TAG: Trajectory Aware Geographical Routing in Cognitive Radio Ad Hoc Networks with UAV Nodes

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Abstract. Routing real-time packets in Cognitive Radio Ad Hoc Networks (CRAHNs) with mobile nodes is a challenging task. Mobile SUs can move into PU regions where the radio spectrum may not be accessible due to PU activity. In this case, real-time packets may be delivered to their destinations beyond their latency constraints. Unmanned Aerial Vehicles (UAVs) are mobile wireless ad hoc nodes that plan for their trajectory at any given time. In this paper, a Trajectory Aware Geographical (TAG) routing for CRAHNs with UAV nodes is proposed. TAG employs the trajectory information of UAVs and avoids selecting a UAV as a next hop if the UAV will fly inside a PU region or close to it. This strategy protects real-time packets from experiencing a long delay due to the PU activity. Our simulation results show that TAG effectively decreases the average end-to-end delay compared to Greedy geographical routing in the considered scenario.

Keywords: routing, ad hoc networks, cognitive radio, UAV, real-time.

1 Introduction

A Cognitive Radio Ad Hoc Network (CRAHN) is one example of applying cognitive radio capabilities to wireless ad hoc nodes. It consists of two types of nodes with different priorities for spectrum access. Primary Users (PUs) are licensed users and have higher priority to access the radio spectrum. On the other hand, Secondary Users (SUs) are unlicensed users and have lower priority in a CRAHN. SUs may access the licensed band opportunistically without making any harmful interference to PUs. They need to have the information about the activity and the coverage area of PUs to access the spectrum dynamically. This information can be obtained by an SU through sensing or querying a geolocation database. The geolocation database provides a radio resource map [1] for SUs to use for dynamic spectrum access. Database-assisted spectrum access has been applied in some IEEE standards such as IEEE 802.22 [2] and the recently proposed IEEE 802.11af (White-Fi) [3].

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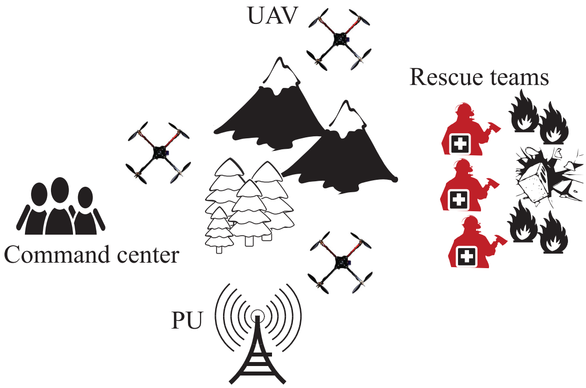

Fig. 1. A CRAHN in a disaster scenario

There are several applications for CRAHNs such as military and disaster scenarios. CRAHNs are appropriate candidates to be applied in disaster scenarios. Nodes in a CRAHN work autonomously and their dynamic spectrum access capability may increase their available radio resources in addition to the unlicensed band. In this paper, we consider the network to consist of flying Unmanned Aerial Vehicles (UAVs) in the air and a number of mobile ad hoc nodes on the ground. Figure 1 illustrates our assumption for a CRAHN in a disaster scenario.

UAVs in CRAHNs are highly mobile nodes that could be employed in a network for various missions. The missions of the UAVs in a disaster scenario are:

- Scanning disastrous area: UAVs scan a disaster area to localize wireless devices on the ground. Moreover, UAVs can construct a map of the area to be used by rescuers.
- Message ferrying: A UAV can act as a ferry in Delay Tolerant Networks (DTNs) when the network is partitioned and has a disconnected topology. In this case, a UAV flies between the location of the ground nodes which are source and destination of packets and carries the delay tolerant packets [4].
- Relaying: In multi-hop communication, UAVs can act as a relay in routing. UAVs can also be placed optimally in the air to improve the performance of the network [5].

Based on the various missions of a UAV in the network, the UAV has different mobility models for different missions. Paparazzi mobility model has been proposed in [6] for a group of UAVs. In a group of UAVs, each UAV must plan for its trajectory at any given time. It should inform its entire neighborhood about the planned trajectory. This should be done periodically by all UAVs to avoid any physical collision between them.

