Extending Cognitive Radios with New Perspectives

(Invited Paper)

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***Abstract*—Over a decade-long research on Cognitive Radio (CR) has provided many solutions to its fundamental challenges such as spectrum sensing and resource allocation. However, most of these solutions are particularly designed either for networks which have a supporting infrastructure (i.e., cognitive base stations) or for ad hoc networks with persistent connectivity. In this paper, we focus on less-investigated cases and highlight their potential for realisation of CR paradigm to a broader domain beyond the extensively researched centralised networks or well-connected decentralised networks. In particular, we analyze the potential of applying delay-tolerant networking paradigm for CRNs and outline how social network analysis and *social* properties can be exploited in the design of CRN solutions.**

***Index Terms*—Cognitive radio, social network analysis, opportunistic communications.**

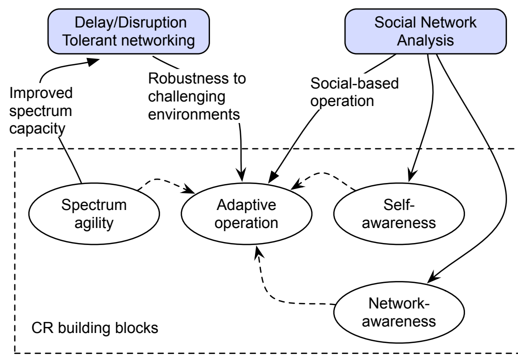


Fig. 1. Potentials of DTNs and social networks for CRNs.

I. Introduction

With the explosion in the number of wireless devices and the increasing use of wireless applications, radio spectrum has become a valuable resource. Constantly increasing demand for spectrum raised the debate on the efficiency of the current regulations, so called *static spectrum access*. In static spectrum access, spectrum bands are allocated to exclusive use of certain technologies via licenses, which are issued for large geographical areas (such as country-wide) and for very long periods (tens of years). However, spectrum use varies spatiotemporally and current regulations restrict the use of spectrum opportunities by users with no licenses (*secondary users*, SU) even when license holders (*primary users*, PU) have no ongoing activity in these bands. As some studies forecasted that demand for mobile services would surpass the supply in near future, such a cumbersome regulatory framework needs to be replaced with a more flexible one that allows agile access to unused spectrum. *Dynamic spectrum access* (DSA) aims to remedy this inefficiency by letting SUs transmit in PU spectrum bands opportunistically when they are not occupied by PUs. In that regard, *cognitive radios* (CRs) implement DSA capabilities as well as a number of functions such as environment-awareness and adaptation.

Since the term CR was coined by Joseph Mitola in early 2000, CR research has developed many solutions to challenges such as spectrum sensing and resource allocation. However, research has largely focused on infrastructure-based networks or multi-hop networks with persistent connectivity. But CR, with its environment-adaptation and adaptive operation capabilities, can also operate under challenging cases, e.g., intermittently connected networks. The current solutions with strong connectivity assumptions do not fit to these cases. Moreover, majority of these solutions lack the context of communications; who are the users of the CR devices, e.g., vehicles, human users, or network devices. We believe that exploiting context and relations among the entities in CR networks (CRNs) helps us to design more efficient protocols for CRNs. For example, given that users of the CR devices are human users and their daily habits follow a highly regular pattern, we can design CR resource allocation schemes that make use of their mobility. Moreover, for a trustworthy operation, it is paramount to model *social* relations among CRs and use them in assessing with whom to cooperate.

The aim of this paper is to highlight the potential of integrating established knowledge from two research domains, namely *delay/disruption-tolerant networks* (DTNs) and *social networks* for devising more efficient CR protocols that are robust to challenging environments and more context-aware. Although we discuss these two paradigms seperately, social network analysis seems to be formidable to grasp the network dynamics and design efficient DTN protocols (e.g., see [1]). The basic motivation of our research is to enrich CR communications for "what-if" scenarios, which have not yet been investigated except very few works [2]–[5]. We believe that these scenarios help expand the CR paradigm to a broader domain beyond the extensively researched centralized or well-connected decentralized networks. Moreover, as depicted in Fig. 1 both approaches enhance CRNs in several ways, e.g., through network-awareness, self-awareness.

