Spectrum Agile Medium Access Control Protocol for Wireless Sensor Networks

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Abstract— **In this paper we describe the design, implementation and performance evaluation of a low-power spectrum agile medium access control protocol for wireless sensor networks. With the ever increasing popularity of wireless embedded devices and networks, spectrum is getting congested, which in turn leads to performance degradation. Since protocols are designed in isolation of each other without appropriate consideration for potential interferences and mechanisms for symbiotic coexistence, they fail to achieve the desired performance characteristics in realistic interfering environments. The performance degradation is more significant for low-power embedded networks as they remain handicapped when competing with less resource constrained networks. We design a protocol that allows sensor nodes to dynamically select an interference minimal channel for data communication. It does not pose any synchronization restrictions on the nodes and effectively handles the dynamics of the network such as new nodes joining and old nodes leaving the network. We describe the various energy efficient spectrum sensing features of the protocol on which the dynamic channel selection is based. Our experiments suggest that even in highly crowded spectrum and environments with random interferences, sensor nodes are able to communicate in a reliable and energy efficient manner.**

I. Introduction

There is a trend in the increasing number of wireless devices and networks being integrated into our daily life, which in turn has led to the crowding of the existing wireless spectrum. Congestion of the spectrum results in mutual interference among devices sharing the same medium. In many networks, especially in the case of sensor networks, the traffic load is generally low and the wireless channels usually remain under-utilized. Dedicating a wireless channel to each network is not only a waste of resources but has also become less practical due to the increasing scarcity of the spectrum [1]. The increasing number of different wireless devices in the shared spectrum requires spectrally efficient operation that goes beyond simplistic Medium Access Control (MAC) layers. Therefore, an efficient use of the spectral resources and the need for symbiotic coexistence features in the medium access procedures has become necessary. Since sensor nodes have only a limited supply of energy and use low transmit power, they always remain handicapped when competing for the same wireless channel against other less power constrained devices. It has been shown by empirical studies that under moderate and high traffic conditions, low power sensor node radios suffer huge packet losses due to interference, e.g., in 2.4 GHz from different WLAN standards [2]. Therefore, in order to avoid collisions and unnecessary retransmissions, spectrum agility becomes an important feature for MAC protocols that are designed for future Wireless Sensor Networks (WSNs). Wireless nodes are required to sense the spectrum and to agree on using a particular interference free channel. This agreement can either be achieved through a dedicated common control channel [3] or in a distributed way through a decentralized channel selection algorithm [4]. The latter approach is more desirable since it does not require devoting a common channel especially for WSNs where the volume of data traffic is typically very small.

II. Related Work

MAC design research in sensor networks has been focussed on low power operation. In order to reduce the energy budget, sensor networks exercise duty cycling schemes, where the radio is turned on/off periodically and energy dissipation is saved while the radio is off. Many solutions have been devised to align the active periods of the radios in order to establish data communication. One popular technique used in WSN MAC protocols is the preamble sampling approach. Preamble sampling protocols allow sensor nodes to follow asynchronous sleep schedules and impart control overhead only when data communication is required. Different techniques have been devised to shorten the length of the preamble required to be transmitted and received in order to conserve energy consumption. It has been shown that the effective control overhead in preamble sampling protocols is very low and their properties are cogent to the typical characteristics of WSNs of low traffic and dynamic nature [5]. While most of these schemes are based on single channel and the focus is only on the energy efficient design, inability to select interference free channel hampers their operation in the presence of environmental interferences. Protocols using multiple channels, which aim at achieving higher throughputs while observing energy conservation such as [6] [7] have the drawback of not being able to cope with channel interferences. The issue of energy consumption together with symbiotic coexistence with other devices and networks becomes important for WSNs in realistic channel conditions.

There have been a number of protocols designed based on opportunistic spectrum access [4] but these have classically been targeted for networks with less constraints and applications with higher data rates. One broader category of classical spectrum agile protocols relies on a dedicated control channel with low interference. The control channel is used for establishing an agreement on the use of the data channel, which is shared with the primary user. Typically the required data rates in WSNs are so low that dedicating a control channel is suboptimal. The other class of spectrum agile networks uses extensive spectrum profiling and advanced learning techniques to predict the spectrum occupation of the primary users [8]. WSNs are limited in resources to perform extensive spectral measurements in order to determine the spectrum holes [9] and establish fine grained spectrum occupancy models of the environment. In [10], the authors establish a model for the co-existence of IEEE 802.15.4 and IEEE 802.11b/g networks in certain operating ranges. However, this requires modification of the timing aspects of the two protocols and does not solve the problem of receiving mutual interferences. Authors in [11] claim that IEEE 802.15.4 compliant CC2420 radio has good properties for alternate and adjacent channel rejection thereby allowing it to coexist with WLAN, Bluetooth and other ZigBee interfering networks. However, their measurements do not take into account the MAC behaviours and therefore in real deployments the performance suffer heavily [10]. Our MAC protocol enables low power spectrum agility for sensor networks. We have designed and implemented a spectrum agile MAC protocol [12] allowing sensor nodes to find interference free channels in unregulated crowded frequency bands and avoiding packet losses in interference prone channels.

