic setup show that we can save 65% of the total energy consumed, with 40%, 63%, and 67% reduction in wake-up, sum of idle-listening and reception energy, and transmitting energy respectively. Moreover, we also demonstrate that a simple power control scheme can further improve the savings to 81%.

The rest of the paper is organized as follows. In Section II, we present an analytical analysis that demonstrates the potential of our dual-radio framework to achieve significant energy savings. Whereas in Section III, we use experimental analysis to verify for such potential and its general applicability by considering all the three mainstream MAC protocols, SMAC, BMAC and SCP-MAC. Details of dual-radio re-implementations of these protocols is presented in Section IV, together with their evaluations. Finally, we conclude in Section V.

II. ANALYTICAL ANALYSIS

We present a simple analytical model that serves two objectives. First, it illustrates the trade-off between using a high-bandwidth radio and a low-bandwidth radio. Second, it demonstrates the potential of efficiently handling such a trade-off using dual radios. We choose a BMAC like protocol for its simplicity. For the illustration, we use two radio transceivers: (1) primary, which is of high-power, high-bandwidth, and operating in higher frequency band (for e.g., CC2420 at 2.4GHz); (2) secondary, a low-power and low-bandwidth radio that uses lower frequency (for e.g., CC1000 at 433MHz). Table II describes some of the symbols used in our model.

Parameter	Symbol
normalized load	l
time required to poll the channel	β
preamble duration (equal to polling interval)	T_p
transmit power (primary/secondary)	E_t (E_t^P/E_t^S)
receive power (primary/secondary)	E_r (E_r^P/E_r^S)
data rate (primary/secondary)	(R) (R^P/R^S)
packet size	D
total number of nodes	N

TABLE II: Description of the symbols used in our model.

With an assumption that every node is within the communication range of all the other nodes, consider time duration of the polling interval, during which one node, with probability l transmits a preamble and then transmits an unicast data packet. All other $(N-1)$ nodes wake-up to sample the channel and only the intended receiver stays awake to receive the data packet while other nodes go back to sleep at the end of the preamble.

Expected energy consumption for idle-listening and preamble reception (E_i):

$$E_i = ((1-l)N\beta E_r) + (l(N-1)(\beta+0.5)T_p E_r) \quad (1)$$

Expected energy consumption for transmitting preamble (E_p):

$$E_p = lT_p E_t \quad (2)$$

Expected energy consumption for transmitting and receiving data (E_d):

$$E_d = l\frac{D}{R}(E_t + E_r) \quad (3)$$

The average total energy consumption for a single polling interval is $E_i + E_p + E_d$. Based on this simple model, we make two observations. First, E_i and E_p are bandwidth-independent, their values are independent of R. Second, E_d is bandwidth-dependent, its value varies with R.

Now consider the case where we use different radios to re-implement BMAC. Let $E_t = E_t^P = E_t^S$, and assume that CC1000's transmission range is at least as long as CC2420's. In addition, we set E_r^P be 2 times that of E_r^S, in line with the values shown in Table I.

In the dual-radio BMAC, bandwidth-independent operations of idle-listening and preamble transmission and reception are carried out on CC1000, which consumes less energy over the same time duration. Similarly, for bandwidth-dependent operations of data transmission and reception, CC2420 is used.

Now, we can rewrite the above equations:

