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An Energy-Efficient MAC Protocol for Cognitive Radio Sensor Networks

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Advisor: Prof. Sangman Moh, Ph.D.

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Acronyms

CRSN	Cognitive Radio Sensor Network
WSN	Wireless Sensor Network
PU	Primary User
SU	Secondary User
i.i.d.	Independent and Identically Distributed
RTS	Request To Send
CTS	Clear To Send
ACK	Acknowledgement
SDR	Software Defined Radio
EE-MAC	Energy-Efficient Medium Access Control

Abstract

An Energy- Efficient MAC Protocol for Cognitive Radio Sensor Networks

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The increase of application areas in wireless sensor networks (WSNs) demands novel solutions in terms of energy consumption and radio frequency management. Cognitive radio sensor networks (CRSNs) are the key technique for ensuring the efficient spectrum management, which facilitate to use the unused licensed frequency spectrum together with the unlicensed frequency spectrum. In WSNs, the sensor nodes powered by energy-constrained batteries necessarily require energy-efficient protocols at routing and medium access control (MAC) layers. In CRSNs, energy efficiency is more important because of the overhead of energy for spectrum sensing and management due to addition of cognitive radio technology. In this paper, an energy-efficient MAC (EE-MAC) protocol for CRSNs is proposed, in which energy is significantly saved by mitigating collision and interference, shortening adaptive sensing time, and reducing retransmissions. The number of retransmissions is reduced by utilizing reliable channels. According to our simulation results, the proposed EE-MAC outperforms the conventional protocols in terms of network lifetime, packet delivery ratio, and energy efficiency.

한글요약

인지 무선 센서 네트워크를위한 에너지 효율적인 mac 프로토콜

대학원, 조선대학교

무선 센서 네트워크(WSN)의 응용 분야가 증가함에 따라 에너지 소비 및 무선 주파수 관리 측면에서 새로운 해결책이 요구되고 있다. 인지 무선 센서 네트워크(CRSN)는 사용하지 않는 면허 주파수 대역을 비면허 주파수 대역과 함께 사용하도록 지원하는 효율적인 주파수 관리를 보장하는 핵심 기술이다. WSN 에서 에너지 절약형 배터리로 구동되는 센서 노드는 라우팅 및 매체 접근 제어(MAC) 계층에서 에너지 효율적인 프로토콜을 필요로 한다. CRSN 에서 에너지 효율은 인지 무선 기술의 추가로 인해 스펙트럼 감지 및 관리에 필요한 에너지 오버헤드 때문에 더욱 중요하게 된다. 본 논문에서는 충돌 및 간섭을 완화하고 적응적으로 감지 시간을 단축하며 패킷 재전송을 줄임으로써 에너지를 크게 절약할 수 있는 CRSN 을 위한 에너지 효율적인 MAC 프로토콜(EE-MAC)을 제안한다. EE-MAC 에서 재전송 수는 신뢰할 수 있는 채널을 활용함으로써 감소하게 된다. 시뮬레이션 결과에 따르면, 제안한 EE-MAC 은 네트워크 수명, 패킷 전달률 및 에너지 효율성 면에서 기존 프로토콜보다 우수한 성능을 보인다.

1. Introduction

The micro-electro mechanical system (MEMS) technology has flourished the manufacturing process of smart wireless sensor nodes in a massive amount [1]. This phenomenon is not so expensive at the moment. Needless to mention, there are wide range of application areas where wireless sensor networks (WSNs) are deployed in order to achieve different objectives. For instance, in military field, enemy's movement monitoring, target detection, nuclear and chemical attack detection can be performed by using sensors which, in turn, helps for taking immediate action accordingly [2]. In smart grid applications, the sensor nodes deployed in different parts of the electrical grid could enhance smart metering and distributed automation [3]. Likewise, flood and fire detection in environmental application area [4] and sensor nodes used in many electronic home appliances, such as microwave ovens, vacuum cleaners, rice cookers, and refrigerators to interact each other, reflects the overwhelming deployments of the sensor networks in our surroundings [5].

However, the existing WSNs operate on unlicensed industrial, scientific, and medical (ISM) bands that are becoming more overcrowded every day, since these bands are shared with other wireless applications. Meanwhile, the licensed bands are not efficiently used, thus leading to a serious imbalance in radio spectrum use. Thus, the need for spectrum management in addition to the conventional energy efficient mechanism is realized. Cognitive radio (CR) technology serves the spectrum management task for WSNs, which offers the opportunity to access licensed spectrum band when they are not in use [6]. The spectrum management process is facilitated by different four distinct steps, which involve spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility [7]. Spectrum sensing is responsible to monitor available spectrum bands, capture their information, and then discover the vacant spectrum band whereas spectrum sharing is the process of allocating the monitored vacant spectrum bands. Spectrum sharing shares the information about the channels such that the neighboring nodes will not use the same band. In addition, spectrum mobility refers to the mechanism, which vacates the licensed spectrum band if there is an arrival of licensed user for its own communication.

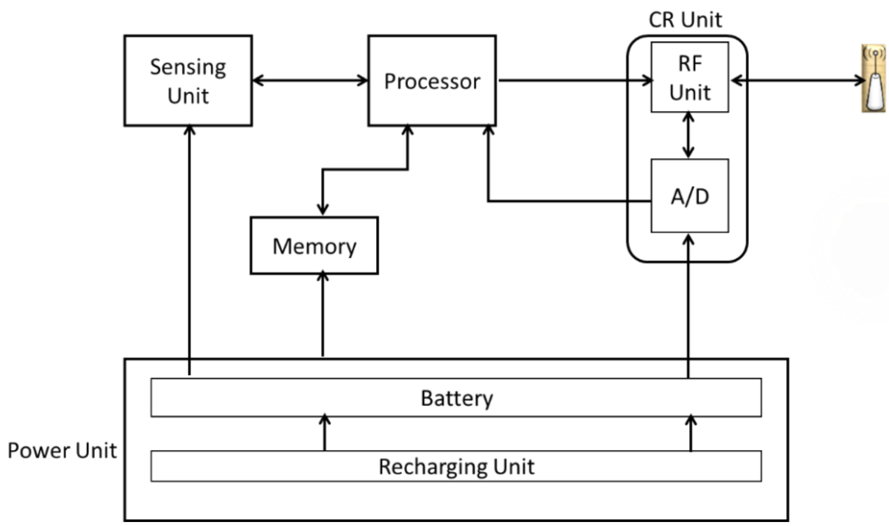

Figure 1. CRSN node architecture

The node structure in cognitive radio sensor networks (CRSNs) is illustrated in Figure 1. The CRSN node has an extra unit, that is, cognitive radio transceiver. This cognitive radio transceiver has the characteristics to adapt the parameters such as carrier frequency, transmission power and modulation in order to perform the cognitive task.

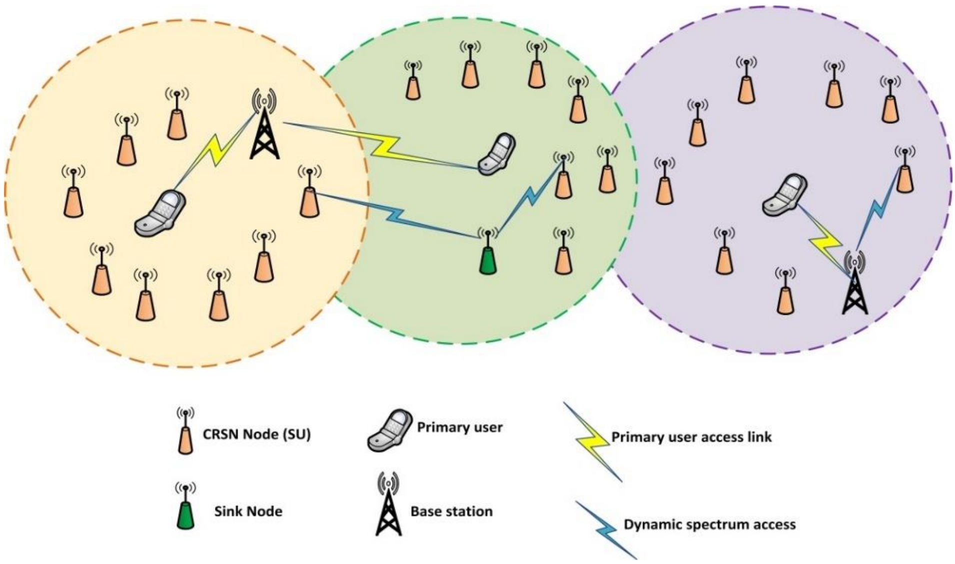

Figure 2. A typical architecture of CRSNs

Figure 2 depicts the typical CRSN architecture. In this architecture, the readings of the sensor nodes are transmitted to the sink in such a way that sensor nodes transmit their readings to the next hops in an opportunistic manner, and eventually, to the sink [8]. In addition to the opportunistic use of licensed spectrum, CRSN nodes can utilize the unlicensed industrial, scientific, and medical (ISM) bands as well without impeding the communication among primary users (PUs).During the period when the CRSN uses the licensed spectrum opportunistically, the CRSN nodes vacates the licensed channel if the PU needs that channel for communication ensuring minimum or no interference for the PU communication.

The traffic of WSN nodes is generally bursty and the nodes are densely deployed. Therefore, the conventional WSNs incur high congestion and collision, which significantly decreases the network performance while increasing the power consumption. Generally, charging those WSN nodes deployed in a difficult terrain is either very costly or inconvenient. The dynamic spectrum access (DSA) feature is the key mechanism that facilitates CRSN nodes to use multiple available channels opportunistically to reduce collision rates and the congestion. Moreover, CRSNs have the capability of adapting to various channel conditions by changing their operational parameters, which ensures higher transmission efficiency by reducing the required reception and transmission energy. In the contrary, unlike conventional WSNs, CRSNs hold the responsibility to protect the licensed user's communication from the interference of CRSNs.

1.1 Research Objective

The major objective of this research is to propose the state-of-art MAC protocol for CRSNs and identify potentials for improvements. We also aim to suggest and evaluate a novel design that can improve the overall network performance including energy consumption. The focus of the proposed protocol is mainly on minimizing adaptive spectrum sensing time and reducing collision and interference with the reliable channel selection algorithm to enhance energy efficiency.

1.2 Contribution

In this thesis, an energy-efficient MAC (EE-MAC) protocol for CRSNs is proposed, which chooses a reliable channel among multiple unused licensed channels via a simple selection algorithm based on channel weight calculation. Because the reliable channel is chosen, the number of retransmissions is decreased and thus energy consumption is significantly reduced. On the other hand, a dedicated control channel called common control channel (CCC) is used not only to mitigate collision between a control frame and data frames but also to allow the parallel transmission of a control frame and a data frame. The less number of collisions reduces energy consumption additionally. Even though CCC id separated from data channels, a single transceiver is used for the reduction of cost and energy. The sensing interval of each channel is adaptively set, which mitigates unnecessary sensing and provides more opportunities for transmission. It is clearly shown from the performance evaluation results that the proposed EE_MAC outperforms the conventional protocol in terms of network lifetime, packet delivery ratio and energy efficiency.

