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A Novel Energy Aware Coded Opportunistic Routing for Social Cognitive Radio Networks

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Abstract. As a huge numbers of heterogeneous devices will be connected in social cognitive radio networks (SCRNs), it needs more frequency spectrum. Moreover, dynamic spectrum availability and heterogeneous devices make it more difficult for routing design in SCRNs. Opportunistic routing (OR) can leverage the broadcast nature of wireless channels, and then can enhance network performance. In this work, we propose an energy aware coded OR (ECOR) in SCRNs, which jointly considers energy efficiency and social feature for designing coded OR. In the proposed OR, we exploit a new scheme for candidate selection and use network coding in data transmission between selected nodes in SCRNs. In addition, we propose a game-theoretic approach to decide forwarding candidate set which is based on auction mechanism. The simulation results demonstrate that the ECOR performs better compared with existing routing in SCRNs in terms of hop count and packet delivery ratio.

Keywords: Coded opportunistic routing · Social cognitive radio networks

1 Introduction

The cognitive radio (CR) [1] has been considered as a promising technology to improve spectrum usage in wireless networks. In CRNs, which exploit CR, it includes two types of users: primary users (PUs) and secondary users (SUs). The spectrum is used in an opportunistic manner, and thus, the spectrum for SUs is varying with locations and time, which is affected by the PU's behavior. The Social CRNs, on the other hand, is a branch of the CRNs where social relationships are established in an autonomous way among objects, things, and human and where social graphs are created. Thus, how to design routing scheme such that it can improve energy efficiency and transmission reliability for SCRNs, is an important issue.

Opportunistic routing (OR) [2], was introduced to enhance the routing performance in wireless networks, which can improve data transmission efficiency and reliability. In OR, the node broadcasts the packet to its neighbors, and then its neighbors will have

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the chance to receive/hear it, hence, they can cooperate in packet forwarding. In SCRNs, because of dynamic spectrum access and heterogeneity in cognitive nodes and channels, it is improper to exploit the traditional routing protocols for SCRNs. Since there is no need for determining next hops in advance in OR, it is more suitable for SCRNs.

Recently, several solutions have been proposed on opportunistic routing in CRNs. Lin *et al*. [3] induced a novel OR for regular and large-scale multi-channel CRNs, which exploits spectrum map established on local sensing information. In the first scheme SMOR-1, it exploits relay selection based on link transmission qualities. For the SMOR-2, it induces stochastic geometry for geographic OR for cooperative diversity. In [4], we proposed a novel OR scheme, CANCOR, for multi-channel CRNs, which incorporates channel assignment in OR protocol for multi-channel multi-radio CRNs. However, all above mentioned works do not systematically discuss how to exploit OR to improve the performance of CRNs. Until comparatively recently, Lin *et al*. [5] proposed a novel statistical QoS control mechanism through cooperative relaying from a network coded opportunistic routing perspective, realizing virtual MIMO communications at session level. Lin *et al*. [6] presented a cognitive and opportunistic relay selection scheme for cognitive M2M networks, which can mitigate detractive interference and efficiently selection the forwarders. However, they did not exploit the features of social networks to improve the performance of SCRNs.

Until comparatively recently, researchers begin to pay attention to investigate the performance of CRNs from the social network perspective [7–16]. They mainly focus on spectrum sensing/sharing [7–13], or queue control [14]. To the best of our knowledge, only two papers [15, 16] consider social networks in designing routing for CRNs. Reference [15] exploits the concept of PU community in designing SUs' routing, ignoring SUs' social behaviors. Reference [16] proposed a social-relationship-aware routing scheme for CRNs. It uses the predicted link reliability for routing and relay decision. However, they did not consider the SUs' energy efficiency and social similarity. Inspired by this, we propose an energy aware coded OR (ECOR) for SCRNs, which jointly considers energy efficiency and social feature. The contributions of this article can be summarized as follows. Firstly, we present a new routing metric, which jointly considers social features and energy. And then, the novel forwarding candidate selection is proposed for SCRNs, which is based on auction model, maximizing payoff. Moreover, the optimal bid price has been proved, which is related to the number of candidates and social features. Finally, we validate the effectiveness of the ECOR protocol by extensive simulations.