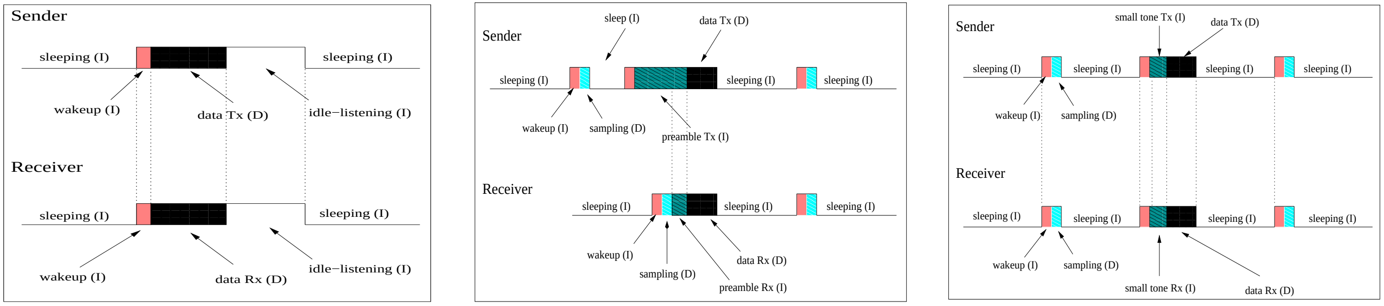
$$E_i = (1-l)N\beta E_r^S + l(N-1)\beta T_p E_r^S + l(N-1)0.5T_p E_r^S \quad (4)$$

$$E_p = lT_p E_t \quad (5)$$

$$E_d = l\frac{D}{R^P}(E_t + E_r^P) \quad (6)$$

In order to evaluate the improvement of dual-radio implementation, we plot how energy consumption varies with N, l and D. Duty cycle is set to 10% and T_p = 20ms. Default values of N, l and D are 3, 0.5 and 64 bytes respectively.

In Figure 1(a), we observe that for small number of neighbors, using only CC2420 is more efficient than using CC1000. However, as the number of neighbors increases, CC2420 becomes less efficient due to the increase cost of overhearing. In Figure 1(b), we see that when load is low, using only CC1000 is more efficient than CC2420 because receive energy dominates. However, as load increases, CC2420 consumes less energy since less transmission energy is used. When packet



(a) Scheduled protocol (b) Preamble sampling (c) Hybrid protocol

Fig. 2: Typical operations of different types of WSN MAC protocols and their categorization as bandwidth-independent (I) and bandwidth-dependent (D) operations.

size is varied, the result in Figure 1(c) shows that when packet size is small, energy needed for idle-listening dominates and CC1000 is more efficient. As packet size increases, per-bit efficiency becomes more important and CC2420 becomes a better option.

The results show that fundamentally, it is not possible to use a single type of radio to satisfy the needs of all these different environments with varying number of nodes, normalized load and packet size. On the other hand, in all cases, the dual-radio BMAC outperforms. As depicted by the "dual-radio" curves in the figures, by combining the two radios to cooperatively implement a single MAC protocol, the overall power consumption is significantly lower.

III. EXPERIMENTAL ANALYSIS

While we have demonstrated the potential of our framework to achieve significant gain by a simple model, it is important to verify for such potential and its general applicability using an experimental analysis. In our experiments, we employ mica2 and micaZ devices respectively built of CC1000 and CC2420 transceivers. Detail measurement is performed on these transceivers for all the three categories of scheduled, preamble sampling, and hybrid protocols. We use SMAC, LPL (BMAC) and SCP-MAC implementations by Wei Ye et al. of USC/ISI [13]. We keep track of the amount of time that radio transceiver spends in its different states so that energy consumed in a state can be calculated by using power consumption value of the device in that state.

We divide the evaluation into two parts. In the first part, we exclusively analyze bandwidth-independent operations, whereas in the second part, we study bandwidth-dependent operations only.

A. Bandwidth-Independent Operations

1) Scheduled protocols: Figure 2(a) depicts the operation of a typical scheduled protocol (SMAC) with its bandwidth-independent and bandwidth-dependent operations marked with (I) and (D) respectively. Synchronized senders and receivers wake-up together and enter active period. Data packets are exchanged during this period typically using CSMA/CA. The major disadvantage of such protocols is their under-performance during lightly-loaded conditions [6, 10]. During such conditions, nodes spend most part of the active portion of the duty cycle in idle-listening. This leads to significant energy wastage. Such wastage can be reduced at least by half by having CC1000 like lower frequency transceivers to perform duty-cycling.

avg. power consumption in mJ/sec at 10% duty cycle							
CC1000				CC2420			
sleep	Wup	Id	**Total**	sleep	Wup	Id	**Total**
0.0027	0.0069	2.13	2.14	0.0027	0.0176	5.40	5.42

TABLE III: Energy consumption of bandwidth-independent operations of scheduled protocols on CC1000 and CC2420.

