Spectrum Aware and Energy Efficient MAC Protocol for Cognitive Radio Sensor Network

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***Abstract*—Dynamic spectrum access in the form of cognitive radio (CR) has gained traction in wireless sensor networks (WSN) because of a) scarcity caused by the proliferation of wireless devices and service and b) it provides spectrum efficient communication for the resource constrained WSNs. However, proper means have to be devised to satisfy the requirements of both WSNs and CRs and to enjoy the benefits of cognition in sensor networks. In this paper, we propose a novel energy-efficient and spectrum aware multi-channel medium access control (MAC) protocol for the underlying cognitive radio enabled sensor network. We designed a spectrum aware multi-channel asynchronous duty cycle approach which caters to the requirements of both the domains. The performance of the proposed MAC is evaluated via simulations. The simulation results are also compared with MCMAC, a multi-channel MAC for WSNs. The comparative results show that the proposed approach outperforms the multi-channel scheme for WSN.**

I. Introduction

Due to recent advancements in micro-electromechanical systems, sensors are becoming tinier and cheaper every day. More importantly, these sensors have the capability to wirelessly communicate with each other. Sensor nodes are deployed to sense the environment which, upon occurrence of an event, generate and forward reports over the network to be received by a sink node.

In addition to that, wireless sensor networks (WSNs) are flexible, fault tolerant, low-cost and can be rapidly deployed. These characteristics of WSNs enable many exciting applications for remote sensing, industrial automation, defense applications and utility metering. For example, some famous defense applications are monitoring friendly forces, battlefield surveillance, battle damage assessment and nuclear, biological and chemical attack detection. Environmental applications of WSNs include chemical and biological detection, as well as tracking the movement of birds, animals and insects. A wide variety of home and commercial applications are available, such as home automation, environmental and traffic monitoring etc.

However, the realization of sensor networks needs to cope with constraints introduced by factors such as link connectivity, limited bandwidth and processing capability. Moreover, the event-driven nature of communication in WSNs generally yields a bursty type of traffic, which results in under-utilization of the transmission medium. Therefore, it is inefficient to use a fixed scheme of channels allocated for these sensor nodes.

Spectrum bands are mostly allocated to fixed services. However, it is shown in [1] that some portions of the bands allocated to fixed services have become very crowded while other portions of the band remain vacant. The under-utilization of the resources generates a need to allocate the available resources more efficiently. Frequency re-use in the form of spectrum sharing can help mitigate the issues such as interference and congestion in bands allocated to fixed services. Research on these issues have led to the development of cognitive radio (CR.

Cognitive radio networks (CRNs) generally comprise primary users (PUs) and secondary users (SUs). PUs have a valid license to use the band and are given priority over SUs which do not have a license to use the band. CR is a technique which senses the spectrum, determines the vacant bands and makes use of the available bands to transmit data. CRs can operate in both licensed and unlicensed spectrum. In the licensed bands, a SU, also called CR user, is given access only when it is not occupied by the Primary User (PU). SUs can access the band as long as they do not interfere with the PUs. The use of cognitive radios in recent communication technologies is motivated by its ability to dynamically access the available bands in the licensed spectrum. This allows the cognitive radio enabled wireless devices to adapt to the spectrum allocation, thereby improving the spectrum utilization.

The use of CR networks (CRNs) in WSNs has led to the emergence of Cognitive Radio Sensor Networks (CRSNs), which is an attempt to combine the favorable characteristics of WSNs and CRNs. As indicated in [2] and [3], cognitive radio enabled wireless sensor networks can help reduce congestion and excessive packet loss, and thereby make transmission more reliable. Enabling sensor nodes with cognition has helped them meet the unique requirements and challenges of WSNs which are traditionally assumed to employ fixed spectrum allocation and characterized by resource constraints in terms of communication and processing capabilities. Sensor nodes enabled with cognitive radios can therefore opportunistically access multiple alternative channels to alleviate these potential challenges.

CRSN is a promising approach for communication, especially in the ISM band, where the radio spectrum is overcrowded. However, the merger of CRNs and WSNsalso introduces a new set of challenges which directly impacts the power consumption level, network and interference faced by the sensor nodes. By introducing an additional constraint of restricted spectrum access, designing energy efficient and spectrum aware MAC for CRSN becomes a challenging task.