The rest of the paper is organized as follows. Section II lists the potentials of opportunistic communications for CRNs and vice versa. Additionally, in this section we present a simplistic scenario to highlight the effect of opportunistic spectrum access on contact capacity of a DTN. Similarly, Section III introduces basic terms of social networks and its potentials for CR research. We also present an example sensing scheme in which CRs consider the social relations both in selection of cooperators and responding to sensing requests. Finally, we conclude in Section IV.

II. Opportunistic CR Communications

A. Background on Delay-tolerant Networks (DTNs)

A delay/disruption-tolerant network (DTN) is a network with unstable and highly unpredictable topology which results in loose connectivity and lack of complete routes from a source to a destination node in the network [6], [7]. This unstability may arise due to several reasons, for example, mobility of the nodes (e.g., vehicular networks), failure of some network components (e.g., post-disaster networks), turning the transceivers on and off (sensor networks), or nature of the networking environment (e.g., space or underwater networks). In stark contrast with tightly connected networks, end-to-end links are mostly missing in DTNs and network may even be partitioned into smaller connectivity islands. Therefore, conventional solutions for mobile ad hoc networks fail in DTNs, as they require a complete route between the two ends before initiating data transmission [6]. Although mobility is the major cause of unstability, it is at the same time an enabler for message dissemination in these challenged networks. Thanks to mobility, nodes can exchange their messages when coming into communication range of each other, and *store* them when they move or no active link exists. A message being forwarded from one hop to the other can finally reach the target destination. Nodes make forwarding decisions based on their knowledge about the network and the nodes. Nodes can build their knowledge base via tracking their encounters (e.g., whom a node encounters, when, and where) and information exchanged during these contacts. Alternatively, nodes can acquire a broader, even global, view of the network offline from an external entity.

DTN paradigm, dubbed as *store-carry-forward*, is paramount not only for enabling communication for challenged networks but also for easing access to data without being controlled by a central authority. While the number of connected devices skyrockets, people's concerns about their privacy and freedom of access to the data also rise. *Mobile opportunistic networks* as a subset of DTNs provide a solution to this concern to some extent by facilitating the means of direct communication between parties without requiring a central service. Furthermore, volume of user generated content (videos, photos) is increasing drastically, turning the network of user devices into a precious source of data dubbed as *mobile cloud* [8]. Using the principles of opportunistic networking, people can access to the data stored in this cloud and can even outsource the computation to the cloud [9], [10].

To the best of our knowledge, potentials of DTNs and CRNs for each other have not been highlighted except two recent works [4], [5]. Zhao et al. [4] articulate that caching at some nodes in a CRN is crucial to achieving a bounded delay at the CRs which request data from other nodes through the channels subject to PU retransmissions. Authors in [5] research on where to replicate data and how much to replicate in an intermittently connected CRN.

B. Opportunities of Opportunistic Communications for CRNs

The term *opportunistic communication* refers to the operation of both DTNs and CRNs. In the DTN context, communication is *opportunistic* because nodes can only transmit if they happen to be at the transmission range of each other at a time. Therefore, an opportunity is the chance to use the wireless link with the encountered node at a certain time and location. In the context of CRNs, communication is *opportunistic* because SUs can transmit in the unused spectrum bands only if PUs do not transmit there. In this case, opportunity has a frequency dimension in addition to time and spatial dimension existing in the context of DTNs. Both kinds of opportunism enrich the realm of wireless communications; the first in the absence or failure of a connected network, and the second in the absence of spectrum resources for the exclusive use of the nodes of interest.