We measure energy consumption of a duty-cycling node for five different duty cycles with duration of the experiment at each of the duty cycles being one minute. The result corresponding to 10% duty cycle is shown in Table III. Performance differences for other duty cycles are similar. As expected, the results show that bandwidth-independent operation of idle-listening (Id) consumes less energy on CC1000 with its consumption being 40% that of CC2420. CC1000 is also efficient in terms of wake-up energy (Wup) resulting in a saving of 61%. Moreover, CC1000 like time-wise efficient transceivers are more efficient in handling synchronization overhead which is not considered in this measurement. We demonstrate this efficiency of CC1000 in the context of hybrid protocols considered below in Section III-A3.

2) Preamble sampling: The operations and their categorization of a typical MAC based on preamble-sampling (BMAC) is depicted in Figure 2(b). Transmission and reception of preambles form the crux of the protocol and these operations are bandwidth-independent, thus being suitable for serving on CC1000 like transceivers.

In our experiments, we consider two sender-receiver pairs of nodes, one with CC1000 transceivers and the other pair with CC2420 radios. The nodes wake-up regularly with a specified interval to poll the channel for activity. On finding the channel busy, they continue to receive the preamble. Otherwise, nodes go back to the sleep state. The length of the preamble is determined by the duration of the polling interval. We transmit a preamble every two seconds for a total duration of 120 seconds. Only the preambles are transmitted, there is no subsequent data exchange.

Table IV compares average power consumption. On the sender, total energy savings of using CC1000 range from 37% to 46%. An interesting observation is that at smaller polling intervals (PI), CC2420 has smaller Id/Rx[1] energy whereas at larger polling intervals, CC1000 consumes less Id/Rx energy. This is because of the following. Energy consumed in polling/sampling the channel is recorded as idle energy and CC2420 is much faster than CC1000 in sampling the channel. As at lower polling intervals, polling frequency is higher, CC1000's polling energy (idle energy) dominates. Now consider larger polling intervals at which the length of the preamble is longer. As CC2420 provides packet-based interface with a maximum limit of 128 bytes on the size of a packet, the long preamble is split into several small packets with the radio idling between successive transmissions of these small packets. On the other hand, CC1000 does not involve such inter-packet idle times as it provides byte-level interface.

On the receiver, CC1000 results in a savings of about 60% at all the considered polling intervals. Given that there are often only 1 sender and many receivers, this is a good news. Saving in the wake-up energy is similar to that of the sender and it ranges from 60% to 72%.

avg. power consumption (mJ/sec) on **sender**								
—	CC1000				CC2420			
PI (ms)	Wup	Id/Rx	Tx	**Total**	Wup	Id/Rx	Tx	**Total**
100	0.14	0.40	1.55	2.11	0.35	0.06	2.92	3.34
200	0.07	0.19	3.07	3.34	0.17	0.11	5.71	6.00
300	0.04	0.12	4.61	4.78	0.11	0.16	8.39	8.67
400	0.03	0.08	6.14	6.27	0.08	0.19	11.17	11.45
500	0.02	0.04	7.67	7.74	0.05	0.23	14.01	14.30
avg. power consumption (mJ/sec) on **receiver**								
—	CC1000				CC2420			
PI (ms)	Wup	Id/Rx	Tx	**Total**	Wup	Id/Rx	Tx	**Total**
100	0.13	1.24	0.00	1.38	0.34	2.90	0.00	3.24
200	0.06	2.32	0.00	2.39	0.16	5.56	0.00	5.73
300	0.04	3.42	0.00	3.46	0.10	7.98	0.00	8.093
400	0.02	4.46	0.00	4.49	0.072	11.05	0.00	11.13
500	0.02	5.63	0.00	5.66	0.05	13.97	0.00	14.02

TABLE IV: Energy consumption of bandwidth-independent operations of preamble sampling on CC1000 and CC2420.