It is to be noted that existing WSN schemes cannot simply be used as the CRSN node must now handle additional aspects such as spectrum sensing periods, broadcast over a network-wide common channel, and the need for a high-priority access mechanism for the distribution of spectrum

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sensing and decision results.

On the other hand, hardware constraints and energy considerations inhibit the exploitation of existing CR based schemes in CRSNs. Sensor nodes cannot function as a software-defined radio (SDR) equipped SU nodes because of the power, computation, sensing and accessing constraints inherent in WSNs. Sensing and accessing constraints limit the number of licensed data channels a sensor node can sense and access. In addition, the SUs have to expend more energy in order to search for available data channels. The methods used for the spectrum sensing such as energy detection, matched filter detection and cyclo-stationary feature detection require significant energy for algorithmic computations.

In light of the aforementioned issues, there is a need to design an energy efficient and spectrum aware communication protocol. In this paper, we propose a multi-channel medium access control protocol (CR-WSN MAC) for CRSN which caters to the unique requirements of both WSNs and CRNs. The proposed scheme employs an asynchronous duty cycle approach for channel acquisition and data transmission. CR-WSN MAC is designed to overcome the shortcomings of the existing schemes.

The rest of this paper is organized as follows: Section II reviews the related work. In Section III, a description of the system model is given. Section IV describes the proposed MAC protocol for CRSNs. Simulations results are presented in Section V, followed by the conclusion in Section VI.

II. Related Work

There exist several single channel protocols for WSNs such as [4], [5] and [6], which focus on providing energy efficient schemes for data transmission. However, it is observed that the multi-channel schemes outperform the single channel protocols in terms of communication performance and energy consumption. Since existing single channel schemes do not work well in the multi-channel environment, several multi-channel protocols for WSNs have been proposed in literature. In [7], authors proposed MCMAC and Y-MAC was proposed in [8]. Both, MCMAC and Y-MAC, are synchronous multi-channel protocols which can dynamically assign multiple channels to nodes so that multiple communication links can be used for simultaneous transmissions in the same region.

As mentioned earlier, the stated WSN schemes be exploited as the CRSN node must now handle additional challenges associated with spectrum sensing such as quiet periods, broadcast over a network-wide common channel, and the means to distribute spectrum sensing and decision results.

Similarly, there exist many MAC protocols for CR based networks. For example the authors in [9] proposed an efficient spectrum sensing and access scheme which takes into consideration hardware constraints such as operational limitations of a single radio, partial spectrum sensing, and spectrum aggregation limits. The authors in [10] proposed the C-MAC protocol which gave higher aggregate link throughput and robustness to spectrum change using multiple transceivers.

However, existing schemes for cognitive radio networks have several shortcomings such as idle listening, requirement for multiple transceivers, dependence on network-wide synchronization, and poor performance under bursty traffic in densely deployed networks that render them impractical for CRSNs.

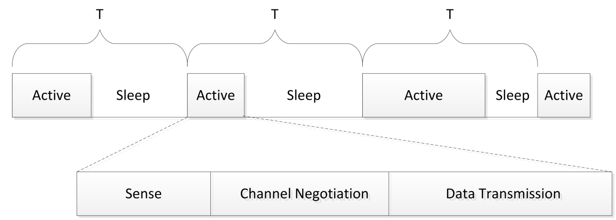


Fig. 1. Cognitive radio sensor node sleep/awake cycle

Recently, studies that combine the wireless sensor networks (WSNs) with CR have attracted a lot of interest. The combination is called cognitive radio sensor network (CRSN) and is defined as a distributed network of wireless cognitive radio sensor nodes that sense an event signal and collaboratively communicate their readings over available spectrum bands in a dynamic, multi-hop manner, ultimately satisfying the application-specific requirements [4].

It is to be noted that the current research in CRSN mostly focuses on designing a conceptual framework for CRSNs. In [2] and [11], a CRSN framework along with its advantages and potential issues is discussed. Energy efficiency and QoS provisioning in CRSNs is studied in [12], [13], [14] and [15]. However, little work has been done on designing energy efficient and spectrum aware MAC protocol for CRSNs.

III. System Model

The proposed system consists of a network comprising primary users (PU), secondary users (SU), data channels and a common control channel (CCC). Each primary user is allocated one licensed (data) channel; therefore, the number of data channels is equal to the number of PUs in the system.