The remainder of this paper is organized as follows. The proposed routing protocol ECOR is introduced in Sect. 2, which mainly contains three key components: network model, candidate decision based on auction model, and data transmission based on network coding. Section 3 gives the performance evaluation of ECOR. Finally, Sect. 4 concludes this paper.

2 ECOR Design

In this section, we will present a coded OR for SCRNs, called energy aware coded opportunistic routing, ECOR. Next we will describe the network model, candidate selection and prioritization and data transmission based network coding.

2.1 Network Model

In this paper, we exploit an interweave model [4], in which the SUs can only transmit data in the channel that there is no PU activity occurs. In this model, it consists of C channels, num_s SUs and num_p PUs. Each SU is provided with the same number of radios R and exploits a half-duplex model. And also, a time-slotted model is exploited for SU, with a fixed slot duration T. Each slot includes a sensing period with duration T_s and a data transmission period with duration T_t. The usage pattern of a given channel follows an independent ON/OFF state model with the lengths of busy and idle periods in the exponentially distributed with rate parameters λ_{busy} and λ_{idle} over busy and idle transition respectively. Note that, the SUs have social relationships between them and are heterogeneous.

2.2 Candidate Decision Based on Auction Model

In this subsection, the candidate decision strategy is presented, which includes social ties, energy consumption, and auction model.

(1) Social ties

In real life, people who carry smart mobile devices (i.e., SUs for SCRNs) always have social relationship among themselves. We called that the SUs have social features in SCRNs, which have the same interests, or purpose, or family relationship. Individuals belonging to the same community will meet each other with high probability and regularly. Compared with dynamic information, social ties and behaviors between nodes in the same community tend to be stable over time. Hence, we can characterize the social ties between two nodes according to the history information of these two nodes, which can be expressed:

$$ST_{i,j}(T) = \chi SPM_{i,j}(T) + (1-\chi)socsim_{i,j}(T) \tag{1}$$

where $SPM_{i,j}(T)$ means the social pressure metric (SPM) of the nodes i and j [17] during time T, $\chi(\in[0,1])$ is the weight factor, which is set to be 0.5 in simulation, $socsim_{i,j}(T)$ means the social similarity between nodes i and j during time T, which can be reflected by formula (2).

$$socsim_{i,j}(T) = com_{i,j}(T)/(n_i(T) + n_j(T)) \tag{2}$$

where $com_{i,j}(T)$ means the number of common neighboring nodes for node i and node j during time T, $n_i(T)$ denotes the number of node i's one-hop neighbors during time T, and $n_j(T)$ denotes the number of node j's one-hop neighbors during time T.

(2) Energy consumption

Let $E_{iC}(T)$ as the energy consumption of the node i for successfully sending one packet to its downstream nodes during time T. It includes three parts: the energy $E_{iF}(T)$ (used to forward a packet), the energy $E_{iR}(T)$ (used to receive/hearing a packet), and the energy $E_{iACK}(T)$ (consumed to send an ACK). Thus, we can obtain

$$E_{iC}(T) = E_{iF}(T) + N_c \times E_{iR}(T) + E_{iACK}(T) \tag{3}$$

where Nc is the i's one-hop neighbors during time T. Also, we assume it subject to (0, 1) uniform distribution.