3) Hybrid protocols: The operation of a typical hybrid protocol (SCP) is illustrated in Figure 2(c). Its operation is similar to scheduled protocols in that the nodes are synchronized. However, unlike scheduled protocols, the channel is polled for activity at every wake-up. If activity is found, the node continues to receive the packet, otherwise, it goes back to the sleep state. This behavior is similar to that of protocols based on preamble sampling. Nevertheless, since nodes are synchronized, a short preamble (wake-up tone) is sufficient rather than long preambles.

As we can see from the figure, sleeping, wake-up, and transmission and reception of tones are bandwidth-independent. A major source of bandwidth-independent operations that is not depicted in the figure is the synchronization protocol. Synchronization protocols require nodes to spend considerable time in idle-listening looking for schedules. Alternatively, as in the SCP's implementation, bandwidth-independent operations such as preamble-sampling can be used to serve synchronization traffic.

We again use two sender-receiver pairs of nodes, one with CC1000 transceivers and the other pair with CC2420 radios. Synchronization among the nodes is achieved by using synchronization procedure of SCP. Nodes poll the channel periodically with a specified polling interval and the sender transmits only a short preamble once every polling interval (no subsequent data transmission).

The average power consumption is shown in Table V. Given most of the energy consumption is due to the synchronization overhead, a few observations can be noted. First, total energy savings on the sender range from 50% to 55% while savings are more on the receiver, ranging from 69% to 81%.

avg. power consumption (mJ/sec) on **sender**								
—	CC1000				CC2420			
PI (ms)	Wup	Id/Rx	Tx	**Total**	Wup	Id/Rx	Tx	**Total**
500	0.02	1.55	1.28	2.86	0.06	3.38	2.25	5.71
600	0.02	1.83	1.34	3.21	0.05	4.11	2.48	6.65
700	0.01	2.19	1.43	3.64	0.04	5.12	2.53	7.70
800	0.01	2.35	1.53	3.90	0.03	6.03	2.65	8.72
900	0.01	2.64	1.64	4.30	0.03	6.45	2.73	9.22
1000	0.01	2.92	1.76	4.70	0.02	7.56	2.86	10.46
avg. power consumption (mJ/sec) on **receiver**								
—	CC1000				CC2420			
PI (ms)	Wup	Id/Rx	Tx	**Total**	Wup	Id/Rx	Tx	**Total**
500	0.02	2.05	0.53	2.62	0.06	12.28	1.45	13.80
600	0.02	2.17	0.64	2.85	0.05	11.17	1.82	13.05
700	0.01	2.34	0.94	3.30	0.04	11.12	1.99	13.16
800	0.01	2.44	1.08	3.54	0.03	10.89	2.28	13.21
900	0.01	2.69	1.20	3.91	0.03	10.90	2.51	13.45
1000	0.01	2.92	1.33	4.27	0.02	11.37	2.49	13.90

TABLE V: Energy consumption of bandwidth-independent operations of hybrid protocols on CC1000 and CC2420.

Second observation is that as polling interval increases, Id/Rx energy consumption on the receiver increases for CC1000, while it decreases slightly for CC2420. This can be explained as follows. With SCP, when polling interval increases, the synchronization energy increases but the energy spent on polling the channel and tone reception decreases over a given span of time. For CC1000, the decrease in polling and tone reception energy is more than offset by the increase in synchronization cost, resulting in a slight increase in energy usage. On the other hand, for CC2420, the decrease in polling and tone reception energy is slightly higher than increase in synchronization cost. As a result, when polling interval increases, the savings of CC1000 over CC2420 decreases.