1.3 Thesis Layout

The rest of the thesis is organized as follows: The related works for energy-efficient approaches of MAC protocols for CRSNs are analyzed along with open issues and challenges in Chapter 2. This is followed by the network model in Chapter 3. The proposed protocol is presented in Chapter 4 where the principle and operation of the protocol are explained including sensing time adaption procedure, PU activity modeling, and reliable channel selection mechanism. The performance of the proposed EE-MAC is evaluated via ns-2 simulation and compared to the conventional protocol in Chapter 5. Finally, the conclusion and possible future work are covered in Chapter 6.

2. Related Works

In this chapter, the key issues in the energy-efficient design of a MAC protocol for CRSNs are discussed, and the existing MAC protocols are reviewed and compared with each other.

2.1 MAC Design Issues for CRSNs

There are several issues in the design of MAC protocol for CRSNs, which are inherited from both conventional WSNs and cognitive radio technology. The researchers should tackle on the below- mentioned challenges in order to design a MAC protocol for CRSNs:

2.1.1 *Primary activity model:* The arrival and departure of the PU is different for various location areas and time. For instance, in urban area, the licensed channels may have greater occupancy rate whereas in the remote-village area this occupancy will be less. Likewise, in urban area this occupancy rate will be even more during the day-time as compared to the midnight. The spectrum management as well as the energy efficiency is more effective only if the modeling scheme is deemed wisely.

2.1.2 *Efficient Sensing time:* The longer the sensing time for the particular channel, better will be the accuracy for detecting the PU. Thus false alarm probability and the missed detection are greatly minimized. However, the longer time in sensing costs more energy consumption. This analysis of this tradeoff between sensing interval and the sensing accuracy is of paramount importance in order to find the optimal sensing interval.

2.1.3 *Spectrum heterogeneity:* The availability of spectrum bands in cognitive radio varies with time due to uncertain activity of the PU. In addition, different nodes within a network may not have the same available channels. This will directly affect in the channel assignment mechanism. The spectrum heterogeneity of cognitive radio channels therefore need to address not only the traditional spectrum heterogeneity which is inherited by its nature (because of the environment conditions such as interference) but also the variation due to the PU activities which eventually plays pivotal role to increase energy efficiency during the design of MAC protocol. Prediction model, database information, periodic sensing are some of the approach for the dynamic channel assignment procedure.

2.1.4 *Number of Radios*: For an efficient design of a MAC protocol for CRSNs, the number of radios in the sensor node is an important consideration. The whole design process is affected by this number. The implementation of single-radio nodes is quite popular in conventional WSNs, where the main objective is saving energy. In addition, lowering costs and hardware design complexity results in more promising protocols for sensor networks. Two or more radios can be used to make the design of MAC protocols simpler because of the significant features they enable, particularly tuning and accessing different channels simultaneously. These capabilities help the CRSN avoid collisions with PUs and the multichannel hidden terminal problem.

2.1.5 *Number of Transmission Channels:* The selection of the number of transmission channels between pairing nodes in CRSNs determines the design of the MAC protocol. Data can be transmitted using a single channel or multiple channels. In a single-channel scheme, the communicating CRSN pair uses a single channel for data transmission, which eliminates the requirement of reserving more spectrum resources, which in turn makes transmission less complex. In multichannel schemes, two or more channels are used for data transmission between pairing nodes. A scheme that uses multichannel transmissions with a single radio is better in terms of the hardware costs and energy requirements however, the design process becomes more complex. Such a scheme can be implemented using either the channel aggregation or the channel bonding techniques [27].

2.1.6 *Common Control Channel:* Common control channel plays a pivotal role in the design of efficient MAC protocols. In CRSNs, a larger number of exchanges of control messages are required than in conventional multichannel WSNs, in which they are sent over a common control channel. This method is very effective when there is an absence of central network entity for the management. Network initialization, nodes negotiation, reporting of available channels and neighbors list are some of the important functions that are carried out in the control channel [26]. By using the separate control channel for the control packets only, it greatly reduces the collision among the traffic packets and consequently enhances the network performance along with energy efficiency. However, for a large network, it may suffer from the saturation and the DoS (Denial of Service) attack. Moreover, the channels dedicated just for the control packet is a resource constraint approach.

2.1.7 *Security*: PU Emulation and the DoS are the possible attacks in cognitive radio [25, 29]. Some of the cryptographic security methods are proposed in this regard [30]. As, the nodes in CRSN are resource and power constraint, the overhead of this cryptographic security algorithm, which leads to a higher energy consumption should be analyzed wisely.

2.1.8 Cross-layer Design: Generally, in TCP/IP networks, each layer is designed in such a way that there is only a limited interface that connects it to the immediate upper or lower layer. Cross-layering is a technique in which certain parameters from two or more layers can be borrowed or merged as per the requirements of the specific application area and this approach can increase power efficiency in WSN communications. However, these approaches used in conventional WSNs cannot be directly adapted for CRSNs. There have also been some cross-layer designs for cognitive radio, which mainly focuses on increasing throughput and delay while energy efficiency is not considered. To the best of our knowledge, until now, there is not a significant number of cross-layer designs for MAC protocols in existing CRSNs

2.2 MAC Protocols for CRSNs

A number of MAC protocols have been designed and developed for CRSNs not only for preserving valuable energy but also for improving network performance.

2.2.1 Energy-Efficient Cognitive Radio MAC Protocol for Battlefield Communications [9]

This is the MAC protocol is aimed at preserving essential energy in sensor nodes deployed to form a cognitive radio sensor network. It exploits the concepts of multichannel communication coupled with time division multiple access (TDMA) to ensure traffic balancing and efficient channel use. This protocol achieves significant savings in power by employing a sleep-wake strategy wherein the nodes that are not communicating are put into a doze mode.

More importantly, frame length varies dynamically as per the number of nodes to achieve an improved network performance. The protocol provides strong criteria for determining how each of the secondary users chooses the appropriate channel at the appropriate time. It is a multichannel MAC protocol with dynamic channel selection making sure that communication among PUs is not hindered. This is achieved by dividing the system time into fixed time intervals as shown in Fig. 3. Each time window is allocated for a certain purpose, and this process has been rightly named as the channel-slot aggregation technique. A communication segment is allocated for each channel and time slot, denoted by the pair (l, t), where l is the channel and t is the time slot. A communication segment can be occupied, free or tentatively assigned based on the status of the channel involved (whether it is in use, free or is likely to be used in the next segment). In fact, the proposed MAC structure consists of four main windows, namely the beacon window, the sensing window, the AITM window, and the communication window. A periodic beacon signal is broadcasted during the beacon window to ensure synchronization of all CR users. Moreover, during the sensing window, a thorough channel sensing process is performed in order to survey the channels and find spectrum opportunities. During an AITM window, all CR users tune to their radio interfaces and exchange communication control messages for resource allocation. Finally, during the communication window, CR users perform communication through the selected channels. The beauty of this diversity technique lies in the fact that the CR nodes set the upper-bounded transmit power for each available channel based on their characteristics, ultimately contributing to energy efficiency. Additionally, it contributes in elimination contention among nodes and in decomposing traffic among multiple channels.

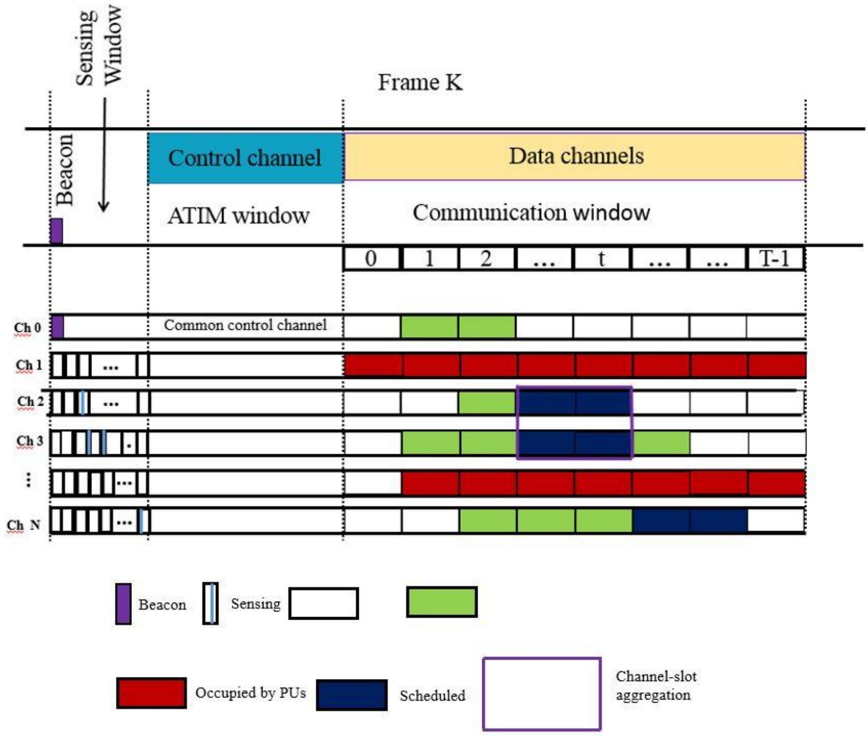

Figure 3. Frame structure of the energy-efficient cognitive radio MAC protocol for battlefield communications

2.2.2 ENC-MAC: Energy-efficient Non-Overlapping Channel MAC for Cognitive Radio enabled Sensor Networks [10]

The ENC-MAC protocol uses two half-duplex transceivers; one is for control messages and the other one is for data. In Fig. 4, a complete time structure of this protocol is presented.