(3) Auction model

Suppose in our proposed OR, we select two classes of candidate sets CFS_1 and CFS_2, which CFS_1 is a primary set, CFS_2 is a backup selection. In proposed model, let source S denote the auctioneer and the forwarding nodes denote the bidders. The i^{th} bidder's cost is v_i, and the bidder offers price of node i is b_i^p which i is in the first class CFS_1 and the b_i^s is the bidder price of node i which i is in the second class CFS_2. Note that we have $CFS_1 \cap CFS_2 = \emptyset$. Hence, the payoff function of the node i can be expressed as:

$$u_i = \begin{cases} b_i^p - v_i & i \text{ is in the first class } CFS_1 \\ b_i^s - v_i & i \text{ is in the second class } CFS_2 \\ 0 & otherwise \end{cases} \tag{4}$$

So, the forwarding cost can be expressed as

$$\theta_i = \frac{1}{|N(i)|} \sum_{j \in N(i)} ST_{i,j}(ETX_i + \alpha E_{iC}) \tag{5}$$

where ETX_i is the ETX of node i to the destination D, $N(i)$ is the i's one-hop neighbors.

Hence, we have

$$v_i = \frac{\theta_i}{\frac{1}{|N(i)|} \sum_{j \in N(i)} ST_{i,j}(ETX_s + \alpha E_{initial})} \tag{6}$$

which ETX_s is the ETX of source S to the destination D, and $E_{initial}$ is the initial energy. It is easy to know that the distribution of v_i is uniformed. So, the expected payoff of i can be calculated

$$u_i = (b_i - v_i) \prod_{j \neq i} P(b_i < (b(v_j)) \tag{7}$$

where $P(b_i < (b(v_j))$ denotes the probability that node i has minimum bid.

According to the characteristics of v_i, we have

$$P(b_i < (b(v_j)) = P(\Phi(b_i) < v_j) = 1 - \Phi(b_i) \tag{8}$$

and

$$\prod_{j \neq i} P(b_i < (b(v_j)) = [1 - \Phi(b_i)]^{N(i)-1} \tag{9}$$

So we have

$$\max u_i = \max_{b_i}((b_i - v_i)[1 - \Phi(b_i)]^{N(i)-1}) \tag{10}$$

After derivation, we can obtain

$$\begin{aligned} b^*(v_i) &= \frac{1}{|N(i)|-1} - \frac{|N(i)|-2}{|N(i)|-1} v_i \\ &= \frac{1}{|N(i)|-1} - \frac{|N(i)|-2}{|N(i)|-1} \frac{\theta_i}{\frac{1}{|N(i)|}\sum_{j \in N(i)} ST_{i,j}(ETX_s + \alpha E_{initial})} \end{aligned} \tag{11}$$

The bidding node i bids $b^*(v_i)$ such that all bidders payoff are maximized. In addition, the prioritization of forwarding candidates are set according the price, the node with low price has high priority.

2.3 Network Coding Based Data Transmission

In ECOR, we exploit network coding (NC) [18] for data transmission between selected trust nodes which is to improve the transmission performance. The ECOR uses the intra-session NC (IaSNC) in which the coding operations are based on intra-session (the packets are from the same session).

In IaSNC, the S will divide data into small generations of k packets, PKT_1, …, PKT_k, which are called original packets. The S linearly combines the k packets in current generation and keeps sending the linear combinations from the current generation until the destination feedbacks the generation acknowledgement. After receiving the generation acknowledgement from the destination, it moves to the next generation. When the node receives a coded packet, it will check to determine whether or not there exists the linearly independent between the received coded packet and the previously received packets of the same generation. If so, it will store it, otherwise, it drops it. In addition, the node can re-code received coded packets base on linear combination operations. After receiving any k linearly independent coded packets, the D can recover the k native packets, and then returns an acknowledgement to the source. So, the source will stop sending the linear combinations of the current generation, and moves to the next generation. In our simulation, the maximal k is set to be 10.

Similar to Ref. [19], we exploit the credit counter for coding and forwarding condition. Each credit counter is used for a channel in multi-channel wireless networks. Hence, for each node, we should maintain $|C|$ credit counters. In addition, we take channel availability into account for credit calculating in ECOR. Next, we will give a novel method for calculating the value of credit for node i corresponding to the channel c, which can be expressed

$$credit_i(c) = \frac{z_i(c)}{\sum\limits_{c \in C} (u(c) \sum\limits_{j > i} z_i(c)(1 - \rho_{ji}(c))} \tag{12}$$

where $u(c)$ is the channel availability, $\rho_{ji}(c)$ denotes the packet loss rate from node j to node i on the channel c, and $z_i(c)$ is the expected number of transmissions that j must make on channel c.