Similar to DTNs, CRNs due to their secondary position in the primary bands have to consider the case of intermittent connectivity. That is to say when a PU suddenly reappears in a band in which CR operates and the CR cannot immediately find another channel, it has to consider *store-carry-forward* type of operation on which DTN paradigm is built. DTNs consider such cases as the norm whereas CR literature contrarily assumes the existence of another reserved channel (e.g., an ISM channel) for such abrupt appearance of PUs. Hence, DTN-like operation relaxes such assumptions making CRNs resilient to challenges of the communication environment. Considering it from the DTN's viewpoint, we can also argue that DTNs also benefit by incorporating *cognitive capabilities* (e.g., DSA) into their operation. For sparse networks, contention for the wireless bands is not an issue, however, for denser networks, DTNs are subject to low data transmission rate during contacts as unlicensed spectrum bands are also becoming overly crowded. Since nodes are mobile, contact duration is usually short and communication using ISM bands falls short of meeting a satisfactory transmission capacity (also referred to as *contact capacity*), and thereby leads to low network performance. As a solution, DTN nodes can exploit the unused spectrum bands at other licensed frequencies and can offload some of the traffic to alternate bands. This offloading consequently decreases the contention for the spectrum. If the peculiarities brought by CR operation are handled appropriately, DTN nodes can enjoy higher transmission efficiency.

Naturally, this new modality brings out new challenges. From the CRN's viewpoint, existing message dissemination schemes have to cope with the uncertainty of the PU traffic. Different from DTNs, CRNs have another design dimension: the spatial and temporal change in the available spectrum bands. Hence, we have to take into account not only the contacts among peers but also the location(s), *where* these contacts occur and related spectrum occupancy characteristics. As in DTNs, CRs can combine their knowledge about the

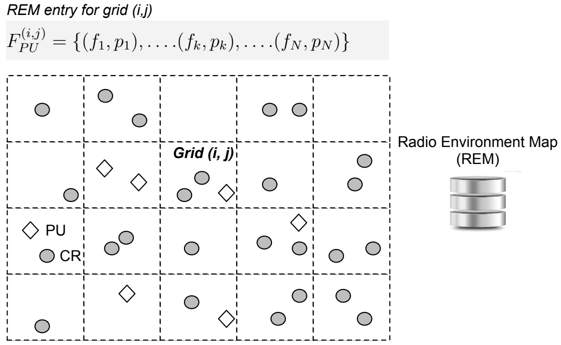


Fig. 2. A toy example for intermittently connected CRN.

network (e.g., meeting rates, community information) via their own observations with the knowledge they acquire from the Radio Environment Map (REM) [11]. REM is a network entity that stores a wide range of information about the network such as the terrain information, allowed transmission power limits, and more significantly expected PU frequency occupancy probabilities at a specific location. Depending on the dynamicity of the network conditions, a CR can decide on how often it contacts REM and can get up to date information. In addition, a CR can download the REM of the areas it visits frequently and use that information later in deciding which channels to sense. For example, in a network as in Fig. 2, REM stores $F_{PU}^{i,j}$, the frequency occupancy information about each grid (i, j). The record includes the list of channels (f_k) and their steady probabilities of being idle (p_k). With this information in addition to encounter histories and mobility information, CR can select the best channels on its way to destination.

From the DTN viewpoint, the major challenge is the overhead of spectrum sensing. In a conventional DTN, nodes can immediately exchange their messages whereas in CR-enabled DTNs first they have to seek for spectrum opportunities. The more time spent for sensing, the less remains for transmission. However, the additional capacity afforded by the discovered white spaces can compensate for this loss due to sensing. Therefore, the interplay among cost of spectrum sensing, discovered bandwidth, and contact capacity is central for understanding under which conditions DTNs can benefit from DSA. In the next section, we present an example scenario to highlight the basic tradeoffs in such a system and compare its contact capacity with conventional DTNs.

C. Contact Capacity Analysis

Suppose an opportunistic network of CRs as in Fig. 2. When two CRs meet, they stay in contact for average T seconds. These CRs can either use the ISM band with data rate B bps, or they can transmit through both ISM and PU bands that are discovered after spectrum sensing. Assume that there are N frequencies licensed to PUs and frequency i is idle with probability p_i where $p_i \sim \mathrm{U}(p_{min}, p_{max})$ with mean p. A CR can access to any of these bands after sensing the spectrum and finding it idle. We assume CRs can sense the spectrum with negligibly low detection error by tuning their sensing time τ where $\tau = \alpha T$ seconds. We refer to α as the *sensing overhead multiplier*. We assume CRs can sense several channels sequentially and aggregate the discovered opportunities using non-contiguous OFDM techniques (called $k-agile$ radios in [12]). Given that each PU band has data rate equal to βB where β is the *PU channel capacity multiplier*, we model the contact capacity under three scenarios:

