



A multi-stage resource-constrained spectrum access mechanism for cognitive radio IoT networks: Time-spectrum block utilization



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ABSTRACT

Extravagant demands for wireless communications have resulted in the shortage of spectrum, such that unlicensed spectrum bands are overcrowded, whereas licensed bands are not utilized efficiently. Moreover, content discovery and retrieval using the traditional host-centric approach of IP-based networks adds more burden on the wireless spectrum, such that, each time a request is initiated by the mobile service requester, a new routing path is discovered to retrieve the service from the service provider. Cognitive radio (CR) technology has been proposed to enable efficient and opportunistic spectrum band usage through the utilization of vacant licensed channels. This can offer huge spectrum to enable efficient large-scale deployment for IoT networks. Moreover, Information Centric Networking (ICN) has been proposed to decouple the service requester from the provider such that in-network content caching is used to allow for the retrieval of services within a mobile node's proximity. The integration of CR and ICN will be essential for enabling envisioned IoT services within smart cities. In this article, we consider the multi-user single-transceiver coordinated spectrum access problem in CR-IoT networks under the overlay spectrum sharing model. We formulate the spectrum access problem as a multi-stage rate/channel assignment optimization problem. The objective is to maximize the overall network throughput by maximizing the achieved sum-rate over all contending CR-IoT devices. Specifically, we propose a novel resource-constrained channel assignment policy that provides a proper utilization of the available time–frequency units. The proposed policy also exploits the packet fragmentation capability to further enhance network throughput. Moreover, we envision a scenario where our proposed solution can be adapted to information-centric cognitive radio-based networking for IoT smart city applications. We showcase the significant improvement achieved by our proposed solution over state-of-the-art schemes through simulation results.

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1. Introduction

Today's complex and intricate computerization and communication capabilities of both wired and wireless devices are paving the way for richer and more effective IoT services and applications. With the deployment of the 5G telecommunication technology, data flow rate issues due to the uncontrollable increase in the number of wireless IoT devices has been addressed [1,2]. However, many other issues need to be considered in regards to

the shortage of the spectrum bandwidth. Multi-channel cognitive radio networks as well as Information Centric Networking (ICN) will be inseparable in the near future. These combined technologies will enable the provision of smart services and applications within the broad concept smart cities [3,4]. Basically, ICN enhances the distribution of the network content by decoupling service providers and requesters, whereas cognitive radios enable the efficient and opportunistic use of best wireless channels in its vicinity through licensed channels. To this end, the fifth generation (5G) cellular network supports high data rates, thus supporting IoT applications such as autonomous self-driving vehicles [5–7], which will enhance service provisioning and accommodate the requirements of clients. This will in essence provide better quality of service (QoS) and quality of experience (QoE) for users. To provide such high quality services in 5G and

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IoT systems, wireless networks must adopt multiple types of functional networks such as software defined networking (SDN), information centric networking (ICN), device-to-device (D2D) and cognitive radio (CR) communication [8–11].

Moreover, the current Internet architecture cannot accommodate the rapid growth of network traffic originating from continuous, repeated and excessive service requests from content providers, especially, in the mobile heterogeneous IoT smart city scenario. The majority of today's smart IoT devices are wirelessly connected to a plethora of access points with different communication protocols to retrieve data from content providers. Data and services are retrieved from content providers that are most of the time not located within the proximity of the IoT device, hence, overwhelming the communication spectrum with excessive and repeated content retrieval.

A plethora of communication technologies have been proposed over the last decade to provide high data rates, requiring more spectrum bands. The spectrum is a very limited resource and is statistically allocated to Primary Radio (PR) users. The licensed spectrum band cannot be used by other PR users (licensed users); whom own portions of the spectrum. Moreover, user demands are becoming more stringent in terms of lower cost per bit, which requires very high spectrum efficiency [12,13]. Recent studies from the Federal Communications Commission (FCC) show that licensed spectrum bands are heavily allocated, but lightly utilized. Therefore, a need for a new technology that provides high data-rate with high spectrum efficiency and dynamic spectrum allocation has appeared, namely CR [14,15].

CR is a new technology that allows unlicensed users to opportunistically access the licensed and unlicensed portions of the spectrum to improve spectrum efficiency. It has four main functionalities; spectrum sensing, sharing, management and mobility. Nodes equipped with CR are capable of changing the transceiver parameters in accordance to changes in the environment. CR has the ability to sense the Radio Frequency (RF) environment and detect available spectrum opportunities (i.e., white region spectrum holes [16]). It also has the capability of re-configurability; in which the CR can reconfigure its own operating parameters to establish its communication. The spectrum sharing in CR Networks (CRN) is based on the idea of Dynamic Spectrum Access (DSA), where CR users can opportunistically access any portion of the spectrum. This opportunistic access can enable efficient IoT deployment and support the communications of large number of IoT devices. This requires a new Media Access Control (MAC) protocols that effectively utilize the available spectrum resources in CR-IoT networks.

Dynamic spectrum allocation (DSA) has become a well-known solution for increasing spectrum efficiency and the realization of dynamic spectrum sharing (DSS), where CR enables such opportunistic DSA. By doing so, seamless delivery of IoT services will be improved numerously [17]. Such spectrum allocation schemes need new MAC protocols to meet their demands. In order to increase spectrum efficiency, several attempts were made to maximize the CRN's throughput. Most of the previously surveyed schemes were based on conventional CSMA/CA MAC protocol. Many attempts were made to design efficient MAC protocols for CRNs (e.g., [12,18–20]) with the objective of increasing network throughput and spectrum efficiency while meeting predefined specifications. Most of them rely on unrealistic CR specifications (i.e. multiple transceivers and infrastructure network architecture), where it is not suitable for low cost CR-IoT devices. Another class of scheme considers cooperation between CRN and Primary Radio Networks (PRNs), in which the CRN operates in transparent mode to PRN.

ICN was introduced to rejuvenate traditional networking, in which the focus has shifted to the specific data content rather

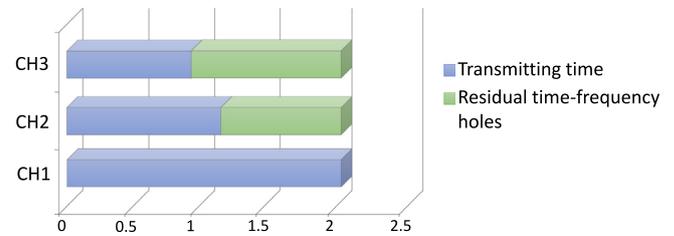


Fig. 1. Residual time–frequency holes resulted when using OPT-MAC.

than the location of data storage. IoT devices directly request data according to data names rather than IP addresses. Such a concept makes the concept of smart cities, considered as networks with large-scale data request, a preferable solution towards fast and reliable time-sensitive applications. Moreover, intermediate nodes not only act as relays or route data from the content provider to the requester, but also act as in-network cache sites. This enables data distribution, where service requesters can obtain the desired content or service from a node within its proximity. This eliminates the need to discover and maintain end-to-end routing paths. Hence, highly dynamic and mobile networks (e.g. pedestrian or vehicular nodes within a smart city) gain access to the desired content efficiently.

In this article, we propose a resource-constrained channel assignment protocol that aims at maximizing network throughput and spectrum efficiency through a smart scheduling multi-stage optimization technique in CR-IoT networks. We assume a single half-duplex transceiver and operate under overlay spectrum access, where CR-IoT devices only access idle PR channels [12] to provide a more realistic scenario for low-cost IoT equipment.

1.1. Motivation

A novel distributed channel allocation scheme for CRNs was proposed in [21] which aims at maximizing the overall throughput achieved in the CRN by maximizing the sum-rate of the contending CR nodes' transmission. The authors have also proposed a new carrier sense multiple access with collision avoidance based (CSMA/CA-based) channel access protocol (OPT-MAC) for CRNs. The scheme uses the access window (AW) for collecting information about the SINR, data size, available channel list, and to announce the CR transmission requests. The objective of the work is to maximize the sum-rate for all contending CR nodes under SINR and interference constraints. However, OPT-MAC [21] showed a significant performance improvement but without utilization for the available white region spectrum holes (i.e. unused spectrum portions), which can be utilized to increase spectrum efficiency. By applying OPT-MAC to different link rates, varying transmission time results. For instance, assume a channel/user assignment using OPT-MAC for three available channels assigned to three CR nodes with link rates of 8 Mbps, 14 Mbps and 18 Mbps, respectively. Fig. 1 demonstrates the time–frequency distribution for this assignment.