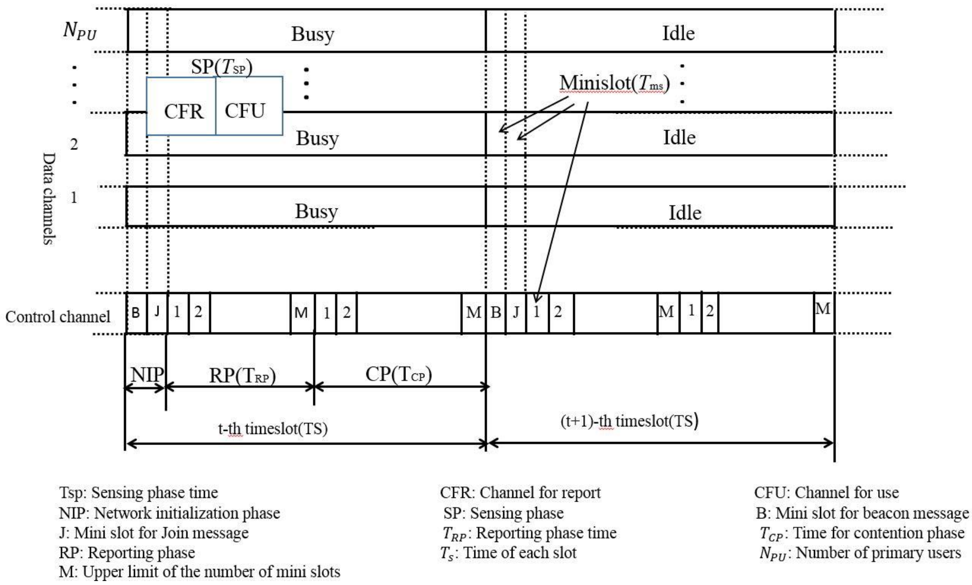

Figure 4. Operation of the ENC-MAC protocol

The operation of the ENC-MAC protocol can be explained in four distinct phases: the initialization phase, the sensing phase, the reporting phase, and the contention and data transmission phase. During the initialization phase, the synchronization of a new SU is done by using a beacon message. The beacon message can be obtained from the existing master SU. If there is no master SU, then the new SU becomes the master SU and sends its beacon message to the other nodes along with a timestamp. Then the SU node competes for control of the channel to join during a J mini slot, which follows an 802.11 DCF back-off mechanism. After gaining access to the control channel, the master SU broadcasts a message on it using a J mini slot. The channel for report (CFR) is known to the SU and records the SUs identifier list. The SU index is maintained by listening to the exchange of join messages and during the reporting phase. In case of failure of the master SU, the SU having the lowest index value will act as a master SU and transmit beacon messages to other nodes. During the reporting phase, the nodes cooperate by sharing information obtained by sensing about the states of channels. This information is conveyed in the report messages, which contains three fields: index of SU (to identify the SU), CFR (for reporting on the data channel of that SU) and result (either idle or busy). The SU, after receiving the report message, updates the ACL. The contention phase involves the channel reservation process, which also deals with control message collisions. For this purpose, there is an exchange of request-to-send (RTS) and clear-to-send (CTS) messages with a specified back off time (the same one as in the 802.11 DCF protocol). This process is carried out at the beginning of each slot. However, a modification is done on these messages by adding the CFU field. This CFU field facilitates the reservation of the CFU between the sender and the receiver. The other nodes overhear the RTS/CTS exchange and update their channel vectors accordingly to avoid multichannel hidden problem. Then, when sensing during the second mini slot of the following timeslot of the sensing phase, the winner SU senses the channel for use (CFU) in order to guarantee that the channel will still be available in the next slot.

2.2.3 ECR-MAC: An Energy-Efficient and Receiver-Based MAC Protocol for CRSNs in Smart Grids [11]

This is a receiver-based ad-hoc MAC protocol, which employs preamble sampling and next-hop competition based on transmission energy consumption. It exploits the broadcast nature of the wireless medium and adopts an auction mechanism with multiple receivers. No particular node is selected as the receiver node. The sender node broadcasts the data packet, the receiving nodes compete in an auction process, and the winner forwards the data to the next hop towards the gateway. In this auction mechanism, each node makes an offer by showing the energy required for a single-hop operation. When an offer is published, other nodes compare this energy requirement with its own. If the existing offer is better than its own, the node simply does not try to compete. Otherwise, it presents its offer of a lower energy requirement. The node making the best offer will be the winner and thus forward the data. Therefore, this process describes how the receiver with highest energy efficiency wins and forwards the data. In addition, the preamble approach is used, which ensures higher energy efficiency. This is an approach in which each node performs asynchronous low power listening; nodes are capable of scheduling their own sleep/active cycle individually. Nodes sleep most of the time and switch to active mode after each checking interval (CI). In addition, each node is awake for a short period of time (Clear Channel Assignment-CCA) while in active mode. The longer the preamble transmission from the sender is compared with the CI before the data packet is sent reduces the number of missed detections of the preamble. In addition, this facilitates achieving lower duty cycles (less than 1%) without using scheduling or synchronization methods just by tuning the CI and CCA.

2.2.4 A Cluster-based Energy-Efficient MAC Protocol for Multi-hop Cognitive Radio Sensor Networks [12]

The cluster-based energy-efficient MAC protocol (KoN-MAC) was designed to allow nodes in multi-hop networks to select interference free channels dynamically. The main concept of KoN-MAC is that a node can determine available channels just from sensing a subset of the available channels rather than sensing all the channels. This subset of channels is the polled-channel set. Within the cluster of sensor nodes, a certain node will be selected as the cluster head (CH), and the gateway nodes (CG) will conduct communication between adjacent nodes. In addition, the remaining nodes are considered as cluster members (CM).

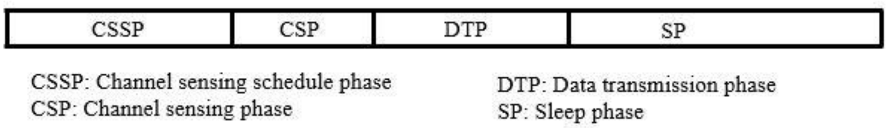

Figure 5. Superframe structure of the KoN-MAC

This cluster-based MAC Protocol, being a scheduled-based MAC- Protocol, uses four separate phases that comprise the superframe interval: the channel sensing schedule phase (CSSP), channel schedule phase (CSP), data transmission phase (DTP), and sleep phase (SP). These phases are shown in Fig. 5. The CSSP has two kinds of slots: transmission slots and channel-sensing slots. The CH uses the transmission slot to transmit its own channel weight table to the rest of the nodes of the cluster. On the other hand, the channel sensing slots are used for cooperative sensing. Therefore, in each cluster, the CH holds the results sensed by the nodes and cooperative sensing is achieved using a data fusion method. On the other hand, the CSP is the phase in which channel allocation for the cluster member nodes of a cluster is carried out. Data transmission slots are also allocated in this phase. During the DTP phase, the members of a cluster transmit data in their assigned slot.

Now, in this Section, the challenges related to multichannel access, multi-hop networks and cognitive radio technology will be clearly explained, and an idea for overcoming them, proposed by the author, is presented. The main issues with multichannel access are the traditional hidden and exposed terminal problems combined with the multi-channel hidden terminal problem. This is simply because a single half-duplex transceiver in a sensor node can either transmit or receive the packet at a given time on the control channel or the data channel. In addition, the performance of any wireless network decreases as the number of nodes increases. Finally, the challenge of cooperative sensing, information of PUs, dynamic channel selection and channel switching mechanisms also arise when considering cognitive radio technology. Aside from this, the KoN-MAC protocol also deals with the sleep/active mechanism for saving energy in each node. According to the author, two-hop neighbor nodes are responsible for the multi-channel hidden terminal problem (which occurs when the same channel is selected by two neighboring nodes). While in this cluster-based structure, two-hop neighbors may be within the same cluster or in adjacent clusters. If they are within the same cluster, the CH schedules communication. If they are in adjacent clusters, they tend to select different channels and hence the probability of having multi-channel hidden terminal problems decreases. Likewise, to enhance channel selection accuracy of channel, and that SUs have different probabilities to use different channels in the presence of PUs, the concept of channel weight is used. Channel weight is used to distinguish the channels from each other and ensures that nodes select the best channel based on the information available on channel weight. Every node will maintain its own channel weight table, which consists of different states (i.e., idle, busy, communication, and collision). Nodes will update their channel weight table immediately after sensing. A channel is idle if the SUs find the channel available for access, whereas it is considered as busy if the SUs detect the presence of PUs in that particular channel. These channel states will be determined in the CSSP, whereas collisions and communication happen in the DTP. Successful transmission of data on a channel by SUs is referred to as communication and the arrival of PUs or SUs while an SU is transmitting is considered a collision.

2.2.5 CR-WSN MAC: An Energy-Efficient and Spectrum-Aware MAC Protocol for CRSNs [13]

This is yet another energy-efficient MAC protocol for CRSN. Since there is no synchronization overhead, it has been claimed that this MAC protocol is more energy-efficient than synchronized ones. In this protocol, the coverage area of PUs is assumed to be smaller than that of SUs, and that SUs use a dedicated common control channel for the exchange of channel reservation data. The preamble packets sent on the CCC are short and multiple in number. Since this short preamble contains the address of the destination node and the channel sensing results, it enables non-destination nodes to go into sleep mode after hearing only the first preamble, rather than having to wait for an extended preamble.

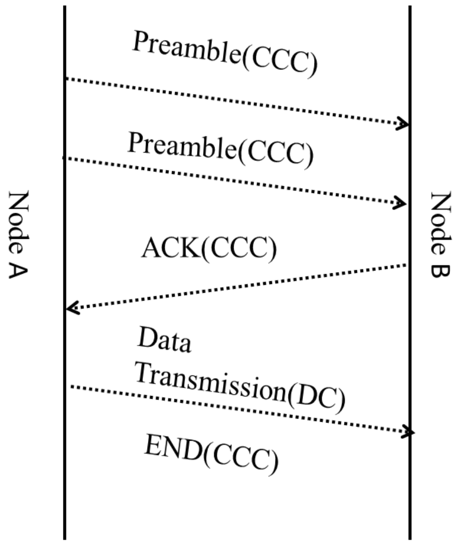

Figure 6. Operation of the CR-WSN MAC protocol

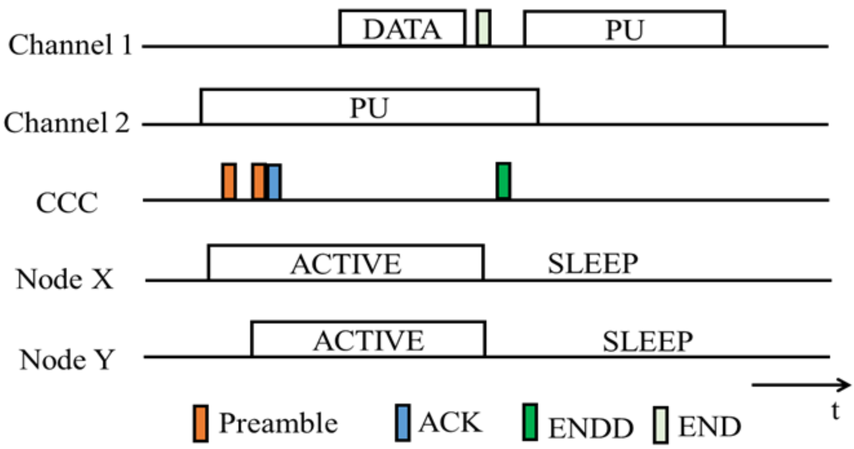

Figure 7. Timing diagram of the CR-WSN MAC protocol

Each sensor node follows a sleep/active cycle and senses all the data channels, thus storing the status of each channel in a vector at the start of each cycle. Each node listens to the CCC while active and, if a data transmission request is not found, switches to sleep mode. Otherwise, after receiving data transmission request, the receiving node resets its timer and sends an ACK message (which contains the ID of the data channel to be used) on the CCC to ensure that data transmission is carried out on the selected channel, as shown in Fig. 6. Since the transmission process on a data channel is considered to be the combination of packet transmission and channel sensing intervals, a periodic sensing approach is used in order to mitigate interference between PUs and SUs. The senders and receivers discard a packet if the presence of a PU is detected and leave that particular data channel free from SU transmissions. Finally, an end of transmission message (ENDD) is broadcasted on the CCC so that other nodes listening to the CCC update their channel state vector accordingly. The ENDD contains identifiers containing information about the latest sensing results obtained by the pair of nodes taking part in the transmission on that data channel. Fig.7 depicts the communication flow described above.

