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Spectrum-Availability Based Routing for Cognitive Sensor Networks

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ABSTRACT With the occurrence of Internet of Things (IoT) era, the proliferation of sensors coupled with the increasing usage of wireless spectrums especially the ISM band makes it difficult to deploy real-life IoT. Currently, the cognitive radio technology enables sensors transmit data packets over the licensed spectrum bands as well as the free ISM bands. The dynamic spectrum access technology enables secondary users (SUs) access wireless channel bands that are originally licensed to primary users. Due to the high dynamic of spectrum availability, it is challenging to design an efficient routing approach for SUs in cognitive sensor networks. We estimate the spectrum availability and spectrum quality from the view of both the global statistical spectrum usage and the local instant spectrum status, and then introduce novel routing metrics to consider the estimation. In our novel routing metrics, one retransmission is allowed to restrict the number of rerouting and then increase the routing performance. Then, the related two routing algorithms according to the proposed routing metrics are designed. Finally, our routing algorithms in extensive simulations are implemented to evaluate the routing performance, and we find that the proposed algorithms achieve a significant performance improvement compared with the reference algorithm.

INDEX TERMS Internet of Things, cognitive sensor networks, data forwarding, spectrum-availability, retransmission.

I. INTRODUCTION

Currently, more and more objects with capacity of computing and wireless communication are being designed and deployed to construct pervasive computing environments, which leads to the era of the Internet of Things (IoT) [1]. With the wide deployment of wireless objects and mobile applications, the unlicensed portions of wireless spectrums especially the ISM bands have become increasingly crowded. The Federal Communications Commission (FCC) stated that the current spectrum resources are static allocated and utilized in some limited geographical regions, and that the expectation of utilization is largely under-utilized [2]. To efficiently increase the ratio of spectrum usage, cognitive radio emerged as a promising solution to the problem of low ratio of spectrum utilization [3]–[5]. In cognitive radio environments, primary users (PUs) coexist with secondary users (SUs), in which SUs usually carry cognitive radio devices, which enable them scan and sense the surrounding spectrum utilization; when finding spectral holes, in which no PUs access the related spectrum bands, SUs can opportunistically access these spectrum bands by adjusting their spectrum bands dynamically; in the process of spectrum usage, an SU should abandon its spectrum band at once and then switch to other available spectrum bands when PU arrive.

Recently, researchers have gained much attention to multi-hop Cognitive Sensor Network (CSN) [6]–[11]. A multi-hop CSN consists of distributed wireless sensors which sense an event signal with equipped cognitive radio devices and communicate with each other over the available licensed spectrum bands of PUs in a multi-hop manner [12]. In a multi-hop CSN, an SU senses the surrounding spectrum bands, chooses the most appropriate available channel once identifying the idle channel to transmit data in a multi-hop manner and abandons the channel immediately when detecting the arrival of a PU on the channel. By applying the cognitive radio technique, multi-hop CSNs could increase spectrum utilization, enhance network efficiency and prolong the network lifetime [12], [13].

Among various research topics in networking, routing is an agelong one and has attracted attentions of the research community. The objective of routing is to deliver data packets from sources to destinations. Although plenty of routing schemes [14]–[17] for traditional cognitive radio networks and wireless sensor networks have been designed, these routing schemes would fail if they are directly used in multi-hop CSNs. Routing in multi-hop CSNs becomes a challenge because of the high dynamic of spectrum availability and quality [18]–[20]. First, in a multi-hop CSN for any path from a source SU to a destination SU, a common available channel band that could be used by all SUs in the path usually does not exist. In fact, the goal of traditional routing schemes for wireless multi-hop networks is to identify a path with one common available channel band which can be accessed by all the SUs along the path. Thus, they would fail in multi-hop CSNs due to the absence of any common available channel band. On the other hand, there may exist a path in which each neighboring SUs share a common available channel band even if there does not exist one global common channel along the path. Second, the spectrum availability for SUs changes randomly, so it would be better to estimate the availability from both local and global views. As we know that an SU has to abandon data transmission because of the reclaim of spectrum by PUs, and then applies rerouting. In multi-hop CSNs, the dynamic availability of spectrum bands usually causes frequent spectrum handoffs and reroutings, which in turn would lead to a great decrease of routing performance. So it is important to look for a routing path that causes the least number of rerouting. This requires that the availability of temporarily unavailable spectrum along the path should also be considered. Last but not least, the spectrum quality (e.g., spectrum bandwidths and spectrum average idle time) has a great impact on the path selection in routing. A candidate path may involve multiple channel bands, each of which may have its own spectrum quality and availability. During data transmission, the current chosen channel band may becomes invalid due to the arrival of PUs and new channel band may become available due to the leaving of PUs. This requires that the quality of both current available and unavailable spectrum should be considered in a good routing scheme. Thus, in routing for multi-hop CSNs, it is important yet difficult to utilize efficiently and sufficiently the above mentioned issues.

