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Routing in cognitive radio networks with full-duplex capability under dynamically varying spectrum availability

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Abstract

This paper proposes a routing scheme for full-duplex-(FD)-based multi-hop CRNs that attempts to maximize the packet-delivery-ratio between any source–destination pair by being aware of the time-varying nature of spectrum-availability of the operating environment. The proposed routing scheme consists of path selection and channel assignment. Two design variants are presented: one for inband- and the other for outband-FD CRNs. Our scheme is performed into three phases: path-discovery (to identify a set of feasible routes), channel-selection (to assign channels along each path) and path-selection (to select the highest effective availability-time path). Compared to a reference scheme, the simulation results indicate that being spectrum-availability-aware can achieve significant performance enhancement.

Keywords: Software-defined networking; BLP; Full-duplex; Routing; Multi-hop; Sequential-fixing; Channel assignment

1. Introduction

The recent advances in self-interference suppression (SIS) technologies have made full-duplex (FD) communication practically feasible [1–4]. This permits communicating users to efficiently utilize the available spectrum by allowing simultaneously communication (sending and receiving) over the same channel (inband FD (IBFD)) or over distinct channels (outband FD (OBFD)) depending on the employed SIS technology (i.e., radio frequency and digital baseband interference cancellation) [5–8]. Cognitive radio (CR) is another communication technology that was proposed to further improve spectrum utilization by providing dynamic access to the underutilized primary radio (PR) channels [9–11]. Integrating FD capability in CR networks (CRNs) can significantly improve spectrum utilization by allowing CR devices to opportunistically transmit and receive *simultaneous* packets over the same or different idle channels [3]. Such integration can significantly enhance spectral efficiency and provide massive spectrum opportunities for enabling large-scale adoption of emerging wireless networks (e.g., 5G). Such networks are expected to support multi-hop (device-to-device) communications. The FD-capability of CRs (OBFD or IBFD) requires efficient routing solutions that exploit the FD capability to improve spectrum utilization while considering the life-time of spectrum opportunities.

Most of existing CRN routing protocols were designed assuming half-duplex capabilities of CR devices [10,12,13]. Few routing protocols have been designed to support FD CR communications (e.g., [3,14]). However, existing FD designs were based on the assumption that the lifetime of the idle PR channels is much greater than the packet transmission time [3,14]. This assumption does not hold in a CRN that operates in highly dynamic PR network (PRN) environment (e.g., cellular networks). Thus, it is essential to study the routing deign in FD-based CRNs under highly dynamic lifetime availability of PR channels. In this paper, we present a FD- and availability-aware routing design for CRNs with the goal of improving network performance. Two design variants are provided: the first one is suitable for IBFD CRNs while the second is suitable for OBFD CRNs. Unlike the works in [3,14], our routing is designed for a CRN that coexists with

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highly dynamic PRNs, in which it accounts for the dynamic availability of PR channels. Specifically, our scheme attempts to determine the path with highest average lifetime between a CR source–destination while considering the FD-capability (IBFD or OBFD) and the time-varying PR activities. The proposed scheme first collects a set of feasible paths. Then, for each path in that set, the channel assignment that provides the maximum effective path-lifetime for that path is selected. The effective *path availability* (lifetime) for a given path, is constrained by the availability-time of the bottleneck hop with least average availability-time along that path.[1] The channel assignment optimization is found to constitute a Binary Linear Programming (BLP), which is NP-hard. Thus, a polynomial-time procedure is adopted to provide sub-optimal solutions. Finally, our scheme selects the path with the highest available-time. Simulations are used to investigate the performance of our scheme. The results reveal a significant enhancement in network throughput is achieved over a reference scheme. The results also indicate that the IBFD capability can significantly enhance spectrum utilization over the OBFD. The rest of the paper is organized as follows. Section 2 describes the network architecture. Section 3 presents the problem formulation and proposed routing solution. Section 4 presents performance evaluation results. Finally, Section 5 concludes the paper.