In our proposed routing protocol, UAVs act as relays in a CRAHN. They relay packets between ground nodes but this is not their only mission in the CRAHN.

For example, a UAV node is scanning the area or doing message ferrying while a ground node is using this UAV opportunistically to relay real-time packets.

Generally, routing in ad hoc networks can be categorized into two main classes: topology based and location based (geographical).

Topology based routing is based on the topological information of ad hoc nodes. Such a global information should be collected in one node and then an end-to-end route can be established. AODV, DSR and OLSR are some examples of topology based routing protocols in ad hoc networks [7]. These routing protocols are vulnerable to the dynamics of the network and produce large amount of overhead for route maintenance in case of frequent link breaks. Initial attempts for routing in CRAHNs were modifications on the topology based protocols like [8]. CRAHNs with UAV nodes are highly mobile and link availability is uncertain in this type of network. Therefore, adoption of the topology based protocols is not an appropriate solution.

Geographical routing is another class of routing in ad hoc networks that is based on geographical location of ad hoc nodes. It is assumed that each node obtains its position using Global Positioning System (GPS) or any other localization method. All the nodes inform their neighbors about their current position using periodic, small size beacon packets. Besides, the destination position is provided by a location service in the network. Having the position of all neighbors and the destination, a node in each hop selects the closest neighbor to the destination as the next hop to forward a packet.

The distributed decision making (hop by hop) in geographical routing makes it an appropriate candidate for CRAHNs. In case of a link break, the route maintenance can be done with less overhead in geographical routing comparing with topology based routing. However, each link break effects on packet routing latency in the network. Therefore, the routing protocols must avoid unstable links in real-time packets routing.

In a CRAHN, a mobile SU like a UAV can move inside a PU region or too close to it where the transmission of the UAV may make interference for PU receivers. In this situation, the UAV is not allowed to transmit while the PU is active. Therefore, link breaks may be more frequent when the UAV flies inside a PU region or too close to it. When a link between two nodes in a route breaks, existing packets in the buffer of the transmitter node should wait for a new link to be established. This delay may not be tolerable for real-time packets.

In this paper, a Trajectory Aware Geographical (TAG) routing protocol is proposed. In TAG, each UAV informs all its neighbors about its future position based on its planned trajectory. Knowing the future position of all neighbors, a UAV forwards a real-time packet greedily if the closet neighbor to the destination is far from PU regions. On the other hand, TAG avoids greedy forwarding if the closest UAV to the destination will fly inside a PU region or too close to it in the future.

The remainder of this paper is as follows: Section 2 surveys the state of the art for routing protocols in CRAHNs and some of the related works in UAV ad hoc networks. Section 3 describes the network model that is assumed in this paper.

TAG routing is described in Section 4. Section 5 is the performance evaluation of the proposed routing protocol and discussion. In the last section, we conclude the paper and propose the future works.

2 Related Work

In this section, we survey some of the existing geographical routing protocols in ad hoc networks and CRAHNs.

GPSR [9] is one of the first and most cited works among geographical routing protocols in ad hoc networks. In GPSR, the main metric to choose a next hop (next forwarder of a packet) is the distance to the destination. SEARCH [10] is an early work that has adopted geographical routing for CRAHNs. It uses RREQ and RREP, like AODV, to establish an end-to-end route from the source to the destination. The difference between AODV and SEARCH is that the latter does not flood the RREQ packets in the network and forwards them in a greedy manner using the geographical position of neighbor nodes. RREQ is sent in all available channels between nodes. Nodes that are located inside a PU region do not participate in the route establishment. Destination collects all the RREQ packets which have been passed through different routes and selects optimal combination of paths and channels. The main drawback of SEARCH is inherited from the topology based protocols that is the need for rerouting in case of link breaks. LAUNCH [11] is another geographical routing in CRAHNs. It uses control packets to establish a link between two nodes. In LAUNCH, a source node sends RREQ to all neighbors which are closer to the destination and waits for their RREP. Its metrics to select a node as a next hop are the distance to the destination and stability of the link regarding to the probability of PU appearance and the channel switching time. It produces high overhead for link establishment in each hop which can degrade the throughput of the network with frequent link breaks. OCR [12] is a geographical opportunistic routing in CRAHNs that considers distance, link throughput and link reliability. It applies a heuristic algorithm to find the optimized combination of next hop and channel. It repeats this algorithm for each packet. The drawback of OCR is waiting time for each packet to find an idle channel to send the request to its neighbors. TIGHT [13] is another geographical routing in CRAHNs. Authors of this work assume that each SU senses the environment and finds the location of PUs and their coverage area. SUs share this information with their neighbors. An SU selects the closest neighbor to the destination, if this neighbor is not affected by a PU. In the case, in which the greedy forwarding fails due to the closeness to a PU region, TIGHT selects next hop such that to traverse the perimeter of PU regions. It finds the shortest path to the destination without selecting nodes that are located inside a PU region. This strategy is an alternative for greedy routing and based on the current position of the nodes.