B. Bandwidth-Dependent Operations

We now focus on bandwidth-dependent operations, in particular, the RTS/CTS/DATA/ACK exchanges. We compare three different options. In the first two options, the entire exchange is respectively performed on CC1000 and CC2420. In the third option (dual-radio), the RTS/CTS exchange is performed on CC1000 and DATA/ACK transmission on CC2420. Our experiments involve five RTS/CTS/DATA/ACK exchanges with an inter-exchange interval being 5 seconds. We then compute average energy consumption per exchange. Moreover, as we are interested in energy spent solely in transmission, reception, and CSMA/CA operations such as backoffs and carrier sensing, we do not record the energy consumed between

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[1] The term "Id/Rx" denotes the sum of the energy/power consumed in idle-listening and reception.

packet arrivals.

Table VI compares the performance of all the three options. First, we consider an unexpected observation that at the sender Id/Rx energy consumed on the dual-radio is more than that is spent in the case of CC1000. This is because of the fact that more idle energy is spent on the dual-radio as CSMA/CA is performed twice, once on CC1000 for RTS transmission and again on CC2420 before transmitting the data packet.

Second, we consider total energy consumption. At the sender, CC2420 is 3.85 and 2 times more efficient than CC1000 and dual-radio respectively. While at the receiver it is 3.5 and 1.5 times more efficient than CC1000 and dual-radio respectively. The bit-wise energy efficiency of CC2420 dominates and makes its performance the best. Hence, the approach of using CC1000 to implement operations such as random backoffs, carrier-sensing, and waiting-times involved in the RTS/CTS exchange is actually less efficient. In fact, when one looks at the details, we notice that the duration of these operations are more bandwidth-dependent than bandwidth-independent. This is because they operate on time-slots and the duration of time-slots is a function of bit-rate.

avg. energy consumption per RTS/CTS/DATA/ACK (mJ) on **sender**								
CC1000			CC2420			dual-radio		
Id/Rx	Tx	**Total**	Id/Rx	Tx	**Total**	Id/Rx	Tx	**Total**
0.55	1.75	2.31	0.31	0.28	0.60	0.64	0.53	1.23
avg. energy consumption per RTS/CTS/DATA/ACK (mJ) on **receiver**								
CC1000			CC2420			dual-radio		
Id/Rx	Tx	**Total**	Id/Rx	Tx	**Total**	Id/Rx	Tx	**Total**
1.19	0.49	1.69	0.39	0.09	0.48	0.42	0.29	0.74

TABLE VI: Energy consumption of bandwidth-dependent operations on CC1000, CC2420, and dual-radio.

IV. DUAL-RADIO FRAMEWORK: IMPLEMENTATION AND EVALUATION

In this section, we realize the proposed framework by re-implementing BMAC and SCP-MAC protocols into dual-radio versions. It is not required to re-implement the SMAC separately as such a re-implementation results in a operation similar to the dual-radio SCP-MAC — before starting to transmit a packet on CC2420, a sender is required to transmit a short preamble on CC1000 in order to wake-up receiver's CC2420 and moreover, SCP and SMAC share a common synchronization scheme [6].

We carry out evaluations on our dual-radio device which is built as follows. We build a simple "integrated" node where one mica2 (CC1000) and one micaZ (CC2420) are connected to a PC via programming boards such as MIB520. The two motes communicate with each-other via our gateway program running on the PC, thus emulating a dual-radio device.

In the dual-radio BMAC, energy-saving operations of periodic wake-up, channel polling, and preamble transmission and reception are carried out on CC1000. Whereas data is communicated on CC2420. A typical transaction occurs as follows. A dual-radio sender initiates by sending a preamble on CC1000. The receiver detects and continues to receive the preamble with waking-up its CC2420 at the end of the preamble. The sender also wakes-up its CC2420 on completing the preamble transmission. Finally, an RTS/CTS/DATA/ACK exchange is carried out on the woken CC2420 radios.