To sufficiently consider the dynamic spectrum availability and spectrum quality, we define two routing metrics. In the routing metrics, all candidate paths are evaluated by the defined routing metric. For each path, the spectrum quality is computed for each current available channel band, and the availability and quality of temporarily unavailable channel bands are also considered in the routing metric. The purpose of the paper is to propose novel routing approaches that can increase routing performance and reduce the number of rerouting with the consideration of the above issues. In the following, we summarize the main contributions of this work:

- To fully utilize the global and instant spectrum usage information especially the temporarily unavailable spectrum resources, we define two novel routing metrics with the restriction of one retransmission permitted. One is delivery success probability and the other is average transmission delay. The two routing metrics estimate the spectrum availability and the dynamics from the global statistical spectrum usage and the local instant spectrum resources.
- With the restriction of one retransmission permitted, we design two related routing algorithms for multi-hop CSNs. Their focus is finding the path with the maximum delivery success probability or the minimum average transmission delay, respectively, from all the candidate paths.
- To validate the routing performance of our algorithms, extensive simulations are conducted compared with the state of the art for multi-hop CSNs.

We organize the rest of the paper as follows. We first introduce the related works in Section 2, and present the network model, routing metrics and problem formulation in Section 3. We then provide the related routing algorithms in section 4, and evaluate route performance in Section 5. Finally, the paper is concluded in Section 6.

II. RELATED WORKS

Since the dynamic spectrum access paradigm was introduced, researchers have taken numerous efforts on using cognitive radio technology in different issues in CSNs. Dedicated survey on CSNs can be found in [12] and [22]. As for routing issues in CSNs, numerous approaches have been proposed [5], [20], [22]–[31] by using various of routing metrics. Technically, opportunistic routing and on-demand routing are the two routing categories in CSNs. In the following, we briefly summarize the existing routing categories in CSNs.

A. ON-DEMAND ROUTING IN CSNs

The main focus of on-demand routing is how to select a path among multiple candidate paths from a global view. AODV [32] is the typical on-demand routing scheme, which usually includes on-demand path discovery that tries to find end-to-end paths and path maintenance which is caused by PUs' reclaim of the spectrum. Chowdhury and Felice [20] designed the spectrum-aware routing protocol (SEARCH), in which a greedy geographic strategy is used to broadcast route requests on each spectrum channel, and finally the destination SU chooses the path with the minimal hop count to the source SU and the minimal interference with PUs through the receiving routing requests. In fact, due to the absence of estimating the future spectrum availability, the route selection in SEARCH is very correlated with spectrum dynamics in applications. Feng *et al.* [33] proposed the shortest path routing scheme with the consideration of spectrum handoff scheduling and also an active-rerouting mechanism which is applied upon the arrival of PUs. Badarneh and Salameth [22] introduced the maximum success probability (MaxPoS) for multi-hop CSNs, which estimates the quality of available spectrums between any two neighboring SUs. In MaxPoS, the delivery success probability between any two neighboring SU nodes can be estimated by the probability that the current available band will be accessible from the current time to the required minimal transmission time for a given data packet; in fact, for any two neighboring SUs with several common bands, the delivery success probability is defined as the maximal one from all the available spectrums without consideration of the number of the available common bands; for a multi-hop candidate path, the delivery success probability is defined as the minimal value for all neighboring SUs in the path. In MaxPoS, the source SU determines the optimal path that has the maximal delivery success probability. However, for any two neighboring SUs only one band is finally selected without the consideration of all the available and the currently unavailable channels. As we know that due to the dynamic availability of each spectrum channel and the absence of the above consideration, the number of rerouting in MaxPos is large, thus causing decreased route performance. Jin *et al.* [23] designed the geographic routing protocol (TIGHT), where the source SU chooses the optimal path with the shortest distance to the destination along the boundary of PU regions to avoid the interference with PUs. In sparse applications with less PUs' activities, TIGHT performs well, but achieves poorly in the high dynamic spectrum-availability applications.

B. OPPORTUNISTIC ROUTING IN CSNs

The main focus of opportunistic routing in CSNs is how to determine the priority sequences of the neighbors for each intermediate node. Each intermediate SU broadcasts data packets to its neighbors at the network layer, whilst at the MAC layer only one SU will reply and act as the next relay according to the reception results and its priority. In [24], an opportunistic cognitive routing (OCR) protocol is proposed, where the priority of a relay node is determined by its spectrum quality and position, such as the channel throughput, the channel reliability, and the distance advancement to destination. Cai *et al.* [26] constructed a cross-layer distributed opportunistic routing protocol, in which the spectrum sensing and the relay selection are jointly considered with the purpose of decreasing the delivery delay from source to destination. Ji *et al.* [34] analyzed the optimization problem of spectrum dynamics and spectrum utilization efficiency, and proposed a semi-structure spectrum-aware routing (SSR) scheme with energy efficiency. They introduced the forwarding zone for each SU, and allowed a single SU select its next relay node from those possible relay neighbors, thus decreasing the delivery latency and the energy consumption. Although the probability of retransmission can be decreased by using the broadcast mechanism in opportunistic routing schemes, they sometimes enter the local optimization in CSNs because the spectrum availability from both the local and global point of view is not considered.