None of the mentioned works consider movement of nodes toward PU regions in CRAHNs. They select next hop based on the current position of the nodes.

Mobility of the nodes is an influencing metric on performance of a routing protocol that has been neglected in many existing works.

UAVs in a CRAHN have a planned trajectory to do their mission in a network. Based on our knowledge these mobility information have never been used in decision making of existing routing protocols. There are several works to predict next position of nodes based on the history, velocity and direction of movement but they are based on the probability and proposed for mobile nodes with unknown trajectory of mobility. Authors in [14] and [15] proposed prediction based routing in UAV ad hoc networks. They do not consider the planned trajectory of the UAVs to find the future position of a UAV. Using the planned trajectory of a UAV can provide more accurate estimation about the future position of a UAV than prediction based methods. The main contribution of this paper is to use the knowledge of the planned trajectory of UAVs in CRAHNs to route real-time packets with strict delay constraints.

3 Network Model for Disaster Scenario

In a disaster scenario as assumed in this paper, the network infrastructure has been damaged by a natural disaster like an earthquake and all nodes should work in ad hoc mode. There are some ad hoc nodes on the ground to do the rescue operations and management of these operations. Figure 1 shows rescue teams and a command center that are ad hoc nodes on the ground. There is a need for packet exchange between ad hoc nodes on the ground but the distances between these nodes are bigger than the radio transmission range. Moreover, some natural barriers avoid placing any vehicular communication node on the ground for relaying. In such a scenario, we assume that there is a group of UAVs in the air.

We also assume that UAVs plan their trajectory based on their missions. Before any movement, a UAV must inform its entire neighborhood about its flying trajectory. This should be done periodically by all UAVs to avoid any physical collision between them. We will use trajectory information in our TAG routing protocol.

Moreover, it is assumed that all the nodes are SUs (UAVs or ground nodes) and access the spectrum using a geolocation database. The geolocation database is located in each SU and provides the location of PUs and their coverage area in the network. In each geographical location, an SU queries the database using its geographical position to find out if it is allowed to use the spectrum or not.

Considering the mobility of UAVs, we classify the states of a UAV in a CRAHN regarding to its distance to the PU region.

- Far from a PU region: UAV is located far from a PU coverage area. It can receive and transmit without making any interference to the PU receivers.
- Close to a PU region: UAV is outside a PU region but its transmission range has an overlap with the PU coverage area. In this case, the UAV can receive from other UAVs (or SUs) but it is not allowed to transmit when the PU is

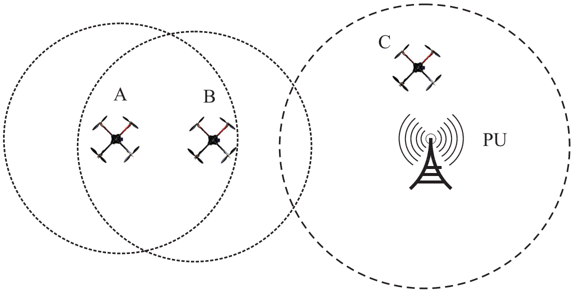

Fig. 2. States of a UAV in a CRAHN

active. The UAV may cause interference to PU receivers which are inside the PU coverage area.

