

Dynamic resource allocation for opportunistic software-defined IoT networks: stochastic optimization framework

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ABSTRACT

Several wireless technologies have recently emerged to enable efficient and scalable Internet-of-Things (IoT) networking. Cognitive radio (CR) technology, enabled by software-defined radios, is considered one of the main IoT-enabling technologies that can provide opportunistic wireless access to a large number of connected IoT devices. An important challenge in this domain is how to dynamically enable IoT transmissions while achieving efficient spectrum usage with a minimum total power consumption under interference and traffic demand uncertainty. Toward this end, we propose a dynamic bandwidth/channel/power allocation algorithm that aims at maximizing the overall network's throughput while selecting the set of power resulting in the minimum total transmission power. This problem can be formulated as a two-stage binary linear stochastic programming. Because the interference over different channels is a continuous random variable and noting that the interference statistics are highly correlated, a suboptimal sampling solution is proposed. Our proposed algorithm is an adaptive algorithm that is to be periodically conducted over time to consider the changes of the channel and interference conditions. Numerical results indicate that our proposed algorithm significantly increases the number of simultaneous IoT transmissions compared to a typical algorithm, and hence, the achieved throughput is improved.

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1. INTRODUCTION

With the exponential growth of Internet-of-things (IoT) applications and services, it is expected that more than 50 billion devices will be connected to the internet by 2020. IoT networking connects varied wired and wireless devices and systems. The enormous number of connected wireless IoT devices significantly increases the demand for more spectrum resources and efficient spectrum utilization. Software-defined networking enabled by cognitive radio (CR) technology is considered as a major approach to improve spectrum utilization and provide wireless access to a large number of connected IoT devices. Wireless CR technology allows for rapid deployment of scalable, reliable and intelligent IoT networking. CR technology brings intelligence right to the edge of an IoT network. The intelligent offered by the CR at the edge nodes provides a complete connectivity stack virtually between any type of wireless sensors and an IoT controller.

(a) Motivation

Due to the fact that the demand in the IoT services and applications is exponentially increasing, CR technology allows to use underutilized spectrum using dynamic spectrum access technique. In a CR network (CRN), CR users, also known as secondary or unlicensed users, are aware about licensed spectrum that used by existing Primary User (PU) networks. CR users can opportunistically access the licensed spectrum by changing their transmission parameters, in order to avoid affecting ongoing PUs' transmission. This has motivated the need for a new spectrum access technology that introduced in CRNs, such that the spectrum utilization is enhanced without affecting the PUs operation. A CRN is different from the traditional multi-channel wireless networks. Most importantly, CRN experience out-of-system and in-system random interference. Another characteristic of a CRN is that users may need to transmit with a relatively low signal power, with power masks constraints, in order to avoid causing harmful interference to the PUs [1]. On the other hand, the applications supported by the IoT devices are very diverse, requiring heterogeneous uncertain bandwidth and rate demands. When applying CR technology in IoT networks (CRIoT networks), these peculiar characteristics call for new stochastic channel access mechanism that can efficiently utilize the available spectrum to maximize the number of simultaneous CRIoT transmissions with minimum total transmission power, and improved network throughput[2–9].

(b) Contributions

Previous channel assignment approaches in traditional multi-channel and CR wireless networks were designed assuming average interference conditions, fixed channel bandwidth and fixed spectrum demands per user. In this work, we propose a stochastic bandwidth/channel/power allocation algorithm that improves the network performance. The maximization problem can be established as a two-stage stochastic binary linear program. It is worth mentioning that the interference is a continuous random variable that is highly-correlated over time [1, 10–15]. Thus, our optimization problem has an infinite realizations. Therefore, solving for an optimal solution is impossible. Instead, we propose a suboptimal sampling solution that exploits the interference's correlation.