In this work, we aim to design spectrum-aware routing scheme for CSNs, which takes account for both dynamics of spectrum availability and quality from the view of local and global spectrum information. We also provide novel routing metrics which evaluate the statistical spectrum availability and the minimal delivery delay, with the goal of minimizing the number of rerouting due to the PUs' arrivals.

TABLE 1. System notations.

Symbol	Meaning
C	the set of orthogonal channels
B	the channel bandwidth
λ_i^k	the rate of PU i uses channel k
μ_i^k	the rate of PU i does not use channel k
$T_{\text{on},i}^k$	the random variable of PU i uses channel k
$T_{\text{off},i}^k$	the random variable of PU i does not use channel k
ν_k	the transmission rate over a channel k
N_0	the thermal noise power density
s	the size of packet
$P_{i,j}^k$	the received power for SU j from SU i over channel k
p_k	the delivery success probability through channel k
p_0	the largest delivery success probability through all available channels
v_k	the probability that channel k remains accessible when the first attempts fails
$T_{i,j}$	the transmission delay from SU i and to neighbor SU j
$P_{\text{suc}}(i,j)$	delivery success probability from SU i to neighbor SU j
TSP_p	the delivery success probability in path p
TTD_p	the transmission delay in path p

III. NETWORK MODEL AND PROBLEM FORMULATION

We first provide CSN network model, and then analyze our routing metrics followed by the problem definition of routing in CSNs. For ease of illustration, Table 1 lists the notations used in this work.

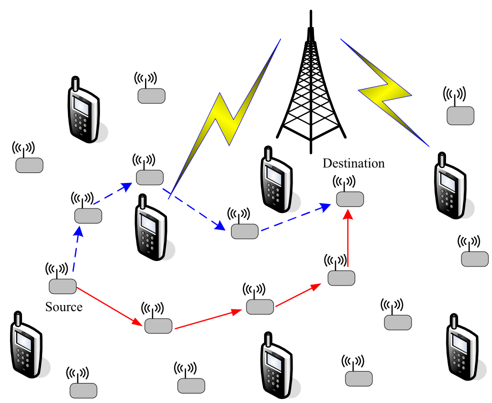

FIGURE 1. The network model of CSNs.

A. NETWORK MODEL

A multi-hop CSN consists a number of static PUs and SUs, illustrated in Figure 1. In a multi-hop CSN, data transmission adopts a multi-hop manner if the distance from the sender to the receiver is beyond the transmission range of the sender. To make routing easier, the network is assumed to be connected, which means at least one route path exists for any pair of SUs.

In a CSN, each PU is allowed to access only one channel band from an orthogonal channel set $C = \{c_1, c_2, \ldots, c_m\}$. There exists a common control channel (CCC), over which SUs exchange the controlling messages. Besides the common channel, each SU can switch to and access any of the available licensed channels with the equipped half-duplex cognitive radio [35]. As aforementioned, each SU has to abandon the channel and switch to one available licensed channel at once if a PU arrives and reclaims of the channel. To make routing easier, over a given channel, each SU is assumed to transmit data with the fixed transmission power.

As in other references (e.g. [36]), the PUs' activities are formulated by an alternating renewal process, named ON-OFF model, over a channel. In the ON-OFF model, the process of PU i accessing channel $k \in C$ obeys a Poisson process, where $T^k_{\text{on},i}$ represents the ON period with rate λ^k_i, and $T^k_{\text{off},i}$ represents the OFF period with rate μ^k_i. So, the availability and unavailability that a PU accesses channel k can be denoted by T^k_{on} and T^k_{off}, respectively. By using cognitive radio technology, each SU could sense the channel usage of PUs. We assume the channel usage patterns change slowly with time, and an SU could obtain the patten of surrounding PUs' spectrum usage by conducting cooperative channel sensing with surrounding SUs. In this paper, we do not discuss the parameter estimation of the spectrum usage patten, which can be found in [37].

B. ROUTING METRICS

In this sub-section, we first introduce the initial routing metrics from a statistical point of view only, in which no instant information (e.g., the current spectrum availability) is considered, and then introduce our novel routing metrics considering both the instant information and the global statistical data.

1) ROUTING METRICS WITHOUT INSTANT INFORMATION CONSIDERED

Based on the alternating renewal process theory, we could obtain the limiting probability that a PU i does not access a given channel k at any given time. We denote the above probability by $\mathrm{P}^k_{\text{off},i}$, which can be computed by

$$\mathrm{P}^k_{\text{off},i} = \frac{\mu_{i,k}}{\mu_{i,k} + \lambda_{i,k}},$$

where $\mu_{i,k}$ represents the rate of PU i not using k, and $\lambda_{i,k}$ represents the rate of PU i using k. The meaning of the limiting probability indicates that we can infer that a given PU i does not uses channel k at any time with probability $\mathrm{P}^k_{\text{off},i}$ even if we do not obtain the actual spectrum usage information about PU i on channel k. Similarly, we can infer the probability a given PU being in active state over a given channel, denoted by $\mathrm{P}^k_{\text{on},i}$.

