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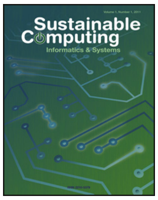

Opportunistic channel selection MAC protocol for cognitive radio ad hoc sensor networks in the internet of things

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ABSTRACT

Internet of things (IoT) constitutes networked devices that can gather and exchange information. The scarcity of the available spectrum used by a large number of devices in IoT is a challenge. Spectrum scarcity changes the whole paradigm of spectrum access in order to increase utilization of the limited resource. Cognitive radio ad hoc sensor networks (CRASN) also operate on the same principle and exploit spectrum holes for efficient utilization of the spectrum. In a multi-channel CRASN, the dynamic nature of primary user (PU) activity and the resulting frequent channel switching require an efficient medium access control (MAC) protocol. A channel selection scheme cannot solely perform well without help of the MAC protocol. As a result, most of the channels remain underutilized, and eventually, overall system performance degrades. In this paper, an opportunistic MAC protocol for CRASN is proposed, and is compared to the IEEE 802.11 MAC protocol with round robin and random channel selection schemes. Furthermore, an opportunistic channel selection scheme (OCSS) is proposed. The simulation results confirm the effectiveness of the proposed approach in comparison of the round robin and random channel selection schemes.

1. Introduction

The internet of things (IoT) is growing rapidly in the wireless communications domain. It was first introduced by Ashton in 1999, and the foundation of IoT was laid by Weiser [1]. The IoT consists of sensors, mobile phones, etc. One of its goals is for all connected devices to interact with each other and cooperate with their neighbors [2]. The wireless sensor network (WSN) is the effective medium to be integrated into the IoT [3–5]. Some predict that the number of smart devices will grow to 500 billion [6] by 2020. Another goal of the IoT is to provide reliable connectivity between smart devices. A number of sensors need to communicate with the sink for reading, decision making, etc. Due to spectrum scarcity, we need to rely on technologies like cognitive radio (CR) [7] to increase spectrum utilization and reuse. CR technology can automatically detect the radio environment, tune the transmission parameters, and dramatically improve spectrum efficiency. Therefore, CR can be integrated into the IoT paradigm. The cognitive radio ad hoc sensor network (CRASN) does not have an infrastructure backbone. In a CRASN, each user needs to have all the CR capabilities and, based on local observation, is responsible for all communications [8]. The cognitive radio ad hoc network (CRAHN) [9] is a preliminary model, according to federal communications commission (FCC) guidelines [10], consisting of multi-channel communications. Furthermore, a CRAHN uses the standard IEEE 802.11 medium access control (MAC) protocol with a CR capability for communications.

The widely used CRAHN module is the state of the art in the CR field [11]. Primary user (PU) activity is modeled by the exponential ON-OFF model [12]. An ON (busy) state reflects a channel that is occupied by the PU. The OFF (idle) state shows a channel is available for other communications. A CRAHN follows the cognitive cycle model [13] for CR user activity, and implements channel selection at the link layer or at the routing layer. Link layer management in a CRAHN is the key to maximizing goodput for CR users. The CRAHN implements two channel-allocation schemes: random and sequential. In random allocation scheme, the CR user randomly chooses a channel from among the available channels. Under sequential channel allocation scheme, the CR user selects a channel via round

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robin algorithm. The impact of the channel allocation scheme in a CRASN is still an unexplored research area.

Therefore, in this paper, we propose an opportunistic MAC protocol based on Legacy IEEE 802.11 to intelligently cater to channel switching and to notify the next-hop neighbor to make changes accordingly for seamless communications. There is no impact from the channel switching scheme until it eventually tunes back to the receiver's receive channel. Hence, the proposed method reduces time waste by tuning to a new channel based on the channel selection scheme, improves overall efficiency, increases channel utilization, and eventually increases the overall goodput of the system. Opportunistic channel selection is essential in CRASN to choose the best channel for transmission. It is essential in improving the successful transmission probability of packets with less latency and it eventually increases the overall throughput of the system. Subsequently, energy efficiency can be achieved because more packets can be successfully transmitted within a given time. The role and responsibilities of opportunistic channel selection are to intelligently cater to channel switching and to notify the next-hop neighbor to make changes accordingly for seamless communications. Additionally, it can reduce the time waste by tuning to a new channel based on the channel selection scheme and hence increases the channel utilization and goodput. Therefore, we propose an opportunistic channel selection scheme (OCSS) to further improve the goodput of the system.

The rest of this paper is structured as follows. Section 2 discusses related work. In Section 3, we explain our proposed MAC protocol. Section 4 explains OCSS for the CRASN. Section 5 provides the details of the simulation environment and discusses the results. Finally, Section 6 concludes the paper.

2. Related Work

In [14], a preemptive opportunistic CR MAC protocol was proposed. The proposed protocol consists of three main phases: network initialization, reporting, and contention. An exclusive sensing and preemption mechanism are utilized by the proposed method to transmit data and to report sensing results without collision. The authors concluded that the proposed protocol outperforms over the existing CR MAC protocols in terms of the end-to-end delay and throughput. In [15], a distributed medium access control (DMAC) protocol based for CRAHNs was proposed to mitigate the hidden and exposed node problems of multichannel PUs and SUs. In the proposed protocol, transmit power is adjusted based on the distance between SU and communication pairs. Therefore, the channel reuse and throughput can be enhanced. The authors in [16] proposed an opportunistic MAC protocol for cognitive radio networks. In the proposed scheme, SU contains two transceivers. One transceiver is used for the control channel, while the other is used as a cognitive radio. The authors integrate the spectrum sensing at the physical layer and packet scheduling at the MAC layer, and dynamically utilize the available frequency spectrum.