(c) Organization

The rest of this paper is organized as follows: Section 2 presents the related work. In Section 3, the problem model, description and formulation are introduced. Section 4 explains the process of channels assignment and bandwidth allocation in the access window. Section 5 shows the numerical results for the performance of our proposed scheme compared with traditional approaches. Finally, Section 6 presents conclusions.

2. RELATED WORK

Channels assignment in CRNs is different from the traditional networks, due to the fact that channels availability changes over time due to licensed users activities. Moreover, CR users are power constrained, such that their transmission power should not exceed a certain limit to avoid causing harmful interference to licensed users. Consequently, satisfying CR users data rate demand becomes challenging. Therefore, we are motivated in this work to consider these factors for our proposed adaptive channels assignment technique.

For concurrent channels assignment, in [16] authors proposed a scheme that allows a group of CR users to be assigned channels instead of one user at a time, also they assumed channels do not have a fixed bandwidth as a practical assumption, therefore, network throughput is increased. In [16, 17], a guard band notion is introduced between idle channel blocks, in order to minimize the effect of adjacent interference and maximize spectrum efficiency, such that in [17], the number of required guard bands are reduced when grouping idle channels as one block.

Two channels assignment methods are developed in [18], in order to maximize spectrum efficiency: the static single-stage method when a centralized spectrum manager does not exist, the second method is an adaptive two-stage technique which is suitable for centralized spectrum manager. In addition to the uncertainty of the channels, the authors also consider two aspects in their models: the fact of adjacent channels interference and channels bonding and aggregation. In addition to many proposed protocols in literature that aim to enhance network capacity, throughput and optimize transmitted power [1, 19, 20]. Fair channels assignment and energy optimization are considered in [21].

CR users transmission power should be controlled, in order to avoid interference with neighbor licensed users transmission [22]. For CR Ad-Hoc Networks (CRAHNs) [23], transmission power control and spectrum assignment methods are developed to enhance network capacity. Spectrum assignment method is

presented in [24] and solved using a learning technique, also an adaptive power allocation method is solved as an optimization problem. The harmful interference reduction to licensed users is studied in [25], also using the deep-reinforcement learning technique [26], mobile CR users empowered to change their physical location when jamming is high. Researchers have studied network connectivity in CRNs, especially, it is essential in routing stability. Noting that its connectivity is different from traditional networks, since the licensed spectrum availability changes over time. In [27], links are established in a way that minimizes interference and enhance connectivity degree. Also, authors in [28] proposed some CR transceivers to be maintain the lowest threshold for connectivity. For routing protection in terms of connectivity, a resilient method is introduced in [29–31]. Also, CR users packets recovery due to primary users activity is studied in [32].

3. MODELS, PROBLEM DESCRIPTION AND FORMULATIONS

3.1. Network model

In this work, we will consider the scenario of a single-hop opportunistic wireless cognitive (unlicensed) radio network (CRN) that tries to exploit spectrum holes in the presence of different (legacy) primary radio networks with channels. CR user acts as a secondary user by continuously scanning the frequency spectrum and identifying underutilized channels to exploit opportunistic access.

The CRN comprises a collection of single-hop users between which requests for packet transmission arise. Each CR user can transmit over one of the M available channels. This can be seen as M possible links. Due to the nature of wireless CRNs, a channel (link), which is occupied by a CR user, cannot be allocated to other CR users in its one-hop communication range. Furthermore, each channel link experiences a random primary network interference conditions, and each CR user has a random demand data rate. To satisfy a given demand, a bandwidth must be allocated for each channel. Because of the radio capability restrictions, the maximum bandwidth (B) that can be used over the various channels is constrained. Therefore, the optimization problem is to determine channel bandwidths that maximizing the over all network throughput (bandwidth utilization) while selecting the set of power resulting in the minimum total transmission power. This problem lends itself to a natural two-stage stochastic integer linear programming. That is, the maximum bandwidth, which can be used by CRN, must be allocated to the various channels before the rate demand and the interference conditions can be known. Once B has been allocated to different channels, CR requests can be served in a manner that allows efficient spectrum use with minimum total power consumption. The optimization of bandwidth/channel/power is an adaptive algorithm that is to be periodically conducted over time to account for the changes for the channel and the primary network interference conditions. The distributions of the rate demands and the interference power are dynamically updated based on localized spectrum and control information observed over the previous transmissions time.