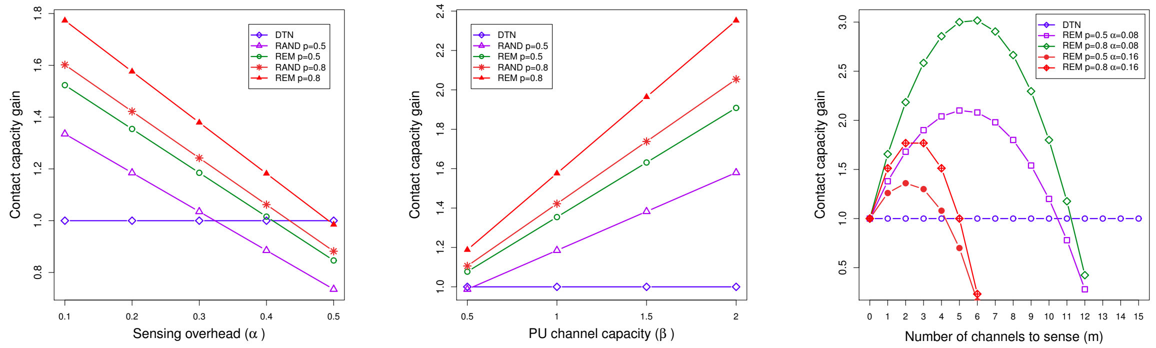
- DTN: If nodes use only ISM bands, the capacity C_{dtn} is TB bits per contact.
- RAND: In this case, nodes can use the PU bands. However, since they do not have any a priori information about the spectrum availabilities, they first communicate via ISM band to determine on which channel to tune and sense. Assuming that this coordination takes δT seconds, contact capacity is:

$$C_{rand} = T(1 - \alpha - \delta)(1 + \beta p)B. \qquad (1)$$

- REM-supported: In this case, nodes possess the information about the spectrum availabilities via accessing the REM. Hence, both nodes with the same (or similar) information decide to sense the channels according to their probability of being idle values. Compared to RAND, REM support enables CRs to select the channels with the highest p_i. Without loss of generality, we denote the channel with the j$^{\text{th}}$ highest probability with p_j, e.g., p_1 is the channel with the highest availability probability. If nodes can sense and aggregate m channels, the resulting capacity C_{rem} is as follows:

$$C_{rem} = T(1 - m\alpha)(1 + \beta \sum_{j=1}^{m} p_j)B. \qquad (2)$$

Fig.3 illustrates the *contact capacity gain* which measures the ratio of resulting capacity to C_{dtn} in each scenario. In these scenarios, CR senses only one channel out of four PU channels (i.e., $m = 1$ and $N = 4$) and we set $\delta = 0.01$. As Fig.3(a) shows, benefit of cognitive access degrades with increase in sensing overhead (α). For high p, REM-supported operation provides higher capacity below $\alpha = 0.5$ and for lower p below $\alpha = 0.4$. Regarding RAND, since CRs randomly select a channel, C_{rand} is lower than C_{rem} as expected. In comparison to C_{dtn}, C_{rand} is higher for $\alpha < 0.4$ for high PU channel availability, and $\alpha < 0.3$ for lower availability. Hence, should the REM access not be possible, conventional DTN is the better choice for high sensing overheads. Regarding the effect of β for $\alpha = 0.2$, we observe that cognitive operation brings significant gains as depicted in Fig. 3(b). Finally, Fig. 3(c) depicts the effect of sequential sensing. We increase m from 0 to 15. The case with $m = 0$ corresponds to a conventional DTN scenario where cognitive operation is disabled. The maximum number of channels that can be sensed during a contact time is restricted by the number of channels ($N = 15$) and sensing overhead (α). For example, in case $\alpha = 0.08$ twelve of fifteen channels can be sensed whereas it is only six for $\alpha = 0.16$. However, as Fig. 3(c) shows, after some point



(a) Contact capacity with increasing α.

(b) Effect of β capacity.

(c) REM-supported sequential sensing.