III. Protocol Details

Our spectrum agile MAC protocol (SA-MAC) is based on the preamble sampling principle. Using a lightweight channel selection strategy, a transmitting node dynamically selects the interference free channel based on the spectral characteristics and sends a preamble followed by the data. Unlike single channel MACs, a receiving node sequentially scans all the frequency channels in the available pool and is able to detect activity in the channel being used by the transmitter. At the same time, the receiving node is able to ascertain the presence of external interferers and their strengths. Since our protocol is based on the preamble sampling scheme and uses a distributed channel selection algorithm, it suits well to dynamic and scalable WSNs. Fig. 1 shows the Low Power Listening (LPL) operation of the MAC protocol, where nodes A, B and C poll the channels asynchronously from each other. Unlike the classical definition of duty cycle for single channel MACs, which is defined as the ratio of on-time of the radio to the sum of the on-time and the sleep duration, the duty cycle of SA-MAC however is defined to be the ratio of radio on-time in one of the channels to the total period when it is repeated. This is because even if the radio is on in another channel, it is invisible and the transmitter therefore needs to send a longer preamble to compensate it. SA-MAC shortens the length of the preamble sequence to achieve energy conservation by combining together different techniques from single channel protocols such as MFP-MAC [13], WiseMAC [14] and X-MAC [15].

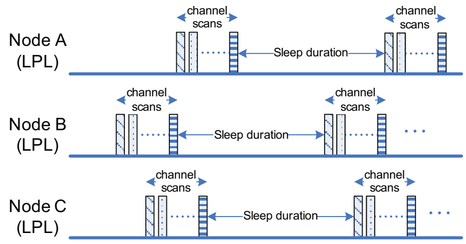


Fig. 1. Preamble sampling operation in SA-MAC protocol.

A. Preamble Optimization

Duty cycling MAC protocols require that the active periods (radio on durations) of the receiving node(s) must be aligned with that of the transmitter for a successful data exchange. In preamble sampling MAC protocols, the preamble sequence sent before the data serves as the control overhead to implicitly synchronize the active periods of the transmitter and the receiver(s). Since the sampling periods of the nodes are typically long, the required preamble length to be transmitted/received also correspondingly becomes long causing energy wastage both at the transmitter and the receiver(s). In the following, we describe the preamble shortening techniques used by SA-MAC protocol.

1) Microframes: The monolithic preamble is divided into a series of back-to-back micro-frames (MFP), each containing the information of the destination node, the exact time of the data frame transmission and the sleep schedule of the transmitting node. Upon receiving a micro-frame, a non-addressed node is able to immediately switch back to the sleep state and avoid receiving the unnecessary preamble sequence and the data packet following it. An addressed node also goes to sleep in order to avoid receiving the rest of the preamble frames. However, it awakens again at the right instant to receive data frame(s). Fig. 2 illustrates the operational cycle of the MAC, where the transmitter (TX) first scans all the channels in the pool in order to make sure that there is no on-going transmission. Then it chooses the most suitable channel (based on the algorithm described in Section III-B) and transmits the preamble framelets followed by the data frames. The asynchronous awakening nodes (RX1 and RX2) poll the channel and detect the transmission, receive a

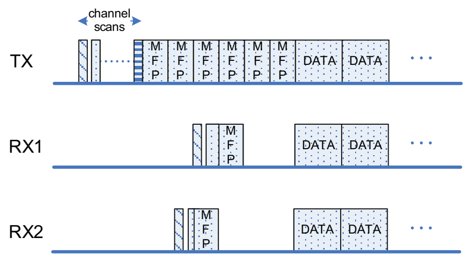


Fig. 2. Broadcast transmission in SA-MAC. Back-to-back MFPs are sent for a duration equal to the periodic channel check interval followed by the data frames.

complete MFP, go back to sleep and awaken again to receive the data frames. Experiments have shown that if the data size is small, waking-up again in order to receive the data frame is less efficient than piggy-backing the data to the preamble framelets. Based on this premise, if the data size is smaller than a certain empirically found threshold, we piggyback the data onto the preamble framelets to form a Data-Frame-Preamble (DFP). A series of back-to-back DFPs serve the purpose of both preamble for control and data. Fig. 3 shows the operational cycle of the MAC for the case of DFP. Note that the randomly waking-up nodes RX1 and RX2 need to receive just one complete preamble frame (DFP). SA-MAC exercises the above described preamble shortening techniques only for broadcast transmission. For unicast transmission, additional information is exploited to further reduce the length of the transmission/reception as described in the later subsections.

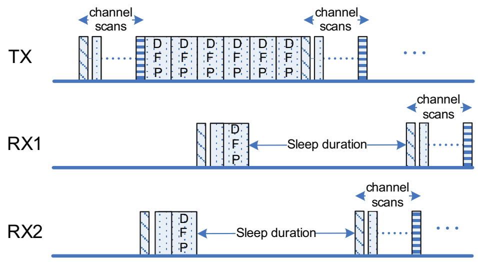


Fig. 3. Broadcast transmission in SA-MAC. Back-to-back DFPs are sent for a duration equal to the periodic channel check interval. The data bytes are piggy backed onto the preamble frames.

2) Neighbourhood Sleep Schedules: SA-MAC protocol maintains the sleep schedules of the neighbouring nodes in order to apply the preamble shortening technique for unicast transmission in a manner similar to WiseMAC [14]. However, unlike WiseMAC which announces the sleep schedules in the acknowledgement frames, sensor nodes in SA-MAC announce their sleep schedule within the preamble framelets. This also allows non-addressed nodes to update their sleep schedule tables. A transmitting node shortens the length of the preamble by delaying the packet transmission until the destination node is scheduled to wake-up. In the ideal case, a transmitter only needs to send one preamble frame just when the receiver is scheduled to wake-up. Unicast transmission implies that the transmitting node wake-ups according to the receiver(s) wake-up schedules but also forces itself not to miss waking-up according to its own sleep schedule so that another potential transmitter would still be able to address it. In unicast transmissions, the amount of energy saved by the transmitting node is proportional to the packet delay interval.