We compare dual-radio BMAC against single-radio BMAC running on CC2420 in a typical setup of a sender and a receiver. Our experiment involves five RTS/CTS/DATA/ACK exchanges with an inter-exchange interval of 5 seconds. We first record total energy consumed in different radio states during the span of our experiment and then use the total in computing average energy consumption per exchange. The comparison is depicted in the left half of the Table VII.

At the sender, savings in the total energy range from 25% to 45%. While we have observed some savings in wake-up energy, the main savings is in the transmit energy. At the receiver, the total energy savings range from 40% to 50%. As expected, most of the savings come from the much lower idle-listening and receiving energy.

We now consider re-implemented dual-radio SCP. The operations of channel polling, transmission and reception of wake-up tones, and synchronization are carried out on CC1000 while bandwidth-dependent operations are served on CC2420. A dual-radio sender starts by transmitting a wake-up preamble (tone) on CC1000. Unlike in dual-radio BMAC, the size of the preamble is small and its transmission is synchronized with the polling at the receiver. On completely receiving the tone, the receiver wakes-up its CC2420. On the sender-side, completion of the tone transmission triggers wake-up process of its CC2420 in order to initiate an RTS/CTS/DATA/ACK exchange.

We compare dual-radio SCP against single-radio SCP running on CC2420. Once the sender and receiver are synchronized, five RTS/CTS/DATA/ACK exchanges are initiated with an inter-exchange interval of 5 seconds. We record total energy consumed during the span of our experiment that also includes time spent in achieving synchronization. We then use the total in computing average energy consumption per exchange. The comparison is provided in the right half of the Table VII.

The energy savings range from 33% to 39% on the sender. On the receiver, savings are larger, ranging from 35% to 55%. These savings are mainly because of the bandwidth-independent operations involved in achieving synchronization.

We now evaluate our framework in a more realistic setup where not every node is in the direct transmission range of all the other. As our dual-radio platform requires two programming boards (one for mica2 and the other for micaZ) and we have only twelve such boards, we use six "integrated" nodes in the evaluation. There are 3 sender nodes with each transmitting to one of its neighbors while other neighbors overhear the transmission. The transmissions are coordinated so that collisions are avoided. Every sender node transmits 10 periodic packets and a random burst of 10 packets, thus emulating a typical traffic load for WSNs.

In this evaluation, we will only show results for the dual-radio BMAC, configured with a polling interval of 500 ms. Moreover, we incorporate an enhancement in our dual-radio BMAC. Unlike in the classical BMAC where every transmission in preceded by the transmission of a preamble, we allow multiple packets of a burst for the same destination to be transmitted on the CC2420 after a single preamble

dual-radio BMAC									**dual-radio SCP/SMAC**								
avg. energy consumption per RTS/CTS/DATA/ACK (mJ) on **sender**									avg. energy consumption per RTS/CTS/DATA/ACK (mJ) on **sender**								
—	dual-radio				CC2420				—	dual-radio				CC2420			
PI (ms)	Wup	Id/Rx	Tx	**Total**	Wup	Id/Rx	Tx	**Total**	PI (ms)	Wup	Id/Rx	Tx	**Total**	Wup	Id/Rx	Tx	**Total**
100	0.96	3.20	3.43	7.62	2.70	1.23	6.16	10.12	100	0.87	14.20	4.67	19.76	2.05	19.72	7.91	29.70
200	0.49	1.77	6.51	8.78	1.29	1.28	11.92	14.51	200	0.39	24.63	8.38	33.41	0.99	36.47	14.73	52.21
300	0.34	2.69	9.62	12.66	0.91	1.34	17.41	19.69	300	0.24	34.38	12.10	46.74	0.63	53.46	21.36	75.47
400	0.30	1.20	12.76	14.27	0.65	1.45	23.07	25.20	400	0.18	45.54	15.88	61.61	0.46	72.54	28.41	101.43
500	0.22	0.97	15.87	17.07	0.51	1.51	28.82	30.87	500	0.18	53.74	19.56	73.50	0.30	79.03	35.04	114.38
avg. energy consumption per RTS/CTS/DATA/ACK (mJ) on **receiver**									avg. energy consumption per RTS/CTS/DATA/ACK (mJ) on **receiver**								
—	dual-radio				CC2420				—	dual-radio				CC2420			
PI (ms)	Wup	Id/Rx	Tx	**Total**	Wup	Id/Rx	Tx	**Total**	PI (ms)	Wup	Id/Rx	Tx	**Total**	Wup	Id/Rx	Tx	**Total**
100	1.05	2.94	0.06	4.07	2.85	5.08	0.08	8.03	100	1.00	7.66	4.18	12.81	2.06	19.46	7.21	28.75
200	0.53	5.16	0.06	5.77	1.30	11.42	0.07	12.81	200	0.45	17.78	7.90	26.10	0.96	38.80	14.08	53.85
300	0.36	7.33	0.07	7.79	0.89	12.69	0.06	13.67	300	0.30	21.74	11.63	33.64	0.63	53.91	20.71	75.27
400	0.30	9.58	0.07	9.97	0.67	13.13	0.07	13.89	400	0.21	28.90	15.37	44.46	0.45	76.94	27.82	105.24
500	0.22	11.81	0.06	12.11	0.57	19.16	0.07	19.82	500	0.17	35.96	19.11	55.21	0.31	95.47	31.76	127.55