2. Network model

We consider a multi-hop FD-based CRN that opportunistically utilizes a set of $|\mathcal{M}|$ licensed PR channels, each with bandwidth W. Let $\mathcal{M}$ denote the overall PR channel list. The CR users geographically coexist with the PR users. Two FD capabilities for the CR users are studied in this paper: IBFD and OBFD. Each CR user in the network can be a source, destination or an intermediate relay node. Hence, for a CR source–destination pair, a number of possible loop-free paths exist, denoted by the set $\mathcal{P}$. The length of each path $p \in \mathcal{P}$ is represented by the number of hops in that path N_p. Each hop h along each path p has a set of idle channels $\mathcal{M}_{h,p} \subseteq \mathcal{M}$ depending on the PRN activities in each hop locality. Each PR channel has two states; BUSY state with period $T_{h,p}^{busy^{(i)}}$ representing that the ith channel is being utilized by the PR devices in a given hop locality h along path p, and the IDLE state with duration $T_{h,p}^{(i)}$ representing that channel i is idle and can be used by the CR users in hop h along path p. The busy and idle periods over each hop h along path p are modeled as exponential-distributed random variables. We define $\overline{T}_{h,p}^{(i)}$ and $\overline{T}_{h,p}^{busy,(i)}$ as the average availability-time (busy time) of channel i over hop h in p. Hence, the idle probability of channel i over hop h in path p at a certain time is given by: $P_{idle} = \frac{\overline{T}_{h,p}^{(i)}}{\overline{T}_{h,p}^{busy,(i)}+\overline{T}_{h,p}^{(i)}}$ [10]. The lists $\mathcal{M}_{h,p}$ can be identified by CR users either through spectrum sensing [11] or with the help of existing big spectrum-data platforms [16,17]. Such platforms continuously perform wireless traffic analysis in background and support on-demand search of idle channels at different locations, which consequently speeds up the process of identifying accurate $\mathcal{M}_{h,p}$ lists [16]. A rate-bandwidth model that supports 1 bps for each Hz of bandwidth for all channels is considered. Particularly, each idle PR channel can provide a transmission rate of $R = W$ bps if the received signal-to-noise-ratio (SNR) is greater than a predefined threshold μ^*, or 0 otherwise. We define a full-capacity path between a given source–destination pair as the path that utilizes the FD capability by allowing no-time sharing between interfering hops with supported data rate of R.

[1] The performance of a multi-hop path is restricted by the performance of the bottleneck hop that has the worst performance in the path [3,15].

3. Problem definition, formulation and solution

3.1. Problem statement and design consideration

Given the network model, our problem is defined as: For a source (S) and destination (D), set of paths between them, type of CR FD capability (IBFD/OBFD) and set of idle channels over the hops in each path, our goal is to find the path p^* that has the highest lifetime between S and D along wi h the full-path capacity channel selection while considering the time-varying PR activities over the various channels subject to the following design constrains:

- **C1.** Channel-per-hop constrain: Only one channel can be assigned to each hop.
- **C2.** IBFD Interfering-hop constraint: To achieve path-capacity R with no time-sharing, interfering hops that are one-hop a way cannot simultaneously utilize the same channel (hop h and $h+2$ cannot be assigned same channel). The adjacent hops can utilize the same channel at the same time (hop h and $h+1$ can use same channel).
- **C3.** OBFD Interfering-hop constraint: To achieve capacity R with no time-sharing, adjacent hops (and interfering hops) cannot be assigned a same channel (i.e., hop h, $h+1$ and $h+2$ cannot simultaneously utilize the same channel).
- **C4.** SNR constraint: the received SNR over an assigned channel i should be $\geq \mu^*$.