3) Preamble Strobing: SA-MAC combines the neighbourhood sleep schedule based optimization with preamble strobing technique [15] for unicast transmission. After transmitting a preamble frame, the transmitter waits for an acknowledgement of the frame from the potential receiver. Subsequent preamble frames are transmitted after timing out for the acknowledgement of the previously transmitted preamble frame.

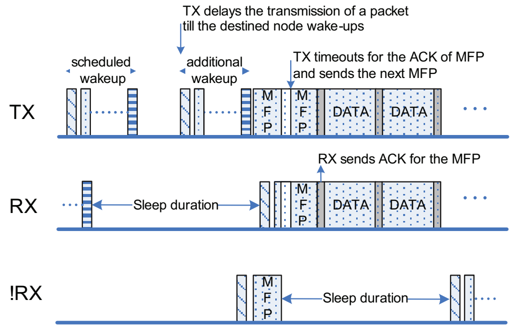


Fig. 4. Unicast transmission for SA-MAC, where neighbourhood sleep schedule information is combined with preamble strobing technique. After an MFP is acknowledged, data frame(s) are immediately sent.

After receiving the acknowledgement for a DFP, a transmitter stops sending further DFP frames as the data (within the DFP) has already been delivered to the destination node. In the case of an MFP, after receiving the acknowledgement, a transmitter immediately sends the data frames. In this way a transmitter only needs to send a reduced preamble sequence. In SA-MAC, a transmitter first tries to delay the transmission until the scheduled wake-up time of the receiver and exercises preamble strobing. This is beneficial because as time passes, clock drifts are established between the sensor nodes and the sleep schedule estimation of the neighbours become imprecise. Furthermore, due to the mobility of the nodes, the neighbourhood information itself does not remain reliable. SA-MAC has the ability to compensate the clock jitters established in the neighbourhood sleep schedule estimation over time due to genetic inaccuracies of crystal oscillators through the preamble strobing principle. In the best case, with perfect timing estimation of a neighbour's sleep schedule, only one microframe is needed to be transmitted and in the worst case the length of the preamble transmission becomes equal to the periodic channel check interval (similar to the broadcast case). Fig. 4 shows the unicast transmission for the case when the transmitter (TX) does not have the perfect knowledge of the receiver's (RX) sleep schedule. After timing out for the acknowledgement of the first MFP, the transmitter sends the next MFP frame which is acknowledged by the receiver and

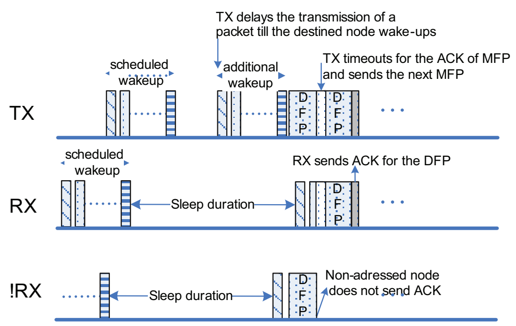


Fig. 5. Unicast transmission for SA-MAC. After a DFP is acknowledged, the transmitter stops sending further DFPs.

the data frames follow immediately. A non-addressed node (!RX) on the other hand goes sleep after receiving an MFP for the entire duration of the transmission. Fig. 5 shows the unicast transmission for the DFP case where after receiving a complete DFP frame, the destination node sends an acknowledgement, which marks the completion of the transmission and the transmitter stops sending further DFP frames.

B. Channel Weighting Algorithm

Efficient spectrum sensing is an important aspect of the protocol. A more realistic and practical metric obtained from WSN radios is the spectral energy detection. It may be noted that scanning all the channels is quite exhaustive for the nodes and leads to high energy consumption during idle listening. The selection of the communication channel is carried out using a heuristic based method. We associate weights to each of the channel in the pool. The weights are readjusted according to a channel activity each time when channel assessment is performed. If a particular channel is sensed as idle, its weight is increased by one. When data communication is initiated (whether the radio is in the transmit mode or in the receive mode), the channel weight is increased by two. Even if the node is not the destination, we will still increase the weight associated with that particular channel by two. The underlying rationale is that as communication establishes in a particular channel, it is the best channel from the point of view of the transmitter and both the receiver(s) and the non-addressed node(s) should increase the weight associated with the channel by double the factor as that of finding a channel idle. However, upon detecting an interferer, the channel weight is decreased by three. The protocol also maintains a history of the channel activities. The number of events in the channel history is a variable exposed by the MAC through an API and depends upon the sampling time and the channel conditions. The channels are sorted in the descending order of their weights. If the channel weights are equal, the channel with higher score for the last activity is stored first in the sorted pool. Since the channel with the highest weight is assessed first in the low power listening operation, this scheme increases the chances for using the channel with the highest weight and therefore saves energy for the receiving node(s) as they do not need to scan further channels in order to detect the communication channel of the transmitting node.

During the LPL operation, the protocol requires the nodes to scan all the available channels in the pool one by one. The larger the number of channels in the pool, the higher is the energy consumption per LPL operation. So it is desirable for the nodes to converge on a smaller subset of the channels depending upon the subjected interferences. In order to minimize the channel scans, the protocol governs a distributed channel expansion/contraction strategy. It uses double thresholds, $T1$ and $T2$ with $T1 < T2$. Initially, a bigger channel pool is created with all the weights equal to $T2$. Over the time, depending on the channel conditions and if the weight of a channel goes below $T1$, it is deleted from the pool. This way sensor nodes converge to less interfering channels. Owing to completely distributed nature of this scheme, sensor nodes may experience local interferences which may differ from others and this may possibly lead to different sets of channels in the pool. Our empirical observations however show that such a case arises rarely in real deployments. On the contrary, if the channel weights in the contracted channel set gets deteriorated over time, the pool size is expanded and new channels are popped-in with their weights initialized to $T2$. The selection algorithm gives lower priority to adding channels that have been deleted from the channel pool. Also the channels adjacent to interfering channels are given less precedence in order to avoid wider band interferers.