The large amount of energy is consumed during the processing and transmitting operations of SU in CRANS [17,18]. Therefore, it is important to design a MAC protocol requiring less energy while showing high throughput. The authors in [19] introduced the energy efficient cognitive radio communications for IoT and proposed a channel selection criteria avoiding retransmission in CRAHNs for SUs to utilize the IoT based devices. Their results demonstrate that the proposed protocol shows high throughput with less energy consumption.

The minimum interference based channel selection technique was proposed in [20,21]. They select the channel having minimum interference. However, it lacks maximizing connectivity and in result increases the interference. In [22], authors select the channels covering the maximum number of neighbors. This approach induces interference on those particular channels. SURF [23] is the network layer solution that classifies the channels based on PU occupancy and connectivity. In SURF, a sender and receiver are closely located, and tune to the same channel to ensure effective and reliable connectivity. It also injects too much interference to adjacent channels. CRAHN already caters this problem in spectrum sensing block. Above mentioned channel selection schemes are based on cross-layer collaboration with the lower layers. Hence, the layered approach in communications is broken.

A CRAHN link layer solution based on an interface assignment policy was proposed by Pardeep and Vadiya [24]. It classifies the available interface as either fixed or switchable. A fixed interface stays on a specific channel for a longer time period, whereas a switchable interface can change to other channels. Therefore, all CR users classify one interface as the fixed interface and a second interface as switchable. When CR users require communications with a neighbor node, they adjust the switchable interface to the channel used by the fixed interface of the neighbor node and start transmitting. Every interface implements a spectrum-sharing scheme based on carrier sensing multiple access with collision avoidance (CSMA-CA) using acknowledgment (ACK) and frame retransmissions at the MAC layer. The CRAHN extends the MAC scheme to consider interference induced by PU on a CR user. When a CR user starts receiving a packet from another CR user, it checks two conditions: first is if the PU transmits on the same or an adjacent channel, and second, if the receiver starts transmission at the time of reception. Under either of those conditions, the CR receiver will calculate the power injected by the PU on the given channel and the actual signal-to-interference-plus-noise ratio (SINR). If the SINR is below a given threshold, the CR receiver discards the packet from the CR sender.

Under the IEEE 802.11 distributed coordination function (DCF) protocol [25], a sender ensures that the medium is idle before attempting to transmit. It selects a random backoff interval less than or equal to the current contention window (CW) size, based on the uniform distribution, and then decreases the backoff timer by 1 for each time slot in which the medium is idle. If the medium is determined as busy, the station will suspend its backoff timer until the end of the current transmission. Transmission commences when the backoff timer reaches zero. When there are collisions during transmission, or when transmission fails, the station invokes the backoff procedure. To begin the backoff procedure, the contention window size, CW, which takes an initial value of CW_{min}, doubles its value until it reaches the maximum upper limit, CW_{max}, and remains at the CW_{max} value, when reached, until it is reset. Then, the station sets its backoff timer to a random number uniformly distributed over the interval [0, CW] and attempts to retransmit when the backoff timer reaches zero again. If the maximum transmission failure limit is reached, the retransmission stops, CW is reset to CW_{min}, and the packet is discarded [26]. The access mechanism of IEEE 802.11 is shown in Fig. 1. Fig. 2 depicts the request to send (RTS) frame structure. In frame, RA is the address of the intended receiver. TA is the address of the sender. The duration value is the time in microseconds required to transmit the data frame, the clear to send (CTS) frame, the ACK frame, and three short interframe space (SIFS) intervals. The SIFS is the minimum interframe space. The sender transmits RTS to the receiver and on successful reception of the RTS frame, the receiver responds with a CTS frame. A frame check sequence (FCS) is used to determine integrity of the frame. Fig. 3 shows the CTS frame structure. The RA holds the RTS sender's address, which is copied from the RTS TA field. The duration value is calculated by subtracting the time required to transmit CTS and the SIFS interval from the duration field of the received RTS frame. The neighboring nodes of both sender and receiver, overhearing the RTS and CTS frames, defer their transmissions for the time specified in RTS/CTS duration field. Therefore, all the nodes maintain a

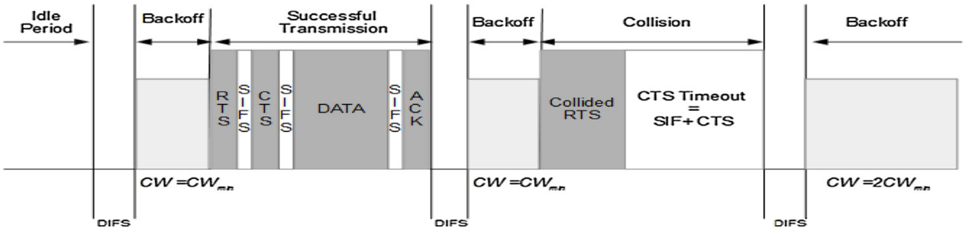


Fig. 1. Channel Access Mechanism of IEEE 802.11.