We assume that there are N SUs deployed in the network. Moreover, SUs are equipped with a half-duplex transceiver that switches among $\mathcal{M}$ data channels and a CCC. The SUs can either receive or transmit on the data channel but cannot do both simultaneously. Furthermore, the SUs can transmit or receive on only one data channel at a particular time. Therefore, the SU cannot sense or transmit/receive on another channel if it is currently sensing or transmitting/receiving on a different channel.

In addition to SUs, there also exists $\mathcal{M}$ PUs, which can access the data channels at any time instant. The arrival and departure of the primary users follow an exponential distribution with mean inter-arrival time θ and ϕ, respectively. θ denotes the mean time for the channel states to change from idle to busy whereas ϕ denotes the mean time for the channel states to change from busy to idle.

Data channels, when not occupied by PUs, can be used by the SUs. Secondary users follow an asynchronous sleep/awake cycle. Upon wake up, SU senses the spectrum and prepares a channel availability vector. After channel sensing, the SU listens to the CCC for an incoming request. SU can also send a transmission request to other SUs on the CCC. The subsequent data transmission is carried out on one of the idle data channels which is common to both sender and receiver.

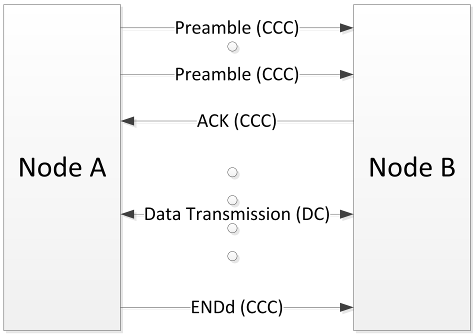


Fig. 2. MAC for cognitive radio sensor network.

The state of the channel can be sensed by each secondary user through channel sensing. We assume that the coverage area of primary users is either comparable or smaller than the secondary users. Therefore, if the secondary user senses a particular channel to be idle, the channel will not necessarily be detected as idle by transceivers of other secondary users.

The proposed CR-WSN MAC protocol employs a CCC where secondary users exchange control information for data channel reservation. The control channel can be either statically assigned or dynamically selected. In this paper, we will not go into details of how the CCC is selected and we only assume that control channel is always reliable and available.

IV. CRSN MAC Protocol Design

In this section, we propose an energy efficient and spectrum aware MAC protocol for CRSN, CR-WSN MAC. The objective of the proposed protocol is to provide an energy efficient communication environment for the resource constrained sensor nodes. Therefore, we propose a duty-cycle based asynchronous multi-channel MAC for the underlying sensor network to improve the energy efficiency. The duty-cycled approach is similar to [5] and [6], which avoids the synchronization overhead and therefore makes the proposed scheme more energy efficient than synchronized MAC protocols such as S-MAC.

Additionally, the proposed protocol sends a series of short preamble packets on CCC instead of an extended preamble, like B-MAC. The short preamble packets carry the address information of the destination node along with channel sensing results. Consequently, non-destination nodes can go to sleep as soon as they hear the first short preamble, instead of remaining awake until the extended preamble ends. Moreover, the destination node can reply with an ACK and channel ID in between two successive short preambles to stop the preamble and start the data transfer on the indicated data channel.

As depicted in Fig. 1, each sensor node follows a sleep/awake cycle and the awake period is further divided into three phases. The three phases are spectrum sensing phase, channel negotiation phase and data transmission phase respectively. The details of each phase is as follows

A. Spectrum Sensing Phase

At the start of the sensing phase, SU senses a subset of the channels and maintains the status of each channel in the subset in a vector. The total number of data channels is divided into m_{sub} unique subsets where each subset has equal number

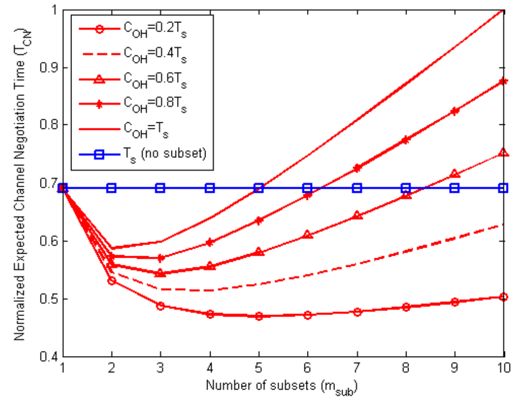


Fig. 3. Comparison of Expected Channel Negotiation Time (T_{CN}) for different number of subsets (m_{sub}).

of channels and all the subsets have different channels. Data channels are sensed in a particular order such that the order of the sensed data channels in channel vector prepared by each SU is the same. The information regarding the number of subsets, m_{sub}, and the elements comprising the subsets is known by the SUs *a priori*.