2.2.5 A Multi-constrained QoS-Aware MAC Protocol for Cluster-Based CRSNs [14]

This protocol focuses not only on energy consumption, but also on various QoS constrains of data packets such as reliability and delay. To realize such a delay-and-reliability-aware traffic, separate slots are assigned, namely the guaranteed time slots (GTS). A dynamic data and backup channel assignment mechanism reduces the number of retransmission, which, in turn, saves significant amount of energy. The GTSs and post-contention periods are dynamic, which also helps in saving energy if there is less traffic generated by the sensor nodes. The operation of this MAC protocol can be explained in four different phases, as shown above in Fig. 8. These phases are the cooperative sensing channel selection phase (CSCSP), slot allocation and channel assignment phase (SACAP), DTP, and SP. The DTP is further divided into GTSs and post contention access period (PCAP). Another phase is the SACAP, in which GTSs are allocated for traffic from the nodes, which are delay constrained and have a shorter lifetime. This is followed by the selection of the data channel and GTS backup channels for each of the GTSs. Then, the cluster head assigns channels to each node that requested transmission. Channels are assigned in such a way that the channel having a high channel weight will get multiple slots whereas low ranking channels will be assigned only a single slot.

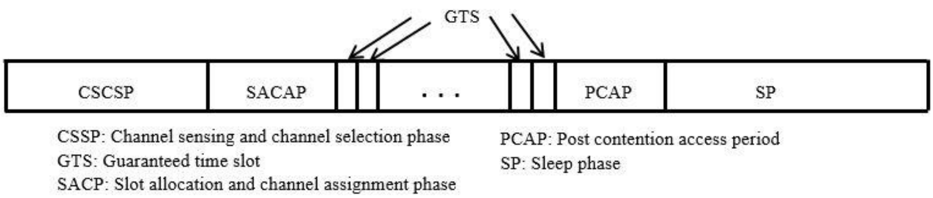

Figure 8. Superframe structure of the multi-constrained QoS-aware MAC protocol

For best-effort traffic, no slots are allocated and it employs CSMA/CA mechanisms to transmit packets during the PCAP phase. The DTP phase is further divided into GTSs and the PCAP where best effort transmissions of best-effort data are carried out using a random back-off mechanism. The remaining lifetime of the packet is regarded as a decision making parameter for transmission order. Packets having the lowest lifetime will be transmitted first, and so on. Packets received from cluster members are now collected in the cluster head and are transmitted to the next CH using a CSMA/CA-based medium access mechanism, until they reach the sink. Finally, during the sleep phase, the transceiver switches to sleep mode in order to save energy.

The proposed multi-constrained QoS aware MAC protocol makes differently constrained QoS-aware traffic possible. Moreover, since the best channels are selected, data retransmission rate is also reduced, thus reducing power consumption. In addition, calculations using the subset of available channels reduce the sensing overhead, which also helps in saving energy. However, additional computational overhead is required for defining and processing various parameters. The proposed multi-constrained QoS aware MAC protocol makes differently constrained QoS-aware traffic possible. Moreover, since the best channels are selected, data retransmission rate is also reduced, thus reducing power consumption. In addition, calculations using the subset of available channels reduce the sensing overhead, which also helps in saving energy. However, additional computational overhead is required for defining and processing various parameters.

2.2.6 Cognitive Adaptive Medium Access Control in CRSNs [15]

The Cognitive Adaptive Medium Access Control protocol has been proposed in literature, which follows an on-demand spectrum sensing mechanism. This protocol adapts the spatial correlation of the nodes so that the spectrum correlating (CN) nodes and the spectrum representative (SR) nodes are aligned. The SR node is the ones which take part in sensing the spectrum. The operation of this MAC protocol is divided into three phases, namely, the spectrum measurement phase, the channel contention phase and the transmission phase.

During the spectrum measurement phase, when a data transmission request reaches a node (either by an event or a forwarding request), that particular node first checks the neighboring table to see whether there are SR nodes. If there are, the node becomes a CN node and then selects an SR node. Otherwise, if no SR node is found on the neighboring table, the node acts as an SR node and it performs the spectrum sensing. A hello beacon is transmitted after the periodic hello interval in order to update the nodes status in the table. On the other hand, if the node satisfies the conditions to be a CN node, it sends a request for spectrum information over the common control channel to the selected SR node on its neighboring table. However, there is a chance that the time interval for receiving back an acknowledgement from the specified SR node may expire. In this case, the CN node tries to find another SR node from the neighboring table. If there are no more SR nodes to probe, then the CN node becomes an SR node and starts the spectrum measurement process again during the channel contention phase, the CN node sends a negotiation request with its available channels in order of priority over the common control channel to the receiver node. The receiver node does not have enough information at this point about the available channel list, so it switches to the spectrum management phase again and looks for available channels. An acknowledgement message is transmitted only to that sender node with a list of the preferred available channels the sender node then it switches to the receivers preferred data channel. If there are no available common channels, then the sender node switches into a new spectrum management phase again.

The data transmission phase is the one in which real data transmissions are carried out using a CSMA mechanism. The sender node has to confirm again whether the preferred channel is still appropriate for data transmission or not, and if the receivers preferred available channel is not suitable for the sender node, the sender nodes sends the preferred channel list to the receiver again through the receivers preferred channel. The receiving node then switches to the data channel suggested by the sender node for the real data transmission, and thus both the sender and the receiver nodes tune into the same data channel. In case of failure of transmission of this data, the nodes switch into the contention phase again and follow the steps accordingly.

The unique feature that is proposed in this study is that if the size of the data to be sent from the sensor node is small, then this data is sent with an RTS packet by a process of piggybacking. Likewise, the acknowledgement (ACK) packet is also piggybacked on the CTS. This mechanism is beneficial in terms of reducing transmission overhead for small data packets. However, it is not explained how to decide if the size of the packet from a node is small enough to piggyback.

Energy is saved during the sensing phase by adopting an adaptive sensing period. In order to find an efficient value for the sensing period (i.e., a decent balance between fast and fine sensing), channels are rewarded whenever successful data communication is carried out through them. Likewise, a penalty is given to a channel after every transmission failure occurs on said channel. The sensing overhead at the nodes is reduced by using the information of the spatial correlation of the nodes. Thus, the obtained result is shared to the neighboring nodes. Cooperative sensing, adaptive duty cycles, and on demand spectrum sensing are the main mechanisms that are responsible for saving energy in this protocol.

2.2.7 MAC Protocol for CR-WSN without a Dedicated Common Control Channel [18]

This protocol uses two half-duplex transceivers; one is the control transceiver while the other one is the data transceiver. The control transceiver of each sensor node rendezvous during the channels default time, which is used for exchanging control message and check the status of neighboring nodes. Channel time is divided into default time slots of length‘t + I data’. A representation of ‘K’ channels with a fixed interval is shown in Fig. 9.

The operation of this MAC protocol begins with a fast sensing process, the result of which is recorded in a channel status table. The channel status table contains three categories of statuses, according to different channel situations: when an incumbent user is active on the channel, when channel is in an idle state and when the status of the channel is uncertain. Then, the nodes tune their control transceiver to the default slot of the channels. If no incumbent user activity is detected after sensing, the node which was selected after the contention process (R1) sends a channel negotiation message (CNM) to the intended receiver node (R2), which is received through a selected common available channel, as shown in Fig. 10. A CNM resume (CNM-RES) message is sent to the receiver node while the others update their channel status table. On the other hand, if the activity of an incumbent user is found, the nodes skip the current default time slot and wait for the next one for another negotiation round.

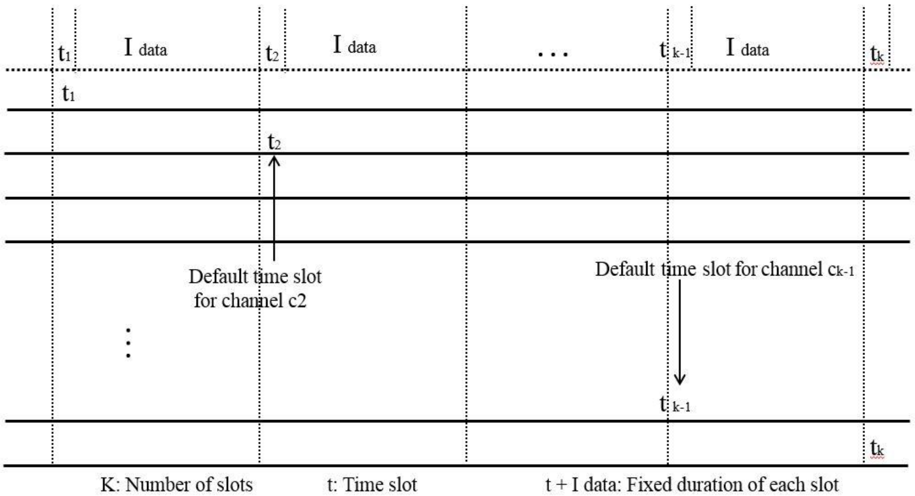

Figure 9. Channels with default time slots

Then preferred channel list (PCL) in the sensor node is estimated. This list consists of a ranking of the channels using an exponentially weighted moving average filter. For the same channels, the priority detected for different sensor nodes may vary depending on geographical location and time. Sensor nodes select the common available channel having the highest priority, and then both the sender and receiver nodes hop to that channel. Data transmission then commences on that particular channel. For energy saving purposes, the control transceivers also switch to a doze state when a PU is detected and according to the estimated density nodes.

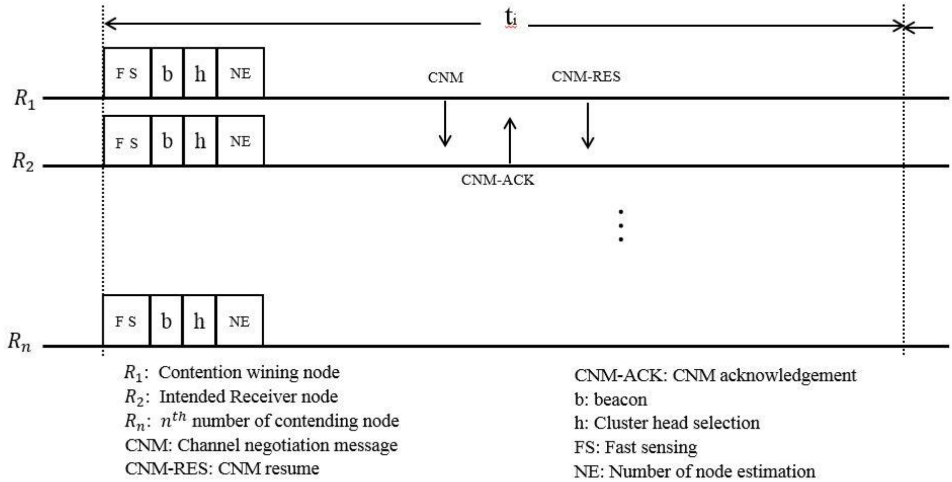

Figure 10. Channel negotiation in the default slot

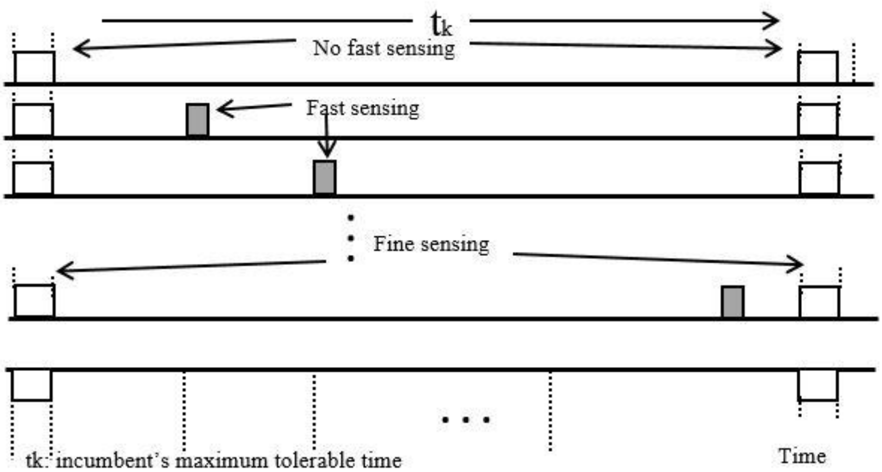

Figure 11. Approximate illustration of fast and fine sensing

Fig. 11 shows how channel sensing is adaptive. Fast sensing is initially carried out, but since this is not enough to identify whether a channel is either in a busy or idle condition, three possible status are determined: idle, busy, and uncertain. After performing fast sensing for up to the maximum incumbent user interference tolerable time (tk), fine sensing is carried out. This reduces the number of false alarms and enhances the QoS.