– Inside a PU region: UAV is inside a PU coverage area. It is not allowed to transmit when the PU is active and may not receive from other UAVs (or SUs) due to the strong interference of the PU transmissions.

Figure 2 demonstrates UAV A, B and C together with their transmission ranges and the mentioned states for a UAV in a CRAHN. UAV_A is "Far from a PU region" and can receive from UAV_B or others. Besides, it can always transmit to UAV_B. UAV_B is "Close to a PU region". It can receive from UAV_A but it is not allowed to transmit when the PU is active. UAV_C is "Inside a PU region" and cannot transmit or receive during PU transmissions.

In our network model, we assume that the PU is highly active and when a node is inside the PU region or close to the PU region it is not allowed to transmit. In the next section, we propose our trajectory aware routing using the mobility information of the UAVs and their states in a CRAHN.

4 TAG: Trajectory Aware Geographical Routing

In a disaster scenario, different types of traffic may be forwarded between ground nodes or UAVs. The data belongs to different applications with specific requirements. One of the most common requirements of the applications is delay constraint. Considering the mobility model of a UAV and its states (mentioned in Section 3), it cannot access the radio spectrum during its flying time when it is located "inside a PU region" or "close to a PU region". Depending on the closeness of a UAV to a PU region, packets inside the buffer of the UAV may experience some queuing delays. According to the strict delay constraints for real-time traffic, a UAV node with a planned trajectory that is inside or too close to a PU region should not be participating in real-time packets routing. Greedy geographical routing protocols consider distance as the main metric for the next hop selection without paying attention to the state of a UAV and its mobility. With using distance metric for the next hop selection, real-time packets may be received by a destination beyond their delay constraints.

In our proposed Trajectory Aware Geographical (TAG) routing, the next state of UAVs is considered using their planned trajectory to avoid long queuing delay in the buffer of UAVs for real-time packets. TAG uses periodic beacon packets in each neighborhood to collect local information. In TAG, a beacon has one additional field for the next position of a UAV. A beacon in TAG routing contains current location (l_t) of the node at the time of current beacon time (t) and its next location (l_{t+1}) at the time of next beacon time ($t+1$). The next location of a UAV can be estimated from the its planned trajectory. Having the current and the next location of all neighbors, a source UAV queries the geolocation database to find the next state of a candidate (neighbor) UAV. If the next state of a candidate UAV is "inside a PU region" or "close to a PU region", it is not a good candidate to be selected as next hop to forward a real-time packet, even if the UAV is the closest neighbor to the destination. TAG uses Algorithm 1 in each hop to select the next hop for a real-time packet.

Algorithm 1. TAG routing

procedure NEXT HOP SELECTION
  for n `neighbors` **do**
    $State(n) \leftarrow 1$
    if $l(t+1) = insidePU || closetoPU$ **then**
      $State(n) \leftarrow 0$
    if $State(n) = 1$ **then**
      $f(n) \leftarrow \frac{1}{Dn}$.
    else
      $f(n) \leftarrow 0$.
Next hop $= argmax f(n)$.

$State(n)$ is a variable that reveals the next state of the UAV_n in a CRAHN. If the next state of candidate n is "inside a PU region" or "close to a PU region", then $State(n)$ is 0. When the next state of UAV_n is "far from a PU region", the value for $State(n)$ is 1. $f(n)$ is the utility function for each candidate neighbor n and D_n is the distance of UAV_n to the destination.

TAG behaves greedily and selects the closest neighbor to the destination if the next state of a neighbor UAV is "far from a PU region". On the other hand, it avoids a UAV that will fly close or inside a PU region. This strategy protects real-time packets from experiencing a long delay due to the PU regions.

5 Performance Evaluation

In this section, we evaluate the performance of the proposed TAG routing algorithm. To do this, we modeled a CRAHN in OMNeT++. The model is based on the disaster scenario depicted in Figure 1. We compare TAG with a geographical routing protocol that only uses the distance to destination as the metric for next hop selection. The distance based geographical routing will be called Greedy routing in this paper.