3.2. Formulation and proposed solution

To maximize the overall end-to-end network performance, the proposed routing scheme is performed through three consecutive phases: the first phase aims at collecting the possible set of paths $\mathcal{P}$ between S and D using a path discovery algorithm. The second phase attempts at finding the optimal channel assignment that maximizes the lifetime of each path subject to the design constraints. The last phase selects the optimal path p^* with the highest effective availability-time among all possible paths with capacity R.

3.2.1. Path discovery

Our scheme starts by broadcasting a Rout Request (RREQ) messages over a dedicated control channel with the purpose of defining the set of loop-free feasible routes $\mathcal{P}$ between the source S and destination D. Once the first RREQ is received by D, it waits until a pre-specified timeout expires to permit collecting enough RREQs. Upon timeout, the destination determines the set of loop-free paths $\mathcal{P}$ between S and D as described in [3].

3.2.2. Channel assignment

To mathematically represent the channel assignment problem along each defined path $p \in \mathcal{P}$ for OBFD and IBFD CRNs with no time-sharing, we introduce a binary variable $x_{h,P}^{(i)}$ such that:

$$x_{h,P}^{(i)} = \begin{cases} 1, \text{ if the } i\text{th channel is allocated to } h \text{ in } p \\ 0 \qquad , \text{Otherwise.} \end{cases} \tag{1}$$

The SNR constraint (**C4**) can be guaranteed by fixing $x_{h,p}^{(i)} = 0$ for every channel $i \in \mathcal{M}$ over hop h in path p with SNR $< \mu^*$. Hence, the main objective is to maximize the average path availability-time for each path $p \in \mathcal{P}$, subject to **C1** and C2 for the IBFD CRN and **C1 and C3** for the OBFD CRN.

Problem formulation for IBFD CRNs

Network performance of path p is constrained by the average availability-time of the assigned channel of the bottleneck hop along that path (the assigned channel with minimum average lifetime). Thus, our channel assignment problem along each path p is expressed as a *Maxmin optimization* with the target of maximizing the minimum average availability-time for each path (effective path availability-time) by determining the binary variables $x_{h,p}^{(i)}$. For OBFD capable CR users, the assignment problem for a given path p can be expressed as:

$$\max_{x_{h,p}^{(i)}} \min_{\in\{0,1\}} \left\{ \sum_{i=1}^{M} \overline{T}_{1,p}^{(i)} x_{1,p}^{(i)}, \sum_{i=1}^{M} \overline{T}_{2,p}^{(i)} x_{2,p}^{(i)} .. \sum_{i=1}^{M} \overline{T}_{p,N_p}^{(i)} x_{p,N_p}^{(i)} \right\}$$
$$s.t. \quad \sum_{i=1}^{M} x_{h,p}^{(i)} \le 1, \forall h \in \{1 \dots N_p\}$$
$$x_{h,p}^{(i)} + x_{h+2,p}^{(i)} \le 1, \forall i \in \mathcal{M}, \forall h \in \{1 \dots N_p - 2\} \tag{2}$$

Our binary-optimization problem with the maximin objective function in (2) can be converted into a binary-linear program (BLP) using the following two-step methodology [3]: we add an auxiliary-decision variable Z that is a lower-bound on each of the individual summation in the objective of (2), then we change the objective to $\max Z$ and add the following set of constraints $\sum_{i=1}^{M} \overline{T}_{p,N_p}^{(i)} x_{h,p}^{(i)} - Z \ge 0, \forall h \in \{1 \dots\dots N_p\}$. The main idea is that the minimum of the set of individual summations is the largest value that is less than or equal to each of the individual summations. By maximizing Z and adding the lower-bound constraints, our optimization can be written as BLP as:

$$\text{maximize}_{x_{h,p}^{(i)}, Z} \{Z\}$$
$$s.t. \quad \sum_{i=1}^{M} x_{h,p}^{(i)} \le 1, \forall h \in \{1 \dots N_p\}$$
$$x_{h,p}^{(i)} + x_{h+2,p}^{(i)} \le 1, \forall i \in \mathcal{M}, \forall h \in \{1 \dots N_p - 2\},$$
$$-\sum_{i=1}^{M} \overline{T}_{h,p}^{(i)} x_{h,p}^{(i)}, < -Z, \forall h \in \{1 \dots N_p\}. \tag{3}$$