3.2. Assumptions and feasibility conditions

Before formulating our optimization problem, we first state our assumptions and feasibility conditions.

- There are two sets: $i \in I$: channels, and $j \in J$: CR users.
- The rate demand \tilde{d}_j is a discrete uniform random variables, $\forall j \in J$.
- Each CR user maintains an K -entry historical-data table. The i th entry in the table consists of one fields indicating the previously observed interference over the i th access window (AW) time.
- The rate demand (\tilde{d}_j) and the interference ($\tilde{P}_I^{(i)}$, $\forall i \in I$) are independent random variables.
- The interference ($\tilde{P}_I^{(i)}$, $\forall i \in I$) is a continuous positive random variable with unknown distribution.
- The interference at different channels is independent and identically distributed (iid).

To ensure a feasible spectrum sharing, we introduce these constraints:

- At most one channel can be assigned for one transmission.
- A channel cannot be assigned for more than one transmission.
- Rate demand constraint: the data rate provided by a channel should be greater than the rate demand of the request that associated with that channel.
- The CR-to-PU spectrum mask: the maximum allowable transmission power of CR users must be constrained by a power mask, such that the CR users will not cause unacceptable interference to primary users.
- The signal to interference noise ratio (SINR) at a CR user should be greater than the minimum required threshold at the selected channel.

3.3. Problem formulation

The problem of bandwidth/channel/power allocation can be formulated as a two-stage stochastic programming. In the first stage, the maximum bandwidth, which can be used by CRN, is allocated to the various channels before the rate demand and the interference conditions can be known. Then, in the second stage, we allocate/select channels/powers to different CR users such as the total power consumption is minimized.

To formulate the problem, we introduce the indices, data, random variables, and decision variables:

- Sets (indices): $i \in I$: channels, and $j \in J$: CR users.
- Data: B is the total bandwidth that can be allocated to the various channels, M is the number of channels that are to be considered, N is the total number of users, $P_{th}^{(i)}$ is the thermal noise power at the i th channel, and μ^* is the minimum required signal-to-Interference-and-noise-ratio.
- Random variables: $\xi = (\tilde{d}_j, \tilde{P}_I^{(i)})$: the random variables that represent the demand and the interference at various channels and different users.
- Random Data: $P_j^{(i)} = \mu^*(P_{th}^{(i)} + \tilde{P}_I^{(i)})$: the required transmit power over the i th channel for the j th user over the various channels.
- Decision variables: X_i : is the amount of capacity to be assigned to the i th channel. $\alpha_j^{(i)}$: is channel assignment indicator that is given by:

$$\alpha_j^{(i)} = \begin{cases} 1, & \text{if channel } j \text{ is assigned to the } i\text{th transmission;} \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

With these notations, the general-recourse model for bandwidth/channel/power problem is given as:

$$\begin{aligned} \max_{X_i} & E[h(X, \xi)] \\ & \sum_{i=1}^M X_i \leq B \\ & X_i \geq 0 \quad i \in I \end{aligned} \quad (2)$$

where $h(X, \xi)$ represents the channel utilization when the demand for service and the interference are given. This function is represented by the optimal value function of a second-stage program. Based on the above notation, the second stage problem can be formulated as follows:

$$\begin{aligned} \max & \sum_{i=1}^M \sum_{j=1}^N \alpha_j^{(i)} - \sum_{i=1}^M \sum_{j=1}^N \alpha_j^{(i)} P_j^{(i)} \\ & \sum_j \alpha_j^{(i)} \leq 1, i \in I \\ & \sum_i \alpha_j^{(i)} \leq 1, j \in J \\ & \sum_i \sum_j \alpha_j^{(i)} \leq M \\ & \alpha_j^{(i)} \in \{0, 1\}, i \in I, j \in J \\ & X_i \log_2 \left(1 + \frac{P_j^{(i)}}{\tilde{P}_I^{(i)} + P_{th}^{(i)}} \right) - \tilde{d}_j \geq (\alpha_j^{(i)} - 1)\theta, \quad i \in I, j \in J \end{aligned} \quad (3)$$

where θ is a very large number. Clearly, the formulation in (3) is a two-stage stochastic binary linear program.

