

A Multichannel MAC Protocol for IoT-enabled Cognitive Radio Ad Hoc Networks

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Abstract

Cognitive radios have the ability to dynamically sense and access the wireless spectrum, and this ability is a key factor in successfully building Internet-of-Things (IoT)-enabled mobile ad hoc networks. This paper proposes a contention-free token-based multichannel MAC protocol for IoT-enabled Cognitive Radio Ad Hoc Networks (CRAHNs). In this, secondary users of CRAHNs detect activity on the wireless spectrum and then access idle channels licensed by primary users. CRAHNs are divided into clusters, and the channel to use for transmission is determined dynamically from the probability of finding idle primary-user channels. The token-based MAC window size is adaptive, with adjustment according to actual traffic, which reduces both end-to-end MAC contention delay and energy consumption. High throughput and spatial reuse of channels can also be achieved using a dynamic control channel and dynamic schemes for contention windows. We performed extensive simulations to verify that the proposed method can achieve better performance in mobile CRAHNs than other MAC schemes can.

Keywords: internet of things IoT, medium access control, cognitive radio ad hoc networks, multichannel, MAC, contention-free

1. Introduction

Internet of Things (IoT) is a global network of devices, each with a unique address and links to other devices. It allows devices (and their users) to communicate with other devices/users at any time, independent of location, network, or service provider. In recent years, the IoT has become a topic of intense interest within the field of communication technology. In Machine-to-Machine (M2M) communication with portable devices, communication methods that depend on maintaining a fixed location will not meet the needs of human users, who will want to move the devices, so communication on the so-called Internet of Mobile Things has become a common application [1]. IoT applications such as smart sensors, smart home applications, and monitoring devices must be connected by wireless transmission technology to achieve ubiquitous information access and seamless communication if they are to fulfill the promise of the IoT [2].

Mobile ad hoc networks use a peer-to-peer, infrastructure-free decentralized wireless network and are easy to construct. Because of this, there are many practical uses for such networks, including for personal and home use, military use, and facilitation of emergency rescue operations. The nodes of such networks can be M2M IoT nodes such as smartphones and smart-sensor nodes. A Mobile Ad Hoc Network (MANET) is a typical example of an IoT-enabled mobile network [3-4].

So-called cognitive radios can make networks more efficient. The main feature of cognitive radio is that it can both sense and access different channels on the wireless spectrum. When a part of the spectrum licensed by Primary Users (PUs) is idle, Secondary Users (SUs) can take advantage of this. SUs temporarily uses the licensed spectrum to complete communication

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without interfering with PUs and without interfering with other SUs, thereby improving the utilization of the wireless spectrum. This concept is part of the next generation of network technology and is known as dynamic spectrum access to form cognitive radio networks. A network of IoT devices with cognitive radios will be able to use a dynamic spectrum access scheme to find an available channel in a way that does not interfere with PUs' ability to rely on IoT communication within MANETs.

In [5-6], the authors proposed a busy tone-based MAC protocol. This protocol uses data-transmission priority to reduce delay. Nodes access a channel by checking the broadcast busy tone and then transmitting data when the channel is available. The busy tone prevents the channel from being temporarily grabbed by a general data node. However, under this method, when the amount of data (such as multimedia materials) to be transmitted increases, the functionality of the busy tone will not be sufficient, and the amount of delay for data and multimedia delivery will not be guaranteed.

In Time-dynamic Multiple Access (TDMA) schemes, as a method to optimize resource utilization, each node is assigned a time slot to avoid collisions caused by contention. In [7], the author proposed a decentralized TDMA mechanism for adaptive control of data traffic. In [8], the authors proposed the TDMA-based "Distributed Packet Reservation Multiple Access" (D-PRMA) scheme, in which higher transmission priority is given to data and multimedia nodes than to general data nodes. However, the number of time slots allocated to the data and multimedia nodes in D-PRMA is determined from the total number of nodes, meaning that when the number of nodes increases, the system will not scale well.