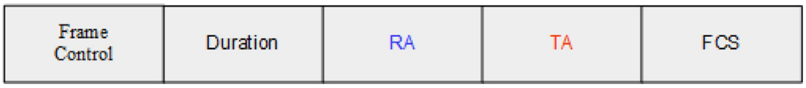


Fig. 2. IEEE 802.11 RTS Format.

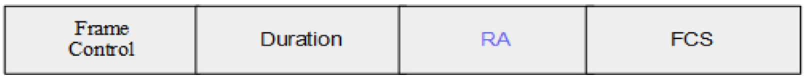


Fig. 3. IEEE 802.11 CTS Format.

Fig. 4. Modified IEEE 802.11 RTS Format.

network allocation vector (NAV), which is updated according to the RTS/CTS duration field. All nodes overhearing RTS/CTS remain idle and do not sense the channel for the NAV period.

As explained earlier, each CR user is equipped with both fixed and switchable interfaces. The channel assignment to an interface is assumed to use a distributed protocol. The fixed interface stays on the specified channel for time intervals longer than for the switchable interface. The CR user vacates the fixed channel as soon as the PU is detected. Afterwards, it switches to the new channel, and information about the new fixed channel being used by the fixed interface of the affected node is then broadcast to the neighborhood. The switchable interface can switch to the available channels to maintain network connectivity. The CRAHN relies on IEEE 802.11 MAC for its operation. Hence, if MAC is not properly modified according to the CR environment, it will hamper the overall performance of the system. The sender always switches to the new channel after a predetermined time, called the channel utilization interval. After the channel utilization interval, the system checks the channel switching policy [11]. If the channel switching policy is to always switch to the new channel, then for future transmissions MAC chooses the next channel according to the channel allocation policy. The sender starts transmission on the new channel. However, the receiver is listening to the fixed interface on the specified channel. Hence, transmission is only successful if it is gets to the receiver's receive channel. Therefore, a lot of communication time is wasted until the sender tunes back to that specific channel. The time wasted varies depending on the channel allocation policy.

Another notable factor that cannot be undermined is fairness in utilization of the channels. Increasing the fairness has a direct impact on channel utilization [27]. Hence, it may increase the overall goodput of the system.

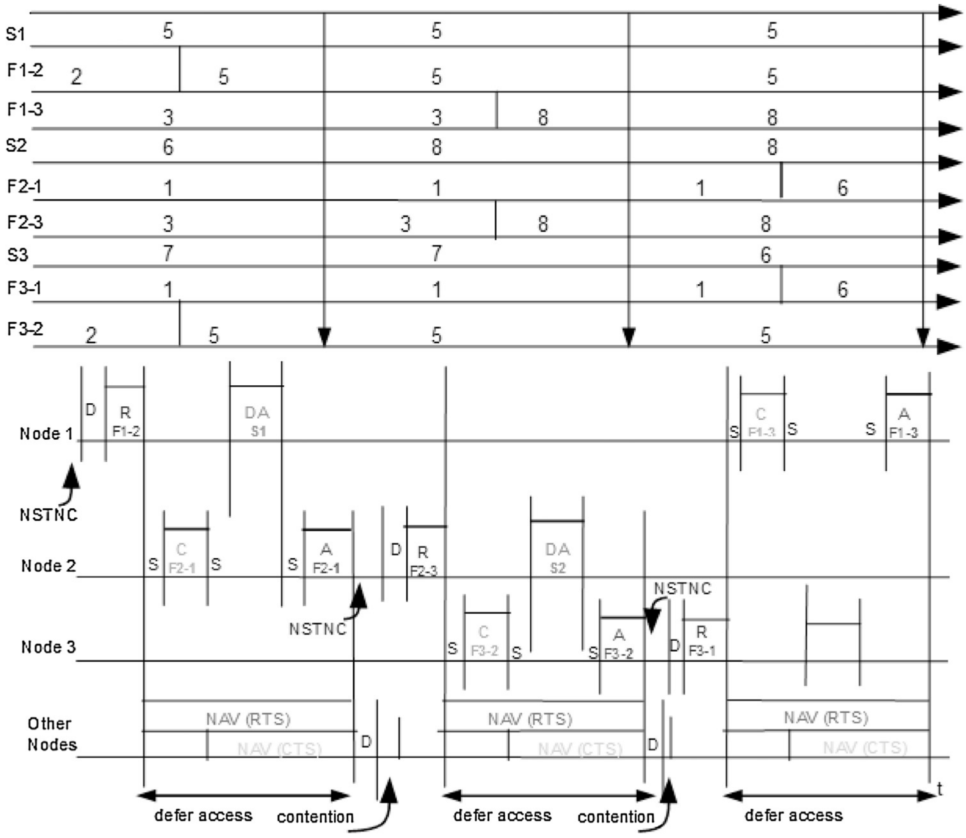
Recently, there have been researches based on game theory, artificial intelligent and genetic algorithms to implement the distributed and intelligent decision making algorithms in IoT sensors. A framework for data delivery in large-scale networks for disaster management was proposed in [28] proposed a framework for data delivery in large-scale networks for disaster management. The proposed approach is energy efficient and designed to optimize the current network status to guarantee Quality of Service (QoS).