Variable rates for the same packet size results in different transmission times. Some nodes will finish their transmissions before others. The channel used by the fastest node will be idle until all nodes finish their transmissions. We call this idle channel time the “residual time–frequency hole” as depicted in Fig. 1. Moreover, integrating OPT-MAC with AW defers all neighboring nodes from accessing the channel until all participant nodes in the established AW finish their transmissions. This is important in multi-hop scenarios to achieve better performance outcome [22].

The work in this article attempts to answer the question of how can we exploit time–frequency holes while maintaining

exclusive channel occupancy with an optimal distributed channel assignment scheme. Hence, the goal is to increase the overall spectrum utilization by maximizing the sum-rate achieved over all contending CR nodes. Therefore, we maximize the data transmitted in the time–frequency unit under hardware constraints. Specifically, we aim at increasing the spectrum efficiency by optimally solving the problem of finding the highest sum-rate over all CRs' transmissions and utilizing spectrum holes through a smart and efficient multi-stage optimization algorithm. The proposed algorithm uses a novel scheduling technique, which adopts a multi-stage optimization solution that enables packet aggregation.

1.2. Contribution

Our main objective in this paper is to increase spectrum efficiency by enhancing the overall network throughput. We maximize the sum-rate of all contending CR users and maximize the number of data packets to be transmitted in the available time–frequency units. Specifically, we propose a new channel assignment scheme that is resource/data size-aware to optimally solve the maximum sum-rate problem and exploit efficiently the available time–frequency blocks.

The main contributions of the proposed work are as follows:

1. Optimally solved the maximum sum-rate for the contending CR users problem defined in [21].
2. Implemented and designed a smart multi-stage optimization channel assignment scheme that increases the overall network throughput while considering hardware constraints, where each CR node has a single half-duplex transceiver, under the overlay spectrum access technique.
3. Compared the performance of the proposed algorithm to OPT-MAC protocol [21].
4. Conducted an intensive evaluations to study the effect of the number of CR-IoT users, channels and packet size on the proposed algorithms.

1.3. Paper organization

The rest of the article is organized as follows: Section 2 discusses some of the existing state-of-the-art in channel optimization in CRNs. Section 3 describes the system and network models. Section 4 defines and formulates the problem. Section 5 provides discussion in regards to the proposed channel assignment schemes, namely, SMART-F MAC, SMART-V MAC, SMART-V1 MAC, and SMART-V2 MAC. Discussions in regards to the convergence condition are provided in Section 6. Section 7 presents our proposed spectrum access mechanism that can realize our proposed algorithms in a distributed manner. Simulation setup, performance evaluations and result discussions are given in Section 8. Finally, we conclude the paper and provide some remarks and suggested ideas for future work in Section 9.

2. Related work

Mapping channels, capacity analysis, as well as channels reservation for the purpose of attaining optimal channel utilization in different types of wireless networks has been a hot topic for researchers since the introduction of wireless networks [23]. Channel assignment in CRNs differs from traditional wireless networks in terms of interference, where maximizing the performance of CRNs is achieved by reducing the interference among primary and secondary users. Moreover, the spectrum assignment issue for CRNs has seen many different schemes and MAC protocols for different design criteria. Some of those solutions opportunistically and dynamically utilize the available white region

spectrum holes such that spectrum efficiency is improved. The CR technology has its own design issues and challenges, which should be reflected on the MAC protocol design. Aside from the work described in [21], many state-of-the-art solutions have been considered for CRN issues. This section will consider some of the related work in relation to resource-aware channel assignment for spectrum block utilization for CRNs.

Wei et al. [19] proposed a fair multi-channel assignment mechanism for distributed CRNs using a new MAC framework for sensing and contention resolution. A channel aggregation technique is used for secondary users to enable multi-channel selection. The solution analytically formulates a channel assignment problem in accordance to Jain's fairness criterion shown to be a quadratic integer programming problem. The objective of the work is to find a channel assignment through aggregation with maximized fairness for all secondary users to improve spectrum efficiency and throughput. The work included simulation tests to compare of the trade-off of throughput performance and fairness performance compared to a distributed single channel assignment scheme [24] and a greedy multi-channel selection scheme [25].

Zhao et al. [26] proposed a distributed channel allocation method for D2D communication with blind rendezvous to enable collision-free concurrent transmission over multiple channels. A receiver-oriented channel allocation algorithm is used to reduce interference. Each sender–receiver pair can obtain an appropriate channel for collision-free transmissions without reliance on a centralized entity. The proposed algorithm runs on terminal nodes and relies on local information. The authors in [27] proposed a solution to combine CR with a biological mechanism called reaction–diffusion to provide efficient spectrum allocation for cognitive IoT that supports smart resource allocation. The quantization of qualitative connectivity–flexibility trade-off is formulated to determine the optimal number of members in a cluster in order to maximize the throughput subject to minimizing communication delay. The reaction–diffusion algorithm is used to provide cluster load balance. Different simulation scenarios were considered in their testings in regards to spectrum homogeneity and heterogeneity.

Tan et al. [28] proposed overlapping and non-overlapping channel assignment algorithms to maximize throughput within CRNs. Distinct set of channels are assigned to secondary users in the non-overlapping channel assignment technique. A greedy channel assignment algorithm is used to allocate the channels in an iterative manner, such that, in each iteration users calculates the increase in throughput for the best available channel. Thus, the solution attains maximum throughput when the number of non-overlapping channels is large. On the contrary, the overlapping channel assignment techniques uses a non-overlapping channel assignment first, then an overlapping channel assignment is performed thereafter. Previously allocated channels are assigned to the remaining secondary users in the CRN. One negative aspect in regards to this solution is that primary users' activities are not incorporated in the algorithm causing frequent channel switching for secondary users.

Li et al. [29] proposed an access delay model that considers imperfect spectrum sensing and multi-channel multi-secondary user transmission. Two scenarios are considered, namely, i) secondary users do not use a contention scheme, and ii) secondary users employ a modified distributed coordination function based CSMA/CA. The reaction–diffusion mechanism proposed in [27] is adopted for the first scenario. The second scenario uses a self-adaptive step-length algorithm to search for the optimal values of spectrum sensing parameters. Li et al. [30] also proposed a sender-jump receiver-wait blind rendezvous algorithm for CRNs. Their solution not only guarantees rendezvous, but also allows for