In another approach, a TDMA mechanism that combines data and multimedia transmission in a hybrid MAC protocol based on the carrier-sense with multiple access with collision avoidance protocol (i.e., CSMA/CA) has been proposed [9] for ensuring the quality of service (in terms of time delay) for data and multimedia nodes and maximizing channel utilization for general data transmission. In [10-11], the authors suggest that the contention-window size in the MAC protocol should be adjusted according to node density and node movement speed to ensure that system performance is not degraded owing to changes in data traffic.

Clustering is the process of partitioning nodes in a network into many clusters for the purpose of improving system performance. In general, the clustering of nodes that sense the wireless network can improve the scalability and stability of the system. Clustering also provides opportunities for nodes in clusters to cooperate on channel sensing and access [12-13].

In an IoT-based wireless sensor network using TDMA, the nodes are partitioned into multiple clusters. A MAC protocol to reduce energy consumption and delays by collecting data within clusters (intra-cluster data) and between clusters (inter-cluster data) has been proposed [14]. IEEE 802.11ah is a MAC protocol that operates over long distances at low frequencies with low power consumption and allows for a large number of M2M IoT nodes [15]. However, the MAC protocols in [14-15] cannot satisfy the need for differentiated Quality-Of-Service (QoS) within IoT MANETs.

An opportunistic spectrum access MAC protocol has also been proposed for a cluster-based multichannel wireless network [16]. The authors prove that the nodes using this protocol must repeatedly contend without clustering. Multiple occurrences of contention lead to increased delays in data delivery, and increased delays reduce system performance.

In [17], the authors proposed a Token-based MAC Protocol (TA-MAC) for a mobile network. TA-MAC operates in a fixed channel and two-hop environment. However, in real environments, channels are a relatively rare and valuable resource. Thus, most systems do not have a fixed channel on which they operate. In [18], the authors proposed a Distributed MAC Protocol (DAH-MAC) for a MANET. However, DAH-MAC can only be used in a fully interconnected one-hop environment and only in a single-channel environment. In practice, general MANETs are multi-hop and multichannel environments.

Toward addressing the deficits of existing protocols, in this paper, a contention-free token-based MAC protocol is proposed for an IoT-enabled multichannel multi-hop MANET based on cognitive radio. In the proposed protocol, the nodes will be divided into some clusters, and the proposed contention-free reservation mechanism is based on a token ring to ensure QoS for IoT delay.

The remainder of this paper is organized as follows. The system model is introduced in Section 2. The detailed token-based MAC protocol for IoT-enabled MANETs is introduced in Section 3. Performance evaluation is discussed in Section 4, and the final section presents our conclusions.

2. System Model

In [17], the authors proposed a Token-based Adaptive MAC Protocol (TA-MAC) for an IoT MANET. TA-MAC can be used only in an existing single-channel and two-hop environment. However, in the real world, channels are a relatively rare and valuable resource. Thus, most systems do not operate on a fixed channel, and the system performance when using a single channel will be much poorer than that when using multiple channels.

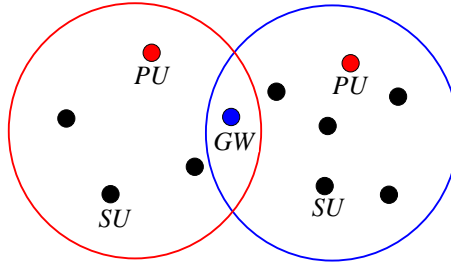


Fig. 1 System model for CR-based IoT-enabled multichannel MANET

The use of multiple channels will solve the problems associated with the single-channel restriction if the contention among Cognitive Radio (CR) devices can be overcome in a CR-based IoT-enabled MANET. Furthermore, though TA-MAC can be applied to two-hop environments, there are still many problems to be solved before TA-MAC can be applied in multichannel and multi-hop MANETs. These questions include avoiding interference with channel use by PUs, switching between PU channels, and ensuring QoS. The system model for a CR-based IoT-enabled multi-channel MANET is shown in Fig. 1.