3.4. Suboptimal sampling problem formulation

Since the interference over different channels is a continuous random variable, the problem instance as described above has an infinite number of scenarios. Therefore, a solution with a deterministic equivalent is not possible. However, by noting that, the interference conditions measured at a certain channel are highly correlated. Thus, the K most recent observed interference scenarios are considered to find a suboptimal solution. To account for the dynamic (random) changes in the interference conditions, our optimization program is an adaptive algorithm that is to be periodically conducted over time (Access window). Now, given the K -entry interference table and considering the constrained listed above, the deterministic equivalent for one scenario ω (ω is one realization) can be formulated as follows:

$$\begin{aligned}
 & \max \sum_{i=1}^M \sum_{j=1}^N \alpha_j^{(i)\omega} - \sum_{i=1}^M \sum_{j=1}^N \alpha_j^{(i)\omega} P_j^{(i)\omega} \\
 & \text{s.t.} \sum_{i=1}^M X_i \leq B \\
 & \sum_j \alpha_j^{(i)\omega} \leq 1, i \in I \\
 & \sum_i \alpha_j^{(i)\omega} \leq 1, j \in J \\
 & \sum_i \sum_j \alpha_j^{(i)\omega} \leq M \\
 & \alpha_j^{(i)\omega} \in \{0, 1\}, i \in I, j \in J \\
 & X_i \log_2 \left(1 + \frac{P_j^{(i)\omega}}{P_I^{(i)\omega} + P_{th}^{(i)}} \right) - d_j^\omega \geq (\alpha_j^{(i)} - 1)\theta, \forall i \in I, \forall j \in J \\
 & X_i \geq 0, i \in I
 \end{aligned} \tag{4}$$

$$\tag{5}$$

4. HISTORICAL SAMPLING/ ACCESS WINDOW

At the beginning of an AW and given the interference or demand conditions over the previous AW, the maximum bandwidth, which can be used by CRN, is allocated to the various channels, this conducted in the first stage. This can be achieved by solving the deterministic equivalent for the K-historical samples. In the second stage, where the interference and rate demands are realized, we allocate/select channels/powers to different CR users such as the total power consumption is minimized. During the current AW time, the interference conditions and rate demands are recorded. Then the above process is repeated over and over for every AW time. To illustrate this mechanism, we consider a CRN scenario as shown in Figure 1, where 6 CR pairs content to access 3 different channels. Figure 2 shows the associated timing diagram for decisions or stages of our optimization problem.