3. IEEE 802.11 MAC protocol for CRASN

It is assumed that all the nodes initially know the fixed interface channel using some distributed protocol. Furthermore, it is not feasible to establish a common control channel (CCC) in licensed bands for a CRASN, as it is in the CRAHN [29]. All the nodes maintain a channel lookup table for each node in the network. We assume that the channel switching policy always switches to the new channel in a CRASN. Hence, the sender has to select the new channel after the channel utilization interval according to the channel allocation policy. Whenever the receiver receives a packet that did not arrive on the fixed interface channel, it is discarded. The maximum retry limit for RTS is 7, as specified in the IEEE 802.11 standard.

We modify the IEEE 802.11 standard RTS to accommodate the channel information for communications, as shown in Fig. 4. With a single-hop transmission, the information is intended for the receiver. In a multi-hop scenario, this channel information is also communicated for the next-hop. The receiver channel is set by the new switchable channel. The sender transmits RTS to the receiver. On reception of RTS, the receiver updates its lookup table by modifying its own fixed receive channel to the new switchable channel of the sender by extracting the channel field from the RTS. Furthermore, neighbors that overhear will update their lookup tables by modifying the receiver channel field. The receiver transmits CTS to the sender. After successful reception of CTS, the local channel lookup table is updated. All the nodes on the other channels are notified about the channel update of the receiver using the routing protocol. The sender starts transmitting on the new channel until the channel utilization interval expires.

Let us explain the whole procedure with the help of an operational example. Initially, we use a round robin algorithm to assign a fixed interface channel to each node. All the nodes are listening



Switchable Interface (S) Sender Node (1..N), Fixed Interface (F) Sender Node (1..N) - Receiver Node (1..N), DIFS = D, RTS = R, CTS = C, SIFS = S, DATA = DA, ACK = A, Node Switches to New Channel = NSTNC

Fig. 5. Timing Diagram for the Operational Example.

to a specified channel for any incoming frames. Fig. 5 portrays the timing diagram of the operational example. S_i denotes the switchable interface of sender node i. $F_i - j$ denotes the fixed interface of sender node i for receiver node j. D denotes the DCF interframe space (DIFS). R represents the RTS. C indicates the CTS. S designates the SIFS. DA marks the data. A denotes the ACK. NSTNC stands for "node switches to new channel." Fig. 5 shows three transmission cycles. In the first cycle, node 1 starts communications with node 2. Suppose that node 1 switches to channel 5 and conveys the new channel information to node 2 using RTS on F1 − 2. Node 2 updates the fixed interface channel accordingly and transmits CTS to the sender on F2 − 1. Upon successful reception of CTS, the sender updates the fixed interface channel local lookup table F1 − 2 for node 2 and notifies all nodes using the routing protocol about the channel update of the receiver. Hereafter, the sender starts transmission on channel 5. Assume that node 2 wins contention for next transmission cycle and starts communications with node 3. Node 2 switches to channel 8 and conveys the new channel information to node 3 using RTS on F2 − 3. Node 3 tunes to the new channel for the fixed interface and sends CTS to node 2 on F3 − 2. Henceforth, node 2 starts transmission. Presume that in the next transmission cycle, node 3 starts communications with node 1. Node 3 switches to channel 6 and conveys the new channel information to the receiver using RTS on F3 − 1. The receiver tunes to the new channel for the fixed interface and transmits CTS to the sender on F1 − 3. The sender starts communications with the receiver. This cycle repeats till the end of the communication.

4. Opportunistic channel selection scheme

Frequent channel switching is costly and affects the overall system performance in a CRASN. Another important factor is that all channels are homogeneous, having equal bandwidth. However, channel impairment, interference caused by adjacent channel traffic, and PU arrival actually make it heterogeneous bandwidth. This effect can be seen by monitoring channel utilization. Keeping all these considerations in mind, we propose an OCSS to select the new channel based on successful MAC data frames during the channel utilization interval in order to increase the goodput of the system. We divide our algorithm into two parts: training and channel selection based on data frame transmissions. The training phase runs once for all the channels at the beginning. Based on the result, phase 2 initializes and runs till the end of the algorithm. In phase 1, nodes choose all the channels in a sequential order for transmission during the channel utilization interval and total up the successful data frames. Afterwards, the nodes enter phase 2 and select the specific channel with the highest number of successful data frame transmissions, i.e., the best channel for communications. Thereafter, each node continues transmission in the new channel. The successful data frame transmissions are calculated again after the channel utilization interval expires. The node enters phase 2 again and checks whether the number of successful data frame transmissions is still the highest among the channels or not. If so, the node keeps using the same channel; otherwise, the channel may not be optimum anymore and then the node can switch to the channel that does have the highest number of successful data transmissions. This cycle repeats till the end of communications. This cycle repeats till the end of communications. The pseudo code is shown in Algorithm 1.