2.1. Clustering

In the paper, a CR-based MAC protocol will be designed for IoT multichannel and multi-hop MANETs. In these networks, the system nodes will be partitioned into several one-hop clusters, meaning the nodes in each cluster must be completely interconnected within the node. Each cluster node will sense the PU channels. The idle PU channel with the highest probability of being successfully used will be chosen as the data channel, ensuring the best stability of the obtained data channel. The cluster formation and cluster head are determined by the degree of importance [18].

2.2. Dynamic data channel

The token-based MAC protocol presented in this paper is based on the TDMA scheme. Each SU in the token-based MAC protocol must receive a token to transmit a message. In traditional TDMA, each node can transmit messages in its designated time slots, which are assigned in advance. In the proposed system, the receiver and transmitter information will be included in the token and exchanged with the next transmitter. When a node receives a token, it checks the destination address to see whether the address matches its own. If the destination address is not the node's address, the node discards the token; otherwise, it accepts the token.

Choosing the data channel is done via a dynamic scheme, with the choice determined by the probability of successfully picking an idle PU channel. Only one transceiver is used for each SU node to reduce the hardware cost and improve the practical application. The cluster heads will sense the PU channels, and one of the idle channels will be selected as the data channel. The cluster head then broadcasts the data channel to the cluster members by use of a Hello frame. The chosen channel is the dynamic data channel.

3. Detailed Token-based MAC Protocol for IoT-enabled MANET

In this paper, time is divided into a number of superframes, each of which has two phases (Fig. 2). Table 1 shows the symbols used in the data-channel design for our proposed token-based MAC protocol.

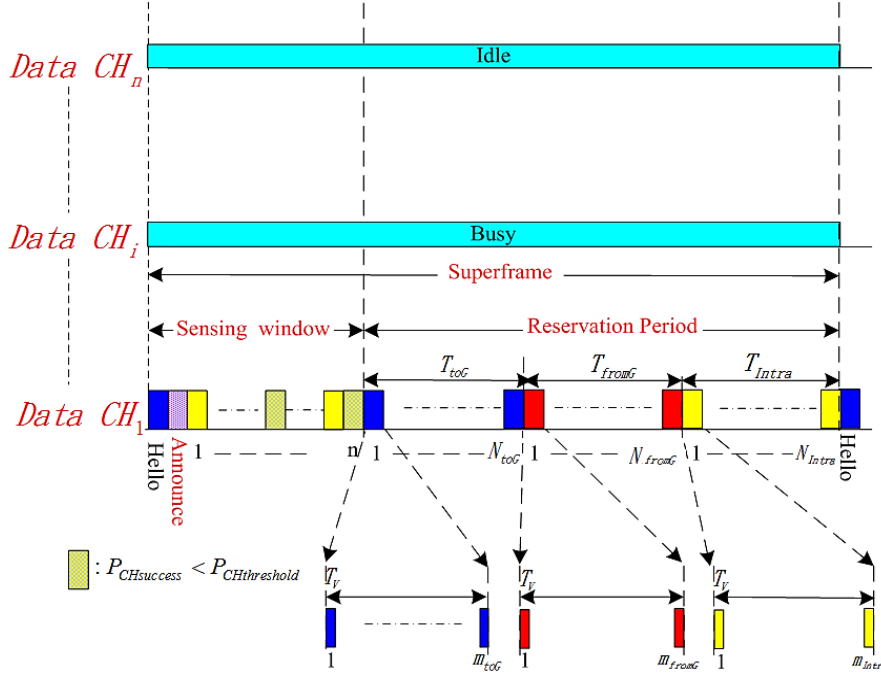


Fig. 2 Data-channel design of CR-based IoT-enabled multichannel MANET

Table 1 Symbols used in describing data-channel design for our proposed token-based MAC protocol