In our model, source and the destination are stationary nodes on the ground, such as a command center and a rescue team. The distance between source and destination is about 1500 meter. The radio transmission range of each node is approximately 250 meter. The source node generates constant bit rate traffic destined to a specific destination. The intermediate nodes, i.e., the UAVs, are mobile following a mobility model proposed in [6]. The speed of a UAV is randomly selected at the beginning of each simulation run and stays constant till the end of simulation. UAVs act as relays between the source and the destination for our TAG routing. The PU is stationary and permanently active. The source and the destination nodes are out of the PU region. However, the state of a UAV may change during a flight, according to one of the three states that were described in Section 3. In order to determine the location and coverage area of the PU, we assume to have access to a geolocation database. Table 1 lists the assumptions of our simulation model.

Table 1. Simulation assumptions

Parameters	Value
Number of channels	1
Data rate	2 Mbps
Simulation time	200 s
Packet length	128 bytes
UAVs speed	0-20 mps
Number of SUs	10
Number of PUs	1

Figure 3 compares the average end-to-end delay for packet routing from the command center (source) to a rescue team (destination) as a function of offered load. The average end-to-end delay of the proposed TAG routing is compared with Greedy routing at different load levels.

Note that the average end-to-end delay differs significantly at lower rates. This is because TAG exploits its knowledge about the next state of a UAV before selecting it as a next hop. In other words, it avoids UAVs as a potential next hop which are close to or inside a PU region. On the other hand, Greedy routing does not consider the next state of a UAV during the selection of the next hop. Therefore, packets that reach such a UAV must wait inside the buffer till it flies out of the PU region.

In our model, we assumed a permanently active PU which is the worst case for SUs. However, even having low activity PUs, forwarding packets to a UAV that will be located inside or close to a PU region causes higher packet delay. TAG avoids such UAVs as a next hop. With increasing offered load, there is a drastic increase in average delay. This is because beyond this point, i.e., the saturation point, packets start to queue up at source node. After the saturation

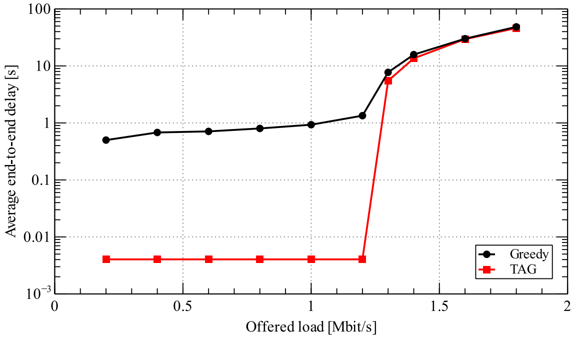

Fig. 3. Average end-to-end delay as a function of offered load

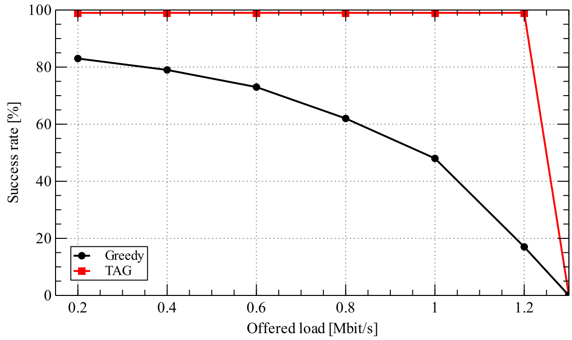

Fig. 4. Percentage of packets that meet the delay constraint as a function of offered load

point, however, the difference between both approaches diminishes and TAG asymptotically approaches Greedy routing.

Averaging the end-to-end delay of all packets cannot clearly illustrate the delay of each individual packet. For real-time applications, however, the maximum delay of each individual packet is of paramount importance. Therefore, in the second experiment, we defined a latency constraint of 10 milliseconds for all packets and calculated the percentage of packets that met this constraint.

Figure 4 depicts the success rate for TAG and Greedy routing at different levels of offered load. In TAG, all packets can meet the defined constraint at low packet rates before the saturation point of the network. On the contrary, Greedy routing can meet the delay constraint for 60 to 80 % of packets at low traffic loads. The reason for the unsuccessful packets at low packet generation rates is again the queuing delay in the UAVs that fly too close or inside a PU region. In Greedy routing, the queuing delay goes beyond the defined constraint for the real-time packets. After the saturation point, at which also the source starts to queue packets, the success rate drops down to less than 1 % of packets and both approaches have approximately similar success rates. Table 2 shows the maximum delay that occurs for real-time packets in TAG and Greedy routing.