Fig. 3. Contact capacity under various α, β, and m settings for DTN, RAND, and REM scenarios.

the benefits begin to decline. Highest gains are achieved at $m = 2$ and $m = 6$ for $\alpha = 0.16$ and $\alpha = 0.08$, respectively. Given that $\alpha = 0.16$, capacity improvement is 0.77 and 0.36 for $p = 0.8$ and $p = 0.5$, respectively. For $\alpha = 0.08$, the increase is more significant: 3.02 and 2.08 for $p = 0.8$ and $p = 0.5$, respectively.

Although we abstracted many realities of CRNs (e.g., accuracy of REM information [11], SU's sensing reliability, or overhead of spectrum switching [13]), what we want to underline with this simple example is that spectrum sensing overhead, PU channel bandwidth, and length of sequential sensing as well as the PU spectrum occupancy probability have to be considered to decide on the best operation mode.

III. Social-awareness in CR Communications

A. Background on Social Networks

A *social network* abstracts a system as a graph $G = (V, E)$ with actors of the system represented as vertices (V) and the interactions among these actors as the links in this graph (E). Once abstracted, *social network analysis* (SNA) or *network science* tools provide the techniques to extract information hidden in the system either about individual nodes or the network as a whole. Some well-established statistical properties of G can be listed as follows: (1) degree distribution, (2) clustering coefficient, (3) centrality such as betweenness and closeness. These metrics are either *node level* metrics (such as 1) or *network level* (such as 2) and either calculated based on *node degree* (such as 1) or based on *shortest paths* (such as 3) [14]. Depending on the domain of the system (e.g., a wireless network or a human protein network), the extracted information may imply some characteristic of the subject matter. For example, the (in/out)-degree of a node can be a good indicator of the importance or involvedness of this node. As network level information, the *diameter* of the network determines how long it takes to communicate between two nodes separated with the maximum distance in this network.

Regarding the real sense of the term *social*, relations among entities imply the nature of these entities' decision making. Putting it into the human inspired networking context [15], we can model radio networks such that radio entities mimic

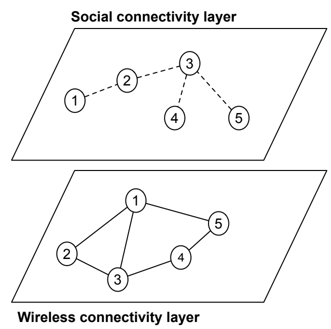


Fig. 4. Two layered view of a network: wireless connectivity layer and social connectivity layer.

human behaviour in decision making. As an example, cooperation willingness in human societies is highly correlated with social ties (i.e., friendship) among the two ends of the cooperation. However, research also showed that even though people do not know each other, they can cooperate because they are in the same community. For instance, people with similar political orientations are shown to approach each other more cooperatively compared to two strangers. Similar to human societies, CRs can decide whether to cooperate or not via learning from their experiences.

SNA has recently attracted many researchers in wireless networks. Kas et al. [14] showed the relation between a node's centrality and its role in spreading information. With this information, network operators can put more attention on protecting the more central nodes against malicious users/contents. Azimdoost et al. [16] provide a theoretical analysis of capacity in *wireless social networks*, similar to the pioneering work by Gupta and Kumar on wireless networks [17]. Other applications of SNA from routing in opportunistic networks to wireless mesh networks can be found in [18] and [19]. Regarding research in CRNs, only a few works examined the social behaviour or SNA in the CRN context. Güven et al. [2] introduce how friendship and community of each CR can be used to improve performance of cooperative spectrum sensing. Briefly, [2] introduce a cooperator selection scheme conditioned on social relations between CRs as well as their sensing performance. Li et al. [3] analyze the dynamics of a CRN (i.e., how channel preference varies) in which CRs share their knowledge about PU channels (e.g., idle or busy) with other CRs as channel recommendations.

B. Social-aware Protocols for CRNs

Taking the definition of a social network, a CRN is unarguably a social network in which CR devices—be it a user handset or a base station or even an operator—have various ties with others depending on their spatial or social properties. We conceptually model a network with two layers: the *wireless connectivity layer* and *social connectivity layer* as in Fig. 4. The former is derived from the physical distance and wireless communication properties between the nodes (i.e., the two nodes connected with a link can communicate) whereas the latter is an abstraction of the interactions/interrelations between the entities (e.g., friendship, community). While the former is more dynamic depending on the users' mobility characteristics, the latter evolves relatively slower. Almost all of the schemes in CRN literature considered only the wireless connectivity layer. However, we believe that for a more realistic and practical CRN, CR protocols should also take the social connectivity layer into account.