T_{toG}	Length of sub-periods to gateway	m_{fromG}	Number of mini-slots from gateway
T_{fromG}	Length of sub-periods from gateway	m_{Intra}	Number of mini-slots inside cluster
T_{Intra}	Length of sub-periods inside cluster	T_v	Length for each data time slot
N_{toG}	Number of sub-periods to gateway	$m_{toG} N_{toG} T_v$	Length of T_{toG}
N_{fromG}	Number of sub-periods from gateway	$m_{fromG} N_{fromG} T_v$	Length of T_{fromG}
N_{Intra}	Number of sub-periods inside cluster	$m_{Intra} N_{Intra} T_v$	Length of T_{Intra}
m_{toG}	Number of mini-slots to gateway	$P_{CHthreshold}$	Success probability threshold

3.1. Control channel

In Fig. 2, the reservation period is divided into three sub-periods: T_{toG} , T_{fromG} , and T_{Intra} . The sub-periods have N_{toG} , N_{fromG} , and N_{Intra} time slots, respectively. Each time slot of T_{toG} , T_{fromG} , and T_{Intra} contains some mini-time slots, named m_{toG} , m_{fromG} , and m_{Intra} , respectively. Each mini-time slot has length T_v , indicating that each node can send data within the slot T_v period if the token is obtained at this time. Therefore, the lengths of T_{toG} , T_{fromG} , and T_{Intra} are $m_{toG} N_{toG} T_v$, $m_{fromG} N_{fromG} T_v$, and $m_{Intra} N_{Intra} T_v$, respectively.

In the sub-period T_{toG} , SU nodes send data to the SU gateway in the same cluster, and the gateway node acts as the relay node for multi-hop connections. In the sub-period, the SU gateway sends data to SU nodes in the same cluster. In the sub-period T_{Intra} , SUs transmits (pairwise) within the same cluster. When the SU source node and the SU destination node are not in the same cluster, an appropriate token must be acquired before the end of the two sub-periods T_{toG} and T_{fromG} , and the

data is then sent in each of the selected sub-time slots m_{toG} and m_{fromG} . If the SU source node and the SU destination node are in the same cluster, then an appropriate token is acquired and transmission is completed in the sub-period T_{Intra} . Whenever a SU node sends data, the token is also sent in a round-robin scheme; the token contains the ID of the next SU node. The selection of the next SU node is determined by the SU sender that holds the token. The token is preferentially sent to a SU node that has not yet obtained the token during the superframe to ensure that allocation of transmission opportunities is fair.

3.2. Detailed token-based MAC protocol for IoT-enabled MANET

Algorithm 1 shows pseudocode for selection of the dynamic data channel in the token-based MAC protocol. Algorithm 2 shows pseudocode for our proposed token-based MAC protocol in cognitive radio ad hoc networks (CRAHNS).

Algorithm 1: Dynamic data channel selection in token-based MAC protocol.

- Clusters formation completed.
- Each SU node sends an important degree to its one-hop neighbors.
- The SU node with the highest degree of importance among one-hop neighbors is chosen as SU_{head} and announces itself as the cluster head.
- The data channel in each cluster will be selected by the cluster head according to an important degree for each channel.

if PU active on equals data channel then.

SU_{head} searches a new data channel according to an important degree.

else

continue

end if

Algorithm 2: Token-based MAC protocol in CRAHNS.

- Initially, the frame lengths of T_{toG} , T_{fromG} , and T_{Intra} are equal
- SU_i judges its own role and waits for a token in the sub-periods T_{toG} , T_{fromG} , and T_{Intra} .
- SU_i checks the number of token accesses among one-hop neighbors, using a token-ring node table
- SU_i sends the token to the next SU, choosing the SU with the lowest number of token accesses

3.3. Sensing-window phase

The time-synchronization function of IEEE 802.11 is used for synchronization, and the cluster head transmits a Hello frame to all cluster members. In previous studies, it is typical to switch to each potential channel when searching for a channel, but listening to each channel consumes more energy than selective listening. Additionally, sensing each PU channel may fail due to sudden activity by a PU or to sensing errors. Each SU must thus check for each PU in each time slot in the sensing-window phase. The duration of each sensing time slot is about the same as the round-trip time when the SU listens for a PU. Therefore, we will use the probability of success to decide whether to listen to each channel; this proposed scheme reduces energy consumption. The number of time slots in the sensing-window phase is the number of PU channels. Each cluster head can adjust its success probability threshold ($P_{CHthreshold}$) so as to achieve the highest efficiency. If a SU cannot find a PU spectrum to use during the duration of the beacon interval, then this SU must find a PU channel during the next

beacon interval. Each communication will be attempted a maximum of three times. After three failures, communication is considered to have failed. When communication has failed, it can remain and contend with other communications in later windows.