By using the Shannon capacity theory, we can obtain the achievable transmission rate through channel k from an SU i to its neighbor SU j only with the statistical spectrum usage data as follows

$$\nu_k = B + \log_2\left(1 + \frac{P^k_{i,j}}{B \times N_0}\right),$$

where N_0, B, ν_k, and $P^k_{i,j}$ represent the thermal noise power density, the channel bandwidth, the transmission rate, and the power received by SU j, respectively. Generally, $P^k_{i,j}$ is inversely proportional to some degree of distance from SU i to SU j, and directly proportional to SU i's transmission power. Under the assumption that the transmission power for each SU is fixed, the transmission rate is sensitive to the two SUs' distance only. For a data packet, an SU takes at least s/ν_k to transmit over channel k, in which the size of the packet is s, and over channel k the achievable data transmission rate is ν_k.

As aforementioned, the transmission of SUs over a channel can break due to the PUs' arrival and the reclaim of the channel, and thus extends the total transmission delay. So, the probability of the successful transmission is related with both the spectrum availability time on the channel and the required transmission time. Like [22], through channel k, the delivery success probability from SU i to its neighbor SU j can be defined by

$$\begin{aligned} P^k_{\text{suc}}(i,j) &= P\left(T_k \geq s/\nu_k\right) \\ &= e^{-s/(\nu_k \cdot \mu_k)} \end{aligned} \quad (1)$$

in which μ_k represents the rate of channel k being unavailable, s represents the packet size, and ν_k represents the rate of transmission through channel k.

From Equation 1, the metric of the delivery success probability includes the influence of the spectrum available time and the influence of the transmission time, so it was applied in previous papers (e.g., [22]). But we observe that the above metric only considers the statistical spectrum usage information, and does not include the instant spectrum usage information, such as whether the channels are used by PUs or not. Moreover, the existing routing metrics (e.g., [22]) only consider the maximum probability of successful transmission over all possible spectrums, and thus achieve suboptimal due to the absence of consideration of all the potential channels especially those temporarily unavailable channels. For example, assuming there is only one available channel over which an SU is transmitting packets, rerouting will occur upon a PU's arrival and reclaim of the channel. As we know, rerouting and retransmitting will increase transmission delay and reduce the routing performance greatly. Due to the dynamic availability of PU's arrival, rerouting and retransmitting will inevitably occur when PU reclaims the channel and there exists no available channels. A good routing metric should consider the above case and decrease the number of rerouting and retransmitting. Thus, it would be better to consider both the instant spectrum usage information and the global spectrum information especially the current unavailable spectrums in routing in multi-hop CSNs to decrease the number of rerouting and retransmission. In the following, we propose our routing metrics with the consideration of the above factors.

2) OUR ROUTING METRICS

In a multi-hop CSN, an SU could select one channel from a set of available channels to transmit data. If the end-to-end transmission delay is not considered, an SU could retransmit data over other channel when the last data transmission is interrupted. Thus, the end-to-end data transmission would finally succeed with the increasing number of retransmission. Even in the case that there exist only one channel between two neighboring SUs, the transmission could also complete due to the fact that an SU can wait until the next availability of the channel. However, it fails in real applications because there usually exist a limited time-to-live (TTL) for any packet that should be abandoned when its TTL decreases to zero. Thus, it is necessary to consider the limited number of retransmission in routing in a multi-hop CSN.

As aforementioned, a good routing metric should consider the number of all the available channels. In fact, the existing routing metric does not consider the dynamics of spectrum availability. Under the condition that the number of transmission over one channel is 1 over any two neighboring SUs, the traditional transmission probability of success over all the available channels is defined as $1-(1-p_1)(1-p_2)\cdots(1-p_m)$, where m represents the number of current available channels, and $p_k = P^k_{\text{suc}}(i,j)$ represents the delivery success probability through channel k. It is evident that the delivery success probability goes up with the number of available channels. In fact, the aforementioned formula is not accurate since the availability of the channels changes dynamically during data transmission.

To estimate more accurately the transmission probability of success between two neighboring SUs, *one retransmission* is allowed for an SU when transiting a packet to its neighboring SU if the first transmission is interrupted by the arrival of a PU. We should mention that, although the delivery success probability becomes larger if more times of retransmissions are allowed, the difficulty of estimating the routing metric increases largely, thus leads to less feasible. So, in this work, with the restriction of only one retransmission permitted, we at the first time define a novel delivery success probability with the consideration of availability and quality of all spectrum channels.

Definition 1: With the restriction of one retransmission permitted, we denote the delivery success probability from an SU i to its neighbor SU j over all channels by $P_{\text{suc}}(i,j)$, that is,

$$P_{\text{suc}}(i,j) = p_0 + (1-p_0)\cdot\sum_{k=1}^{n-1}\left(v_k\cdot\prod_{m=1}^{k-1}(1-v_m)\cdot p_k\right) \quad (2)$$

in which n represents the number of all channels between SUs i and j, $p_0 = P^{k'}_{\text{suc}}(i,j)$ is the largest delivery success probability through all the current accessible channels, $p_k = P^k_{\text{suc}}(i,j)$ represents the delivery success probability through channel k, and v_k represents the probability that channel k remains accessible upon the fail of first attempt of transmission.