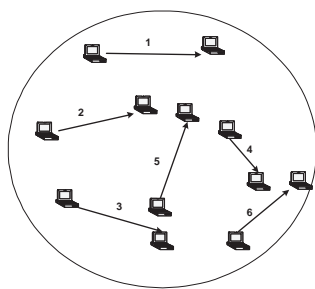


Figure 1. Cognitive radios links

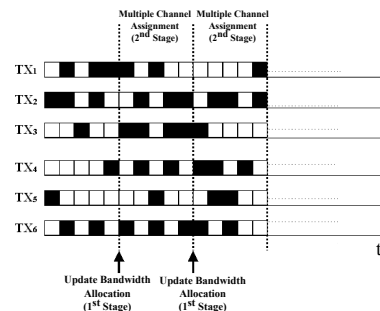


Figure 2. Optimization timing diagram

5. NUMERICAL RESULTS

We illustrate the previously discussed optimization process with a numerical example. We compare the performance of our proposed scheme to that of traditional schemes such as the static allocation [1], weighted average schemes [10] and optimal solution. The static assignment is based on providing a fixed-bandwidth per channel irrespective of the user’s demand. The weighted average attempt at providing variable bandwidth depends on the average users’ demand, rather than the actual demand. The optimal solution is found using a brute-force method that requires an exhaustive search over a large state space that increases exponentially with number of channel and number of CR users. We consider 3 primary users networks ($M = 3$) and 4 CRN links. Suppose that the AW consists of 4 periods, $K = 4$. We set $\mu^* = 3$, $P_{th}^{(i)} = 0.001, \forall i$, and $B = 30$ Mbps.

At a beginning of an AW, assume that the recorded interference $\vec{P}_I^{(i)} : i = 1, 2, 3$ and the rate demand $d_j : j = 1, 2, 3$ are given by:

$$\vec{P}_I^{(1)} = \{0.25, 0.1, 0.15, 0.25\}, \text{ and } \vec{d}_j = \{5, 10, 11, 12\}.$$

$$\vec{P}_I^{(2)} = \{0.5, 0.45, 0.35, 0.35\}, \text{ and } \vec{d}_j = \{5, 6, 8, 7\}.$$

$$\vec{P}_I^{(3)} = \{0.3, 0.2, 0.15, 0.15\}, \text{ and } \vec{d}_j = \{10, 10, 10, 10\}.$$

Also assume that the interference over the next AW is given by:

$$\vec{P}_I^{(1)} = \{0.3, 0.15, 0.2, 0.29\}, \text{ and } \vec{d}_j = \{8, 7, 5, 10\}.$$

$$\vec{P}_I^{(2)} = \{0.48, 0.46, 0.33, 0.31\}, \text{ and } \vec{d}_j = \{6, 8, 5, 5\}.$$

$$\vec{P}_I^{(3)} = \{0.27, 0.24, 0.11, 0.25\}, \text{ and } \vec{d}_j = \{7, 5, 10, 8\}.$$

The reported results are averaged over 100 experiments. Figure 3 shows the details of the two stages of the proposed channel optimization process. The outcome of this process is shown in Figure 4. This figure shows that our stochastic scheme significantly improves network throughput. This improvement is attributed to the the proper bandwidth/channel assignment algorithm.

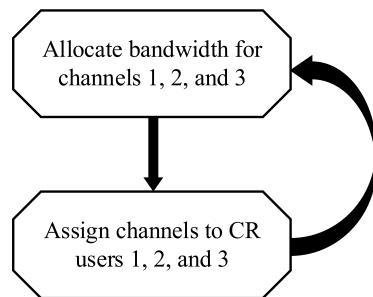


Figure 3. Example that illustrates the optimization process in a dynamic CRN.

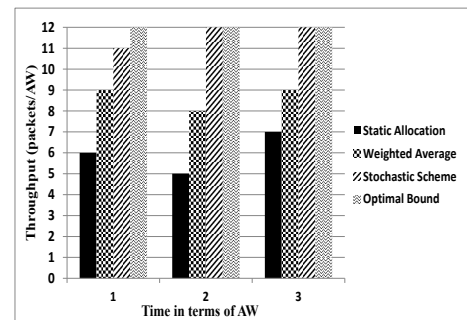


Figure 4. Comparison of different allocation schemes.

6. CONCLUSIONS

In this paper, we propose a novel stochastic bandwidth/channel/power allocation. Our proposed scheme maximizes the CRN throughput through a proper bandwidth/channel allocation process while in the same time minimizes the total power consumption. We proposed a two-stage stochastic bandwidth and channel assignment scheme that dynamically exploits the correlation between the interference conditions and the rate demands to maximize the overall network throughput. Compared to traditional bandwidth/channel allocation schemes, numerical results showed that our proposed scheme reveals significant performance improvement in the overall achieved network throughput.

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