3.4. Reservation-period phase

The reservation period divides the time into a number of time slots and is subdivided into three sub-periods. Any node that wants to transmit data must take turns during this period so as to achieve fairness in a probabilistic sense. A SU node that obtains the token can transmit data, with the token piggybacked on the data. The token is granted to the next node based on a fairness scheme. If a node is given the token but has no data to transmit, the token is passed to the next node.

3.5. MAC protocol dynamic-data-channel table maintenance and frame design

To follow the above steps, each SU node must maintain a channel-status recording table, a Hello recording table, and a token-ring node table. In the IoT-based multichannel MANET, the hidden problems of inter-cluster and intra-cluster communications can be overcome by the TDMA scheme, and QoS for data transmission delay can be ensured. In addition, the proposed method also reduces energy consumption by nodes and increases system throughput.

Table 2 Symbols used in control frames for our proposed token-based MAC protocol

$N_{HelloSuccess}$	Number of successes	$P_{CHsuccess}$	Probability of successful channel
$N_{HelloFail}$	Number of failures	$P_{CHthreshold}$	Minimum critical probability
$P_{HelloSuccess}$	Probability of success	$Neighbor_{ID}$	Number of one-hop neighbors
DVC_{ID}	ID for dynamic data channel	Num_{token}	Number of access tokens received
$Head_{ID}$	ID for cluster head	$Role$	Role of neighbor node
$N_{CHsuccess}$	Number of successes for each channel	$m_{Intra}N_{Intra}T_V$	Length of T_{Intra}
N_{CHfail}	Number of failures for each channel	$P_{CHthreshold}$	Success probability threshold
$Node_{ID}$	ID for the node	$Status$	Join, leave, or dissolve in the cluster
$NextHop_{ID}$	Node ID of the next-hop	SU_{idx}	IDs for SU neighbor
SU_{sender}	SU sender	$Reserve_{slot}$	Number of reserved time slots
$SU_{receiver}$	SU receiver	$Head_{NBRi}$	Number of the neighbor cluster for $Head_{ID}$
$Power_{res}$	Remaining battery energy	DVC_{NBRi}	Data channel ID

3.5.1. Hello recording table

Each SU node must maintain a Hello recording table that records the number of successes ($N_{HelloSuccess}$), the number of failures ($N_{HelloFail}$), and the probability of success ($P_{HelloSuccess}$). The Hello recording table has the following fields (see Fig. 3): DVC_{ID} , $Head_{ID}$, $N_{HelloSuccess}$, $N_{HelloFail}$, and $P_{HelloSuccess}$. DVC_{ID} is the dynamic data channel selected by the cluster head. $Head_{ID}$ is the ID of the cluster head.

DVC_{ID}	$Head_{ID}$	$N_{HelloSuccess}$	$N_{HelloFail}$	$P_{HelloSuccess}$
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Fig. 3 Hello recording table

3.5.2. Channel-status recording table (CSRT)

DVC_{ID}	$Head_{ID}$	$N_{CHsuccess}$	N_{CHfail}	$P_{CHsuccess}$	$P_{CHthreshold}$
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Fig. 4 Channel-status recording table

The cluster head maintains a CSRT, which contains the number of successes ($N_{CHsuccess}$) and failures (N_{CHfail}) for each channel. The SU node selects a channel according to the probability of success. DVC_{ID} is the dynamic-data channel selected by cluster head. $Head_{ID}$ is the ID of the cluster head. $P_{CHsuccess}$ indicates the success probability for one channel. $P_{CHthreshold}$ indicates the minimum threshold for the success probability of one channel. The CSRT has the following fields (see Fig. 4): DVC_{ID} , $Head_{ID}$, $N_{CHsuccess}$, N_{CHfail} , $P_{CHsuccess}$, and $P_{CHthreshold}$.