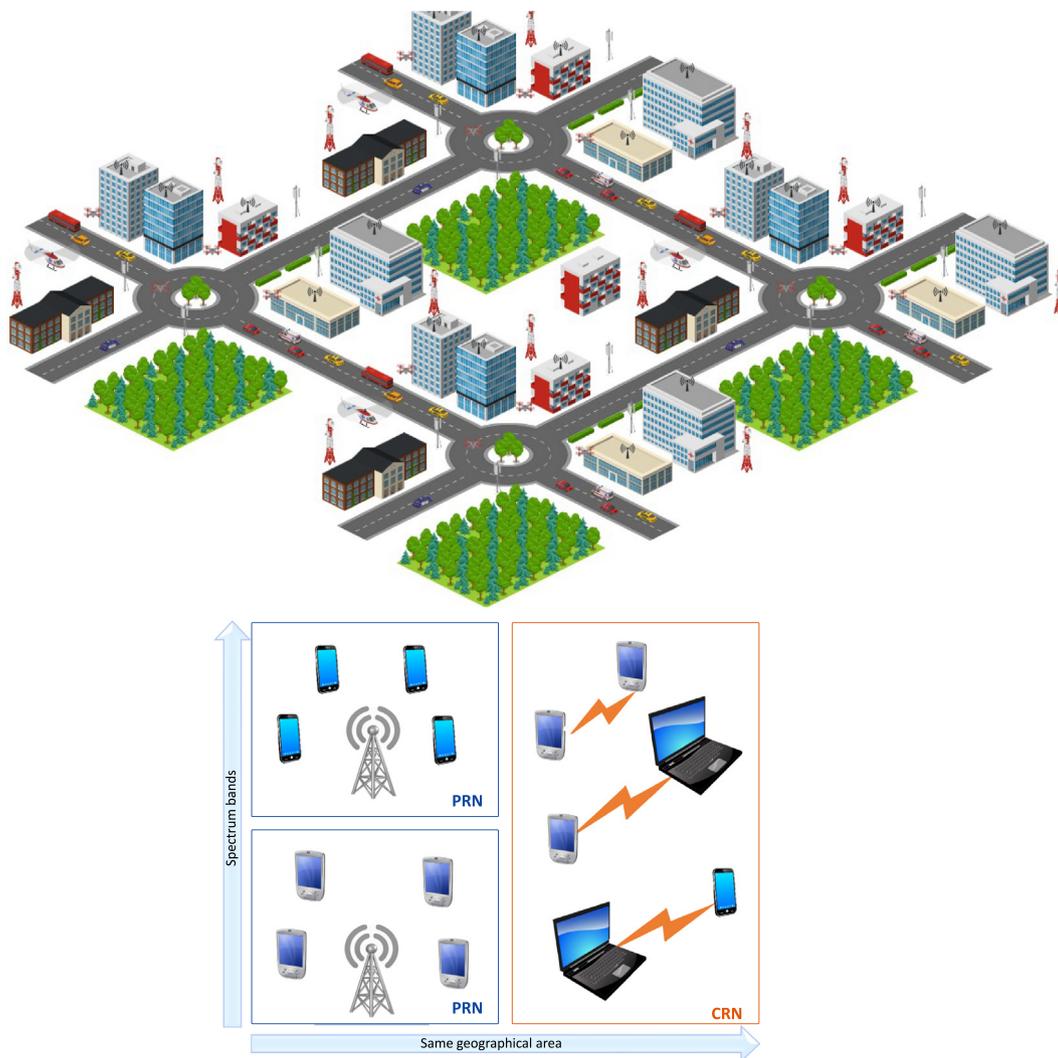


Fig. 2. Network architecture..

any pair of users to rendezvous on all commonly available channels. Moreover, the solution requires no time synchronization and supports both symmetric and asymmetric models. Simulation results show that the proposed solution improves spectrum utilization and robustness.

Wu et al. [31] presented three different channel assignment techniques in CRNs. The first technique uses the available channel information on a particular node to select channel for adjacent links. This technique produces low algorithm efficiency due to the coordination problem that may arise between two nodes of the same link. To correct this issue, a link-based technique is proposed to establish such coordination. The solution reduces the excessive number of rounds needed to complete the channel assignment. It establishes a coordination between the end nodes of each link. The third technique proposed applies maximal matching where it exploits link priorities. Such a solution can worsen channel assignment in highly dynamic scenarios, but simulation results have shown that the link-based algorithm outperforms its counterpart. Moreover, since the proposed algorithm does not take into consideration user activities, frequent channel switching is highly probable.

We summarize other state-of-the-art work quickly to provide the reader with a glance in regards to recent research conducted in the field of CRN channel assignment. The authors in [19] proposed a spectrum assignment scheme called fair multi-channel

assignment FMCA for distributed CRNs. Specifically, they introduced a MAC framework that can sense and access contention resolution and integrated with the FMCA scheme. The channel assignment problem formulated according to Jain's fairness criterion. This algorithm enabled in each CR user in order to find a channel assignment that maximizes the fairness among all users. The authors in [20] presented a scheme that considers different factors to get a multi-channel assignment scheme. Some of these factors like band utilization and users' experiences of using a particular band, possibility that primary user may return in future to take the band that is already assigned to a secondary user and the effect of allocating a particular band on other band seeking users. This scheme yields reduced collision and higher user satisfaction. The authors in [32] introduced a heuristic algorithm that is jointly optimized channel assignment and power allocation for each user that wants to transmit in the cognitive radio network. They reduced the problem complexity by splitting the spectrum and power allocation issues into two sub-optimal problems, then each of them solved separately. The authors in [33] proposed jointly a cross-layer optimization with spectrum aggregation. The main objective is to maximize network throughput under some network constraints. Joint optimization for channel allocation, power control and routing under signal-to-interference and noise ratio (SINR) model were investigated. The proposed MAC protocol in [25] (COMAC) is a distributed MAC protocol for CRNs. COMAC

increases spectrum utilization while providing soft guarantees to PR users' performance. Channel assignment schemes for opportunistic networks that account for adjacent channel interference problem were proposed in [34]. The authors in these works have proposed MAC protocols that aim at maximizing the spectrum efficiency; by minimizing the overall used guard-bands (GBs), and then decrease the blocking probability. However, the proposed protocols in [34] were designed assuming that each channel can support only a fixed basic rate.

3. Network model

We consider an Information-centric single-hop distributed ad hoc CR-IoT network (with no AP) that coexists with multiple PRNs in a smart city scenario. The CR-IoT devices are located in the same locality (single-collision domain), in which each CR-IoT user can directly communicate with any other CR-IoT user. Excessive communication between nodes is reduced due to content caching to nearby mobile nodes. Different types of wireless communication protocols co-exist in both licensed and unlicensed bands. Each PRN has its own orthogonal licensed spectrum bands. We assume that all PRN spectrum bands have equal Fourier bandwidth. In reality, PRNs have different, non-contiguous spectrum bands. In our setup, we overcome this easily by representing the actual PRN spectrum bands by equal virtual PRN spectrum bands. The i th carrier frequency band for a PRN is denoted by f_i . To describe the status of each PR channel, we consider an ON/OFF PR activity model. The ON period indicates the time that the PR channel is occupied by a PR user, while the OFF period represents the time that the channel is idle and can be used by CR-IoT devices. The ON/OFF periods are modeled as an exponentially distributed random variables with means of λ_i and μ_i for each PR channel i , respectively. Each CR-IoT device is equipped with a single half-duplex (HD) transceiver (hardware-constrain), which a realistic implementation for expected low-cost IoT networking. This transceiver can transmit, receive or sense one channel simultaneously. Any spectrum band that is used by PR nodes will be considered part of the black spectrum region (i.e. spectrum bands that cannot be used by CR-IoT nodes). We also assume that any idle channel cannot be used by more than one CR-IoT node at a time. This is called the exclusive channel occupancy policy (or the overlay spectrum sharing scheme). To avoid corrupting PRN transmissions, CR-IoT nodes continuously sense the spectrum to identify white regions to be opportunistically exploited by their transmissions.

Fig. 2 depicts a network architecture as multiple PRNs sharing orthogonal spectrum bands and coexisting with an Information-Centric CR-IoT network that can opportunistically access the available spectrum bands. We assume two network types: 1) Homogeneous networks, where all CR-IoT nodes suffer the same average interference; this yields to link rates that are similarly and randomly distributed based on the amount of interference. 2) Non-homogeneous networks, where some CR-IoT nodes suffer higher interference than other nodes in average; yielding in link rate variety. Both network types were taken into consideration in the simulation and performance testing.

For the network model, $C(t)$ denotes the available channel list extracted from the received control packets (RTS/CTS) in the AW at time t (the different users perform spectrum sensing to identify the idle channels). For our purposes, we assume that a common control channel approach is in place for exchanging control information between CR-IoT users. This channel is pre-defined but is not necessarily licensed (i.e., dedicated to the CRN). For example, it can be one of the unlicensed ISM bands. Let $N(t)$ denote the set of CR-IoT transmission requests at time t . Let L_j denote the data size (in KB) of the CR-IoT transmission request

j . Since our work focuses on channel assignment optimization at a given time epoch, we drop the notation subscript t for convenience purposes. The j th CR-IoT transmission ($j \in N$) is said to be successful if there is an available PR channel i ($i \in C$) such that the achieved SINR ($SINR_j^{(i)}$) for the channel is greater than a given SINR threshold (μ_i^*). The threshold μ_i^* is the required SINR at the CR-IoT receiver of the j th CR-IoT transmission to achieve a bit error rate (BER) that is greater than a given BER threshold over channel i . The achieved rate over channel i for transmission j , namely $R_j^{(i)}$, is a function of the $SINR_j^{(i)}$ [21], as depicted in the equation below.

$$R_j^{(i)} = \begin{cases} f(SINR_j^{(i)}), & \text{if } SINR_j^{(i)} > \mu_i^* \\ 0, & \text{Otherwise} \end{cases} \quad (1)$$

4. Problem definition and formulation

4.1. Problem statement and design constraints

Given the aforementioned network model, the problem statement can be stated as follows: For a given number of CR-IoT users each with single-transceiver and a set of available (idle) channels that coexist in the same finite geographical area with other PR users, the main objective is to coordinate their transmissions through performing proper channel assignment and scheduling such that the maximum sum-rate achieved by all contending CR-IoT users is achieved. This can be achieved by maximizing the utilization of the available time–frequency units. Specifically, we aim at maximizing the overall spectrum efficiency by increasing network throughput through a careful multi-stage sum-rate optimization channel assignment scheme (channel assignment and user scheduling stages). In this article, we exploit spectrum bands over time to increase the spectrum efficiency by optimally solving the channel assignment problem. The needed data for the optimization is extracted from the exchanged control packets (RTS/CTS).