IV. Analytical Expression for Optimal Energy Consumption

We model SA-MAC protocol analytically and derive an expression for the optimum duty cycle giving minimal energy consumption for a given network size. Since the amount of energy consumption directly depends upon the traffic loads and the type of the traffic, we consider the cases of unicast and broadcast communication patterns separately in our formulation. In the following, we derive the expressions for the case when MFP is used by the MAC protocol. Similarly, optimal duty cycle expression for DFP can also be derived.

A. Models and Parameters

Consider a network neighbourhood consisting of $n+1$ nodes and assume that each node transmits data packets of length l_{pkt} periodically at the rate r_{data} per second. Each node spends power in the operations: radio initialization, carrier sensing, packet transmission, packet reception, channel polling and sleep state, which are denoted by $P_{\text{radio\_setup}}$, P_{cs}, P_{tx}, P_{rx}, P_{poll} and P_{sleep}, respectively. In the following, we list the terms used in our model:

Notation	*Meaning*
$t_{\text{poll\_once}}$	Single channel polling interval
n_{ch}	Number of channels to be polled
$t_{\text{radio\_setup\_once}}$	Single initialization duration of the radio
$t_{\text{poll\_period}}$	Channel sampling period
L_{mfp}	Length of a microframe preamble
N_{mfp}	Number of microframes
$t_{\text{cs\_once}}$	Channel carrier sensing interval
l_{pkt}	Length of the data packet
t_{b}	Bit duration
l_{ack}	Length of the acknowledgement frame

B. Broadcast

The overall energy expenditure of a node is the sum of the energy spent in each operation. Normalizing the energy consumption over a channel polling interval is expressed as,

$$E = E_{\text{radio\_setup}} + E_{\text{poll}} + E_{\text{rx}} + E_{\text{cs}} + E_{\text{tx}} + E_{\text{sleep}} \tag{1}$$

$$E = P_{\text{radio\_setup}}t_{\text{radio\_setup}} + P_{\text{poll}}t_{\text{poll}} + P_{\text{rx}}t_{\text{rx}} + P_{\text{cs}}t_{\text{cs}} + P_{\text{tx}}t_{\text{tx}} + P_{\text{sleep}}t_{\text{sleep}} \tag{2}$$

In the following, we consider the normalized individual time durations with channel polling period ($t_{\text{poll\_period}} = L_{\text{mfp}}N_{\text{mfp}}t_{\text{b}}$) as the factor: $t_{\text{poll}} = \frac{n_{\text{ch}}t_{\text{poll\_once}}}{t_{\text{poll\_period}}}$

$t_{\text{radio\_setup}} = \frac{n_{\text{ch}} t_{\text{radio\_setup\_once}}}{t_{\text{poll\_period}}}$
$t_{\text{rx}} = n r_{\text{data}} (1.5 L_{\text{mfp}} + l_{\text{pkt}}) t_{\text{b}}$
$t_{\text{cs}} = n_{\text{ch}} r_{\text{data}} (t_{\text{poll\_once}} + t_{\text{radio\_setup}})$
$t_{\text{tx}} = r_{\text{data}} (N_{\text{mfp}} L_{\text{mfp}} + l_{\text{pkt}}) t_{\text{b}}$
$t_{\text{sleep}} = 1 - t_{\text{radio\_setup}} - t_{\text{poll}} - t_{\text{rx}} - t_{\text{cs}} - t_{\text{tx}}$

A node running SA-MAC requires to receive 1-2 micro preamble frames (an average of 1.5) in order to know the timing information of the data frames and to determine whether the intended packet is destined for it or not. A transmitter on the other hand, needs to send preamble frames for a duration equal to the sampling period (periodic check interval of the channel being used). Unlike single channel preamble sampling MAC protocols, SA-MAC pays the price of scanning multiple channels in the polling operation, which reduces the effective sleep duration for a given sampling period. We have experimented with our test implementation and have observed that the time needed to setup the radio in a particular channel is non-negligible and accounts for the time needed to send commands over SPI or UART interface in order to start the radio in the desired configuration. Additionally, it also includes the time required for the crystal oscillator to stabilize.

Our target is to find the relationship of the sampling period (directly related to duty cycle) which leads to the minimum energy consumption. Since the sampling period is directly related to the length of the preamble, we find the number of microframes corresponding to the minimum energy consumption. Plugging in the terms in equation (2) and taking the derivative w.r.t. N_{mfp} gives,

$$\begin{aligned} \frac{dE}{dN_{\text{mfp}}} = &-\frac{n_{\text{ch}}(P_{\text{poll}} t_{\text{poll\_once}} + P_{\text{radio\_setup}} t_{\text{radio\_setup\_once}})}{L_{\text{mfp}} N_{\text{mfp}}^2 t_{\text{b}}} \\ &+ P_{\text{tx}} r_{\text{data}} L_{\text{mfp}} t_{\text{b}} + n_{\text{ch}} \frac{P_{\text{sleep}}(t_{\text{poll\_once}} - t_{\text{radio\_setup\_once}})}{L_{\text{mfp}} N_{\text{mfp}}^2 t_{\text{b}}} \\ &- r_{\text{data}} L_{\text{mfp}} t_{\text{b}} P_{\text{sleep}} \end{aligned} \tag{3}$$

Requiring $\frac{dE}{dN_{\text{mfp}}} = 0$ and simplifying the terms gives the optimum number of microframes.