2.2.8 CSMA-based opportunistic medium access protocol for CRSNs [17]

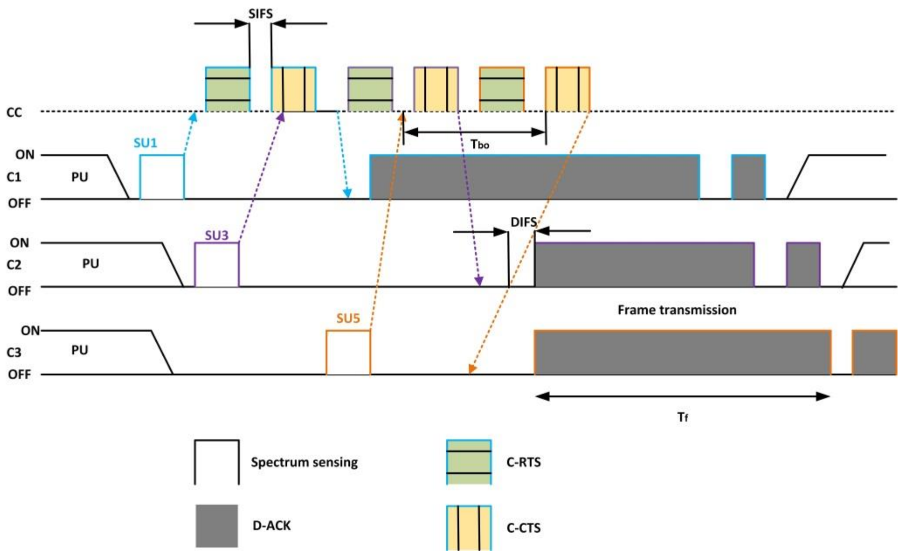

Figure 12. Opportunistic access of licensed channels

This MAC protocol is a CSMA based MAC protocol which opportunistically uses the available channels which is beneficial for CRSNs to reduce collision in the common control channel and the congestion as the different available channels can be accessed in an opportunistic manner when the licensed channels are idle.

The CRSN node having data to transmit first senses all the channels initially keeps the record of available time. After that, it contends for the control channel by sending RTS packets. The RTS packet contains the best channel for the negotiation process which is based on either the channel having minimum interference or maximum available time. When the receiver node receives the RTS packet, it checks the availability of that notified channel in the RTS packet. If it is available, then the CTS packet is sent for the negotiation, else it sends its own preferred best channel to the sender. After this negotiation phase the data is transmitted through the negotiated channel.

As depicted in Fig. 12, S1 is contending for the common control channel for the data transmission by sending RTS packets. At the same time when another sender SU3 overhears the RTS and goes to back off if it has the data to send. The control channel is accessed successfully by SU4 and SU5 if SU3 is in the process of the back-off and then switches to the negotiated data channel for the data transmission. This ensures the simultaneous data transmission through different channel which greatly reduces congestion for the CRSNs and eventually increases the network performance with better energy efficiency. However, the best channel is selected with just by a single parameter (either channel having minimum interference or maximum available time) which is limited to address the issue in a dynamic nature of the channels.

2.3 Comparison of MAC Protocols for CRSNs

In this section, the existing MAC protocols for CRSNs are qualitatively compared and discussed in detail. Table 1 shows the comparison results of the MAC protocols reviewed earlier.

Table.1 Qualitative comparison of existing MAC protocols for CRSNs

MAC protocol	**Network configuration**	**CCC**	**Spectrum sensing technique**	**Channel access mechanism**	**Advantages**	**Limitations**
ECR-MAC [11]	Ad-hoc	Not Specified	Energy detection	Contention based	• Lower duty cycle • Low-power listening is enough for asynchronous preamble packets • Fewer retransmissions in lossy wireless environments	• Longer preamble packet transmission which causes higher energy consumption
Cluster-based MAC [12]	Ad-hoc Cluster	Dedicated	Not Specified	TDMA	• No hidden or exposed terminals • Fewer retransmissions due to backup channel	• Less QoS provisioning
CR-WSN MAC [13]	Ad-hoc	Dedicated	Energy detection	Contention based	• No synchronization overhead for large networks	• Receiver uncertainty problem • Hidden terminal problem
Battlefield MAC [14]	Ad-hoc	Dedicated control channel	Not Specified	TDMA	• Each node can utilize a group of channel-slots	• Synchronization overhead for big networks
ENC MAC [15]	Ad-hoc	Dedicated control channel	Not Specified	Hybrid	• Each node can utilize a group of channel slots	• Requires two transceivers

CAMAC [16]	Ad-hoc	Dedicated	Energy Detection	Contention based	• Low CSMA overhead for small data packets due to piggybacking	• Long channel negotiation process • Hidden-node problem
Multi-constrained QoS MAC [17]	Ad-hoc Cluster	Dedicated	Not Specified	Hybrid	• QoS is promising for different types of traffic • Reliable backup channel	• Hidden and exposed terminal issues are not explained
MAC without DCCH [18]	Ad-hoc Cluster	Non-Dedicated	Energy Detection	Hybrid	• No cost overhead for control channel	• Tight synchronization is mandatory • Not suitable for large networks • Requires two transceivers
CSMA-Based opportunistic MAC [19]	Ad-hoc	Dedicated	Energy Detection	Contention Based	• No overhead for synchronization	• Hidden terminal problem

In [19], the CRSN MAC protocol is proposed which is a CSMA-based opportunistic MAC protocol. The best channel is the channel that has either minimum interference or least occupancy of the PU obtained from the prediction model. However, the channel having least occupancy of PU is likely to suffer from high interference. Moreover, the channel with minimum interference is may possess higher probability of PU activity. Another Mac protocol without dedicated control channel is proposed in [18] that rank the channels according least PU occupancy time. Two separate transceivers are used in this design for control packets and the data packets. The energy consumption is minimized by setting the transceivers go into doze state. This design is complex as the control radio which is used to exchange control packets also goes to doze mode independently along with the traffic radio when there is completion of control packet transmission. Likewise, higher contention is anticipated when there is large number of nodes, as it does not use the dedicated control channel for the control packets.

Another MAC protocol for CRSN is proposed in [16], which focus on acquiring energy efficiency by allowing only the certain nodes to be in active state through the route from the source to the destination. The sensing is initialized only when there is data to send i.e. on demand sensing and implies the adaptive sensing between fast sensing and fine sensing interval. The reduction of CSMA overhead is achieved by piggybacking RTS with data packet and CTS with ACK packet for small data packets. However, the selection of the best channel here is the minimum interference measured which is likely to suffer from high PU activity.

The cluster-based MAC protocol for CRSN is studied in the literature [12] and [17]. The available channels are ranked according to their weight for the effective spectrum hand-off. The weight includes the status of the channel during sensing whether it is idle or busy, the transmission is successful or not and is there any collision on a particular channel or not. The main concept of this protocol is to sense only some of the available spectrum channel rather than sensing all of them, which reduces sensing time and hence conserve energy. The concept of back-up channel is also used. The [17] follows the same operation for the sensing by implying optimal subset of the channel for sensing. It also assigns the back-up channels. Here, the data traffic is classified in four different categories according to the traffic different application and the channel allocation is also carried out based on the type of this traffic type. However, both aforementioned mac protocols for CRSN are scheduled-based protocol which involves in sensing and cluster forming operation even if there is no data to send or very less traffic of the data. In addition, by sensing only the subset of the available channels rather than sensing all channels, it does not seem convincing idea to rank all the available channels

In [13], an asynchronous CRSN MAC protocol is proposed in which the duty cycle of the nodes is made adaptive. This eliminates synchronization overhead thus by conserving energy. Here, a burst of preamble packets is sent to the destination node by the sender node through dedicated channel. The preamble packet includes destination address and the available channels .When the receiver receives the first packet, it send an acknowledgement to stop further packet to the sender nodes and at the same time the neighboring nodes listening to the control channel goes to sleep mode. However, this protocol also does not address the quality of the available channels, which increases the possibility of collision.

[15] Adapts the hybrid access mechanism in which two separate transceivers are used for control and data packets respectively. Synchronization between the nodes is obtained by sending the beacon message from the master node which is determined during the initialization of the network. The node is considered to be the master node when it doesn’t receive beacon message from other nodes for predefined consecutive time slots. After that it goes to the contention process using IEEE 802.11DCF mechanism, to access the control channel.

In this protocol, the cooperative sensing is deployed in such a way that each SU maintains the information of the channels regarding activity of the PU that reduces the collision probability .Moreover, only two mini slots in the sensing phase is enough thus by reducing the sensing time and consequently the energy consumption. However, selecting the master node to send the beacon message and frequent beacon packet transmission among the sensor nodes causes an extra overhead for this protocol.

Similarly, in [11], a receiver-based MAC protocol for the CRSN has been proposed in which the energy is conserved by reducing the number of retransmission and selecting the most energy efficient node as a forwarder for the multi hop network as well as maintaining duty cycle of the nodes to be below one percent. The adaptive sensing operation is also adapted to reduce the periodic sensing time. This protocol, however, does not address the selection of channels in terms of interference among secondary users. Since there remains the probably that the channel having maximum available period in terms of PU activity may suffer from interference among secondary user and has to suffer from retransmission or frequent switching.

The CRSN nodes in [14] set the upper-bounded transmit power for each available channel based on their characteristics, ultimately contributing to energy efficiency. Additionally, it contributes in elimination contention among nodes and in decomposing traffic among multiple channels. For large networks, it suffers from synchronization overhead.