If the value of $credit_i(c)$ is larger than zero, node i generates a coded packet, and broadcasts it on channel c, decreasing the credit counter. Next, we describe the data forwarding process, which includes three key components.

Source node: It continues seeds the encoding packets of the current generation size until it receives corresponding ACK feedback or reach current generation size k.

Relay node: When a relay node receives a coded packet, it will check to determine whether or not there exists the linearly independent between the received coded packet and the previously received packets of the same generation. If so, it will store it, otherwise, it drops it. As well as, the node can re-code received coded packets base on linear combination operations. As we know in SCRNs, there are multiple types of flows. Suppose that there are multiple unicast flows at the relay node, so we can determine the forwarding priority of these flows according to the following rule:

(1) For different types of flows, the forwarding priority is set according to the preset priority.
(2) For the same type flows, we exploit a new metric ς_{f_i} ($\varsigma_{f_i} = \delta_1 n_{f_i(pkt)} + \delta_2 n_{f_i(times)}$ where δ_1 and δ_2 are weight factors, and have $\delta_1, \delta_2 \in [0, 1]$, $\delta_1 + \delta_2 = 1$, in the simulation, we set them to be 0.5 and 0.5, respectively, $n_{f_i(pkt)}$ is the total number of packets of flow f_i currently at the node, and $n_{f_i(times)}$ is the total times that the flow f_i goes through the node in the past time). The flow f_i with higher ς_{f_i} has a forwarding priority.

Destination node: It feedbacks an ACK to the source by short path routing as soon as it can recover the whole generation. When two nodes meet, the ACK of the generation of the flow should be inserted into their packet header exchange before data transmission, which can avoid the transmission of ACKed generation of the flow.

For channel selection, the channel m with higher $u(m)$ is considered as a better channel. Thus, it is given a higher rank. In each channel assignment decision, we choose the channel with highest rank for data transmission.

3 Performance Evaluation

In this section, we present the performance evaluation of ECOR protocol using NS2 [20] and CRCN model [21]. The simulation settings are: the SUs mobility model is random waypoint model in a square area, whose node density is 400 nodes/Km^2. The propagation model is the Two-Ray Ground model. The CBR data packets are 1000 bytes and the data traffic is active in the interval [60, 1000] seconds. Each node generates one data flow to a destination node selected randomly. For each experiment we performed 100 runs computing both the average value, i.e., packet delivery ratio (PDR) and hop count.

In addition, the energy parameters $E_{iF}(T)$, $E_{iR}(T)$, and $E_{iACK}(T)$ are set to 3.6e−3 eu, 1.8e−3 eu, and 0.16e−3 eu. The initial energy of the node is 300 eu. The number of flows is 5. Finally, we give three types of flows, the priorities and parameters are shown in Table 1.

Table 1. MAC parameters for 3 classes

Class	Priority	AIFSN	CWmin	CWmax
Class 1	2	2	3	7
Class 2	1	2	7	15
Class 3	0	3	15	1023

Table 2. Simulation parameters

Number of channels	10
Number of Radios	2
Weight factor α	0.2
Max SU speed	2 m/s
Number of PUs	[2,…,18]
Number of SUs	[20,…,100]
PU coverage	300 m
SU transmission range	120 m
PU transmission range	150 m
Channel data rate	5.4 Mbps
Per channel sensing time	5 ms
Channel changing time	70 µs
Packet size	1000 bytes
Bandwidth	5.4 Mb/s
PU activity parameter λ	[50, …, 400]
Run time	1000 s

The simulation parameter settings are listed in Table 2. We compare ECOR with the following two protocols: CAODV [22] and SoRoute [16] in terms of PDR and hop count.