$$\hat{N}_{\text{mfp}} = \sqrt{\frac{n_{\text{ch}}(t_{\text{poll\_once}}(P_{\text{poll}} - P_{\text{sleep}}) + t_{\text{radio\_setup\_once}}(P_{\text{radio\_setup}} - P_{\text{sleep}}))}{r_{\text{data}}(L_{\text{mfp}} t_{\text{b}})^2 (P_{\text{tx}} - P_{\text{sleep}})}}. \tag{4}$$

It may be noted that since $\hat{N}_{\text{mfp}} \in N$, we take the ceiling value. The expression for the optimum number of microframes is independent of the number of nodes in the network because we consider a congestion free case where all the nodes are able to transmit their queued packets. The network size $n+1$ governs a lower bound, $n \leq (r_{\text{data}} t_{\text{b}} (L_{\text{mfp}} N_{\text{mfp}} + l_{\text{pkt}}))^{-1}$.The optimal sampling time expression is, $S.T._{\text{opt}} = \hat{N}_{\text{mfp}} L_{\text{mfp}} t_{\text{b}}$.

C. Unicast

The total energy consumption of a node for unicast transmission is also expressed by the equation (2). However in the case of unicast transmission, a node happens to be the destination for k packets out of the total n packets it hears from its neighbours. SA-MAC optimizes the preamble length, i.e, the number of microframes to be sent for unicast transmission by using the techniques described in Section III-A. In the best case with perfect knowledge of the neighbour's schedule, only one microframe is needed to be sent. In the absence of any timing information, the number of microframes needed to be sent depends upon the offset between the sleep schedules of the transmitting and receiving nodes. In the worst case, the required number of microframes needed to be sent correspond to the complete periodic channel check interval like the case in broadcast transmission and is given by equation (4). The timing expressions are given as below:

$$\begin{aligned} t_{\text{poll\_period}} &= L_{\text{mfp}} N_{\text{mfp}} t_{\text{b}}. \\ t_{\text{poll}} &= \frac{n_{\text{ch}} t_{\text{poll\_once}}}{t_{\text{poll\_period}}} \\ t_{\text{radio\_setup}} &= \frac{n_{\text{ch}} t_{\text{radio\_setup\_once}}}{t_{\text{poll\_period}}} \\ t_{\text{rx}} &= n r_{\text{data}} (1.5 L_{\text{mfp}} t_{\text{b}}) + k r_{\text{data}} l_{\text{pkt}} t_{\text{b}} + 2 r_{\text{data}} l_{\text{ack}} t_{\text{b}} \\ t_{\text{cs}} &= n_{\text{ch}} r_{\text{data}} (t_{\text{poll\_once}} + t_{\text{radio\_setup}}) \\ t_{\text{tx}} &= r_{\text{data}} (N_{\text{mfp}} L_{\text{mfp}} + l_{\text{pkt}}) t_{\text{b}} + 2 k r_{\text{data}} l_{\text{ack}} t_{\text{b}} \\ t_{\text{sleep}} &= 1 - t_{\text{radio\_setup}} - t_{\text{poll}} - t_{\text{rx}} - t_{\text{cs}} - t_{\text{tx}} \end{aligned}$$

A factor of two appears in the expression for acknowledgement frames because a node needs to send/receive acknowledgement(s) for both MFPs and data frame. In this formulation, only one data frame is considered however, SA-MAC also allows sending multiple data frames with a single preamble reservation. The individual acknowledgements of the data frames need to be included in the model correspondingly. SA-MAC has the intrinsic property to optimize the number of preamble frames needed to be sent/received. However, in the absence of any neighbourhood sleep schedule information, network is designed based on the worst case. Similar to the case of broadcast transmission, in unicast, the network follows a lower bound, $n \leq (r_{\text{data}} t_{\text{b}} (L_{\text{mfp}} N_{\text{mfp}} + l_{\text{pkt}} + 2 l_{\text{ack}})^{-1}$.

V. Prototype Implementation

Our prototype implementation is based on Crossbow's TelosB platform with Texas Instrument's CC2420 radio and MSP430 series microcontroller. CC2420 radio is an IEEE 802.15.4 compliant radio transceiver, which operates in uncoordinated 2.4 GHz ISM band and is prone to interference from commonly used commercial devices and networks, for instance WLANs, Bluetooth, cordless phones, wireless keyboards and projectors, etc. Our test implementation and deployment in realistic scenarios closely highlight the necessity of spectrum sharing and symbiotic coexistence with other networks. We have implemented the MAC protocol in TinyOS 2.x.

VI. Performance Evaluation

We have conducted an extensive performance evaluation of SA-MAC protocol with different parameter settings and under different types of interference conditions. The performance metrics include power consumption, throughput and successful packet delivery ratios under different conditions of traffic loads, number of channels in the pool, sampling periods and radio transmit power levels. The interference effects were studied spatially as well as temporally with varying transmit powers and bandwidth occupation. Furthermore, we have carried out a comparative study against a single channel protocol, B-MAC+ [16], which is the most widely used sensor networking MAC protocol and is the default protocol in TinyOS 2.x for CC2420 radio based platforms. Each experiment was repeated a number of times to obtain better statistical significance.

A. Optimality of Power Consumption: Comparison of Analytical and Empirical Results

In order to validate the analytical model for the optimal power consumption in a given network with a certain traffic load, we carried out power consumption studies. We considered a small non-congested network consisting of only three nodes. One of the nodes is connected to our power consumption measurement setup. The power consumption is based on voltage probing across a small resistor in series to the sensor node using a high end oscilloscope (Agilent's DSO8104A). All the nodes are programmed to use a channel pool size of four, generate broadcast data packets of 100 bytes payload at a rate of 1/16 (0.0625) packets per second and 1/2 (0.5) packets per second at different sampling intervals. Fig. 6 shows the average power consumption for this experiment. It can easily be observed from the figure that at small sampling periods, energy consumption show an increasing trend because of more frequent channel polling operations. On the other hand, the increasing trend in power consumption with higher sampling periods is because of the need to transmit longer preamble sequence. From the figure, it is evident that the optimum sampling period for 1/16 and 1/2 packets per second is obtained at 1 s and 377 ms, respectively.