After sensing the first subset, the SU sets a timer, T_{active}, and listens to CCC for a transmission request from other nodes until the timer expires. If no request is received and the node has no internal data to transmit to other nodes, it sets a sleep timer T_{asleep} and goes to sleep. In this scenario, the node directly enters the sleep phase and duration of both channel negotiation and data transmission phase is zero time units.

B. Channel Negotiation Phase

A different set of actions are followed if the node receives a data request (preamble) from another node before the timer expires (see Fig. 2). It is to be noted that the preamble packets consist of destination ID and channel availability vector. Upon receipt of the preamble packet, receiver chooses one of the data channels common to both transmitter and receiver. Receiving node resets the timer and informs transmitter of the decision by sending an acknowledgment (ACK) over the CCC. The ACK message also contains the ID of the data channel to be used. The data transmission therefore begins on the selected data channel.

However, if the receiver finds that there is no common data channel between the sender and the receiver, it informs the sender by sending an acknowledgment with no channel ID (ANC) over the CCC . Upon sending/receiving an ANC, both the receiver and the sender scan and prepare the channel availability vector for the second sub-set of data channels. Once the scan is complete, sender transmits the channel vector to the receiver over CCC. The receiver compares the two channel vectors and sends an ACK on CCC if a common channel is found. Otherwise, the receiver sends ANC and same steps are followed until a common channel is found.

Assuming that the time required to sense all the data channels is T_s and the control overhead involved in every transmitter-receiver negotiation is C_{OH} then the expected time

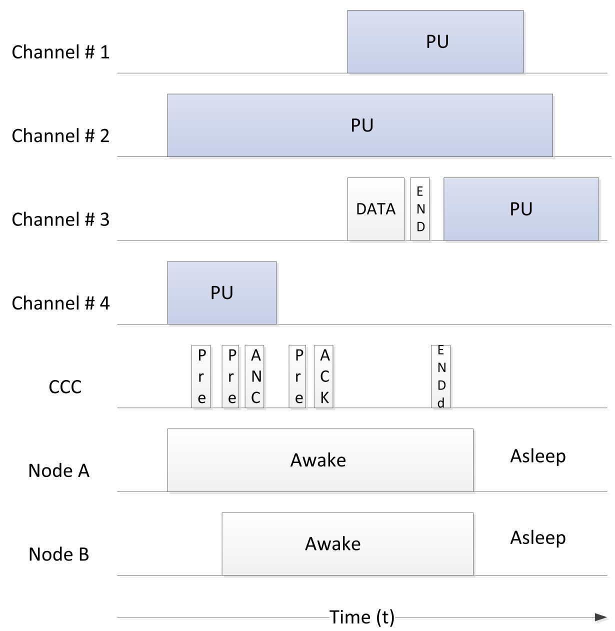


Fig. 4. Timing diagram of CRSN MAC.

for channel negotiation, T_{CN}, can be evaluated as follows:

$$T_{CN} = \sum_{i=1}^{m_{sub}} \frac{i}{m_{sub}^2} T_s + (m_{sub} - 1)C_{OH} \tag{1}$$

It is seen that the expected channel negotiation time, T_{CN}, is smaller than T_s if

$$C_{OH} < \left(T_s - \frac{T_s \sum_{i=1}^{m_{sub}} i}{m_{sub}^2} \right) \times \frac{1}{m_{sub} - 1} \tag{2}$$

Therefore, as depicted in Fig. 3, if the condition in (2) is met then the proposed method of channel sensing will perform better than the schemes which incorporate the channel sensing of all the data channels at the same time.