The proposed MAC protocol considers the following constraints:

1. Hardware constraints: each CR-IoT node is equipped with only a single HD transceiver that can only either transmit or receive at any given time.
2. Maximum transmission power ($P_{\max}^{(i)}$): each CR-IoT node has a limited power to be transmitted over channel i , such that, the power is limited by FCC regulations. The determination of an appropriate power mask is a challenging task, which has been previously investigated in many previous works (e.g., [25]). Specifically, an adaptive neighborhood-dependent power mask on CR communications is derived in [25] such that a soft guarantee on the outage probability performance of PRNs is provided.
3. SINR constraint: the transmission j , $j \in N$, is successful if there is a channel i , ($i \in C$), such that its achieved SINR ($SINR_j^{(i)}$) is greater than a given SINR threshold (μ_i^*). This value is required at the receiver of the j th CR-IoT transmission to achieve a BER that is greater than a given threshold (BER_{th}) over channel i .
4. Exclusive channel occupancy: this means that an occupied channel cannot be allocated to neighboring CR-IoT users.
5. Residual time–frequency units constraint: after the first optimization stage, the time required for the next transmission over the channel i should be less than the time opportunity over the same channel. The time opportunity is calculated such that all transmission times scheduled over channel i should be less than or equal to the time for the slowest rate in the channels after the first optimization stage.

6. Convergence constraint: the optimization is performed until no solution is found or the data size of the scheduled CR-IoT transmission is greater than the maximum data size that can be transmitted.

4.2. Problem formulation

For a given CR-IoT transmission requests N and the set of available channel set C , using the aforementioned constraints, the objective is to maximize the sum-rate of all contending CR-IoT users over the available channel set. This allows the CR-IoT networks to send the maximum number of packets in the available time–frequency units. Therefore, the network throughput and capacity are maximized, thus, increases spectrum efficiency. We first define a new binary decision variable ($x_j^{(i)}$) as follows:

$$x_j^{(i)} = \begin{cases} 1, & \text{if channel } i \text{ is assigned to user } j \\ 0, & \text{Otherwise} \end{cases} \quad (2)$$

The maximum sum-rate over all contending CR-IoT transmission request using the hardware and power constraints is be formulated as follows [21]:

$$\begin{aligned} & \max_{x_j^{(i)}, p_j^{(i)}, R_j^{(i)}} \sum_{j \in N} \sum_{i \in C} x_j^{(i)} R_j^{(i)} \\ \text{Subject to: } & \sum_{j \in N} x_j^{(i)} \leq 1, \quad \forall i \in C \\ & \sum_{i \in C} x_j^{(i)} \leq 1, \quad \forall j \in N \\ & SINR_j^{(i)} - \mu_i^* \leq (x_j^{(i)} - 1)\Gamma \\ & 0 \leq P_j^{(i)} \leq P_{max}^{(i)}, \quad \forall i \in C, \quad \forall j \in N \end{aligned} \quad (3)$$

where Γ is a constant $\gg 1$. This problem formulation is set to be a mixed-integer non-linear programming (MINLP) problem. This kind of problem has a non-polynomial time complexity (NP-hard problem).

Recall that, the maximum possible transmission power over channel i is $P_j^{(i)} = P_{max}^{(i)}$, if the channel is idle, and $P_j^{(i)} = 0$, if the channel is busy by a PR user. Given that, the maximum achievable rate $r_j^{(i)}$ can be calculated $\forall i \in C, \forall j \in N$ for $SINR_j^{(i)} \leq \mu_i^*$ and power values (where $r_j^{(i)} = 0$ when $SINR_j^{(i)} \leq \mu_i^*$). The MINLP can be transformed into a binary linear programming (BLP) problem as follows [21]:

$$\begin{aligned} & \max_{x_j^{(i)}} \sum_{j \in N} \sum_{i \in C} x_j^{(i)} r_j^{(i)} \\ \text{Subject to: } & \sum_{j \in N} x_j^{(i)} \leq 1, \quad \forall i \in C \\ & \sum_{i \in C} x_j^{(i)} \leq 1, \quad \forall j \in N \end{aligned} \quad (4)$$

The resultant constraint matrix of this problem is totally unimodular as shown in [21]. In this case, the BLP problem can be optimally solved in polynomial time, since the optimal solution of its relaxation is the optimal solution of the original problem.

The objective of the optimization problem is to maximize the sum-rate performance over all contending CR-IoT nodes, which was well investigated in [21]. The proposed channel assignment schemes exploit residual time–frequency holes in a different way. Our proposed schemes differ from the one in [21], such that we attempt to fully utilize the available time–frequency units. In addition, we use a variable packet size in our proposed scheme which showed an improvement on CR-IoT network performance.

5. The proposed channel assignment schemes

After solving and performing the optimization, we achieve the maximum sum-rate transmissions set $r_j^{(i)}$. However, the slowest transmission will result in under-utilized resources. Therefore, scheduling algorithms are introduced, namely, SMART-F MAC, SMART-V MAC, SMART-V1 MAC, and SMART-V2 MAC to send the maximum possible number of data packet size in the available time–frequency units. The aforementioned design variants provide a trade-off between the computational complexity and the achieved performance. Specifically, SMART-F is simple but has limited performance. We note here that as number of stages increases the network performance enhances, but at the expense of more computational complexity.

5.1. SMART-F MAC

This is the first proposed channel assignment scheme and the simplest of them all. It aims at maximizing the number of transmitted packets in time–frequency units by exploiting time–frequency holes using different stages of optimization for a fixed-packet size. Given the optimization results of the first stage channel/node assignment, the time required of each transmission request is evaluated. One node may need more time than the others (the node with lowest link rate), where the other nodes will vacate their channels before having the slowest node finish its transmission. Based on the expected link rates, we can cumulatively calculate the time difference between the slowest node and the desired link rate. The time difference is identified as the remaining time opportunity over channel i or simply opportunity ($O_i^{(k)}$), where k denotes the k th optimization stage. Opportunity is calculated as follows:

$$O_i^{(k)} = \begin{cases} \frac{D}{\min(r_j^{(i)})} - B_i, & \forall i \in c, \quad \forall j \in n \\ 0, & o.w. \end{cases} \quad (5)$$

where D is the packet size in KB. The term $r_j^{(i)}$ is the maximum achievable rate over c , such that, c is the set of all available channels, n is the set of the scheduled transmissions, B_i is the busy period of channel i in the current channel assignment. The term B_i can be calculated cumulatively at each channel assignment stage as follows:

$$B_i = B_i + \frac{DKB}{r_j^{(i)}} \quad (6)$$

A given transmission can be scheduled over channel i in the current assignment if the following constraint is met:

$$\frac{D}{R_j^{(i)}} \leq O_i^{(k)} \quad (7)$$

This is a valid assumption to ensure that the transmission j over channel i will finish its transmission before the slowest node finishes its transmission. The optimization iterations are repeated until all the time–frequency holes are fully exploited or no new CR-IoT node can be served in the current channel assignment. After applying the first stage of optimization, a new constraint (constraint 7) should be added to our formulation.

Example 1. Consider a CR-IoT network with five CR-IoT users contending to access three available channels. We assume that each user has the channel/rate values shown in Table 1. The table depicts the link rates of each CR-IoT node for each channel. A zero link rate represents the case when SINR is less than μ_i^* . The first stage of optimization assigns channels (1, 2 and 3) to users (2, 3 and 4) with link rates of (8 Mbps, 14 Mbps and 18 Mbps), respectively. Note that the required time to send one packet over

Table 1
Link rate of each user at each channel (in Mbps).