Below, we list the motivations for the use of both SNA and social properties of a CRN:

Design of network-aware protocols: CRNs are expected to be self-aware; the network is aware of its components, their states, and other information existing in the network as well as its operating environment. SNA is beneficial for both the network designers to develop more efficient protocols and also for the operators to develop new business models. Considering the first, SNA provides some tools for the designer to better comprehend the information both in the social connectivity layer and the wireless connectivity layer, e.g., which users are more in contact with each other, who collaborates with whom. In case the network has some structure (e.g., spatiotemporal change in node density), this structure can be exploited for several purposes, e.g, transmission power adaptation based on the density. Similarly, nodes tracking the connectivity state of the network can adapt their protocols accordingly, i.e., opportunistic communications in case of intermittent connectivity and end-to-end routing otherwise. Definitely, such self-awareness enhances the CRs towards the vision of self-organizing and self-healing systems.

Development of new business models: From the operators' viewpoint, such social-awareness can be used to increase the users' intention to share their resources (e.g., spectrum sensing or relaying). For instance, users acting as relays can expand the coverage and capacity (especially) at the cell edges at the expense of battery consumption. If relaying is based on social relations, then users may be more willing to cooperate compared to relaying for a stranger.

Incentives for cooperation: Due to the compelling challenges of DSA, CRN protocols usually require cooperation between CRs in coping with these challenges. For instance, it is widely accepted that cooperative spectrum sensing achieves higher sensing reliability compared to local sensing since it can overcome the hidden PU problem via exploiting the spatial diversity of cooperators [20]. However, supposing that *real* CRs are smarter to decide autonomously on their actions, the incentives for cooperation may not be very strong. Instead, CRs as social actors can eagerly cooperate with the others if the cooperation is constrained on strength of ties between these two entities. For instance, *cognitive femtocells* can determine on-the-fly the access mode (*open, closed*, or *hybrid*) based on the social tie between the cognitive femtocell (or the associated users) and the external entity asking for admission.

C. An Example Scenario: Social-aware Cooperative Sensing

Suppose a network of $N = 50$ CRs whose friendship relations follow an Erdös-Renyi graph as in Fig. 5(a). We define *social distance* between two nodes as the length of the shortest path between these nodes. Given that each CR is aware of this graph, we define the following cooperator selection scheme. A CR$_i$ computes each of its neighbor CR's (CR$_j$) utility according to its selection algorithm:

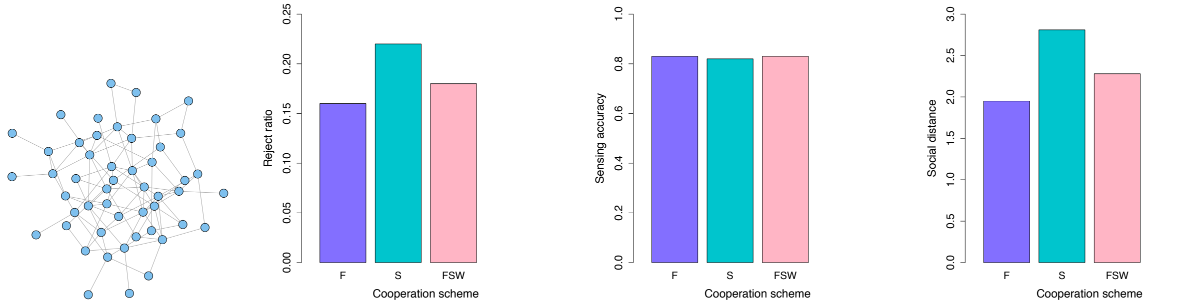
$$u_{i,j} = \alpha_f n_{i,j}^{-1} + \alpha_s p_{j,i} + \alpha_w w_{j,i} \tag{3}$$