When there are various available channels, it is easy to observe that we could obtain a higher delivery success probability if the SU first transmits packets over the channel with the largest delivery success probability. So, in this work, an SU first uses the accessible channel with the largest delivery success probability to increase the transmission probability of success. When the first transmission fails, another transmission occurs if there exists other available channel to its neighboring SU. In the second attempt of retransmission, the SU also tries the channel with the largest delivery success probability at that time to transmit data. If unfortunately the second attempts fails again, rerouting has to be conducted to find an optimal path by the current SU i.

In Definition. 1, we have to compute the probability v_k. When an SU fails to transmit data over channel k at the first time, the availability of the channel falls in two cases: available and unavailable. So, considering the two possible states of the channel k, v_k can be obtained by,

$$v_k = \max\left(e^{-s/(2\cdot v_k\cdot\mu_k)}, \frac{\mu_k}{\mu_k+\lambda_k}\right) \quad (3)$$

where the first part $e^{-s/(2v_k\mu_k)}$ represents the probability of channel k still remaining accessible upon the fail of transmission, and $\mu_k/(\mu_k+\lambda_k)$ represents the limiting probability of channel k remaining accessible.

From Definition 1, we can see that the number of transmission for a packet between two neighboring SUs in one routing is at most 2. There exists a chance of one successful transmission. In this case, the first attempt of packet transmission was not interrupted. On the other hand, if the first transmission fails and there exist available channels, SU i will try another transmission over the channel with the highest transmission probability of success at that time; otherwise, if there exist no available channels, it applies rerouting at SU i.

In the following, the first routing metric is introduced, that represents the delivery success probability for a path with the constraint of one retransmission permitted.

Definition 2: We define the delivery success probability in path p, TSP_p in the following

$$\text{TSP}_p = \min_{(i,j)\in p} P_{\text{suc}}(i,j) \quad (4)$$

in which the tuple (i,j) represents the pair of SU i and its neighboring SU j in path p.

From Definition 2, we see that it does not include the transmission time between two neighboring SUs. In fact, under the assumption that an SU sends a packet successfully to its neighboring SU, we can obtain the transmission time.

Definition 3: Supposing that a packet will be transmitted successfully in at most two attempts, we define the transmission delay from an SU i to its neighbor SU j using all channels, $T_{i,j}$, as follows

$$T_{i,j} = \frac{s}{v_0} \cdot p_0 + (1-p_0) \cdot \sum_{k=1}^{n-1} \left(\left(\frac{s}{2v_o} + \frac{s}{v_k} \right) \cdot v_k \cdot \prod_{m=1}^{k-1} (1 - v_m) \cdot p_k \right) \quad (5)$$

In Definition 3, s/v_0 is the required average time over the channel with the highest transmission probability. So, the value of $s/(2v_0)$ is the required average time at which the first transmission fails. In the following, our second novel routing metric in a path that estimates the total average transmission delay over a path can also be obtained.

Definition 4: Supposing that a packet will be transmitted successfully in at most two attempts, we define the transmission time delay over path p, TTD_p, that is

$$\mathrm{TTD}_p = \sum_{(i,j)\in p} T_{i,j} \quad (6)$$

From Equation 6, TTD_p is the sum of the transmission delays over all pairs of neighboring SUs in the path p. Thus, both the statistical spectrum usage data and the instant spectrum available information are considered in the above two routing metrics, especially the quality of all common channels in a path.

C. PROBLEM FORMULATION

Under the above two routing metrics, the routing problem in CSNs can be formulated with the goal of optimizing the related routing metrics. Thus, for the two routing metrics, the routing problems in CSNs are respectively formulated as follows.

Definition 5: The routing problem with the delivery success probability metric under the constraint that only one retransmission allowed is resolved as follows

$$\max_p \mathrm{TSP}_p \quad (7)$$

Definition 6: The routing problem with the transmission delay metric under the constraint that only one retransmission allowed is resolved as follows

$$\min_p \mathrm{TTD}_p \quad (8)$$

IV. OUR NOVEL ROUTING ALGORITHMS

Taking into accounts both the statistical spectrum usage data and the instant spectrum available information, two novel routing algorithms are designed respectively, named by Maximum Transmission Probability of Success (MaxTSP) and Minimum Average Transmission Delay (MinATD) according to the above two routing metrics.

A. MAXIMUM TRANSMISSION PROBABILITY OF SUCCESS ROUTING

In the MaxTSP algorithm, the objective is to determine the best route path in terms of the probability of the maximum delivery success under the constraint that only one retransmission is permitted.

Algorithm 1 MaxTSP Routing Algorithm

Input: parameters in multi-hop CSN, destination SU D, source SU S
Output: route path with the largest delivery probability of success

Source SU S constructs RREQ messages m
Source SU S broadcasts m through CCC channel to the neighboring SUs
for all each SU x which receives m **do**
  if SU x is the destination SU D **then**
    SU x obtains TSP_p by Equation (4)
  else
    SU x obtains $P_{\mathrm{suc}}(i,j)$ by Equation (1)
    SU x forwards m on over CCC channel
  end if
end for
SU D waists for a predefined time upon receiving the first replica of message m
SU D determines the best route path which has the largest TSP_p by using Definition 5
SU D sends an acknowledgement back to S along the chosen path.