Algorithm 1. Opportunistic Channel Selection Scheme

```
{Phase 1: Training}
Input:
    Number of Channels
Output:
    New Channel
if all channels are not selected then
    select channel in sequence for transmission
end if
calculate the successful transmission of data frames
{Phase 2: Channel Selection based on transmission of data frames}
Input:
    Channels and number of successful data frame transmission
Output:
    New Channel
for select the channel having the most data frame transmission do
use the channel for transmission
end for
calculate the successful transmission of data frames
```

Here, we explain the whole procedure with the assistance of an operational example. In phase 1, node 1 selects all the channels for communication in sequence and calculates the number of successful transmissions for each one. Thereafter, it enters phase 2 to select the best channel according to the number of successful data frame transmissions for each one. Assume that node 1 transmits 1000 data frames on channel 2, which is the highest number of successful transmissions among all the channels. Node 1 selects channel 2 for communications and starts transmission. It again calculates the number of successful transmissions during the channel utilization interval. After the channel utilization interval expires, it enters phase 2 and checks the number of successful data frame transmissions. Suppose node 1 transmits 900 data frames on channel 2, which is still the highest number of successful data frame transmissions among all the channels. In this case, node 1 keeps using the same channel for communications. It again calculates the number of successful data frame transmissions during the channel utilization interval. Assume that node 1 transmits 500 data frames successfully on channel 2 during the channel utilization period. Subsequently, it enters phase 2 and again checks whether channel 2 has more successful data frame transmissions from among all the channels. It finds that channel 5 has more than channel 2. Node 1 switches to channel 5 and starts transmission. This process repeats till the end of communications. Fig. 6 illustrates a timing diagram for the OCSS operational example.

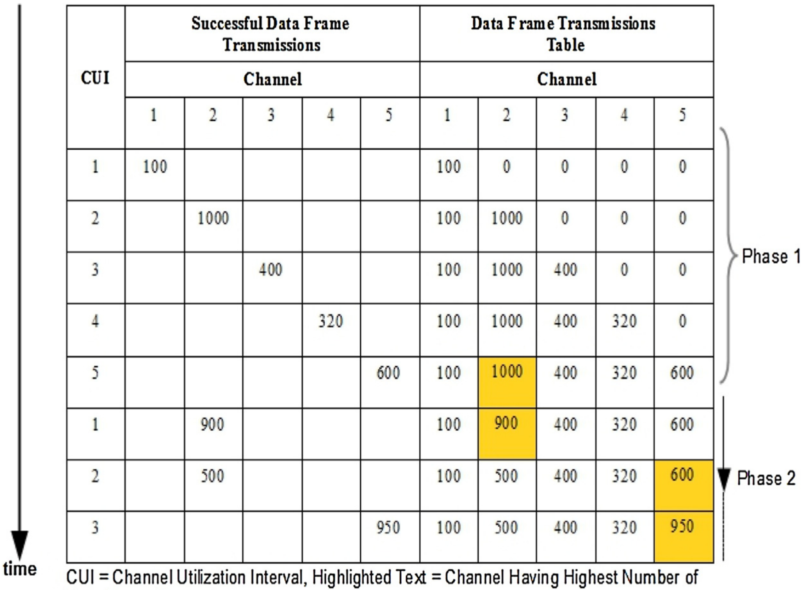
Table 1
Simulation parameters.

Paramters	Type/Value
Radio propagation model	Two-Ray Ground
Channel Type	Wireless
Network Interface Type	Wireless PHY
MAC Type	Standard/Opportunistic IEEE 802.11
Antenna Model	Omni
Transport Protocol	OHTP [8]
Queue Length	100 packets
Cognitive Radio Model	CRAHN
Channel Utilization Interval	1 s

5. Simulation model and discussion

We carried out an extensive set of simulations in network simulator (NS) version 2 [30]. In all the experimental situations, the simulation parameters were the same for a fair comparison. PU activity was kept independent and random during the simulations for all scenarios. The multi-channel CRASN contained 10 channels for communications. All channels were homogeneous. All the results were averaged over 20 simulation runs. The parameters used in the simulations are listed in Table 1 unless specified otherwise. We considered random sensors node placement in a multi-hop scenario to study the standard and opportunistic IEEE 802.11 MAC protocol. There are 20 sensors nodes in the network.

Fig. 7 shows mean channel utilization with increasing numbers of sender nodes for multi-hop communications with standard and opportunistic IEEE 802.11 MAC. The random channel selection scheme was used for channel assignment. The proposed opportunistic MAC protocol, after switching to the new channel, communicates this information to the next-hop using the RTS frame. The next-hop node tunes to the new channel and successfully receives the transmissions from the sender. Afterwards, an intermediate node keeps forwarding to the sink node. For channel switching by the intermediate node, the node follows the same procedure, conveys the information to the sink, and continues



CUI	Successful Data Frame Transmissions					Data Frame Transmissions Table				
	Channel					Channel				
	1	2	3	4	5	1	2	3	4	5
1	100					100	0	0	0	0
2		1000				100	1000	0	0	0
3			400			100	1000	400	0	0
4				320		100	1000	400	320	0
5					600	100	**1000**	400	320	600
1		900				100	**900**	400	320	600
2		500				100	500	400	320	**600**
3					950	100	500	400	320	**950**

CUI = Channel Utilization Interval, Highlighted Text = Channel Having Highest Number of Data Frame Transmissions

Fig. 6. Timing Diagram for Operational Example of OCSS.