3.5.3. Token-ring node table (TRNT)

Each SU node must maintain a TRNT to record the status of the tokens in the neighbor nodes in the cluster. The TRNT has the following fields (see Fig. 5): DVC_{ID} , $Head_{ID}$, $Neighbor_{ID}$, Num_{token} , and $Role$. DVC_{ID} is the ID of the data channel selected by cluster head. $Head_{ID}$ is the ID of the cluster head. $Neighbor_{ID}$ contains a list of the IDs for one-hop neighbor nodes. Num_{token} indicates the number of times that the SU node received the token. $Role$ indicates whether the node is a cluster head, or cluster member or cluster gateway.

DVC_{ID}	$Head_{ID}$	$Neighbor_{ID}$	Num_{token}	$Role$
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Fig. 5 Token-ring node table

3.5.4. Frame format

Hello frame: The synchronization frame sent by the cluster head to the SU neighbor node. The frame includes two fields (see Fig. 6): DVC_{ID} and $Head_{ID}$. DVC_{ID} is the ID of the data channel selected by the cluster head. $Head_{ID}$ is the ID of the cluster head.

DVC_{ID}	$Head_{ID}$
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Fig. 6 Hello format

Announce frame: A node is to join or leave the cluster or, for the cluster head, to dismiss the cluster. Including the following fields: DVC_{ID} , $Head_{ID}$, $Node_{ID}$, and $Status$ (Fig. 7). DVC_{ID} is the ID of the data channel selected by the cluster head. $Head_{ID}$ is the ID of the cluster head. $Node_{ID}$ is the node ID. $Status$ indicates whether the node wants to join, leave, or dissolve the cluster.

DVC_{ID}	$Head_{ID}$	$Node_{ID}$	$Status$
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Fig. 7 Announce format

The token frame is the format of the field is as follows (see Fig. 8):

$NextHop_{ID}$	DVC_{ID}	$Head_{ID}$	SU_{sender}	$SU_{receiver}$	SU_{id1}	— —	SU_{idn}	$Reserve_{slot}$	$Power_{res}$
		DVC_{NBRi}	$Head_{NBRi}$	— —	DVC_{NBRn}	$Head_{NBRn}$			

Fig. 8 Token format

There is the node ID of the next hop. DVC_{ID} is the ID of the data channel selected by the cluster head. $Head_{ID}$ is the ID of the cluster head. SU_{sender} is the sending SU. $SU_{receiver}$ is the receiving SU. $SU_{id1}, \dots, SU_{idn}$ are the IDs of the SU neighbors. $Reserve_{slot}$ is the number of contiguous time slots that one SU can occupy. $Power_{res}$ is the battery energy remaining

in the SU transmitting node DVC_{NBRi} is the ID of the data channel selected by the cluster head of the neighboring cluster i . $Head_{NBRi}$ is the ID of the cluster head of the neighboring cluster i .

4. Performance Evaluation

In our simulation, 10 different topologies are created using 10 different seeds. The results of our simulation show the average values of the 10 different seeds. The simulation is implemented in the C programming language and run on the Linux operating system. The traffic is assumed to be uniformly distributed across all nodes with various overall loads. The number of new connections per second is given as an arrival rate. The number of terminated connections per second is given as a departure rate. The multiplicative inverse of the departure rate is also the average lifetime of a connection. ‘‘PU ON’’ indicates that a PU is in the active state. ‘‘PU OFF’’ indicates that a PU is in the idle state. Energy detection is easy to implement and commonly used as a spectrum-sensing scheme for SUs to sense the active status of PUs [19]. The PU active/non-active state is randomly determined in our simulation. The SUs is not always-on (i.e., not always transmitting messages), and the number of transmitting SUs is not constant. Therefore, the number of active PUs and SUs is not constant, which makes the token-based MAC protocol proposed in this paper scalable. Because the resources of PUs are assigned to and paid for by particular communities (companies, etc.), control by a PU is not impossible in real applications, with the consequence that cognitive radio is a key component of good performance by IoT-enabled MANETs. In all cognitive-radio applications, each node can use two transceivers for transmitting and receiving. In this paper, we need only one transceiver to support both transmission and receiving; we do not need two separate channels.