where $n_{i,j}$ is the social distance between CR$_i$ and CR$_j$; $p_{j,i}$ is the probability of detection performance in case CR$_j$ senses for CR$_i$; and $w_{j,i}$ is the probability that CR$_j$ cooperates with CR$_i$. A CR may reject cooperation depending on its cooperation logic. Each α parameter is in $[0, 1]$ interval and the following holds: $\alpha_f + \alpha_w + \alpha_s = 1$. Note that setting α_s to 1 reduces the selection criterion to sensing accuracy; setting $\alpha_f = 1$ to social distance; and setting $\alpha_w = 1$ to cooperation willingness. Each of these cases has its own use: cooperation with CRs who are closer in social graph may be desirable for ensuring trusted cooperation whereas a scheme accounting for cooperation tendency decreases energy consumption for communicating with these non-responding CRs. Sensing accuracy is clearly fundamental for achieving a reliable sensing.

Once all utilities are computed, CR$_i$ selects two CRs with the highest utilities out of its nine neighbors. We define three schemes according to their selection of α_f, α_s, and α_w:

- F-sense: Cooperators are selected only according to social distance, i.e., $\alpha_f = 1$ in Eq.(3).
- S-sense: Cooperators are selected only according to sensing accuracy, i.e., $\alpha_s = 1$.
- FSW-sense: All three properties are considered equally, i.e., $\alpha_f = 1/3$, $\alpha_s = 1/3$, and $\alpha_w = 1/3$.

Fig. 5(b) depicts the ratio of requests that are being ignored and Fig. 5(c) shows expected sensing accuracy of the selected cooperators. In this scenario, sensing accuracy of a CR is uniformly distributed in the interval [0.7,1] whereas the cooperation mode is negatively correlated to the social distance between the requesting and the requested CR, similar to human societies, i.e., $w_{j,i} \propto n_{i,j}^{-1}$. Fig. 5(d) shows social distance of the cooperators. Unsurprisingly, F-sense lets the CRs cooperate with other CRs that are closer in the social graph (CR$_i$ requested cooperation from CRs 1.95 hop away of which 1.86 hop-away nodes cooperated). Since cooperation tendency is modeled to be negatively correlated to social



(a) An Erdös-Renyi graph. (b) Ratio of rejected requests. (c) Sensing accuracy. (d) Social distance of coop. CRs.

Fig. 5. Comparison of cooperator selection schemes with various degrees of sensitivy to social distance, sensing accuracy, and cooperation willingness.

distance, F-sense has lower reject ratio that is around 0.15. Even though F-sense tries to select CRs that are highly cooperative, uncooperative CRs are unavoidable as average distance between two CRs is 3.28. Regarding accuracy, since all users have identical sensing capability, F-sense's ignorance of sensing accuracy does not hurt its accuracy. However, S-sense's ignorance of cooperation tendency results in higher reject ratio which can be translated into waste of CR resources, e.g., battery life. FSW-sense's consideration of all three factors results a higher social distance in cooperators compared to F-sense yet lower than S-sense.

In this section, we showed how social distance, sensing accuracy, and cooperation tendency affect the selection of cooperators on a simplistic scenario. How CRs can acquire social graph and related overhead as well as information leaked vs. privacy tradeoff need further research. Furthermore, each CR can adapt its decision logic based on its social status (e.g., a central node with many 1-hop friends, or an edge node with loose connectivity). In a realistic setting, models related these factors should cover the complexities of the real world, enable CRs to exploit their states and adapt accordingly.

IV. Conclusion

In this paper, we introduced the potentials of applying two well-established paradigms to CRNs, namely opportunistic communications and social networks. The former enhances the robustness of CRNs against the failures in the infrastructures or expands the CRN application scenarios to more challenging networks, e.g., emergency networks. The latter provides the tools to develop self-aware CRNs by exploiting the characteristics of the network itself or its individual components. With simplistic scenarios, we presented some of the potential improvements brought by these new modalities. We believe that these improvements are paramount for achieving CRNs that are adaptive and self-aware. Some of the interesting directions can be listed as: analysis of the locations of node contacts and designing the spectrum allocation/access schemes accordingly, effect of inacurate REM data on contact capacity, tradeoff analysis (e.g., information leaked vs. benefits) of social-awareness in CRNs.

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