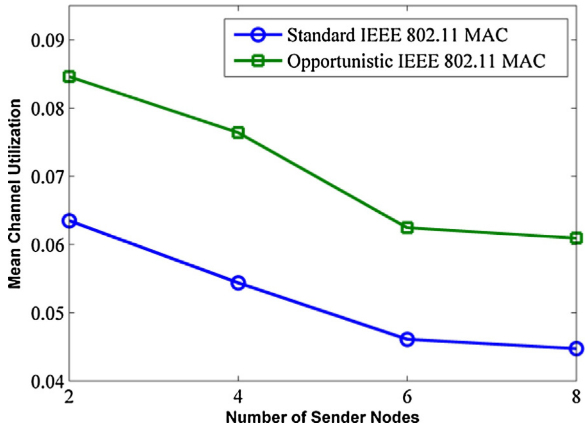


Fig. 7. Number of sender nodes versus mean channel utilization with a random channel allocation scheme.

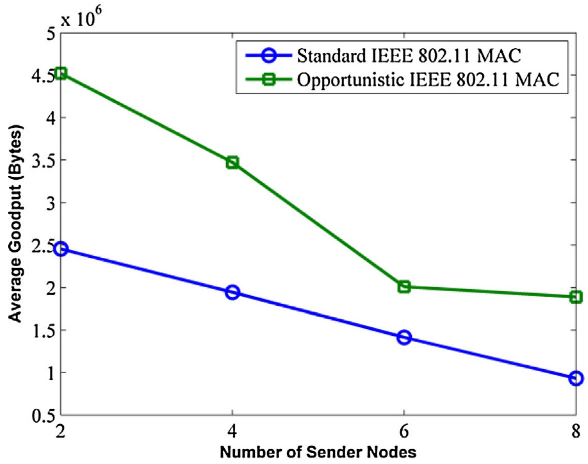


Fig. 8. Number of sender nodes versus goodput with a random channel allocation scheme.

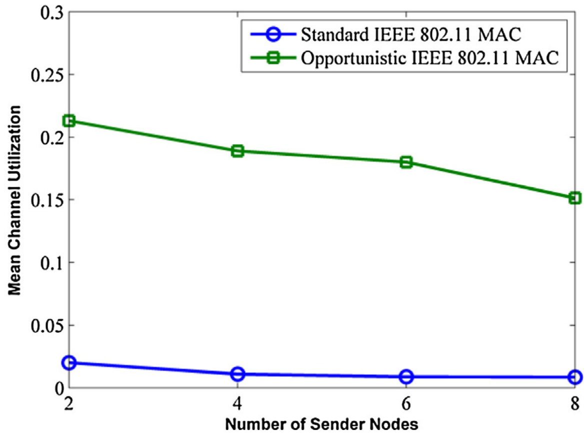


Fig. 9. Number of sender nodes versus mean channel utilization with a round robin channel allocation scheme.

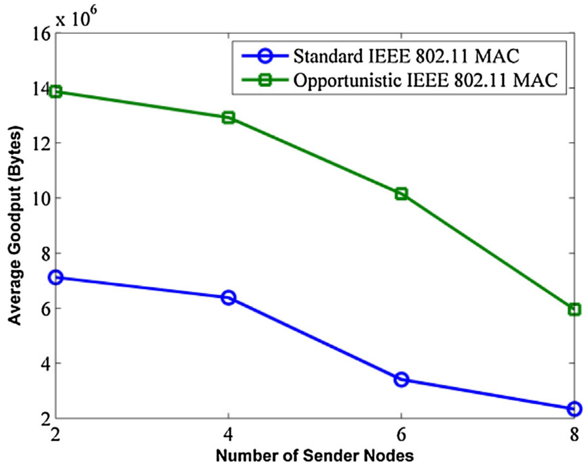


Fig. 10. Number of sender nodes versus goodput with a round robin channel allocation scheme.

transmission. With the standard MAC scheme, random channel selection chooses the new channel, and if it tunes to the receiver fixed interface channel, communications will be successful. Otherwise, the node has to wait till it switches back to the fixed interface channel. Mean channel utilization decreases as the number of sender nodes increases. An increasing number of sender nodes increases channel contention among them. Furthermore, as the number of wireless nodes increases within carrier-sensing range, it reduces mean channel utilization. One of the reasons for a decrease in channel utilization is the backoff state assignment algorithm [31,32]. Fig. 8 displays goodput attained in a multi-hop scenario by a random channel selection scheme with standard and opportunistic IEEE 802.11 MAC protocols. The results show that average goodput decreases as the number of sender nodes increases [33–36]. This means that the wireless network capacity scales sub-linearly with an increasing number of nodes. It is clearly visible from Figs. 7 and 8 that the opportunistic IEEE 802.11 MAC scheme performs better than the standard IEEE 802.11 MAC in terms of mean channel utilization and average goodput.

Fig. 9 exhibits the mean channel utilization of a sender node in multi-hop communications with opportunistic and standard IEEE 802.11 MAC. In this case, a round robin channel allocation scheme was used. Our suggested opportunistic MAC performs better than standard IEEE 802.11 MAC. The modified RTS frame conveys the new channel to the next-hop or receiver. However, under standard IEEE 802.11 MAC with a round robin channel selection scheme, the sender has to wait till it switches back to the receiver's fixed receive interface channel. Opportunistic MAC effectively increases channel utilization. Accordingly, it increases the goodput of the system.

Fig. 10 shows the goodput in multi-hop scenarios using round robin channel selection schemes with standard and opportunistic IEEE 802.11 MAC. The results indicate improvement goodput with our proposed opportunistic MAC protocol. Furthermore, mean utilization and average goodput decrease as the number of sender nodes increases. The reason is the same as explained earlier.