In some scenarios, such as a large assembly, a parade, or a downtown area, there may be hundreds of devices. In the previously described scenario, the requirements for channel bandwidth were high but temporary. In all scenarios, channels are limited resources and controlled by some PUs. Therefore, a key factor effectively delivering on the promise of the IoT is the cognitive radio technique. In our simulation, the number of SUs was set to 400 and the number of PUs to 8. The transmission ranges for SUs and PUs were 200 m and 300 m, respectively. The bounding region has dimensions 600 x 600 m². The mean ‘‘PU ON’’ duration is 300 s. Table 3 shows the parameter values used in the simulation of our proposed token-based MAC protocol.

Table 3 Parameter values for our simulation of the proposed token-based MAC protocol

Simulation time	10000 s	Number of PUs	8
Number of SUs	400	Departure rate	0.5
Bounding region	600 m*600 m	Arrival rate	1,, 512
Transmission range of SU	200 m	PU sensing error	0%, 10%, 20%, 30%
Transmission range of PU	300 m	Mean duration of ‘‘PU ON’’	300 s
Number of active PUs	0, 1, 3	Number of seeds	10

The channel spatial reuse, ε , is defined as the number of SU_s that can simultaneously use one idled licensed channel.

We define ε as follows:

$$\varepsilon = \frac{\sum_{i=1}^n \sum_{j=1}^m C_{single}(i, j)}{\sum_{i=1}^n C_{multiple}(i)} \quad (1)$$

Therefore, the throughput per contention window size for this CRAHN, denoted by ζ , is defined as follows:

$$\zeta = \frac{\varepsilon R_{data} T_s E[CH_{vacant}]}{((n-1)R_{data} + R_{ctrl} E[T])} \quad (2)$$

where R_{data} is the data rate for a PU licensed channel, R_{ctrl} is the data rate for a control channel, T_s is the duration of each time slot, and $E[T]$ is the average duration of a beacon interval for the token-based MAC.

From Fig. 9, we know that the token-based MAC produced the highest spatial reuse of channels when the arrival rate was 512. We observed that the highest channel spatial reuse in the token-based MAC was 4.33 (corresponding to a channel-detection probability = 1.0 and active PUs = 1).

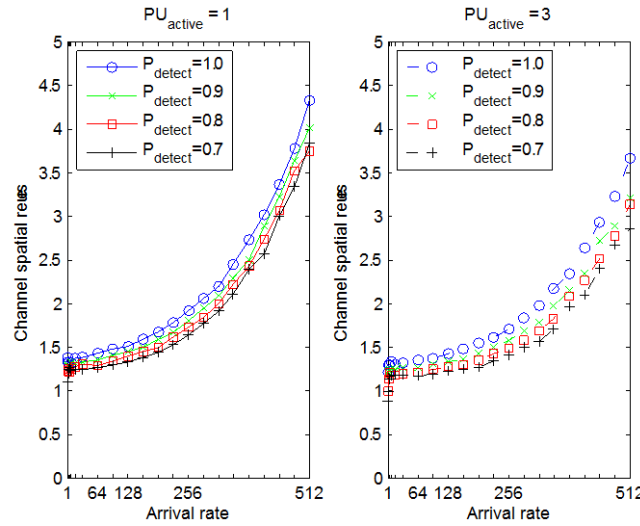


Fig. 9 Comparison of channel spatial reuse in token-based MAC as a function of arrival rate under different probabilities of channel detection in a multichannel CRAHN

Fig. 10 shows the throughput in the token-based MAC as a function of the arrival rate in a multichannel CRAHN. We observed that the highest throughput in the token-based MAC was 8,768 bps under an arrival rate of 256 (corresponding to a channel-detection probability = 1.0 and active PUs = 1).