In the existing MAC protocols for CRSNs, the selection of reliable channel for the effective dynamic spectrum access is limited to only one of the parameter. It is either predicted minimum PU activity or minimum interference on that particular channel. In addition, for cognitive operation, effective sensing is very important not only to protect the PU’s communication but also to enhance various network performances such as network lifetime, packet delivery ratio and energy efficiency. To the best of our knowledge, there is no such CRSN MAC protocols, which focus on adaptive sensing time as well as the selection of reliable traffic channels addressing more than one parameter viz. minimum PU activity and successful transmission.

3. Network Model

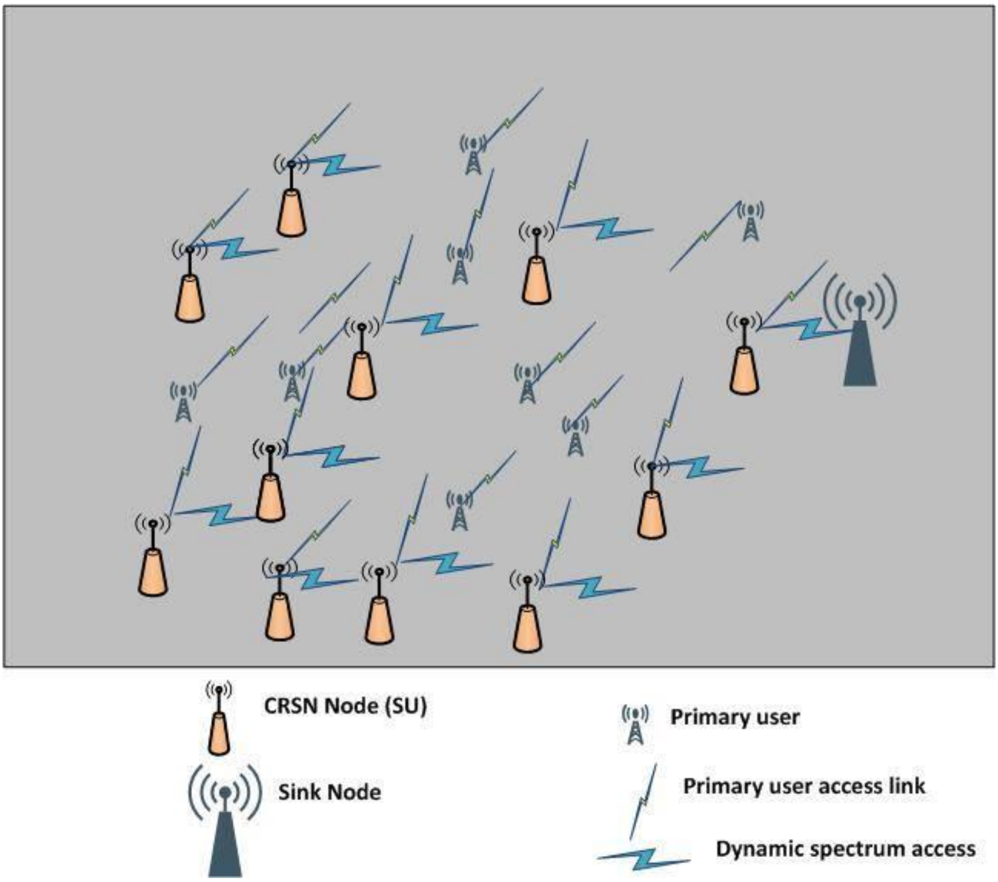

Figure 13. Network model for CRSNs

We consider N PUs and M battery-powered sensor nodes with CR capability are randomly deployed as shown in Fig. 13. M licensed channels are assuumed such that each PU has its own specific channel. PUs utilize the particular licensed channel assigned to it whereas the sensor nodes can opportunistically access the licensed channels for data transmission when the licensed channel is not used by a PU [20]. The CRSN nods are homogenoues in the network, having the same operational parameters. The sensor node transmit their sensed data to the sink node. All the control packets are transmitted by using the dedicated control channel which is not affected by any PU communication. Moreover, we assume that the dedicated control channel is available in the whole network. The sensor nodes can opportunistically tune to the licensed channel for data transmission. The radiation pattern of each node is considered to be omnidirectional.

The sensor nodes and the sink node are generally static in sensor networks [22]. Therefore, we assume that there is no mobility of any nodes. The PUs are also considered to be static. In order to get traffic information in the particular channel, each sensor node is capable of sensing channels. For different nodes, the number of vacant channels and their available time may vary. The activity of PUs for all the available licensed channels is modeled using independent and identically distributed (i. i. d) ON and OFF process with exponential distribution [23]. The effective transmission range of PUs and sensor nodes is set to the 150 m and 250 m, respectively.

4. An Energy-Efficient MAC protocol for CRSNs

In this chapter, an energy-eficient MAC (EE-MAC) protocol for CRSNs is proposed and its operation is discussed in detail. The proposed EE-MAC is based on carrier sense multiple access (CSMA) and utilizes the unused licensed channels opportunistically. The RTS and CTS frames are modified as shown in Figures 3 and 4, respectively. An extra field of channel is added in the RTS frame,which contains the information of the sender's preferred channel for dynamic spectrum access. This channel is the best channel with regard to weight. The weight of a channel will be explained in Section 4.2. Similarly, the CTS frame also contains an extra field of channel which is the preferred channel of the receiver with regard to weight.

Frame control	Duration	Receiver address	Transmitter address	Channel	FCS

Figure 14. Modified RTS frame

Frame control	Duration	Receiver Address	Channel	FCS

Figure 15. Modified CTS frame

4.1 **Operation of EE-MAC**

The operation of the proposed EE-MAC protocol is explained in three distinct phases.

4.1.1 Sensing and Initialization Phase: The sensor node having data to transmit first senses the channels. The available channels are ranked on the basis of the

PU off time. The detail procedure for ranking the available channels will be provided in Section 4.2.

4.1.2 Contention and Negotiation Phase: After sensing, the transceiver is tuned to the common control channel (CCC) to contend among the sensor nodes. If the CCC is found to be idle, both sender and receiver negotiate to use a channel for data transmission. First, a RTS packet is sent after DIFS time, where DIFS stands for DCF (Distributed Coordination Function) interframe space in the IEEE 802.11 standard. By overhearing the RTS packet, the neighboring sensor nodes do not utilize the channel mentioned in the RTS packet because the channel is the best channel of the sender node. If the channel is busy, then it waits for random back-off time. After receiving the RTS packet, the receiver node checks the availability of the channel mentioned in the RTS packet. At that moment, if the mentioned channel is available, the CTS packet is transmitted to the sender node after SIFS time by using the channel, where SIFS stands for short interframe space. The neighboring nodes overhearing CTS do not utilize the specified channel. However, if the receiving node does not contain the channel preferred by the sender as a vacant one, then the receiving node sends its own preferred channel to the sender. If the sender node can utilize the channel, the sender node transmits its data packet by using the channel; otherwise, the current transmission is failed and retransmission will be initiated.

4.1.3 Data Transmission Phase: The data transmission phase is followed after the contention and negotiation phase. Both the sender and the receiver now tune to the negotiated channel. After data packet is transmitted successfully, the ACK packet is sent through the same data channel. The ACK packet is recorded and the weight of the channel is also updated for the particular channel.

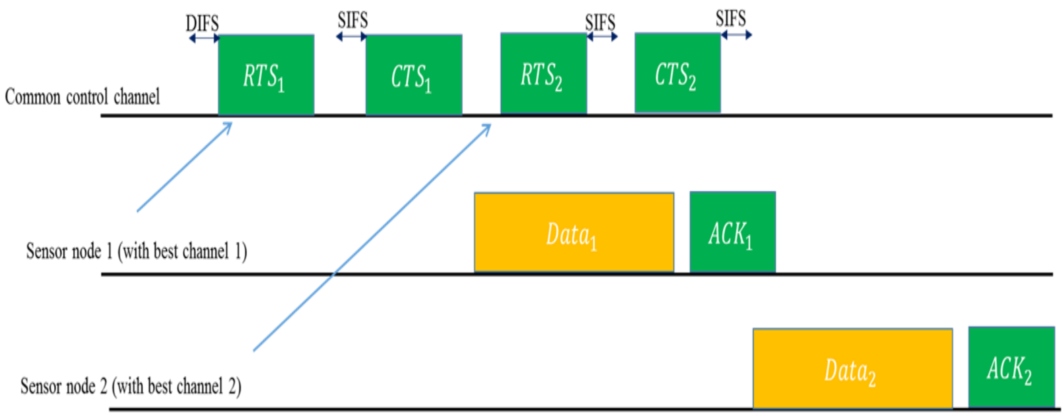

Figure 16. Operation of the proposed EE-MAC protocol

Figure 16 illustrates opportunistic access mechanism of the proposed EE-MAC protocol. There are two sending nodes (sensor node 1 and sensor node 2) having the best channels 1 and 2, respectively. The sensor node 1 sends the RTS_1 packet after DIFS time to the receiving node through CCC. After receiving RTS_1, the receiver sends the CTS_1 packet followed by SIFS time. Then, they switch to the negotiated channel. Thus, sensor node 2 does not need to wait for the whole $Data_1$ to be transmitted from sensor node 1, and it can access the CCC at that time. The sensor node 2 follows the same procedure as sensor node 1 and transmits the $Data_2$ packet through another channel. This ensures the simultaneous transmissions using different available channels. Thus, the utilization of the available channels is significantly improved. The collision among the control frame and data frame is also eliminated by using a dedicated CCC.

4.2 Reliable Channel Selection

Reliable channel selection is very crucial for CRSNs. Retransmission, collision, and interference is the possible hazards. Therefore, the selection of a reliable data channel greatly affects the whole performance of a CRSN. In EE-MAC, the channel having high PU off time should be elected for selecting the reliable channel. Because the proposed MAC protocol utilizes the idle licensed channel opportunistically, the protection of incumbent users is necessarily required. In this regard, it is indispensable to decide the channel in such a way that the communication between sensor nodes is less likely to be affected by the sudden arrival of a PU during transmission. Moreover, there is a possibility that even a channel having high PU off time may possess more interference than other channels, resulting in degraded network performance. Therefore, a reliable channel should be selected by taking the weight of channels into account. The weight of a channel is calculated accordance with PU off time (initially) and successful transmission.

In Algorithm 1, the channel weight calculation procedure is shown step by step. The channel weight is calculated for every unused licensed channel, and the channel with the highest weight is selected as the most reliable channel among available channels. Initially, the PU off time (T_{PU-off}) of each available channel is recorded. Different sensor nodes have a different list of available channels with the PU off time. The rank of each channel is calculated at Step 1 by dividing the PU off time (T_{PU-off}) by scaling factor Ø (line 2). The scaling factor Ø is chosen in such a way that the rank lies between 0 and 1. In Step 2, the weight of each channel is calculated by dividing this with a constant k, where the value of k is chosen between 1 and 10 (line 4). In Step 3, the new weight value is calculated on the basis of the updated value of k after each transmission. When the transmission is successful, the value of k decreases (line 7). For unsuccessful transmission, however, the value of k increases (line 9) and the weight of each channel is updated accordingly (line 11). The channel with the highest weight is considered as the most reliable channel.