The BLP optimization problems are NP-hard, in general. Therefore, we adopt the sequential-fixing procedure to provide sub-optimal solutions to our BLP problem in polynomial-time by solving a series of relaxed LP problems using standard polynomial-time LP solvers [14]. Let $\Psi_p^* = \{i_1^*, i_2^*, \dots, i_h^*, \dots, i_{N_p}^*\}$ be the channel assignment provided by solving our optimization problem for each path p, where i_h^* is the selected channel for hop h in p.

Problem formulation for OBFD CRNs

The channel assignment for the OBFD capable CRNs is another variant of the one in (3) that does not allow CR users to send and receive concurrently on the same channel. Hence, the channel assignment of OBFD CRNs is obtained by replacing the 2nd constraint (**C2**) in (3) with (**C3**), which can be given as:

$$x_{h,p}^{(i)} + x_{h+1,p}^{(i)} + x_{h+2,p}^{(i)} \le 1, \forall i \in \mathcal{M}, \forall h \in \{1..N_p - 2\} \tag{4}$$

3.2.3. Route selection

Given the channel assignment $\Psi_p^*, \forall p \in \mathcal{P}$, the average availability-time of the selected channel for each hop h in p ($T_{h,p}^*$) can be computed as:

$$T_{h,p}^* = \overline{T}_{h,p}^{(i_h^*)}, \ \forall h = \{1, 2, \dots, N_p\}. \tag{5}$$

Given $T_{h,p}^*$, the effective availability-time for path p (T_p) can computed as:

$$T_p = \min\{T_{1,p}^*, T_{2,p}^*, \dots, T_{N_p,p}^*\}, \forall p \in \mathcal{P} \tag{6}$$

Then, the path $p^* \in \mathcal{P}$ that results in the highest effective lifetime is chosen for data transmission from S to D as:

$$p^* = \arg\max_{p \in \mathcal{P}} \{T_p\}. \tag{7}$$

After selecting the path (p^*) and the per-hop channel assignment by the destination, it notifies the CR nodes along the selected path with the computed channel assignment and when to expect receiving their packets.

Observation: To achieve bi-directional flow of information between the source S and destination D with the highest possible transmission rate as required by emerging wireless networks, two directed paths from S to D and from D to S should be found by ruining our algorithm twice. This is because any intermediate node in a path can exploit its FD capability in one direction at any given time by simultaneously receiving packets from the previous node and sending them to the next node in the direction of communication (e.g., in Fig. 1 that shows a 4-hop path along with the channel assignment, node 1 can either receive from S and simultaneously forward to node 2 in the FD forward direction or receive from node 2 and simultaneously forward to S in the backward FD direction). Given this fact, if the same path is to be used for the bi-directional communications, a node in the path can only participate in one direction of communication at a time. This results in time-sharing of the available resources, and hence reduces the achieved path-capacity in each direction. Thus, for next generation wireless networks (e.g., 5G networks), in which high speed transmissions are needed in both direction of communications, separate paths should be used.

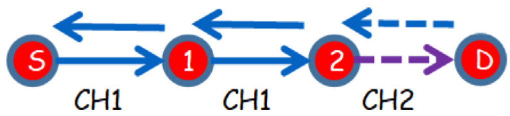


Fig. 1. Impact of bi-directional transmissions over a multi-hop FD path.