The details of the MaxTSP algorithm is illustrated in Algorithm 1, which describes the process that the desired path is constructed by using the first routing metric. When having data packet destined to SU D, SU S first broadcasts the Route Request message (RREQ) through the CCC channel in an AODV manner, which is forwarded on and finally reaches to the destination D. During the broadcasting, the delivery success probability of each SU obtained by (4) is accumulated in the RREQ message along the path. After collecting a number of the RREQ messages, destination D selects one route path by computing the optimal path which has the largest delivery success probability. Then, the destination constructs a route reply message and reply back along the chosen path.

We should note that Algorithm 1 only determines the best path through which the maximum delivery success probability could be achieved, and it does not determines the actual channels in that path. In fact, due to the dynamic availability of spectrum resources, each relay SU carrying packets could choose the channel with the highest value of the delivery success probability from all the available channels at that time under the condition of adopting the path determined by Algorithm 1. Only if there exist no available channels, the relay SU applies rerouting.

B. MINIMUM AVERAGE TRANSMISSION DELAY ROUTING

The details of the MinATD algorithm is illustrated in Algorithm 2, which describes the process that the desired path is constructed by using the second routing metric. The routing selection process is similar with Algorithm 1. The source SU S first broadcasts the RREQ message through the CCC channel in an AODV manner, which is forwarded on

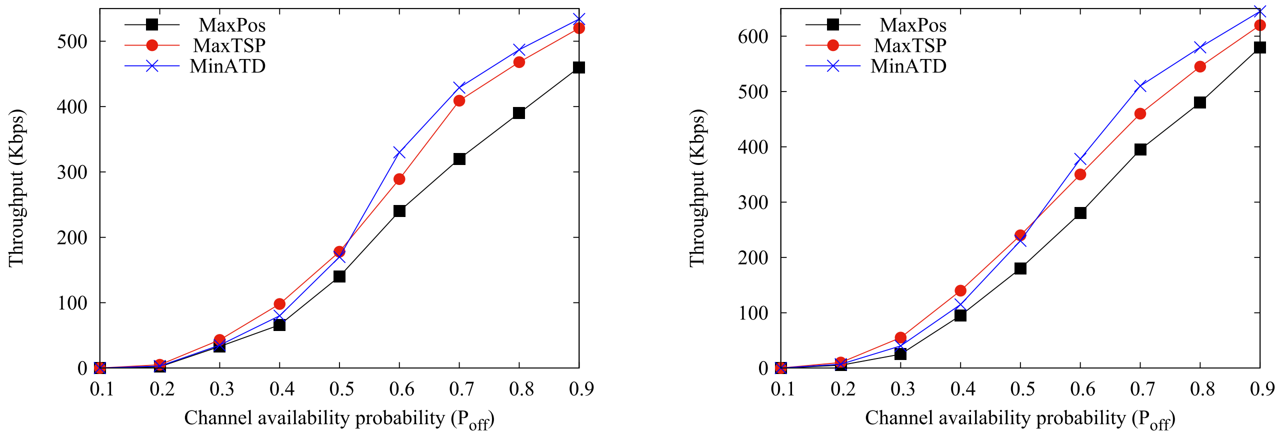

FIGURE 2. PUs availability vs. Throughput. (a) Ptr = 0.1W. (b) Ptr = 0.5W.

Algorithm 2 MinATD Routing Algorithm

Input: parameters in multi-hop CSN, destination SU D, source SU S

Output: path with the minimum expected transmission delay Source SU S constructs RREQ messages m Source SU S broadcasts m through CCC channel

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for all each SU x which receives m do
    if SU x is the destination SU D then
        SU x obtains TTD_p by Equation (6)
    else
        SU x obtains T_{i,j} by Equation (5)
        SU x forwards m on over CCC channel
    end if
end for
SU D waists for a predefined time upon receiving the first
    replica of message m
SU D determines the best route path which has the min-
    imum TTD_p by using Definition 6
SU D sends an acknowledgement back to S along the
    chosen path.
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and finally reaches to the destination D. During the broadcasting, the spectrum information about the transmission delays by using (5) are accumulated in the RREQ message along the path. After collecting a number of the RREQ messages, destination D selects one route path by computing the optimal path which has the smallest average transmission delay. Then, the destination constructs a route reply message and reply back along the chosen path.

C. ROUTE UPDATE

Data transmission may be interrupted due to PUs' arrival, thus leading to retransmission or rerouting. As we know that rerouting consumes more network resources and time than retransmission. Thus, in this work, retransmission is first tried under the constraint that the next relay node remains the same with the predetermined through the original routing. Suppose SU i is sending data to its neighboring SU j over channel k and then is interrupted upon PU's arrival. If this is the second interrupt for SU i during transmission, SU i attempts rerouting using Algorithms 1 or 2. If this is the first interrupt for SU i during transmission, SU i attempts retransmission. First, SU i requests SU j all accessible channels over CCC channel. Then, SU j returns to SU i the set of all available channels over CCC channel. On the reception from SU j, SU i computes the common available channels, and for each channel k' computes the related delivery success probability $P^{k'}_{i,j}$. If there exists a number of common channels, SU i chooses the channel with the delivery success probability, and transmits data over that channel. Otherwise, there exist no common channels between any two neighbor SUs at that time, and then a new route path needs to be discovered using Algorithms 1 or 2.