Table 2. Maximum end-to-end delay comparison (in seconds)

Offered load (Mbit/s)	TAG	Greedy
0.8	0.005	5.8
1	0.005	7.35
1.2	0.005	9.27
1.4	24.38	38.75
1.6	81.89	99.7

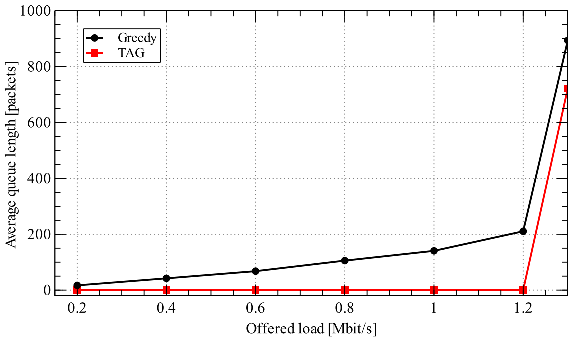

Fig. 5. Average queue length vs. packet generation rate for TAG and Greedy routing

As you can see in the table, the maximum delay in Greedy routing is far beyond the constraint for real-time packets having low packet generation rates. This delay reflects mostly the effect of queuing delay in intermediate UAVs that fly through PU regions.

Figure 5 illustrates the average queue length in the network for both routing protocols. Before the saturation point, the average queue length is approximately zero in TAG because it avoids PU regions. Therefore, in TAG we have no packet queuing due to PU activity. On the other hand, in Greedy routing, there are number of queued packets in low packet generation rates before the saturation point. The average queue length increases rapidly with increasing offered load. Note that we assumed an unlimited buffer in the nodes. However, with a limited buffer, there will always be packet drops in Greedy routing.

In our implementation of TAG and Greedy routing, we defined the beacon validity time equal to two beacon intervals. In other words, if a source node does not receive any beacon from any neighbor, it will not consider this node as the next hop. This is an indirect message from a node to its neighbors that the node has moved to a PU region or close to it and cannot send the beacon. This seems to be beneficial for Greedy routing to stop selecting a node which is inside or close to a PU region after two beacon intervals. Therefore, shorter beacon intervals can improve the performance of Greedy routing.

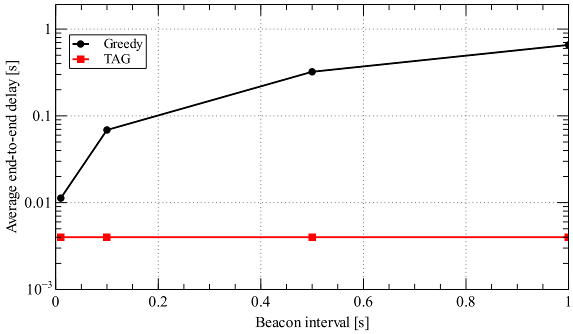

Fig. 6. Average packet delay vs. beacon interval for TAG and Greedy routing

In another experiment, we measured the average packet delay for different beacon intervals, but kept the offered load constant. Figure 6 shows the average packet delay for different beacon intervals in TAG and Greedy routing. For the short packet intervals, the difference between TAG and Greedy routing is less compared to longer beacon intervals. TAG always achieves better average delay because it does not wait for two beacon intervals to know that the neighbor is inside or close to a PU region. TAG recognizes the mobility of a neighbor UAV toward a PU region from its planned trajectory. Moreover, the cost for decreasing the average delay in Greedy routing is increasing the overhead of more beacon generation in the network. In TAG routing, a UAV adds its next geographical location to the beacon and sends it to its neighbors. Therefore, the beacon size in TAG is bigger than Greedy geographical routings. However, the amount of additional overhead in TAG is restricted to two numeric values for the coordinates of the next location of a UAV. The size of this extra overhead in our implementation is 128 bit, i.e., 64 bit for both longitude and latitude. This amount of overhead is the cost for the TAG routing improvements.