	Channel 1	Channel 2	Channel 3
User 1	7	13	6
User 2	8	10	9
User 3	10	14	8
User 4	9	19	18
User 5	5	0	3

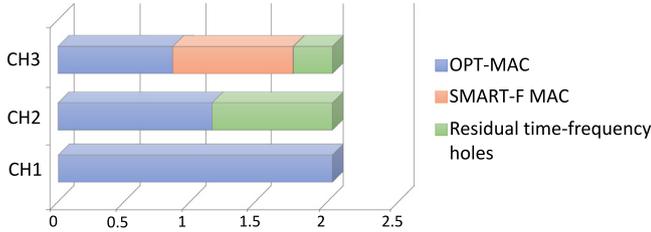


Fig. 3. Enhancement of SMART-F MAC and residual time–frequency holes.

channel 1 is greater than twice the time required to send the same packet over channel 3. Hence, SMART-F MAC will utilize this portion by sending two packets instead of one packet.

Fig. 3 depicts the improvement gain over the OPT-MAC by sending one more data packet over the same channel. Recall that the first stage of SMART-F MAC is the same as OPT-MAC, which logically makes SMART-F MAC outperform OPT-MAC (or at least have the same performance). The figure also depicts significant residual time–frequency holes that are still unexploited.

5.2. SMART-V MAC

SMART-V MAC is an efficient channel assignment scheme that utilizes the residual time–frequency units in a distributed manner by: 1) maximizing the achieved sum-rate over all contending CR-LoT transmissions, 2) enabling for multi-stage optimizations, and 3) utilizing the benefits of using a variable packet size to utilize the available time–frequency blocks. The set of packet size $\mu = \{D/2^0, D/2^1, \dots, D/2^M\}$ contains $(M+1)$ packet size levels. We preferably use these levels of packet size to gain an improvement over SMART-F MAC. In the following subsections we introduce two SMART-V MAC-based channel assignment schemes, namely, SMART-V1 MAC (where $M = 1$) and SMART-V2 MAC (where $M = 2$).

5.3. SMART-V1 MAC

SMART-V1 MAC utilizes the benefit of using a two level variable packet size. In SMART-V1 MAC, CR-LoT nodes' transmissions are scheduled for packets of size D KB at the first optimization iteration and $D/2$ KB for the next scheduled CR-LoT transmissions. Since $D/2$ KB sized packets are half the size of D KB data packets, whenever D KB data packets cannot be scheduled at the current assignment, $D/2$ KB data packets will be scheduled and sent before the slowest rate node finishes its transmission.

To illustrate the operation of SMART-V1 MAC, we consider the same channel/user assignment shown in Example 1. SMART-V1 MAC channel/user assignment and its enhancement over OPT-MAC, SMART-F MAC is depicted in Fig. 4. The spectrum inefficiency decreases by utilizing the spectrum more effectively, hence, an enhancement over the OPT-MAC and SMART-F efficiency is met by scheduling other data packets at the same assignment time; hence sending more data packets in the same time is required for D KB for the slowest CR-LoT node.

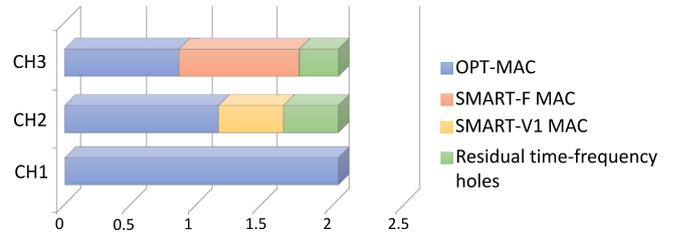


Fig. 4. SMART-V1 MAC improvement gain over SMART-F and OPT-MAC.

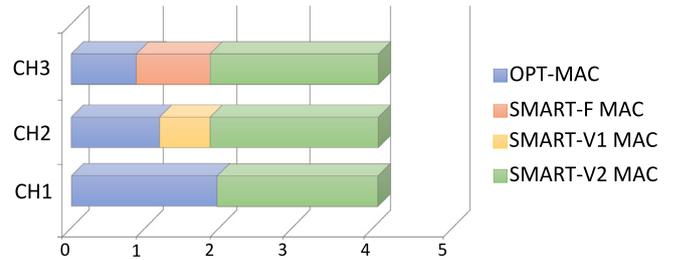


Fig. 5. Improvement gained by the proposed channel assignment schemes on OPT-MAC.

5.4. SMART-V2 MAC

In this scheme, CR-LoT nodes' transmissions are scheduled for D KB at the first optimization and $D/2$ KB or $D/4$ KB packets sized for the next optimization iterations to fit better, which makes it easier to add new packets in the time–frequency holes. In other words, the time required for current assignment is doubled (in comparison to SMART-V and SMART-F MAC protocols). As a result, the residual time–frequency holes are doubled and can be exploited by other CR-LoT transmissions more easily.

Therefore, after the first stage of optimization, assuming packets of size 4 KB (if any) are scheduled, we first calculate the maximum data size ($D_j^{(i)}$) (in KB) of the CR-LoT transmission j that can be transmitted over channel i before the slowest rate transmission finishes as follows:

$$D_j^{(i)} = \left\lfloor D \frac{r_j^{(i)}}{\min(r_j^{(i)})} \right\rfloor \quad (8)$$

where $\lfloor x \rfloor$ represents the floor operation.

After defining the maximum data size, we consider the data packet size of the CR-LoT user as follows:

$$D_j^{(i)} = L_j, \quad \forall L_j < D_j^{(i)} \quad (9)$$

where L_j is the size of the data that are ready to be sent at transmission j . If $L_j < D_j^{(i)}$, then the next stage of optimization is performed after identifying the opportunity in the available channel i . At the end of the k th optimization stage, the data link rates for the served CR-LoT transmissions are set to zero and the remaining time opportunity in channel i ($O_j^{(i)}$) is calculated according to (10). This variable can be calculated as the time difference between the time that is required to transmit over channel i and the required time to transmit the same scheduled packet over the slowest rate channel.

$$O_j^{(i)} = \begin{cases} \frac{D(KB)}{\min(r_j^{(i)})} - B_i, & \forall i \in c, \forall j \in n \\ 0, & o.w. \end{cases} \quad (10)$$

Recall that $r_j^{(i)}$ is the maximum achievable rate over c , where c is the set of the available channels, n is the set of the served transmissions, and B_i is the busy period of the channel i in the

current channel assignment, and it is cumulatively calculated as follows:

$$B_i = B_i + \frac{D_j^{(i)}}{r_j^{(i)}} \quad (11)$$

After performing the first stage of optimization, the served CR-IoT transmission requests from the next channel assignment are removed from the next optimization stage. Formally,

$$R_j^{(i)} = 0, \quad \forall i \in c, \quad \forall j \in n \quad (12)$$

Another constraint is added after the first optimization stage as follows:

$$\frac{D_j^{(i)}}{R_j^{(i)}} \leq O_j^{(i)}, \quad \forall i \in C, \quad \forall j \in N \quad (13)$$

This constraint ensures that the time needed for the scheduled transmission is less than the available time. Using the same settings as outlined in [Example 1](#), [Fig. 5](#) depicts the improvement achieved by the SMART-V2 MAC algorithm on the channel assignment over the other two schemes.

6. Convergence condition

In this section, we formulate the maximum number of iterations (I_{max}) that can be scheduled in one channel assignment for a given M and N values. The convergence condition is set to prevent the channel assignment schemes from entering an infinite loop. SMART-V MAC ends the loop when no more CR-IoT users can be served in the current channel assignment or the data size at the scheduled CR-IoT buffers is less than the maximum possible data size $D_j^{(i)}$. In other words, the convergence condition is taken into consideration, but it can also be a predefined value as well.

Let us assume a CR-IoT network with N CR-IoT transmission requests, C available channels, assuming all the rates of the scheduled CR-IoT nodes are within the range $[R_{max}, R_{min}]$, and M levels of packet size are used. The maximum number of required iterations except the first iteration of optimization is given by:

$$I_{max} = \min \left\{ \left\lfloor 2^M \frac{R_{max}}{R_{min}} \right\rfloor - 1, \quad N - C \right\}, \quad N > C \quad (14)$$

I_{max} occurs when the scheduled CR-IoT transmissions at the first iteration have packets of size D , the CR-IoT node with data link rate of R_{max} has a $D/2^M$ sized packet, and all non-scheduled CR-IoT nodes have rates of R_{min} (at the same channel on which R_{max} occurs at the scheduled transmissions) with packet of the size of $D/2^M$ in their buffers. This statement is represented by $\left\lfloor 2^M \frac{R_{max}}{R_{min}} \right\rfloor - 1$. Furthermore, the number of extra required optimization iterations cannot be more than the difference between the number of CR-IoT transmission requests N and the number of channels C . Note that no extra optimization iteration is needed if the number of channels C is greater than the number of CR-IoT transmission requests N .