Algorithm 1. Channel weight calculation for reliable channel selection

Input: PU off time of channel *c* ($T_{PU-off}(c)$), scaling factor ($\emptyset$)

Output: Weight of channel c ($W(c)$)

1: **Step 1.** Calculate the rank of channel *c*

2: $R(c) = \frac{T_{PU-off}(c)}{\emptyset}$, where $0 < R(c) \leq 1$

3: **Step 2.** Calculate the weight of channel *c*

4: $W(c) = \frac{R(c)}{k}$, where $1 \leq k \leq 10$

5: **Step 3.** Update the weight of channel *c*

6. **If** Transmission is successful

7: $k = k - 1$

8: **else**

9: $k = k + 1$

10: **end if**

11: $W(c) = \frac{w(c)}{k}$

4.3 Adaptive Channel Sensing

In order to utilize the unused licensed channel opportunistically, each sensor node should sense the licensed channel periodically with some interval. The interval is called sensing interval in cognitive radio networks including CRSNs. In the IEEE 802.22 standard [24] for wireless regional area networks (WRANs), both fast sensing and fine sensing are used in two steps, in which the fast sensing represents short sensing interval and the fine sensing does long sensing interval. If the sensing interval is short, the sensor node can make a decision more quickly and utilize the unused licensed channel more efficiently without interrupting PU operation. However, this causes more energy consumption. Hence, the sensing interval should be chosen carefully in order to provide appropriate accuracy in sensing and reduced energy consumption. In this work, the sensing interval should be chosen adaptively on the basis of the maximum successful transmission threshold [16].

In Algorithm 2, the adaptive sensing interval mechanism is illustrated. Initially, the number of timeslots for sensing is randomly chosen between 1 and the maximum number of timeslots allowed for sensing (N) in Step 1. Thus, the sensing interval during network initialization is simply calculated in Step 2. In Step 3, the sensing interval is adaptively updated on the basis of each transmission result. For every successful transmission, the number of sensing interval is decreased linearly with step size Δ (line 7). On the other hand, the number of sensing interval is increased multiplicatively with scaling factor ∂ in case of unsuccessful transmission (line 9). The sensing interval is then updated accordingly (line 11).

Algorithm 2. Sensing interval calculation for adaptive spetrum sensing

Input: Maximum number of timeslots allowed for sensing (N), scaling factor for fast sensing (Δ), scaling factor for fine sensing (∂), timeslot (s)
Output: Adaptive sensing interval T_s

```
1: Step 1. Initialize the number of timeslots for sensing randomly
2:        n = rand(1, N)
3: Step 2. Calculate the sensing interval
4:        T_s = n × s
5: Step 3. Update the sensing interval
6:        if transmission is successful
7:            Decrease n by scaling factor Δ (i.e., n = n − Δ)
8:        else
9:            Increase n multiplicatively with scaling factor ∂ (i.e., n = n × ∂)
10:       end if
11:       T_s = n × s
```

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5. Performance Evaluation

In this section, we compare the performance (network lifetime, packet delivery ratio and energy efficiency) of the proposed EE-MAC protocol with the existing CRSN MAC protocol i.e., CSMA MAC protocol [19] through simulation considering various number of sensor nodes at particular number of PUs (5 and 10). The existing CSMA MAC protocol for CRSNs is a highly cited research work. In addition, it aims at reducing collision among control packets and traffic packets by deploying a dedicated common control channel. Likewise, it first determines the best channel for the dynamic spectrum access like in the EE-MAC protocol. The predefined channel for the dynamic spectrum access helps to mitigate the possibility of collision in data channel due to sudden arrival of PU during transmission. In both protocols, the number of transceiver is also of same number, that is, 1 which suits for the sensor networks as it reduces the hardware cost and energy consumption. To sum up, due to the similarities of the working mechanism and the protocol that has significantly high number of citation, we have chosen this CSMA MAC protocol for the performance comparisons.

5.1 Simulation Environment

We consider one dedicated control channel for the control packet transmission and ten other data channels, which is for data packet transmission. Single transceiver is used in the simulation which is responsible for both control packet transmission and data transmission. The sensors nodes are deployed in a network are of 500*500 m^2. LEACH (low energy adaptive clustering hierarchy) routing protocol [31] is used as the network layer protocol. Simulation is carried out with NS2 [21] and, for each simulation; we have run the code for 5 times .The average of each result is plotted in the graph. The sensor nodes can utilize the licensed channel opportunistically when they are not used by the PUs. The detailed simulation parameters are listed in the following table 2.

Table 2. Simulation Parameters

Parameter	Value
Network Area	$500 \times 500\ m^2$

Number of PUs	5, 10
Number of Transceivers	1
Number of SUs	100
Traffic Type	CBR
Packet size	200 Bytes
PU Modeling	PU ON/OFF model
Routing Protocol	LEACH [31]
Unit Sensing time	10 μs
Initial Energy	2 J
Energy in transmit mode	23.56 mJ
Energy in receive mode	18.6 mJ
Energy in idle mode	18.6 mJ
Spectrum sensing consumption	400 nJ per slot

The three performance metrics; network lifetime, packet delivary ratio, and energy efficiency are evaluated and compared in our performance study.

- *Network Lifetime* is the time when half of the sensor nodes die.
- *Packet delivery ratio* measures the reliability of the protocol which is defined as the ratio of the number of packets successfully received at the sink node over the number of packets sent from different source nodes.
- *Energy efficiency* is measured in terms of energy consumption per bit, which indicates the average amount of energy in joules consumed for the successful transmission of 1 bit of packet.

5.2 Simulation Results and Discussion

In this Section, the results obtained from the simulation for EE-MAC protocol and CSMA MAC protocol are discussed in detail.

5.2.1 Network Lifetime

The network lifetime of both protocols are evaluated in terms of the living nodes over the simulation time.

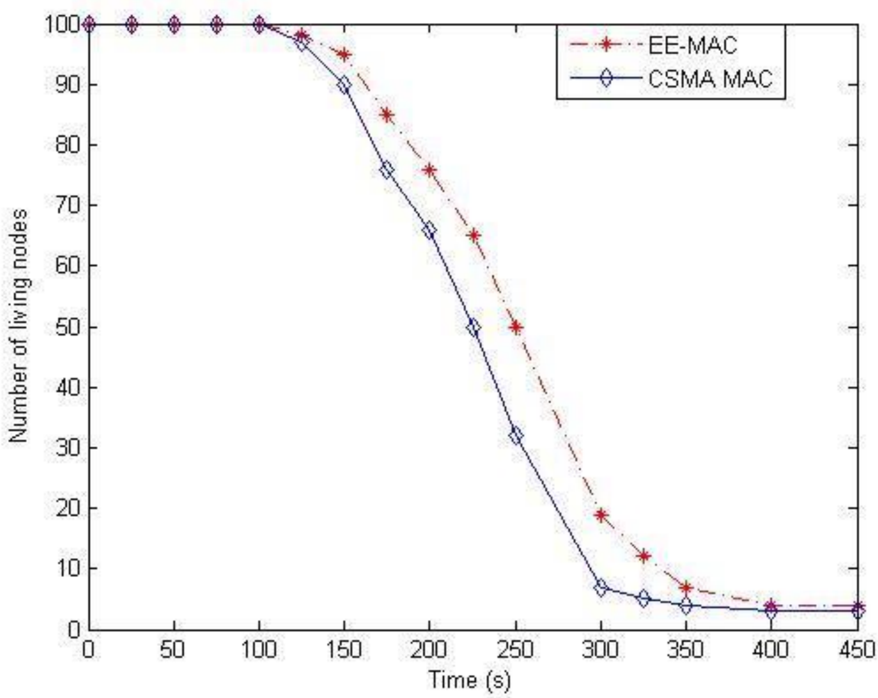

Figure 17. Network lifetime when the number of PUs is 5.

Figure 17 shows the network lifetime of the proposed EE-MAC protocol and the existing CSMA MAC protocol for CRSNs. The number of PUs is set to 5.

The network lifetime of the EE-MAC protocol is better (i.e., 250 seconds) than the CSMA MAC protocol (i.e., 225 seconds). This improvement is because of the adaptive sensing mechanism consuming less energy and the selection of the reliable channel, which is more robust ensuring less collisions and retransmissions.

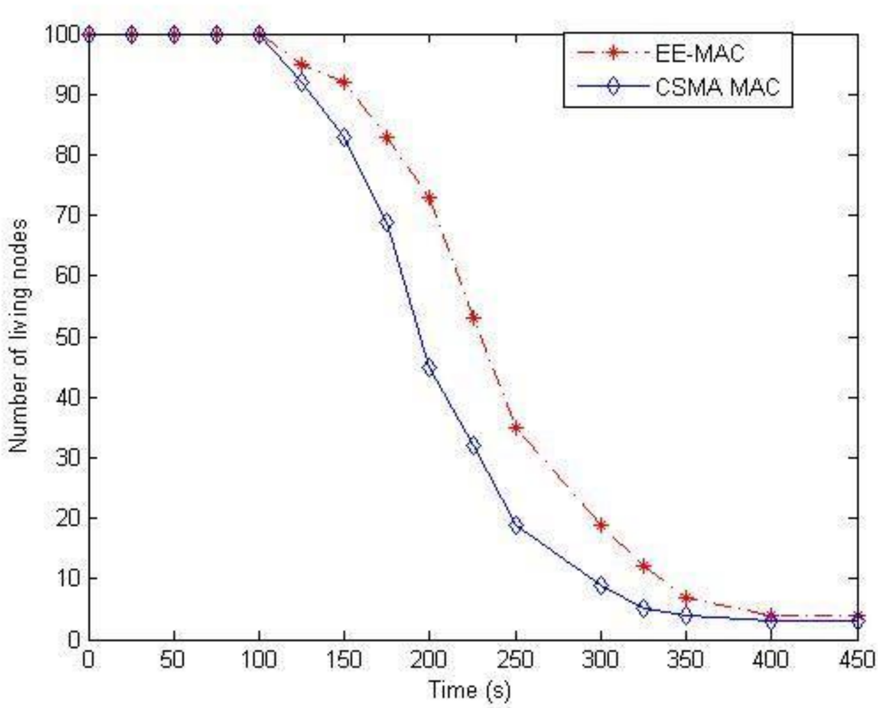

Figure 18. Network lifetime when the number of PUs is 10.

Figure 18 depicts the network lifetime of the CRSN when there are 10 PUs. With increase in the number of PUs, the possibility of the PU returning to a particular data channel during transmission is also increased. Thus, it may require more retransmissions and suffer from the collisions from the PU’s traffic. Although, the network lifetime is decreased with the increase in the number of

PUs, EE-MAC protocol outperforms the existing one. Figure 18 clearly shows that gap between the two protocols for number of living nodes at 10 PUs is even more when there were only 5 PUs. This is due to the proper handling of PU activity in our algorithm. Half of the nodes die at around 190 seconds for the existing CSMA MAC protocol whereas for the proposed EE-MAC protocol, half of the nodes die at around 225 seconds.

5.2.2 Packet Delivery Ratio

In this Section, we evaluate the reliability of the proposed EE-MAC protocol and the existing protocol in terms of packet delivery ratio at particular number of PUs i.e., 5 and 10 respectively.