V. SIMULATIONS

A. PARAMETER SETTINGS

To evaluate the routing performance, our routing algorithms are implemented and simulated in the CSN network environment. The same simulation scenarios are used as in [22]. For the settings of the parameters, the simulation region is a square with $1000 \times 1000\text{m}^2$, in which 50 SUs and 10 PUs are randomly static deployed, respectively. For each SU and PU, the interference range is 550m and the transmission range is 250m, respectively. The average spectrum usage time for PUs varies from 0.5ms to 25ms. Furthermore, we set that the bandwidth for each channel $B = 0.5$MHz, the number of channels is 4, the size of data packet is 2 KB, and thermal noise power density $N_0 = 0.5 \times 10^{12}$W/Hz. The repeated number of the simulations is 100, and each simulation lasts for 300s.

B. SIMULATION RESULTS

1) PUS AVAILABILITY VS. THROUGHPUT

First, we evaluate the throughput of routing algorithms under different PUs' availabilities. Figure 2 illustrates the

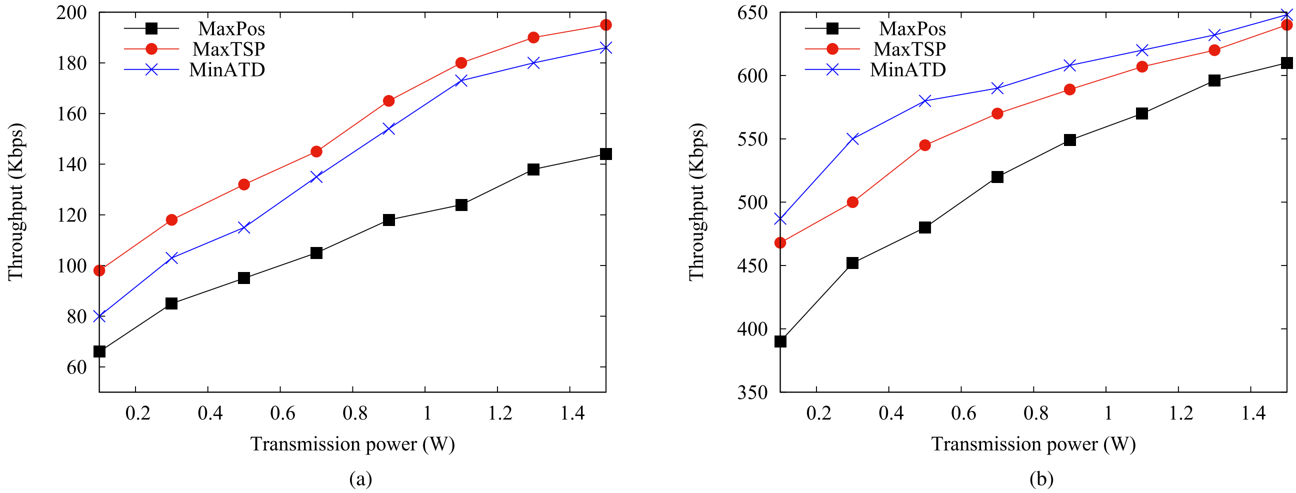

FIGURE 3. **Transmission power vs. Throughput. (a) $P_{off} = 0.4$. (b) $P_{off} = 0.8$.**