3.3. Complexity analysis

The sequential-fixing procedure has a polynomial-time complexity as it is based on using polynomial-time LP solvers. Hence, for each path p, a feasible channel assignment (or no feasible assignment) can be found by solving at most $N_p \max_h\{|\mathcal{M}_{h,p}|\}$ relaxed LP problems with time-complexity that is bounded by $O(N_p \max_h\{|\mathcal{M}_{h,p}|\})$ [14]. According to our routing protocol, the channel assignment problem must be solved for every path $p \in \mathcal{P}$, thus $|\mathcal{P}|$ problems need to be solved. In this case, the complexity of executing our routing protocol is $|\mathcal{P}|$ times the complexity of the sequential-fixing procedure. Since sequential-fixing procedure has a polynomial-time complexity, the complexity of our routing scheme is polynomial and bounded by $|\mathcal{P}| \times O(N_p \max_h\{|\mathcal{M}_{h,p}|\})$. We note that polynomial-time decision making schemes designed for CRNs are acceptable in practice as CR nodes, usually, are equipped with FPGA/DSP processors with multi-gigabit processing speed and highly optimized parallel processing/computing capabilities [18]. Because our sub-optimal scheme has a polynomial-time complexity, the scale of its execution is comparable to practical network decision time, and thus our routing is suitable for practical/online implementations.

4. Performance evaluation

4.1. Simulation setup

The performance of the proposed routing scheme is investigated through simulations for IBFD- and OBFD-based CRNs. When our time-aware (TA) routing is used in IBFD-based (OBFD-based) CRN, we referred to as IBFD-TA (OBFD-TA). The network throughput of our proposed schemes is compared to that of the OBFD-FC (FD-full-capacity) scheme that has been proposed in [14]. The OBFD-FC scheme is a FD-aware routing that does not consider the lifetime of idle PR channels. We note here that both OBFD-FC and our proposed scheme attempt to exploit the FD capabilities to find the path between S and D, over which all hop transmissions can proceed simultaneously, each with a fixed supported data rate R (recall that both protocols adopt a bandwidth model that supports 1 bps for each Hz of bandwidth, in which each channel can support a fixed rate of $R = W$ bps if the SNR $\geq \mu^*$). This results in achieving the maximum possible path-capacity of R over the selected path. The difference between them is that our scheme attempts to find the maximum-capacity path with highest effective path availability-time, whereas OBFD-FC attempts to find the maximum-capacity path of R with least number of assigned distinct channels without being-aware of PR activities and the time-availability of the assigned channels. It is worth noting that maximizing the effective path availability-time increases the chances of delivering the packets to the destination without being interrupted by the PR users, and hence improves the achieved end-to-end throughput and path capacity. Rayleigh fading model with path-loss exponent of 3 is used to present the channel gain between communicating CR users for all PR channels. We set the idle probability of each channel i over hop p along any path to P_{idle}. The thermal-noise power density, maximum transmit power and SNR threshold μ^* are respectively set to 1×10^{-15} W/Hz, 1 W and 5 dB. The data rate of each idle channel is fixed to $R = 10$ Mbps. The location of each CR user is uniformly distributed in a 250 m × 250 m field. Network throughput is used as the key performance measure. Each simulated result is an average of 1000 iterations.

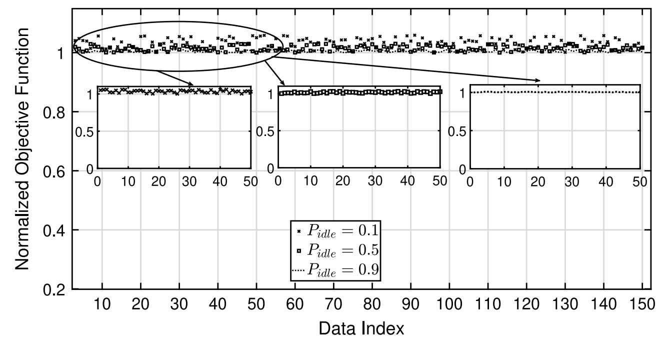
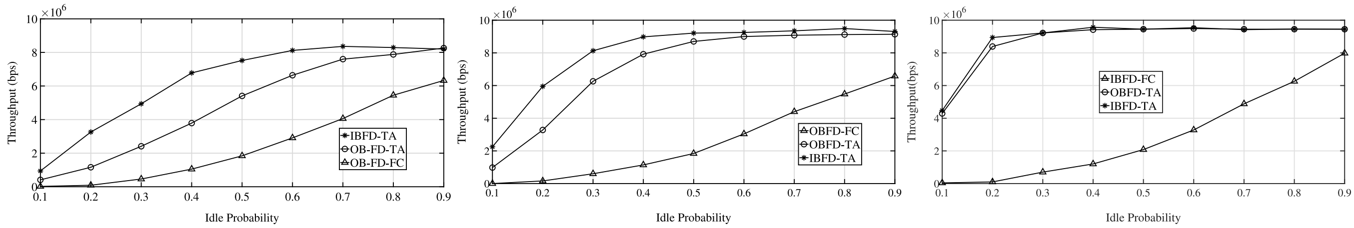