C. Data Transmission Phase

Transmission on data channel is broken down into intervals of packet transmission and channel sensing. Periodic channel sensing is required to minimize the interference between the PU and SUs. If presence of PU is detected by both the sender and the receiver, the transmission on the particular data channel is terminated and the packet is re-transmitted following the same steps.

Finally, end of transmission (ENDd) is broad-casted over the CCC, therefore all other nodes listening to the CCC update their channel state vector accordingly. ENDd is broad-casted on CCC irrespective of whether the transmission was successful or not. However, ENDd contains an identifier which indicates the latest sensing information obtained by the node pair during transmission on data channel. Fig. 4 depicts communication flow between node A and node B.

In this particular example, there are four data channels and the number of subset m_{sub} is 2. Upon wake-up, Node A senses the first subset, i.e. channels 1 and 2, and starts sending the preamble messages to Node B over the CCC. As soon as node B wakes up, it too senses the channels in the first subset following which it listens to the CCC for data request. Upon receiving a preamble message from Node A, Node B compares the two channel availability vectors to decide on a common data channel. However, in this case Node B does not find a common channel therefore it sends ANC to Node A over CCC. Upon receipt of the ANC, both Node A and Node B sense the channels in the second subset. Node A then sends a preamble message with new sensing results to Node B over CCC. Node B compares the two vectors and sends the ID of the common data channel in an ACK. Both Node A and Node B tune their transceivers accordingly and the data transmission begins on the selected data channel. The end of data transmission ENDd is broadcasted over the CCC.

V. Results

In order to evaluate the performance of the proposed MAC scheme, we compare the simulation results by varying different parameters. In the simulation setup, each node is connected to every other node and for each packet, the sender may randomly select a destination node. The number of sensor nodes N was set to 100 with 1 CCC and 6 data channels. Packet arrival was modeled as a Poisson arrival process with arrival rate $\lambda = 1$. Queue size, Q, was set to be 10 and $\mathcal{M}$ was set to be 6. Parameters defining PU activity, θ and ϕ, were set to be 0.3 and 0.04 respectively.

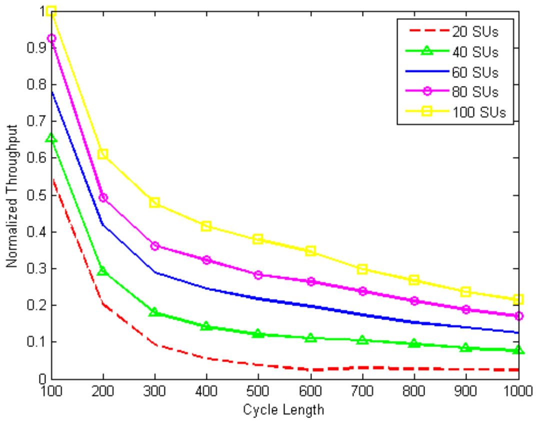
We varied the parameters and obtained the simulation results for throughput, delay and average energy consumption for the proposed MAC protocol.

Figs. 5-7 depict the effect of varying cycle length T and packet size T_d on throughput, energy dissipation and packet transmission delay of the proposed system. Fig. 8, on the other hand, compares the performance of the CR-WSN, in terms of throughput and energy, with a multi-channel MAC for WSN (MCMAC) [7].

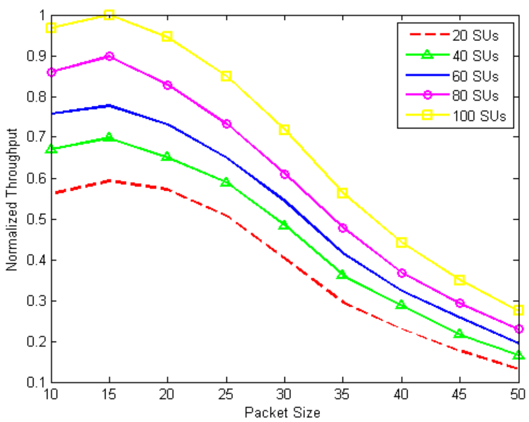
We chose MCMAC as a reference as it is also a multi-channel protocol which requires only one transceiver per node. Therefore, MCMAC serves as a good benchmark for performance comparison.