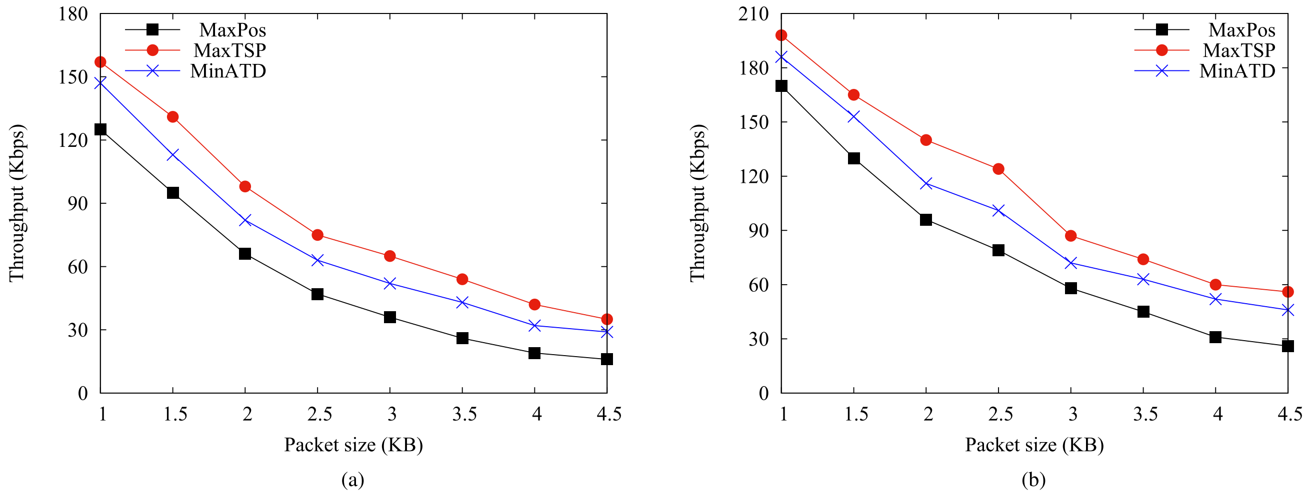

FIGURE 4. **Throughput vs. packet size. (a) Ptr = 0.1*W*. (b) Ptr = 0.5*W*.**

different route throughput for the three routing algorithms under the different PUs's availability probability P_{off}. P_{off} varies from 0.1 to 0.9. As aforementioned, P_{off} means the channel usability by SUs. We set the values of the data transmission power for each node to respectively 0.1W and 0.5W in the two simulation scenarios. From Figure 2, we observe that with the increasing PUs' availability, the route throughput of all the three algorithms increases also from 0 to 600Kpbs. The reason lies in that the number of accessible channels by SUs arises with the decrease of PUs' activities, leading to a higher throughput. Moreover, with increasing the transmission power from 0.1W to 0.5W, an SU achieves a higher transmission rate over each channel, thus increasing the throughput for each routing algorithm. In the two simulation scenarios from Figure 2, we also observe that our two algorithms perform better under different values of P_{off}. The reason lies in that the number and the quality of the spectrum channels impact the route throughput. Specifically, our algorithms take into accounts the quality of all the channels as well as the temporarily unavailable channels, whilst the MaxPos considers only one available channel, leaving the state of other channels unconsidered. So in MaxPos, rerouting occurs often if there exists only one available channel in some pairs of SUs in one path, thus decreases the throughput. In fact, our routing metrics consider and estimate both the number and the quality of all channels especially those temporarily unavailable ones, which decreases the number of rerouting, and thus increasing the throughput.

2) THROUGHPUT VS. TRANSMISSION POWER

We then evaluate routing performance under different transmission power. Figure 3 illustrates the different route throughput for the three routing algorithms under the different transmission power that changes in [0.1, 1.5]W. As aforementioned, a large transmission power means a farther radio range. We set the values of the PUs availability to respectively 0.4 and 0.8 in the two simulation scenarios. From Figure 3, we observe that with increasing transmission power, the throughput increases also. The reason lies in the fact that with increasing transmission power, the transmission range of the packet and the power of received arise also, thus increasing the data transmission rate. Moreover, Figure 3(a) indicates that MaxTSP outperforms MinATD in a low availability of PUs, while Figure 3(b) indicates MinATD performs better in a high availability of PUs. In the environment with a higher availability of PUs, more available channels will exist, in which all the available channels of PUs seldom change to be unavailable simultaneously during data transmission. which then leads to no or less chances of rerouting. Thus, in the scenario with low availability of PUs, the number of rerouting is less and the main focus of routing is finding a path with the minimal transmission delay. Further, the second routing metric considers mainly the transmission delay. So, MinATD outperforms MaxTSP due to the first one uses our second routing metric. Similar analysis can be conducted in a low channel availability.

3) THROUGHPUT VS. PACKET SIZE

Figure 4 depicts the influence of different packet size on throughput, in which the PUs' availability probability P_{off} is 0.4, and the size of data packet varies from 1 to 4 KB. From the figure, we can see that the throughput goes down with the arise of the data packet size. The is because that as the size of data packet increases, the required transmission time increases also, leading to larger probability of PU's arrival and more number of retransmission. As aforementioned, since our proposed routing metrics consider the impacts of the number and quality of all channels, our algorithms outperform better.

VI. CONCLUSIONS

Routing is an difficult yet important issue in CSNs due to the complex dynamic availability of spectrum channels. In this work, taking accounts of the number and the quality of spectrum channels from the global and the instant point of view, we propose two CSN routing metrics. In the first routing metric, the delivery success probability through all possible channels is defined in the constraint that only one retransmission is permitted to reduce rerouting. Similarly, the second routing metric considers the average transmission delay over all possible channels is presented. Based on the two routing metrics, the related routing algorithms are then designed, in which the optimal route is determined in an ON-demand route style. To increase the practicability, the channel assignments are not permanent and any relay nodes carrying packets could choose the channel with the largest routing metric at that time. We conduct extensive simulations, which validates the the route performance of our routing schemes compared with other CSN routing protocol. To increase the practicability and usability in real applications, further research needs to be conducted. Examples of research focuses on the power control strategy and joint opportunistic routing to decrease energy consumption in routing. Moreover, the mobility of both PUs and SUs could also be analyzed to make routing more practical.

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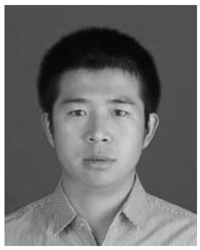

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