All the results acquired with the opportunistic IEEE 802.11 MAC show improvement in the goodput of the system. However, recurrent channel switching consumes time to switch to the new channel. Hence, it reduces transmission time and affects the system. Therefore, we proposed OCSS based on data frame transmissions for the opportunistic IEEE 802.11 MAC protocol. The goal is to increase the system goodput and avoid frequent channel switching. In this scenario, we placed nodes randomly in a 500 m × 500 m area. The nodes randomly picked a receiver for communications. The receiver could be a single hop or multi-hops away from the sender, depending on the location of the nodes. There were 20 nodes in the network. We increased the number of sender nodes communicating with the other nodes. The results were averaged over 20 simulation runs. Fig. 11 depicts the mean channel utilization from round robin selection, random selection, and OCSS with increasing numbers of sender nodes. It is evident from Fig. 11 that mean channel utilization decreases when increasing the number of sender nodes. The justification for the decrement in mean channel utiliza-

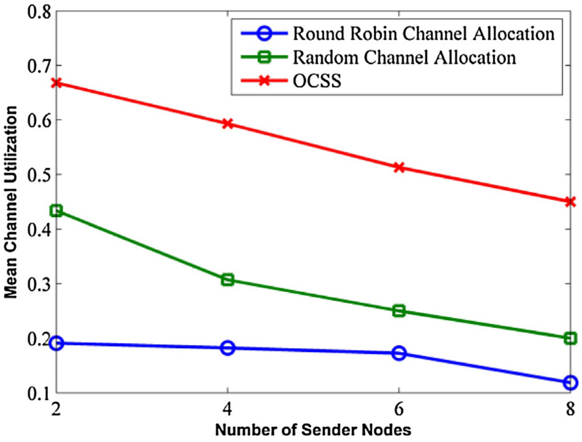


Fig. 11. Number of sender nodes versus mean channel utilization with round robin, random, and OCSS selection.

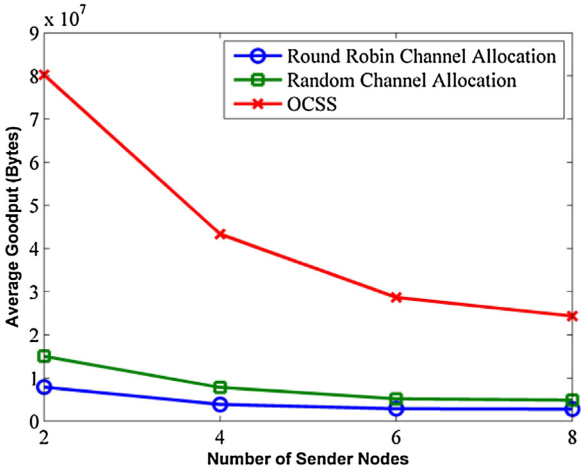


Fig. 12. Number of sender nodes versus goodput with round robin, random, and OCSS selection.

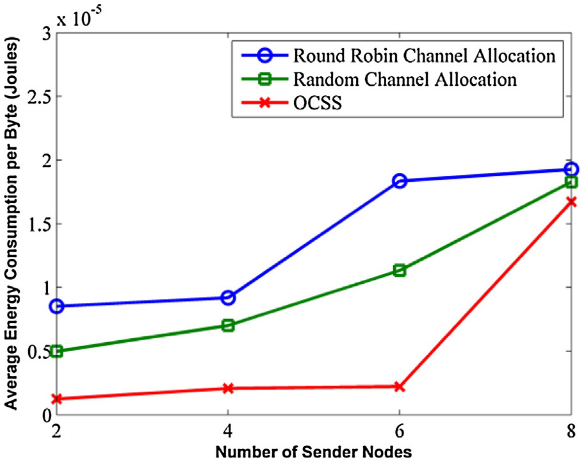


Fig. 13. Number of sender nodes versus energy consumption under round robin, random, and OCSS selection.

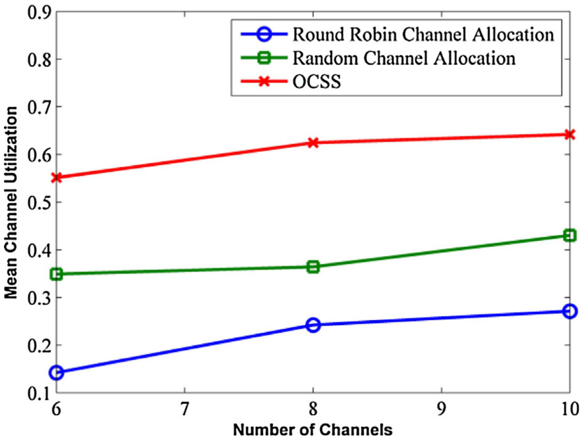


Fig. 14. Number of channels versus mean channel utilization with round robin, random, and OCSS selection.