TABLE VII: Performance comparison of dual-radio versions of BMAC and SCP/SMAC protocols against single-radio versions.

setup	Wup (mJ)	Id/Rx (mJ)	Tx (mJ)	Total (mJ)
CC2420 only	102.33	3197.78	1569.67	4874.03
dual-radio	62.28	1178.42	487.01	1733.976
dual-radio with power control	52.94	403.62	467.13	928.99

TABLE VIII: Comparison in a realistic setup of six dual-radio nodes.

transmission on CC1000. This is an enhancement that is consistent with the preamble sampling framework and at the same time, exploit the availability of dual radios. With two radios available, while the CC1000 is busy in preamble sampling, the CC2420 remains unused. Hence, for this duration, we allow multiple packets for the same destination to be transmitted on the CC2420 after one preamble sampling.

Evaluation results are shown in the Table VIII (in the rows with labels "CC2420 only" and "dual-radio"). The results shown are sum of the energy consumed at all the six nodes during the span of our experiment. While the savings in wake-up energy is similar to the 2 nodes scenario, the savings in receive and transmit energy are substantially larger in the realistic case. The total energy savings is close to 65% over the use of CC2420.

The evaluation brings out another interesting observation. Due to the longer communication range of CC1000, there are some cases where a node is unnecessarily woken on the CC1000 radio while it is not reachable on the CC2420. Additional energy savings are thus possible if the transmission power on the CC1000 is reduced so that it is sufficient to reach an intended receiver of data on CC2420.

We fix the transmission power on CC2420 to the maximum possible value of 0dBm and reduce the transmission power on CC1000 to the minimum value at which the receiver is reachable. By incorporating such power control, we again measure total energy consumption of all 6 nodes. The results are shown in the last row of the Table VIII. The power control results in significant gain with total energy consumption reducing by almost 50% compared to the dual-radio case of without power control. Moreover, with less nodes waking up on the CC1000, there is a 15% reduction in wake-up energy and 66% reduction in Id/Rx energy. While compared to single-radio CC2420, total energy savings is a large value of 81%.

V. CONCLUSION

We proposed a generic framework for WSN MAC protocol implementation using dual radios. The framework is based on the observation that central operations in WSN MAC protocols can be categorized as bandwidth-independent and bandwidth-dependent. We experimentally demonstrated the generic potential of our framework by considering three mainstream protocols, SMAC, BMAC, and SCP-MAC. Moreover, we re-implemented these protocols to dual-radio versions and carried out extensive evaluations. Evaluation results show that in a realistic setup, we can save 65% of the total energy consumed. Further, we also demonstrated that a simple power control scheme can further improve the savings to 81%. We believe that the framework can be useful in general in the design of energy efficient protocols.

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