Fig. 2. Normalized cost (w.r.t. the optimal solution) for $P_I = 0.1, 0.5, 0.9$ and $M = 5$.

4.2. Simulation results

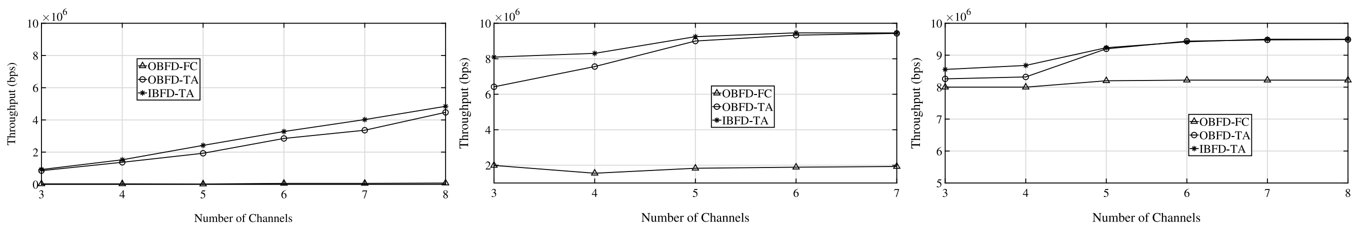
We first study the optimally of the sequential-fixing procedure in solving our channel assignment problem. The sequential-fixing solutions are compared with that of the solutions obtained using the brute-force (BF) method (which uses exhaustive search with non-polynomial time complexity). Fig. 2 shows the normalized cost determined based on the sequential-fixing with respect to the optimal cost (computed using BF) for 150 optimization instances for $M = 5$ and $P_{idle} = 0.1$, 0.5, 0.9. This figure reveals that the sequential-fixing solutions are within 5% of the optimal BF solutions (almost identical for moderate-to-high P_{idle}). Thus, it provides sub-optimal solutions with polynomial-time complexity.

We now study the impact of PR activities on the end-to-end network throughput for various number of licensed PR channels ($M = 3, 5, 8$) in Fig. 3. This figure reveals that network performance improves as PR activities decrease (higher values of P_{idle}) for all routing schemes. This is because as P_{idle} increases, the chances of having more idle channels with higher average lifetime periods increase. Fig. 3 reveals that our proposed IBFD-TA and OBFD-TA scheme significantly outperforms the OBFD-FC scheme, irrespective of M. It also shows that the IBFD-TA scheme outperforms the OBFD-TA. This is because IBFD-TA allows CR users to concurrently send and receive over the same channel, which can spare more