The first experiment (Figs. 1 and 2), we study the impact of SU number on packet delivery ratio (PDR) and hop count. In this experiment, the number of PU is set to be 10 and the PU active parameter is 200 s. As the number of SU number increases, the PDR will increase as well as shown in Fig. 1. In Fig. 2, we can see that the hop count will increase when the number of SU increases. However, the proposed scheme always achieve better performance that other two routing protocols. The reason is that we consider network coding technology and the social feature in SU's communication, and exploit an auction based candidate selection scheme.

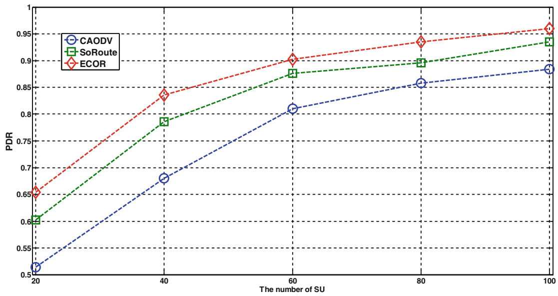

Fig. 1. PDR vs. the number of SU.

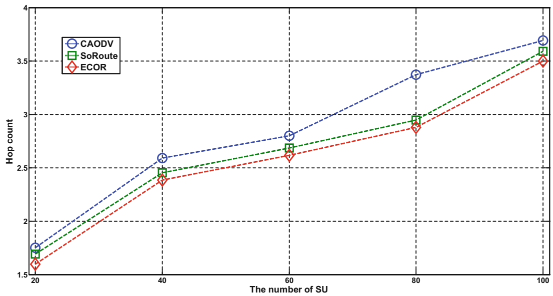

Fig. 2. Hop count vs. the number of SU.

The second experiment (Figs. 3 and 4), we analyze the impact of the number of PU on packet delivery ratio (PDR) and hop count. The number of SU is set to be 50 and the PU active parameter is set to be 200 s. From the figures, we can see that the PDR of all schemes will decrease with increasing the number of PU, the reason is that increasing the number PU means the duration of the free channels is shorter. Moreover, the hop count will increase and then decrease as increasing PU number. However, the proposed scheme will obtain better performance.

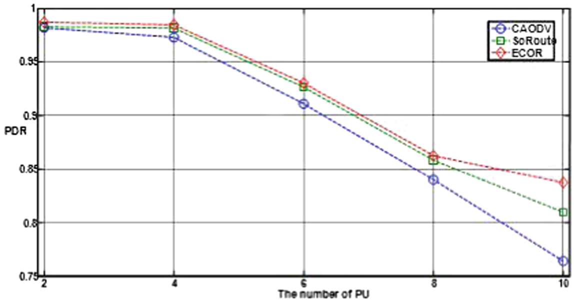

Fig. 3. PDR vs. the number of PU.

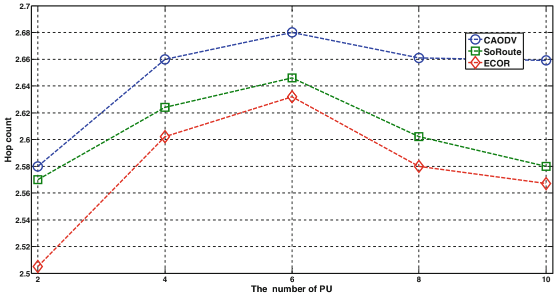

Fig. 4. Hop count vs. the number of PU.

4 Conclusion

Integrating OR with the features of social networks is an effective solution to improve network performance over multi-hop CRNs. This article provides a novel energy aware coded OR protocol for SCRNs, ECOR. In ECOR, we propose a novel method for model social feature of SCRNs. And then, we present an auction model based forwarding candidate selection which jointly considers social features, energy and ETX, In addition, the optimal bid price has been proved, which is related to the number of candidates and social features. In data transmission, we exploit network coding during selected candidate for multi-type flows, which can enhance data progressing. Furthermore, our extensive simulation results exhibit that ECOR performs better than CAODV and SoRoute.

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