We measured the power consumption and timing instants for various operations on the TelosB platform as listed in the Table I. In order to verify the analytical model of the MAC protocol as described in Section IV, we put the measured values in optimal sampling time expression. Table II shows the analytical values for the optimum sampling periods of 1.1519 s and 407.2 ms for data packet rates of 1/16 and 1/2,

TABLE I

PARAMETER VALUES MEASURED ON THE TELOSB PLATFORM.

Parameter	*Measured Value*
Power in receive mode (P_{rx})	58.9 mW
Power in channel polling (P_{poll})	58.9 mW
Power in radio setup ($P_{\mathrm{radio\_setup}}$)	10.7 mW
Power in transmit mode (P_{tx})	46.5 mW
Power in sleep mode (P_{sleep})	3.6 mW
Time for one channel polling ($t_{\mathrm{poll\_once}}$)	15.8 ms
Time for once radio setup ($t_{\mathrm{radio\_setup\_once}}$)	2.4 ms
Time to transmit/receive a bit (t_{b})	1/250000 s

respectively. It can easily be shown that our analytical model very closely adheres to the empirical values.

TABLE II

OPTIMAL SAMPLING PERIODS AT DIFFERENT DATA PACKET RATES.

Data packet rate [s^{-1}]	*Optimal sampling period [s]*
0.0625	1.1519
0.5	0.4072

B. Relationship between Power Consumption, Number of Channels and the Sampling Period

In many sensor network applications, the average traffic load is relatively low so that the idle listening power consumption starts to dominate. Idle listening power consumption is the power expended in the channel polling (or LPL) operation when no data packets are exchanged. Since SA-MAC is based on the preamble sampling principle, it does not require the need for any explicit synchronization of the sleep schedule of the node and the only energy consumption cost comes from the channel polling operation when no data is needed to be transmitted/received. Fig. 7 shows the relationship of power consumption during the channel polling (low power listening) with respect to the sampling period and the number of channels in the pool. The plot is obtained based on the formulation described in Section IV using the experimentally measured values as listed in Table I. We also verified a few plotted values for the LPL operation to the empirically obtained values. It can be observed that the power consumption increases

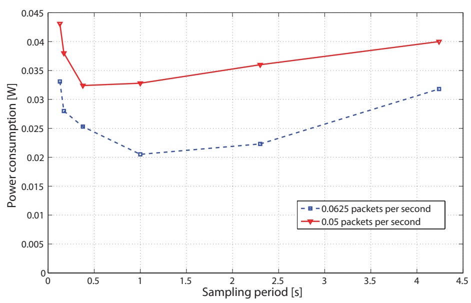


Fig. 6. Power consumption of a node at different sampling periods. In these measurements, a small non-congested network of three TelosB nodes is considered. The nodes use four channels and are in the perfect wireless range of each other with 0dBm of transmit power.

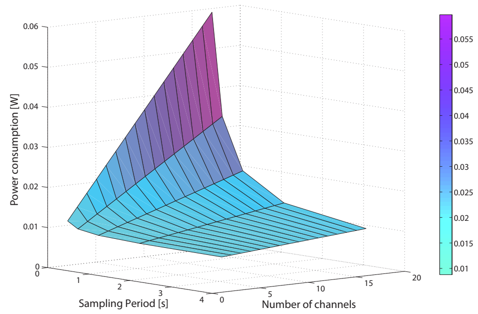


Fig. 7. Relationship of power consumption with the number of channels in the pool and the sampling period on TelosB platform during the low power listening operation.

proportionately with the number of channels, while the power consumption increases exponentially with the sampling period.

C. Throughput and Successful Packet Delivery Ratio Comparisons

A wireless interferer affects the successful packet delivery ratio and the achieved throughput of a MAC protocol. An interferer leads to packet collisions and the need for retransmissions. In CSMA/CA based protocols, the channel unavailability causes congestion backoffs. Thus, besides the successful delivery ratio and throughput degradation, spectral interference also causes increased latency and energy wastage. An interferer is characterized both temporally as well as in spatially. In the following, we describe our experiments for the packet success and delivery ratios of SA-MAC in the presence of interferers of different strengths. We varied the transmit power levels of the nodes and the position of the interferers in order to empirically study the effects of symmetrical as well as asymmetrical interferences. We also conducted similar studies on B-MAC+ protocol running on the same TelosB platform to observe the coexistence behaviour of a single channel protocol. In order to ensure fairness in our experiments, we used the same sampling period, data packet size, radio transmit power and clear channel assessment threshold value on the two protocols. Fig. 8 shows the setup for these experiments. We

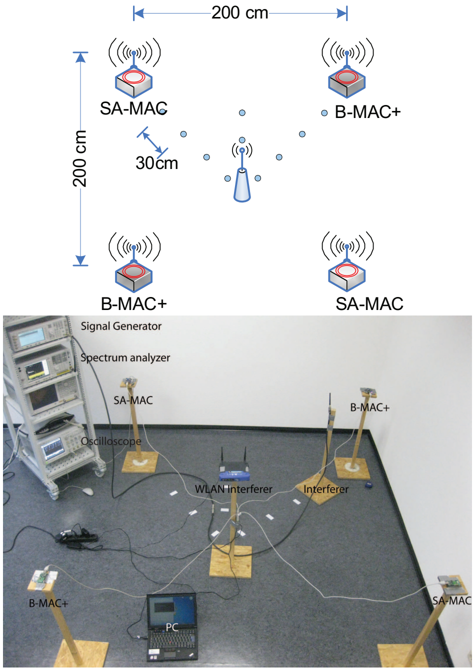


Fig. 8. Experimental setup for studying the co-existence behaviour and performance of B-MAC+ and SA-MAC in the presence of interference. The parameters altered during the experiments include the transmit power of sensor nodes, the spatial position and the strength of the interferer.