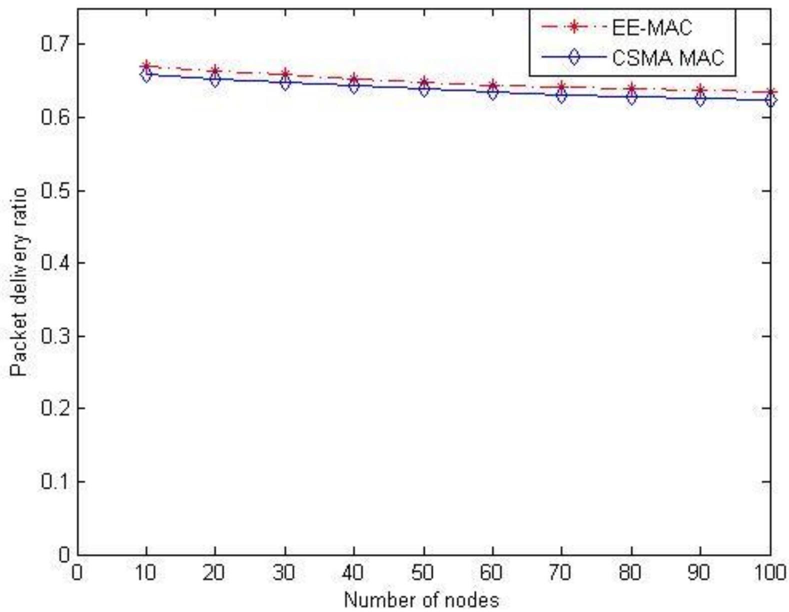

Figure 19. Packet delivery ratio when the number of PUs is 5.

Figure 19 illustrates the packet delivery ratio (PDR) when there are 5 PUs. The graph shows a gradual decrease in the PDR with small value. The decrement is almost linear to both of the protocols. However, the proposed EE-MAC protocol is better when there is more number of nodes as compared to the CSMA MAC protocol for CRSNs. The reason is due to the strong channel selection mechanism, which minimizes the retransmissions and collisions. This phenomenon is not so costly even if there is more number of nodes. Moreover, with introduction of the adaptive sensing mechanism, there is more chance for the nodes to transmit the data, which significantly increases the number successful transmission.

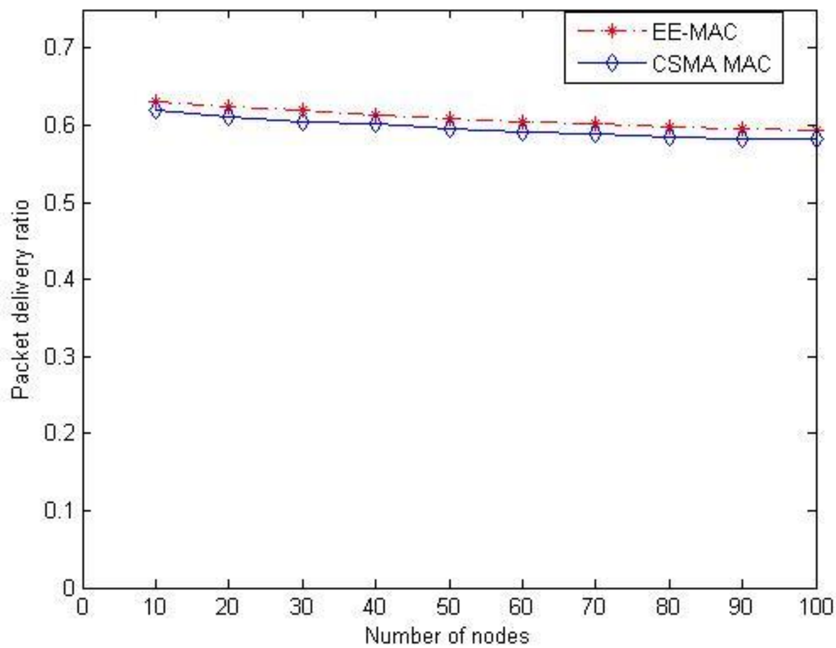

Figure 20. Packet delivery ratio when the number of PUs is 10.

With increase in number of PUs, the network becomes more prone to the collision and retransmission, which significantly reduces the chance of successful transmission and consequently the PDR. Figure 20 shows that when there are 10 PUs, the PDR is decreased almost linearly with increase in sensor nodes. In this regard, our proposed EE-MAC can handle the PUs in a better way. The selection of the channels for the dynamic spectrum access (DSA) considers two factors; maximum available time and the history of successful or unsuccessful transmission, which supplements the protocol to be less prone to the sudden return of the PU in particular data channel during data transmission ensuring transmission that is more successful.

The CSMA MAC protocol is limited to select the channel based on only the predicted available time of the PUs. Due to which there is a possibility of not selecting the best channel for the data transmission and can greatly affected by the PU sudden return. Moreover, when the sensing time is not adaptive, there will be less opportunity for the data transmission. This is the main reason for the betterment of EE-MAC in terms of PDR.

5.2.3 Energy Efficiency

In this Section, the energy efficiency is evaluated in terms of energy consumption per bit for both of the protocols by varying number of sensor nodes at particular number of PUs, that is, 5 and 10 respectively.

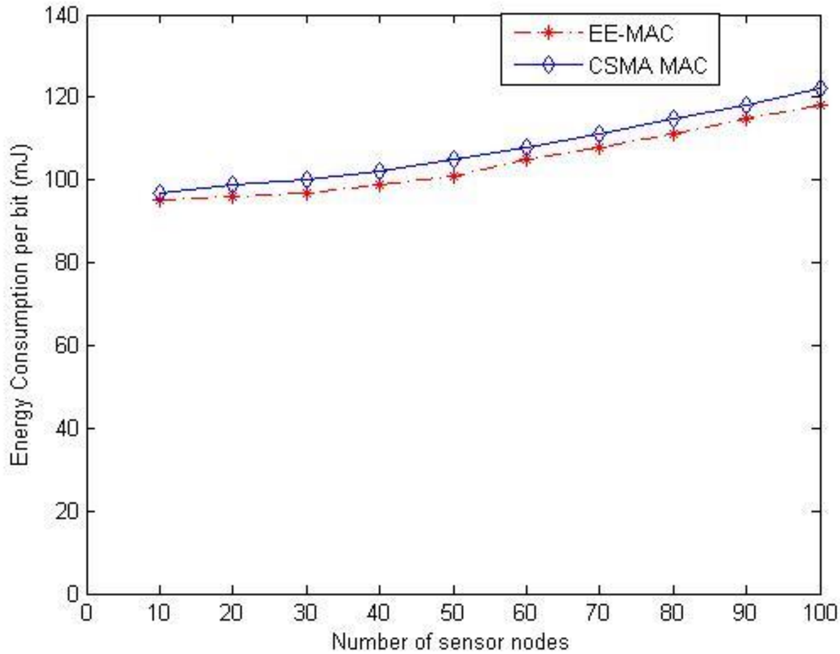

Figure 21. Energy consumption per bit when the number of PUs is 5.

The Figure 21 shows that with increase in number of sensor nodes the energy consumption per bit also increases. The behavior of this increment is almost linear. However, the proposed EE-MAC shows better energy efficiency by consuming less energy in sensing and reducing collisions and retransmissions. Shorter sensing time ensures more opportunity for the data transmission. Moreover, the better channel selection mechanism for the data transmission greatly reduces the retransmission.

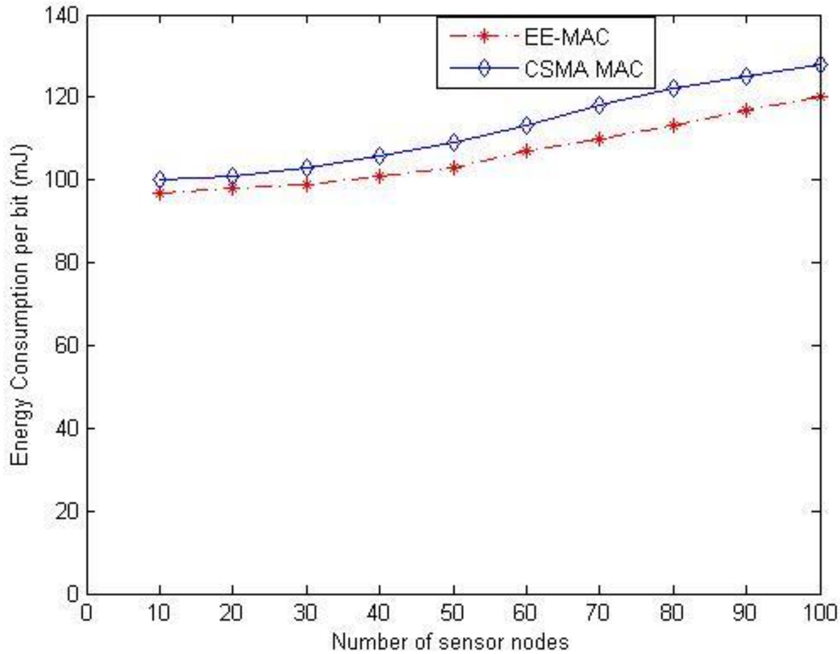

Figure 22. Energy consumption per bit when the number of PUs is 10.

When there is more PUs, the energy consumption per bit of the EE-MAC is better than the CSMA MAC for CRSNs. In Figure 22, it is seen that with 10 number of PUs, the energy consumption per bit increases in both EE-MAC and CSMA MAC protocols. Due to the limited parameters for selecting reliable channel (only the predicted available time), the CSMA MAC cannot guarantee mitigation the collision with PUs traffic and retransmission properly. Because of the fixed sensing time, it spends more time on sensing and less time for the data transmission. This increases the probability to be affected by the sudden PU return in that particular channel during transmission. Due to these reasons, there will be less successful transmission and hence the energy consumption per bit increases. However, EE-MAC protocol caters these issues in a better way ensuring more successful transmissions, and hence provides better performance in terms of energy consumption per bit.

6. Conclusion and Future Work

In this thesis, an energy-efficient MAC protocol named EE-MAC has been proposed for CRSNs. In EE-MAC, the spectrum sensing and selection of a reliable channel for data transmission play a pivotal role in the overall performance of CRSNs. With EE-MAC in CRSNs, network lifetime, packet delivery ratio and energy efficiency are significantly improved. The reliable channel selection procedure is enhanced by considering maximum available time of the data channel for sensor nodes as well as the history of successful or unsuccessful transmission in that particular data channel which makes EE-MAC more vigorous to prevent the collision due to sudden arrival of PUs and retransmission. In addition, the adaptive channel sensing procedure maintains the appropriate sensing accuracy and reduce energy consumption. The comparative results with increasing sensor nodes at different number of PUs (5 and 10) obtained by the simulation result, reveals that proposed EE-MAC outperforms the existing CSMA MAC in terms of network lifetime, packet delivery ratio and energy consumption per bit.

Due to the dynamic nature of the spectrum band in CRSNs, unlike conventional WSNs, the PU activity should be taken account into consideration before designing the duty cycle. This will be our future work. The proposed EE-MAC protocol is limited to the CRSNs with static PUs. To design an extended version of EE-MAC for CRSNs with mobile PUs is another possible future work.

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