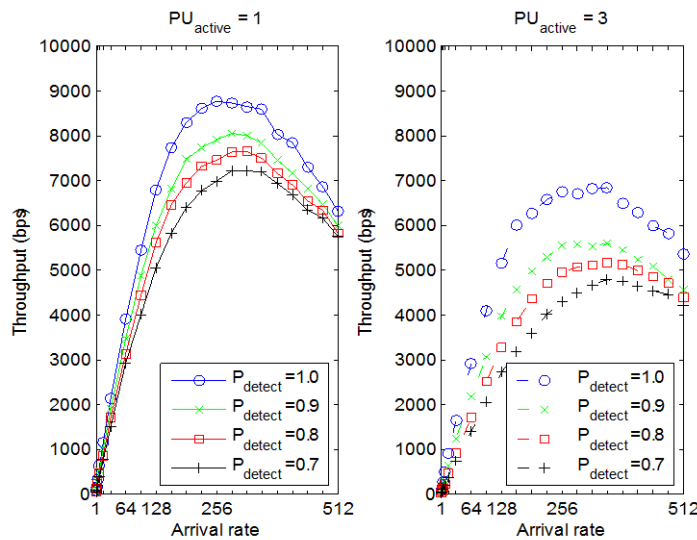


Fig. 10 Comparison of throughput in token-based MAC as a function of arrival rate under different probabilities of channel detection in a multichannel CRAHN

Fig. 11 shows the average MAC contention delay per hop in token-based MAC as a function of the arrival rate in a multichannel CRAHN. The average MAC contention delay per hop for token-based MAC ranged from 12.61 to 14.59 slots (corresponding to a probability of channel detection = 1.0 and active PUs = 1) as a function of arrival rate.

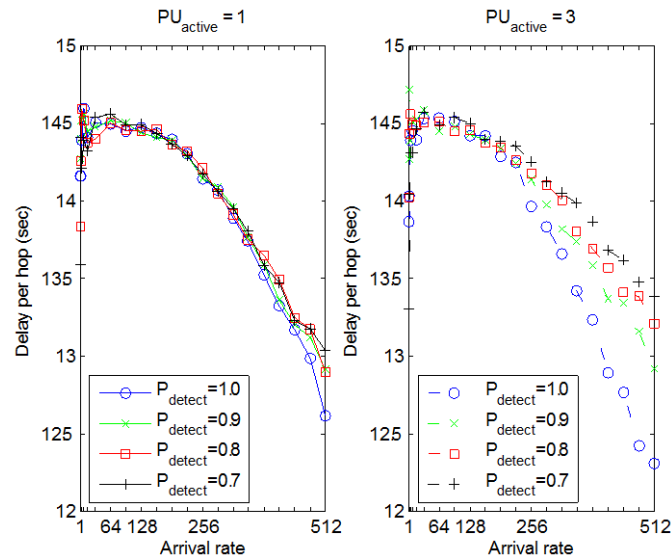


Fig. 11 Comparison of MAC contention delay per hop in token-based MAC as a function of arrival rate under different probabilities of channel detection in a multichannel CRAHN

5. Conclusions

This paper proposed a protocol that used a token-based dynamic-data channel and dynamic-contention window to achieve high channel spatial reuse, high throughput, energy-efficiency, and a low MAC contention delay. In this paper, the proposed token-based MAC scheme effectively achieved not only lower MAC delay but also better per-hop energy efficiency. The simulation results had a best channel spatial reuse for token-based MAC of 4.33, a maximum throughput of 8,768 bps under an arrival rate of 256, and a MAC contention delay per hop of 12.61 to 14.59 slots, with the probability of channel detection at 1.0 and number of active PUs at 1 for all of these values. It is notable that the channel spatial reuse and throughput decreased when the probability of channel detection decreased.

Conflicts of Interest

The authors declare no conflict of interest.

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