Figs. 5a shows the throughput of the system for varying cycle length T. It can be seen that the throughput of the system per cycle decreases with an increase in cycle length. This trend can be explained by the fact that since node transmits at most one packet per cycle, the useful information per cycle decreases with an increase in cycle length. Therefore, the throughput of the system decreases.

It can be also be seen in Fig. 5a that the system with smaller cycle length performs better when the network size is large and the performance degrades with a decrease in network size. However, the difference in performance of different networks becomes smaller with an increase in cycle length. It is to be noted that when cycle length is small, more nodes are awake and have more data to send. Therefore, with an increase in network size, more nodes have data to send which increases overall throughput of the system. However, as the cycle length increases, more nodes are asleep which reduces the effective throughput per cycle; therefore, the throughput performance of different sized networks becomes more closely spaced for larger cycle length.

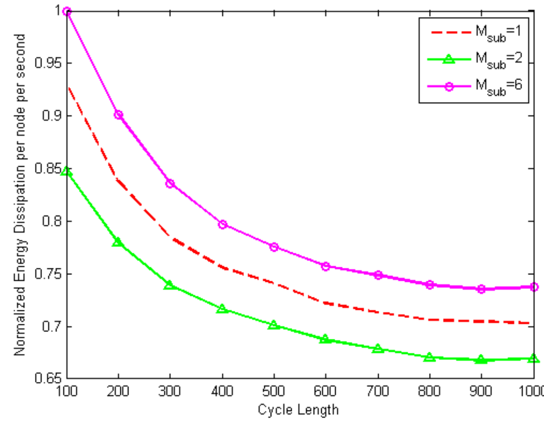


(a) Throughput vs cycle length.

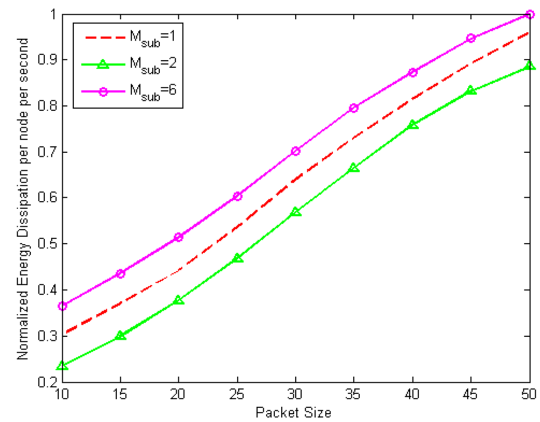


(b) Throughput vs packet size.

Fig. 5. Throughput for varying parameters.



(a) Energy dissipation vs cycle length.



(b) Energy dissipation vs packet size.

Fig. 6. Normalized energy dissipation per second for varying parameters.

Fig. 5b shows the throughput for varying packet size with fixed cycle length. As can be seen in the figure, the throughput initially increases for first few values of packet size but it then decreases with an increase in packet size. An increase in throughput for the first few values of the packet size is due to an increase in useful information per cycle. However, the drop in throughput with an increase in packet size is due to an increase in number of collisions between primary and secondary users. As the packet size increases, there are more chances of a PU interrupting the on-going transmission between the two secondary users. In this figure too, it can be seen that larger networks perform better than smaller networks. As the network size increases, more nodes have data to send which increases the aggregate throughput of the system.

Fig. 6a shows the performance of the system in terms of energy per second for varying cycle length. It can be seen that the energy dissipation decreases with an increase in cycle length. Even though energy consumed in data transmission increases with an increase in cycle length, however energy is saved by non-destination nodes, which sleep for a longer time with an increase in cycle length. This figure also depicts the energy dissipation over time for different values of M_{sub}. It can be seen that the system with $M_{sub} = 2$ outperforms other systems as it saves energy by sensing a subset. However, $M_{sub} = 1$ outperforms the system with $M_{sub} = 6$ because the control overhead incurred in this case is more than the reduction in sensing overhead.

Fig. 6b shows the energy dissipated per second for different the packet sizes. As seen from the figure, energy dissipation increases as the packet size. Energy dissipation increases due to an increase in data transmission per cycle. In this figure too, it can be seen that the system with 2 subsets outperform the systems with 1 and 6 subsets.

Fig. 7 depicts the delay performance of the system with respect to increasing cycle length. It can be seen that the delay increases with an increase in the cycle length. As the cycle length increases, both the queuing and contention delays also increase and the packet has to wait longer, which causes an overall increase in packet transmission delay.