As we mentioned earlier, SMART-F MAC is a special case of SMART-V MAC, where $M = 0$. Accordingly, the maximum number of extra required optimization iterations (I_{max}) for SMART-F MAC is given by:

$$I_{max} = \min \left\{ \left\lfloor \frac{R_{max}}{R_{min}} \right\rfloor - 1, \quad N - C \right\}, \quad N > C \quad (15)$$

The maximum number of iterations occurs when the number of CR-IoT transmission requests is greater than the number of available channels and all non-scheduled CR-IoT transmission requests have R_{max} data-link rates at the same channel on which R_{max} occurs at the scheduled CR-IoT transmissions.

7. Spectrum access mechanism

According to our proposed channel assignment optimization, contending CR-IoT nodes in a given locality should be known to all CR-IoT devices in that locality before assigning channels to devices. This issue of announcing the SINR information of all contending CR-IoT devices can be solved in single-hop networks during an admission control stage (an access window (AW) implemented over a common control channels) [21]. The purpose of the AW is to exchange control information, announce transmission requests, SINR information, available channel list to all contending CR-IoT pairs. This ensures that the same control information needed to solve our channel assignment problem is received by all communicating pairs in the network. When all control exchanges occur (end of the access window), all contending nodes will have all same necessary information to perform the proposed channel assignment (our algorithms run at each CR-IoT node simultaneously). Based on the collected information, each node solves the same optimization problem that already imposes exclusive channel occupancy and avoids assigning the same data channel to different communicating CR-IoT communicating pair. This results in the same outcome of the channel assignment at all CR-IoT devices, and hence each transmitting-receiving pair can tune their transceivers to the allocated channel. It is worth noting that all the needed control information can be made available for all contending CR-IoT devices by exchanging the traditional control packets used in any CSMA-CA spectrum access mechanism. This means that no extra overhead is needed to implement our proposed protocols.

Practical Considerations: The collision in our channel access mechanism is dealt with through the admission control phase and by imposing the exclusive channel occupancy policy. For single-hop networks, where all CR-IoT users can hear each other, collisions due to hidden terminal problem is minimal. However, as any other CSMA/CA-based protocol, control packets lost can still happen in practical scenarios due to collisions, fading, shadowing, etc. In this case, some nodes will not have all the information needed to perform the channel assignment and collision can happen between data packets. In this case, no acknowledgment will be sent and, hence the collided packets are re-transmitted.

8. Simulation results

Simulation tests were conducted using Matlab, where the performance of the proposed schemes was compared with that of the OPT-MAC protocol [21]. The OPT-MAC protocol is based on maximizing the sum-rate achieved by all CR users with fixed packet-size. According to the OPT-MAC protocol, the channel assignment is done in a single-stage, resulting in underutilized time–frequency spectrum opportunities. We note here that our proposed protocol simultaneously assigns channels to different contending users, Thus, our scheme has a complete knowledge (aware) of potential contending CR-IoT users, their demands and SINR information similar to the compared with OPT-MAC protocol. Existing CR-IoT MAC protocols perform the channel assignment sequentially, where each user is individually being assigned channels using a CSMA/CA-like channel access (CR users are not aware of future potential CR-IoT contending users), This can significantly affect network throughput as demonstrated in [21]. Thus, for a fair comparison, we compare the performance of our protocol with that of OPT-MAC as both assign channels simultaneously to CR users. Different scenarios were developed by varying several variables to test the performance of the CR-IoT networks in terms of achieved throughput.

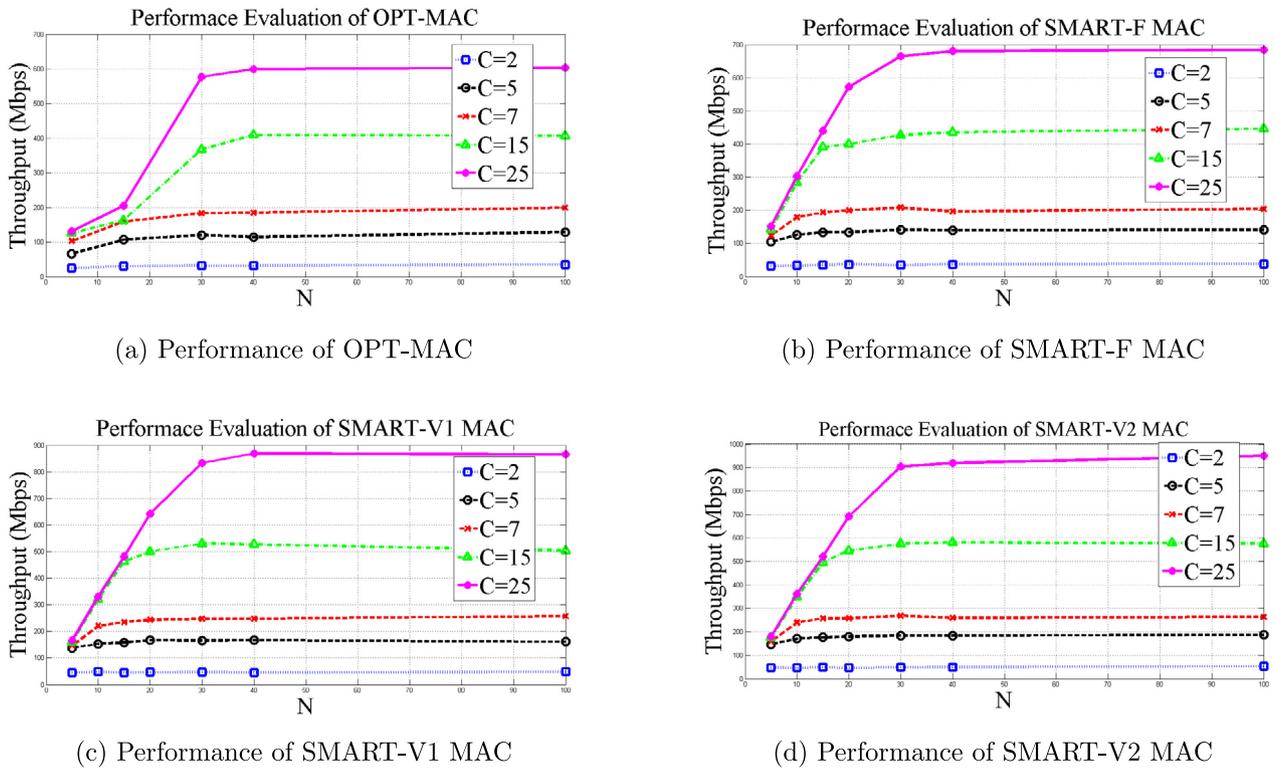


Fig. 6. Network Throughput vs. number of channels.