6 Conclusion

UAVs are autonomous flying wireless nodes that can be employed in disaster scenarios. They may have various missions in the network and their flying trajectory is usually according to their mission. At any given time they have a planned trajectory and follow it. In this paper, a geographical routing protocol was proposed that employs UAVs trajectory information to avoid routes inside or close to PU region. TAG routing improves average end-to-end delay, maximum delay, and success rate for real-time packets in the network comparing with Greedy geographical routing. UAV is one of the applications for TAG routing. It can be applied to other types of wireless ad hoc networks that consist of nodes with defined trajectories. One of the potential applications for TAG could be Vehicular Ad hoc NETworks (VANETs) with driver-less cars that have been proposed recently. Employing TAG in VANETs with autonomous vehicles is one of our future works.

References

1. Zhao, Y., Gaeddert, J., Bae, K.K., Reed, J.H.: Radio environment map enabled situation-aware cognitive radio learning algorithms. In: SDR Forum Technical Conference (2006)
2. Cordeiro, C., Challapali, K., Birru, D., Sai Shankar, N.: IEEE 802.22: the first worldwide wireless standard based on cognitive radios. In: First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks(DySPAN), pp. 328–337 (2005)
3. Flores, A.B., Guerra, R.E., Knightly, E.W., Ecclesine, P., Pandey, S.: IEEE 802.11 af: A Standard for TV White Space Spectrum Sharing. IEEE Communications Magazine 51(10), 92–100 (2013)
4. Simon, T., Mitschele-Thiel, A.: A self-organized message ferrying algorithm. In: 14th International Symposium and Workshops on a World of Wireless, Mobile and Multimedia Networks (WoWMoM), pp. 1–6 (2013)
5. Rubin, I., Zhang, R.: Placement of UAVs as communication relays aiding mobile Ad hoc wireless networks. In: Military Communications Conference (MILCOM), pp. 1–7 (2007)
6. Bouachir, O., Abrassart, A., Garcia, F., Larrieu, N.: A mobility model for UAV Ad hoc network. In: International Conference on Unmanned Aircraft Systems (ICUAS), pp. 383–388 (2014)
7. Rajaraman, R.: Topology Control and Routing in Ad Hoc Networks: A Survey. SIGACT News 33(2), 60–73 (2002)
8. Cacciapuoti, A.S., Calcagno, C., Caleffi, M., Paura, L.: CAODV: Routing in mobile Ad-hoc cognitive radio networks. In: Wireless Days (WD), pp. 1–5 (2010)
9. Karp, B., Kung, H.-T.: GPSR: Greedy perimeter stateless routing for wireless networks. In: Proceedings of the 6th Annual International Conference on Mobile Computing and Networking, pp. 243–254 (2000)
10. Chowdhury, K.R., Felice, M.: SEARCH: A Routing Protocol for Mobile Cognitive Radio Ad-hoc Networks. Journal of Computer Communications 32(18), 1983–1997 (2009)
11. Habak, K., Abdelatif, M., Hagrass, H., Rizc, K., Youssef, M.: A Location-aided routing protocol for cognitive radio networks. In: International Conference on Computing, Networking and Communications (ICNC), pp. 729–733 (2013)
12. Liu, Y., Cai, L.X., Shen, X.: Spectrum-aware Opportunistic Routing in Multi-hop Cognitive Radio Networks. IEEE Journal on Selected Areas in Communications 30(10), 1958–1968 (2012)
13. Jin, X., Zhang, R., Sun, J., Zhang, Y.: TIGHT: A Geographic Routing Protocol for Cognitive Radio Mobile Ad Hoc Networks. IEEE Transactions on Wireless Communications 3, 4670–4681 (2014)
14. Rosati, S., Kruzelecki, K., Traynard, L.: Speed-aware routing for UAV Ad-hoc networks. In: IEEE Globecom Workshops, pp. 1367–1373 (2013)
15. Lin, L., Sun, Q., Wang, S., Yang, F.: A geographic mobility prediction routing protocol for Ad hoc UAV network. In: IEEE Globecom Workshops, pp. 1597–1602 (2012)