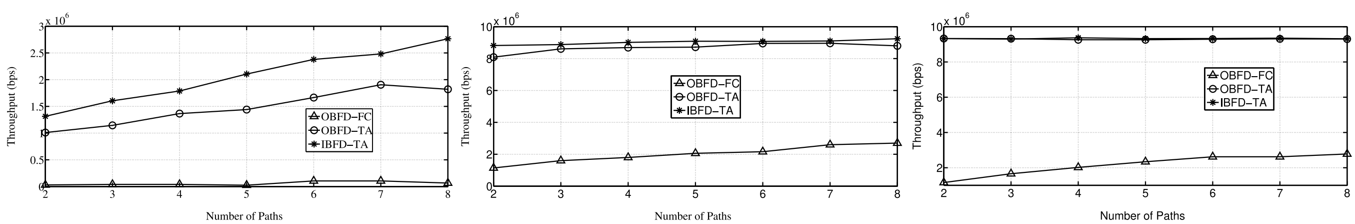
(a) $M = 3$. (b) $M = 5$ (c) $M = 8$

Fig. 3. Throughput vs. P_{idle} for various number of channels.



(a) $P_{idle} = 0.1$ (b) $P_{idle} = 0.5$ (c) $P_{idle} = 0.9$

Fig. 4. Throughput vs. M under different PR activities.



(a) $P_I = 0.1$. (b) $P_I = 0.5$ (c) $P_I = 0.9$

Fig. 5. Throughput vs. number of collected paths $|\mathcal{P}|$ for various P_I and $M = 5$.

channels for other CR users and improve spectrum utilization. This figure also shows that the performance improvement is higher at larger values of P_{idle}. Fig. 4 investigates network throughput as a function of M for different values of P_{idle}. This figure reveals that network throughput increases with increasing the number of PR channels for all schemes. It is clear that our proposed IBFD-TA scheme significantly outperforms the OBFD-TA OBFD-FC algorithms under moderate and high PR activities (small values of P_{idle}). The reported performance enhancement under moderate-to-high PR activities is of practical importance. This is because CR users are expected to share the spectrum with cellular PRNs. Such type of PRNs operates with moderate-to-high activities, resulting in small values of P_{idle}. This figure also shows that the IBFD-TA and OBFD-TA schemes provide comparable performance under larger values of M and/or P_{idle}. This is explained as follows. As M (P_{idle}) increases, more available channels become available for CRs. This increases the chances of finding distinct channels that can be assigned to different hops in OBFD scheme, resulting in more full-capacity path candidates that can be used for transmission. Hence, comparable performance to IBFD scheme can be achieved. Finally, the impact of the number of collected paths $|\mathcal{P}|$ on network performance is investigated in Fig. 5 under low, moderate and high PR activities for $M = 5$. It shows that network performance, in general, improves as $|\mathcal{P}|$ increases. This is expected as increasing $|\mathcal{P}|$ increases the candidate paths, and hence increases the chances of finding more full-capacity paths with higher effective lifetime, resulting in improved throughput. The figure also shows that our scheme outperforms OBFD-FC, irrespective of $|\mathcal{P}|$. Under high channel availability (large values of P_{idle}), this figure reveals that increasing $|\mathcal{P}|$ does not improve system performance due to the higher availability of channels, and hence fewer number of paths are needed.

5. Conclusion

This paper investigates the problem of route-selection and channel assignment in IBFD- and OBFD-based CRNs. In OBFD case, each CR user can simultaneously transmit and receive over different channels. Whereas in IBFD case, each CR device can concurrently transmit and receive over the same or different channels. Unlike previous FD-based routing schemes that assume long lifetime of idle PR channels, our joint routing and channel assignment is lifetime-aware that attempts to find the path with the highest effective lifetime availability between communicating pair. The proposed routing is performed into three phases: route discovery, full-capacity channel assignment and path selection. The channel assignment is sub-optimally computed using a polynomial-time procedure for each path. Simulations results revealed that our routing schemes achieved significant performance gain over previous FD scheme.

CRediT authorship contribution statement

Haythem Bany Salameh: Conceptualization, Formal analysis, Methodology, Investigation, Writing - original draft, Writing - review & editing, Supervision. **Haneen Khasawneh:** Investigation, Software, Validation, Data curation, Visualization.

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.

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