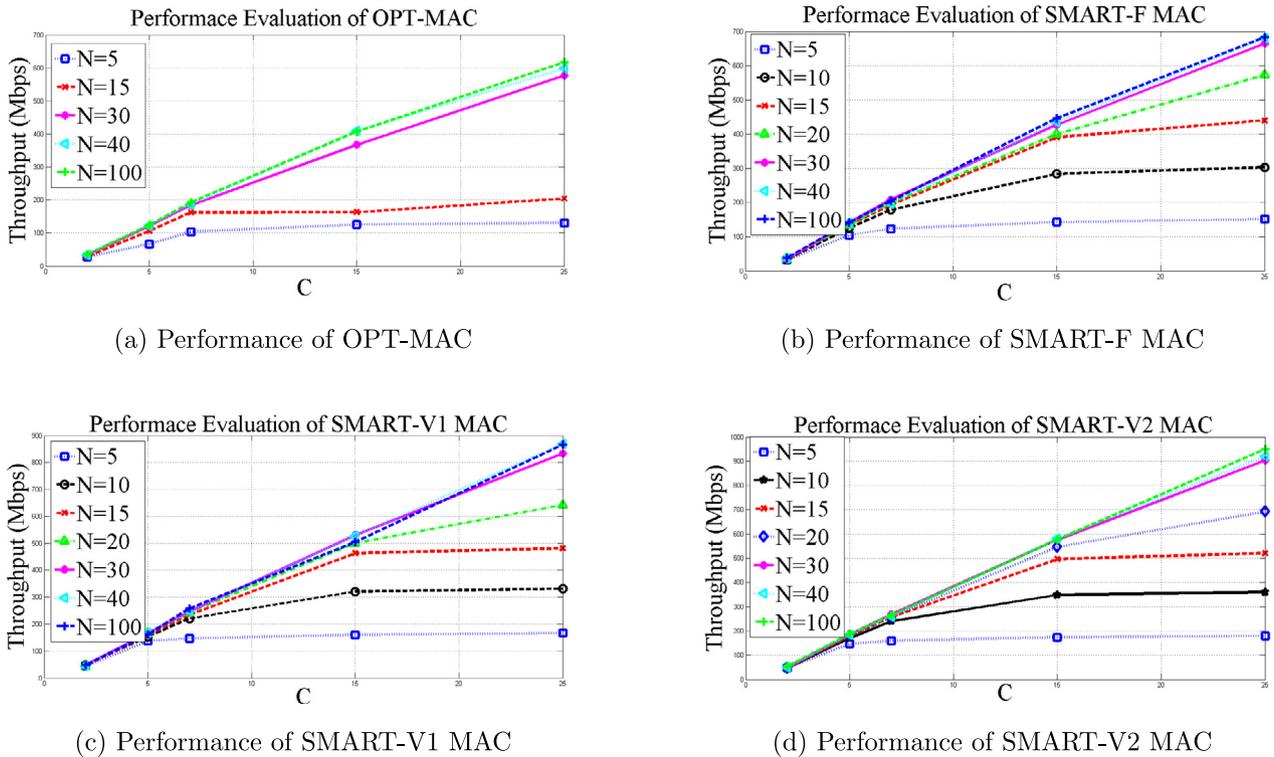
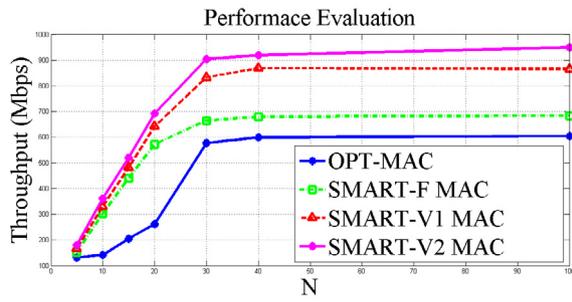


Fig. 7. Network Throughput vs. Number of channels under non-homogeneous demand.

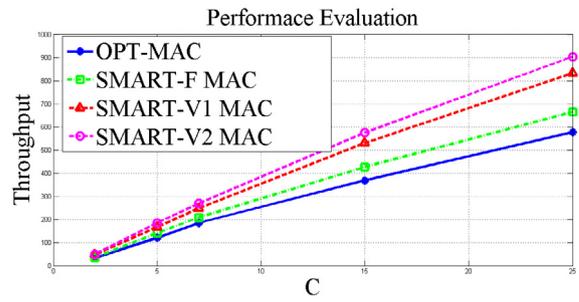
8.1. Simulation setup

We consider a CR-IoT network with N CR-IoT nodes that shares the same set of available channels C . All CR-IoT nodes co-exist in the same geographical area within the same region with

random link rate generation. The following non-homogeneous demand scenarios with varied link rates were tested: 1) CR-IoT nodes suffering from high interference consistently and low data-link rates, 2) CR-IoT nodes suffering from moderate to high interference, and 3) CR-IoT nodes suffering from low interference.

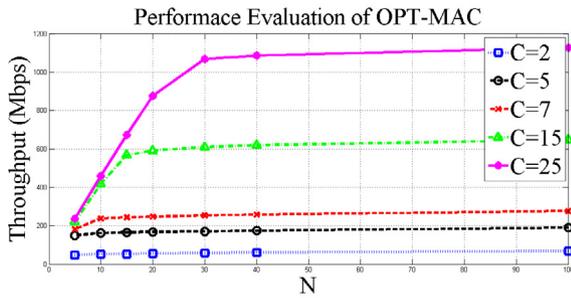


(a) Throughput vs. number of nodes

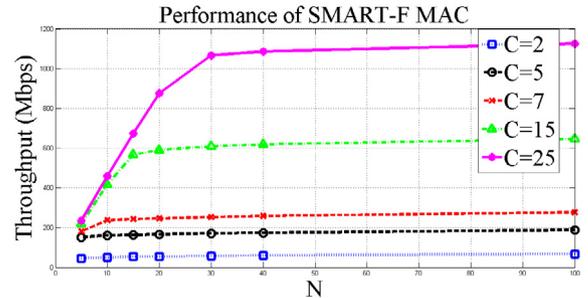


(b) Throughput vs. number of channels

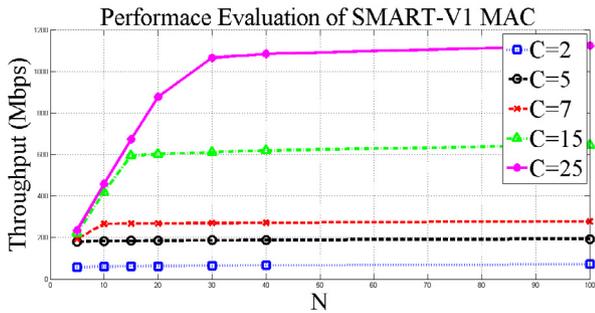
Fig. 8. Performance evaluation of the proposed schemes compared to OPT-MAC.



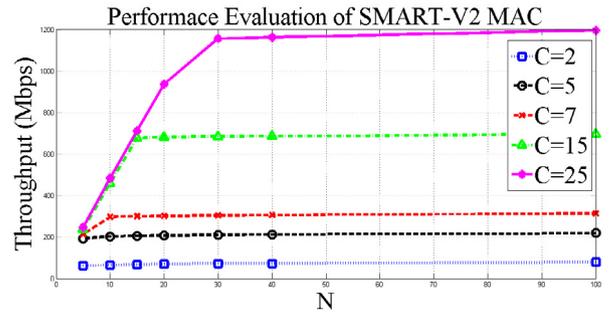
(a) Performance of OPT-MAC



(b) Performance of SMART-F MAC



(c) Performance of SMART-V1 MAC



(d) Performance of SMART-V2 MAC

Fig. 9. Network throughput vs. number of nodes.

Furthermore, homogeneous demand scenarios were also considered, such that all CR-IoT nodes have link rates within the same range between zero and 60 Mbps. A zero-link-rate means that the SINR at the receiver is below the SINR threshold. All CR-IoT links in the homogeneous demand scenarios have random link rates at each channel but all within the same range. We assume saturated network traffic. Packets are generated in the network with exponential random variable length that are randomly assigned to CR-IoT users.

8.2. Results and discussion

We conducted intensive simulation experiments to evaluate the performance of our proposed schemes and compare their performance with OPT-MAC under homogeneous and non-homogeneous demand conditions. The results are split into two main groups based on the rate demand conditions.

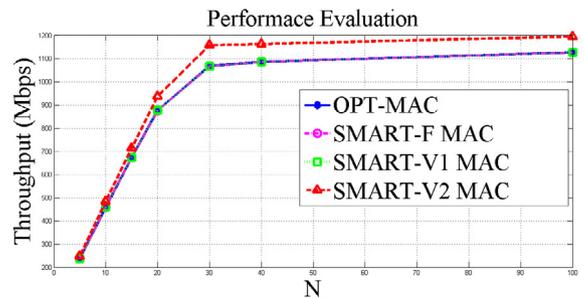


Fig. 10. Throughput vs. number of nodes at homogeneous demand.

8.2.1. Results under non-homogeneous demands

Intensive simulations were performed to evaluate both the proposed channel assignment schemes and OPT-MAC as well. In this section, we assume non-homogeneous demands. Fig. 6

depicts network performance of each scheme for different numbers of channels C versus the number of nodes N . It can be stated that increasing the number of nodes will enhance the achieved throughput until a certain number of nodes reach some value depending on the number of available channels. This is valid since when large numbers of nodes are involved in performing optimization, better rates will be achieved. Note that under non-homogeneous rate demand scenarios, some nodes suffer from high interference and thus low rates as depicted in Fig. 6(a). We also note that increasing the number of channels for a given number of nodes (where the number of nodes is less than the number of channels) does not significantly enhance the network throughput. This can be explained by understanding the OPT-MAC operations. In OPT-MAC, when the optimization is performed and node/channel assignment is conducted, some scheduled nodes will have rates that differ from others, which makes some nodes complete their transmissions before other nodes. However, no node/channel assignment will be performed until all scheduled nodes complete their transmissions. In other words, increasing the number of available channels will not significantly increase the link rate of the nodes that suffer from interference.