used Agilent's E4438C signal generator and a WLAN access point as the interferer sources. We altered the transmit power levels and the location of the interferers to study the behaviour of symmetrical as well as asymmetrical interferences on the throughput and successful packet delivery ratio. We placed the sensor nodes on raised wooden foundations to avoid the grounding effects of the antenna radiation pattern. The sensor nodes were connected to a PC over the USB port, which was used for setting different parameters for nodes and collecting the experimental statistics.

In one of the experiments, we placed the interferer of variable strength in the middle of the square grid as shown in Fig. 8 and measured the throughput and packet successful ratios of SA-MAC and B-MAC+. Both nodes of each of the two MAC protocols transmit a data of 100 bytes at every 500 ms with a radio transmit power of 0 dBm. B-MAC+ channel overlaps with the wide-band interferer while one of the four channels used by SA-MAC is non-overlapping with the interferer.

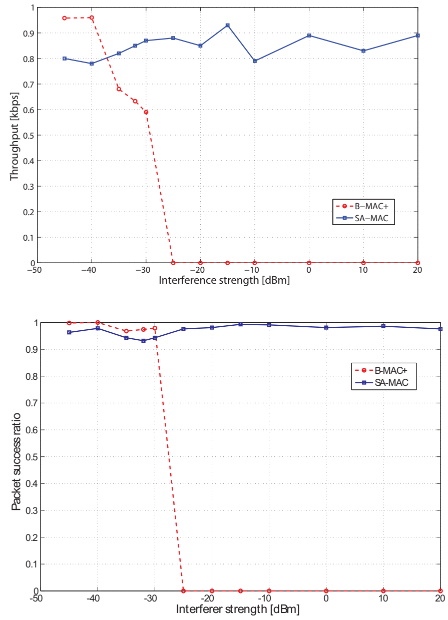
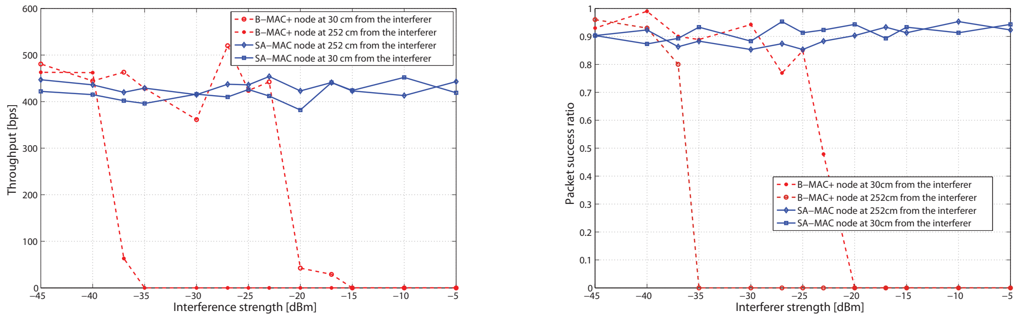


Fig. 9. Aggregate throughput (top) and successful packet delivery ratio (bottom) achieved for B-MAC+ and SA-MAC in the presence of an interferer at equidistant from the nodes. All the nodes transmitted a packet size of 100 bytes at the rate of 0.5 packets/second and operated at a sampling period of 1s with radio transmit power of 0dBm. The two B-MAC+ and SA-MAC nodes were placed at a distance of 282 cm from each other.

It can be seen from Fig. 9 that the aggregate throughput of SA-MAC remains relatively stable over the range of interferer strengths. B-MAC+ on the contrary, shows a gradual degradation until -30 dBm followed by a sharp drop in the throughput. The gradual drop was because of the less reliable carrier sensing of the channel which caused the node to go to sleep without transmitting a packet. At higher interference strengths, B-MAC+ nodes found the channel busy and did not transmit at all. The packet success ratio follows only a sharp drop at -30 dBm for B-MAC+. The reason being that when the B-MAC+ node transmitted a packet at 0 dBm, it was received by the other node with high reliability. Owing to the CSMA/CA nature of the protocol, at higher interference strengths when



(a) Average throughput.

(b) Average successful packet delivery ratio.

Fig. 10. Throughput and successful packet delivery ratio achieved for B-MAC+ and SA-MAC in the presence of an interferer at asymmetrical distance from the nodes. All the nodes used the rate of 0.5 packet/second and operated at the sampling period of 1s with radio transmit power of -15dBm. The two B-MAC+ and SA-MAC nodes were placed at a distance of 282 cm from each other.

the channel was completely jammed, no transmission took place and no energy was wasted in packet collisions. In contrast to B-MAC+, SA-MAC showed a high successful packet delivery ratio throughout because of its ability to dynamically avoid interfering channels. The protocol is based on the preamble sampling principle and the channel weight for each individual channel in the pool is updated each time the LPL operation is performed. The channel which is found to be currently free and has the highest weight is selected for data transmission. Since the channel selection is based on per data transmission basis, SA-MAC effectively deals with random interferences. In our demonstration in ACM's SigComm in August 2009 [12], we showed the dynamic adjustment of channel weights based on the user controlled interference.