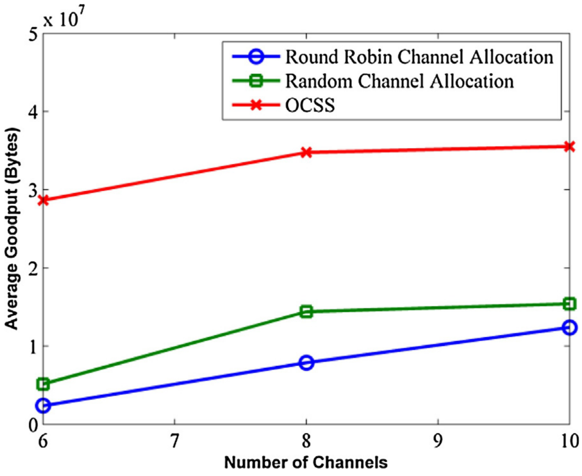


Fig. 15. Number of channels versus goodput with round robin, random, and OCSS selection.

tion was given earlier. OCSS reduces the chance of saturation for any channel, and distributes communications to all channels for different nodes. Increasing the number of sender nodes increases channel contention, and total transmission time is distributed among all the nodes. Hence, it adversely affects mean channel utilization. The decline in mean channel utilization decreases the goodput of the system. OCSS outperforms other channel schemes and increases channel utilization of the system. Consequently, it attains better average goodput, compared to the other schemes.

The average goodput of the system decreases when increasing the number of sender nodes. This is clearly depicted in Fig. 12.

Energy consumption is a key design consideration for sensor networks. We used the standard power consumption for each state as given by Feeney and Nilson [37]. Fig. 13 shows the average power consumption per byte when employing different channel selection schemes. The total energy is the sum of the energy consumed in idle, receive, and transmit states. It is clearly seen that OCSS consumes the least energy for communications, compared to round robin and random channel selection schemes. Hence, it increases the overall life span of the sensor nodes. Moreover, average energy consumption for transmission increases with the number of nodes, and nodes consume more energy in the idle state.

Fig. 14 represents the number of channels and mean channel utilization with round robin, random and OCSS channel selection. In this experiment, there are eight sender nodes, and we increase the number of channels to study the impact on mean channel utilization and goodput. Channel utilization increases when increasing the number of channels for all the channel selection schemes. OCSS performs well and attains higher channel utilization than round robin and random channel allocation schemes.

It is apparent from Fig. 15 that increasing the mean channel utilization directly affects system goodput, and consequently,

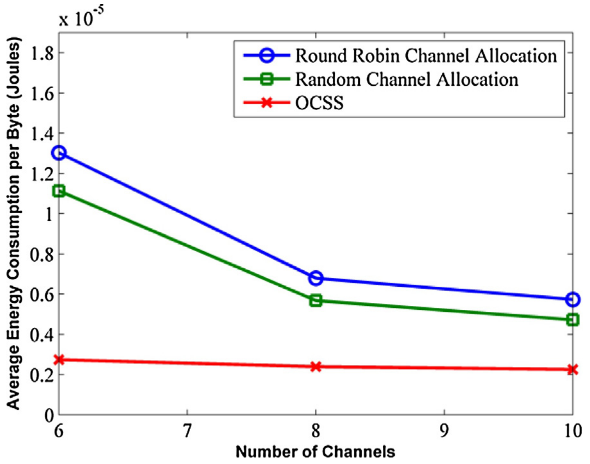


Fig. 16. Number of channels versus energy consumption under round robin, random, and OCSS selection.

OCSS achieves better average goodput. Moreover, it consumes less energy to transmit more bytes, in comparison to round robin and random channel selection schemes. Fig. 16 portrays the average energy consumption for communications with different channel selection schemes. The escalation in the number of channels increases the chance of transmission for nodes and requires less time. Hence, nodes are able to transmit more data while consuming less energy. OCSS attains higher goodput with the least energy consumption for communications. Thus, it saves precious energy in sensor nodes and extends the lifetime of the nodes.

6. Conclusion

In this paper, we investigate CRASNs using the standard IEEE 802.11 MAC protocol. The goal is to verify performance under channel switching. The channel switching policy always switches to a new channel. Therefore, the switchable interface changes to the new channel after the channel utilization interval. Hence, a node always switches to the new channel based on the channel selection scheme. First, we propose a modification to the standard 802.11 MAC protocol, naming it opportunistic IEEE 802.11 MAC. Opportunistic IEEE 802.11 MAC intelligently caters to the problem of channel switching, and the receiver synchronizes with the sender for seamless communications. We compare the opportunistic IEEE 802.11 MAC with standard IEEE 802.11 MAC using random and round robin channel selection schemes in a multi-hop experimental scenario. The outcome indicates betterment in terms of channel utilization and goodput of the system. Second, we propose an opportunistic channel selection scheme based on successful data frame transmissions for opportunistic IEEE 802.11 MAC. The aim is to reduce channel switching and increase the goodput of the system. We consider two network scenarios. In the first scenario, we vary the number of sender nodes. In the second scenario, we vary the number of channels available for communications. The results show that OCSS outperforms round robin and random channel allocation schemes in terms of channel utilization and goodput. Hence, it increases mean channel utilization and the goodput of the system. In the simulations with NS version 2, we used the default values of sensing and operational interval which are provided by the simulator. The sensing interval and operational interval of a CRAHN module is not optimized. If the sensing interval is too short, the probability of misdetection increases. On the other hand, longer sensing interval increases the sensing reliability but decreases the goodput of the system. This optimization problem of sensing interval under an imperfect sensing model can be a further work. Additionally, we intend to dig into the compulsive and strenuous problems of the optimization of channel selection by applying the machine learning algorithms to increase the goodput of the systems efficiently.

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