Fig. 8a compares the performance, in terms of throughput, of CR-WSN MAC against MCMAC. It can be seen that MCMAC performs slightly better than CR-WSN when the network size is small. However, the performance of MCMAC degrades, compared to CR-WSN MAC, with an increase in the network size. Since more nodes have data packets to send, the performance improvement per step decreases in MCMAC due to congestion, packet loss and unavailability of the data channels. On the other hand, with an increase in network size,

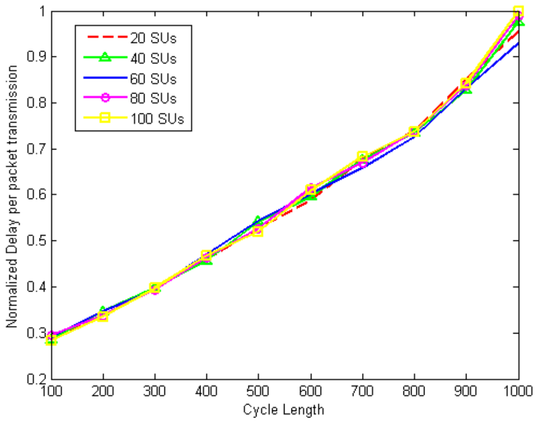
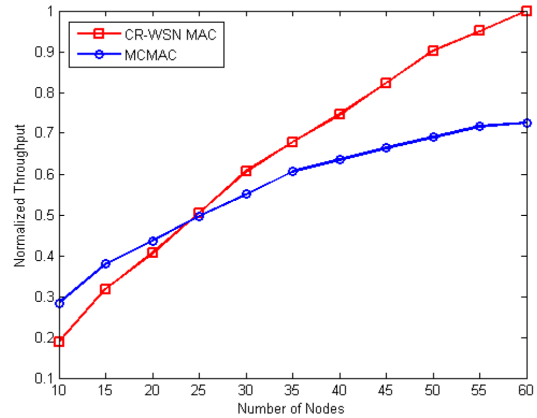
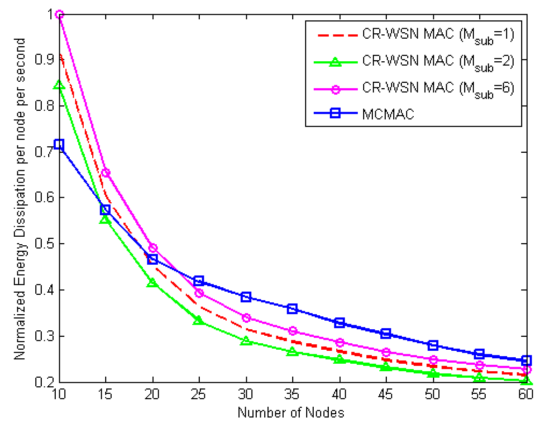


Fig. 7. Normalized delay for varying cycle length.



(a) Throughput vs network size.



(b) Energy vs network size.

Fig. 8. Performance comparison of CR-WSN MAC with MCMAC.

the throughput performance of CR-WSN MAC improves as the use of CRs in the WSN helps to reduce congestion and excessive packet loss. Lastly, Fig. 8b depicts the performance comparison in terms of energy dissipation between CR-WSN MAC and MCMAC. It can be seen that the energy dissipated per node decreases with an increase in the network size. With an increase in network size, more nodes go back to sleep as they fail to get access to media, therefore spending less energy. However, CR-WSN MAC performs better than MCMAC as more energy is spent in MCMAC during the synchronization phase of the protocol.

VI. Conclusion and Future Work

In this paper, we proposed a multi-channel MAC scheme for CRSNs. We analyzed the performance of the proposed scheme via simulations. We also compared the performance of CR-WSN MAC with MCMAC and it was seen that the proposed protocol outperforms MCMAC.

In future work, we intend to incorporate co-operative sensing in the proposed scheme. As seen earlier, spectrum sensing can effect the performance of the system. In the proposed scheme, we divided the channels into subsets which reduced the overall energy consumption of the system. Based on this, we intend to extend the proposed scheme to support co-operative sensing, which may further improve the performance of the system in terms of reliability and network lifetime.

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