In order to study the effect of asymmetrical and spatial interferences, we placed an interferer at a distance of 30 cm from B-MAC+ and SA-MAC nodes. The distance of the other nodes from the interferer was 252 cm in this case. We repeated the experiments as described above with a 100 bytes long packet transmitted every 500 ms. Fig. 10(a) shows the throughput of SA-MAC and B-MAC+. It can be observed that SA-MAC shows a remarkably stable throughput even in the presence of the asymmetric interference. B-MAC+ nodes placed at distances of 30 cm and 252 cm, on the other hand show a sharp drop in the throughput at -37 dBm and -20 dBm, respectively. This is because the node closer to the interferer started to detect the channel busy at much lower interference strength than the node which was further away and hence the node tended to skip packet transmissions. We may observe a very low throughput between -20 dBm and -15 dBm. This is because the transmitter further away from the interferer detected the channel being free during this range and transmitted a packet which got garbled due to the interference and was not correctly recovered at the receiver. In the case of SA-MAC, the channel weighting algorithm automatically assigns lower weights to the interference prone channels which helped it to achieve high throughput and packet success ratios. Fig. 10(b) shows that SA-MAC gave a stable packet delivery rate. Similar to the throughput trends, B-MAC+ experienced sharp degradation in the packet success ratios. It may be noted that between -25 dBm and -15 dBm, B-MAC+ node located at 252 cm from the interferer transmitted many more packets than those delivered.

D. Successful Packet Delivery Rates in Harsh Multi-Channel and Multi-hop Scenarios

In order to study the effects of multihop communication in a network with non-uniform and irregular interference from different sources, we have designed the experimental setup as shown in Fig. 11. We put five SA-MAC nodes in a line and adjust the transmit power level of each node to -15 dBm so that only the adjacent node(s) are in the wireless range of a particular node. Two interferers of strength -25 dBm are placed at the opposite ends of the network. The interferers' frequency and bandwidth are chosen so that they overlap with IEEE 802.15.4 channels, 11 to 13 and 16 to 18, respectively. The SA-MAC channel pool was initialized with consecutive channels from 11 to 18 and the MAC is let to choose the contracted channel pool size of 6, 4, 2 and 1. We developed an application so that a packet of size 50 bytes generated from node A makes multiple hops (order of 2) and comes back to A. In the 2 hop case, the packet generated from A goes to B and then returned back to A. In the four hop case, the packet from A goes to B and then to C. The packet comes back to node A from C via node B. In this way we were able to have multihop scenarios of 2, 4, 6, 8, and 10 hops in the network.

It can be observed from Fig. 12 that as the number of hops increases, the successful packet delivery ratio goes down and as the number of channels in the pool decreases, there

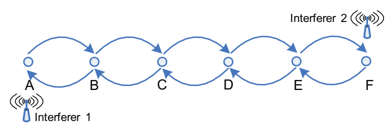


Fig. 11. Experimental setup for measuring the packet success ratio over multiple hops when using different number of channels in the pool and when the network is subjected to different channel interferences across the two ends.

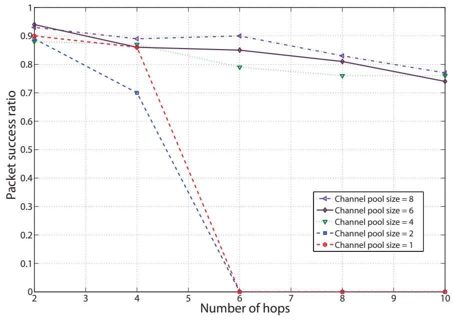


Fig. 12. Packet success ratio over multiple hops in the presence of non-uniform interferences at the two end of the networks. The transmit power of the nodes is set to be -15dBm and packet size used is 50 bytes.

is a decreasing trend in the packet delivery ratio. It is clear that in this harsh scenario for channel pool size of 1 and 2, the network is partitioned and the far end nodes converge to channels which are not common with the other nodes. This causes the success ratio to drastically fall in the cases of channel pool size of 1 and 2 beyond 4 hops. In order to deal with this potential problem, a bit encoded channel-map information (consisting of 1-2 bytes) which is embedded inside the preamble frames so that during the convergence phase, the nodes may also make use of the two hop neighbourhood information. Furthermore, the result shows that SA-MAC works perfectly fine if there exists at least one free channel at a given time. SA-MAC puts no constraint on the permanent availability of the channel as it can dynamically choose the free channel in an opportunistic fashion at the instant when communication is required.

VII. Conclusions

In this paper, we describe in detail the design, implementation and performance evaluation of SA-MAC protocol. Spectrum agility is an important feature for low power embedded wireless networks in order to coexist in the inevitable crowded spectrum. We have shown through prototype implementation that our lightweight distributed channel selection algorithm based on just the local sensing information is realizable on the COTS sensor node platforms. SA-MAC protocol is able to work reliably with a high degree of packet success ratios even in the presence of heavy interferences as confirmed by our experimental results. On the contrary, contemporary solutions running on the same sensor node platform without any spectrum agility features fail to achieve stable throughput in interfering channel conditions. SA-MAC combines together various preamble optimization techniques from different single channel preamble sampling protocols in order to achieve energy efficiency. We have also presented the analytical model of the protocol and derived the expression for optimum energy consumption in a particular network with a given amount of traffic volume. Our analytical expression complies to the empirical results for the optimal energy consumption obtained through our prototype implementation. We have also carried out experiments for asymmetrical interferences in multihop scenarios and have observed that only in acute channel unavailability and permanently polarized interference, the network gets broken. To the best of our knowledge, our effort is one of the first attempts to design, implement and evaluate a spectrum agile MAC protocol for low power embedded sensor networks, which allows sensor nodes to dynamically find interference minimal channels in unregulated crowded frequency bands for establishing reliable communication.

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