Fig. 6(b)–(d) depict the throughput achieved using SMART-F MAC, SMART-V1 MAC and SMART-V2 MAC versus the number of nodes, respectively. Note that the residual time–frequency holes resulted from rate variety is enhanced in our proposed schemes (i.e. Fig. 6(b)–(d)). Network throughput significantly increases as the number of channels increases even when the number of nodes is less than the number of channels (unlike the case in OPT-MAC).

Fig. 7(a)–(d) depict the network throughput achieved from OPT-MAC, SMART-F MAC, SMART-V1 MAC and SMART-V2 MAC versus the number of channels, respectively. We notice that when the number of nodes equals to 50, network throughput saturates earlier at OPT-MAC compared to our proposed schemes. The same reason discussed before is behind this. Our proposed schemes effectively enhance network throughput, even if the link rates are largely different.

Fig. 8(a) depicts the throughput improvement of SMART-F, SMART-V1 and SMART-V2 compared to OPT-MAC using 25 channels. From Fig. 8, we can sort channel assignment schemes in descending order based on their performance as: SMART-V2, SMART-V1, SMART-F and OPT-MAC. Specifically, increasing network throughput means better spectrum efficiency. Thus, our proposed schemes provide higher spectrum efficiency and better performance than OPT-MAC. In Fig. 8(b), the number of nodes is fixed at 30 to evaluate each channel assignment scheme versus the number of available channels C . The figure depicts the enhancement of our proposed schemes in comparison with OPT-MAC. SMART-V2 MAC outperforms OPT-MAC, SMAERT-F MAC and SMART-V1 MAC by up to 207%, 39% and 16%, respectively.

8.2.2. Results under homogeneous demands

It is worth mentioning that although the proposed schemes outperform OPT-MAC under all network conditions, however, homogeneous demand, as mentioned earlier, is a special case when all CR-IoT nodes experience the same average interference. This results in uniform data-link rates between 0 to 60 Mbps (zero means $\text{SINR} < \text{SINR}_{th}$). The performance of OPT-MAC under this condition is evaluated. The performance seems to be near optimal as shown in Fig. 9(a), but no guarantees are provided. However, we can conclude that the SMART-F scheme outperforms OPT-MAC. Moreover, SMART-V2 outperforms all schemes. Finally, SMART-V1 shows a better performance than SMART-F.

It can be stated that all the proposed algorithms have almost the same behavior and the same performance. This is true as

Fig. 10 shows, but SMART-V2 still slightly outperforms all other algorithms. This refers to the use of packets of size of D KB (if any) at the first stage of the scheme, which increases the time difference between two scheduled nodes. This facilitates adding new packets of sizes $D/2$ and $D/4$ KB. The three schemes (OPT-MAC, SMART-F MAC and SMART-V1 MAC) perform approximately the same when applying homogeneous demands, while SMART-V2 outperforms them all. Such results can be explained as follows: when applying BLP on homogeneous demand networks it is rare to see scheduled nodes with rates difference greater than half. Thus, SMART-F MAC and SMART-V1 MAC act like OPT-MAC.

Fig. 11(a)–(d) depict the performance evaluation of each scheme as a function of the number of channels. This figure reveals that SMART-V2 outperforms all other schemes (i.e., SMART-V2 MAC outperforms OPT-MAC, SMAERT-F MAC and SMART-V1 MAC by up to 31%, 15% and 14%, respectively).

9. Conclusion

In this article, we designed and developed multi-stage optimization channel assignment schemes for cognitive-radio information-centric networks. The schemes aim at maximizing network throughput by maximizing the achieved sum-rate over all scheduled CR-IoT nodes and exploiting the available time–frequency units in the smart channel assignment schemes. Two channel assignment schemes were introduced, namely, SMART-F MAC and SMART-V MAC. The SMART-V MAC is further subdivided into two channel assignment schemes, namely, SMART-V1 MAC and SMART-V2 MAC when $M = 1, 2$, respectively. SMART-F MAC exploits the available time–frequency units by a multi-stage optimization scheduling method. In SMART-V MAC, we leverage the use of variable packet sizes in exploiting time–frequency holes and compromise the size of packets used at the first stage of optimization to efficiently increase spectrum efficiency as conducted in SMART-V2 MAC. Simulation results show the improvement of network throughput when adopting the proposed schemes compared with the traditional OPT-MAC algorithm. Simulations were conducted under homogeneous and non-homogeneous rate-demand network scenarios. SMART-V2 MAC outperforms OPT-MAC, SMAERT-F MAC and SMART-V1 MAC by up to 31%, 15% and 14% respectively under homogeneous rate-demand conditions and by up to 207%, 39% and 16% respectively under non-homogeneous rate-demand conditions.

Declaration of competing interest

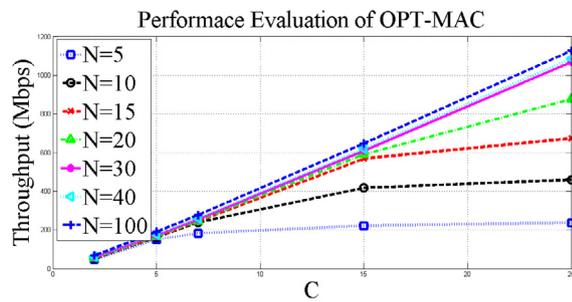
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRedit authorship contribution statement

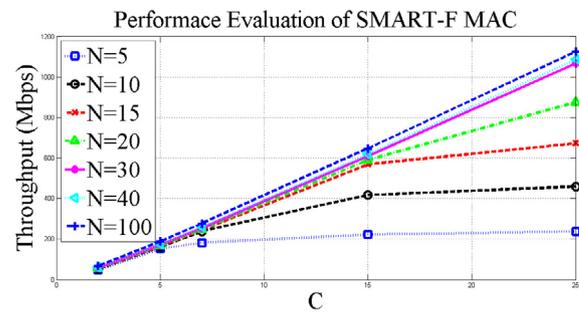
Moayad Aloqaily: Data curation, Writing - original draft, Writing - review & editing. **Haythem Bany Salameh:** Conceptualization, Methodology, Software, Writing - review & editing, Supervision. **Ismaeel Al Ridhawi:** Visualization, Investigation. **Khalaf Batieha:** Conceptualization, Methodology, Software, Data curation, Writing - original draft. **Jalel Ben Othman:** Visualization, Investigation.

Acknowledgment

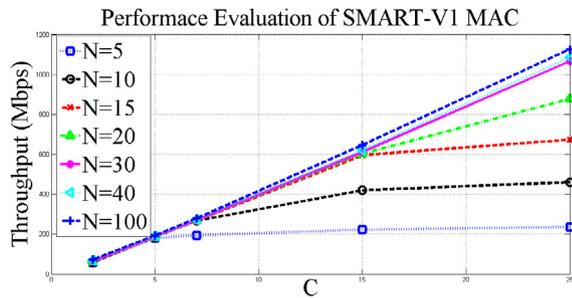
This work was supported by the College of Engineering, Al Ain University, United Arab Emirates, under Grant ERF-20.



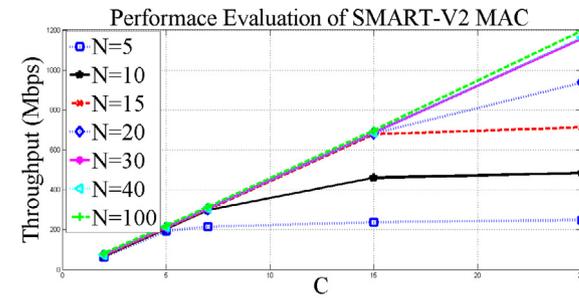
(a) Performance of OPT-MAC



(b) Performance of SMART-F MAC



(c) Performance of SMART-V1 MAC



(d) Performance of SMART-V2 MAC

Fig. 11. Performance evaluation of each scheme as a function of number of channels.

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