Resilient End-to-end Connectivity for Software Defined Unmanned Aerial Vehicular Networks

Gökhan Seçinti*,†, Parisa Borhani Darian†, Berk Canberk*,† and Kaushik R. Chowdhury†
*Department of Computer Engineering, Istanbul Technical University, Istanbul, TURKEY
Email: secinti@itu.edu.tr, canberk@itu.edu.tr
†Electrical and Computer Engineering Department, Northeastern University, Boston, USA
Email: secinti@northeastern.edu, borhanidarian.p@husky.neu.edu, canberk@northeastern.edu, krc@coe.neu.edu

***Abstract*—Unmanned Aerial Vehicular (UAV) networks extend wireless access for devices without infrastructure coverage, and also help establish a connectivity backbone during military reconnaissance and disaster events. This paper focuses on the design of a resilient end-to-end connectivity paradigm under unique architectural and scenario assumptions. First, the UAVs themselves are equipped with multiple interfaces that use standardized protocols, with associated variation in data throughout, range, and bit error rates. Second, there may be adversarial agents seeking to disrupt connectivity through targeted jamming in 3D spaces. Third, we assume an overlay software defined control plane, where the UAVs function as software switches, able to execute forwarding commands and determine preferred routes under controller directives. Our proposed approach devises metrics that influence the choice of the wireless interface and weights edges formed between UAV pairs. Further, it also uses a multi-layer graph model and creates maximally separated paths in 3D space to ensure resiliency to jamming. Simulation results conducted for urban scenarios reveal 34% improvement in enhanced resiliency for end-to-end outages by trading off 12% increase in latency over competing approaches.**

I. Introduction

Unmanned aerial vehicular (UAV) networks are poised to usher in new economic opportunities in a number of industry sectors, aside of deployment in public safety, disaster management and defense applications. Timely delivery of data is the primary objective in UAV operations. In such cases, they may coordinate their positions to form a 3D mesh network, where UAVs forward traffic to next neighbor, ultimately forming a route to the sink or base station. Such a forwarding action becomes complicated when multiple different wireless interfaces are present. In this paper, we assume that each UAV has three interfaces/standards- LTE direct, 802.11ac and 802.11ad. Which interface to select given geographic separation, possibility of occlusion of the line of sight, and their respective advantages in supporting high data rate, low link latency, and wide coverage area is an open challenge. Adversarial jamming involves emitting high power beams that blanket out all RF communication is a given area. This can cause catastrophic interruption to a UAV network if multiple UAVs are affected by the jamming beams. One way to counter this effect is by distributing data forwarding routes through multiple different combinations of UAVs, with as much geographical separation as possible between the UAVs belonging to two different paths. This problem has been explored in a different context in terrestrial networks [1], where a multi-path Internet routing algorithm for connecting Internet service provider backbones is devised using a metric that measures physical diversity of the paths. Such redundant paths provide reliability for sudden loss of end-to-end (e2e) connectivity resulting from a node failure. However, simply calculating various disjoint paths is not an effective solution to capture dynamic 3D nature of UAV networks where the routes defined for a specific e2e connection may be affected by a common jamming source because of the spatial proximity of the paths. This condition nullifies the advantage of multi-path routing.

In this paper, we propose a routing framework that enables resilient communication through paths determined by a software defined network (SDN) controller. Using inputs like location and channel availability and with the awareness of the topological map of the environment, the controller builds a connectivity graph for the network. Each pair of UAVs is assigned a *connectivity layer* if their locations and positions allow the use of one of radio access technologies (RAT). The controller then runs multiple iterations of a shortest path algorithm for UAVs while ensuring every successive route discovered is composed of UAVs that have not yet participated in previous explored routes, and also spatially separated in space. To the best of our knowledge, this is the first study on a resilient multi-path routing framework specifically for software defined (SD)-UAV networks. The main contributions of this paper include the following: (i) a SD-UAV network architecture that allows selection among different classes of wireless standards such as LTE, 802.11ad, 802.11ac, (ii) a resiliency multi-path routing that minimizes the impact to UAVs under jamming events, and (iii) a multi-layer graph model and a centralized routing protocol that combines (i) and (ii). The rest of this paper is organized as follows. The related work is given in sec. II. The routing framework and the performance evaluation are explained in sec. III and sec. IV respectively. We conclude the paper in sec. V.

The preliminary version of this work is accepted to appear in IEEE Communications Magazine in January, 2018.

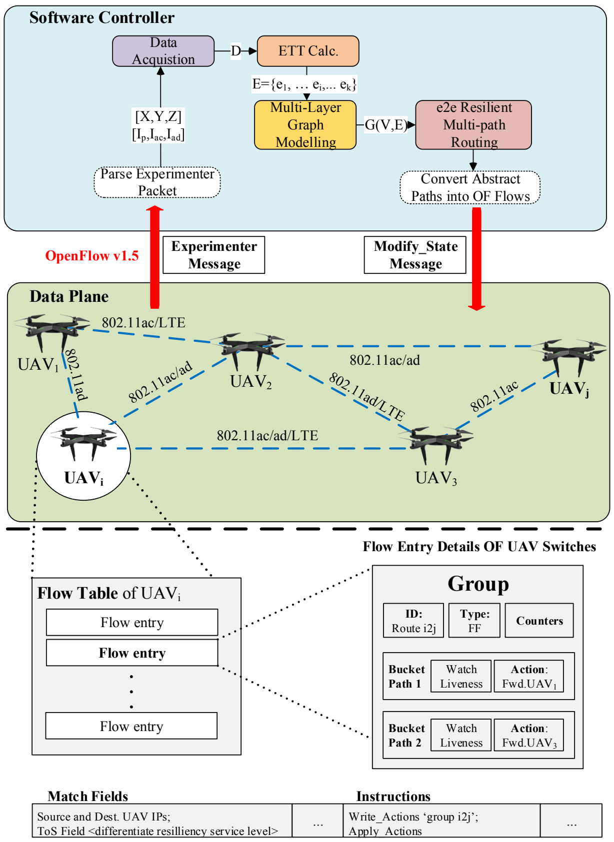


Fig. 1: Proposed SD-UAV network architecture

II. Related Work

While there are various studies on e2e routing for ad hoc and vehicular networks, UAV networks are still in a nascent stage with many open challenges [2]. At a general level, neither resiliency of the network nor the implementation of software-defined approaches to UAV networks has been covered so far in the published literature. [3] proposes a speed-aware routing algorithm that is applied in context of high speed UAVs. This algorithm focuses on calculating optimal paths among UAVs using a traditional networking approach by estimating single-interface link conditions over the network. In [4], the network layer challenges of UAV networks in traffic surveillance applications are addressed, where UAVs receive control instructions from a base station and send back the images, video, and data that require high-bandwidth, asymmetric data communications. Bekmezci et al. [5] classify the multi-UAV system as flying ad-hoc network with the understanding such a network has different characteristics from classical ad-hoc networks in term of node mobility, node density, frequency of topology change, radio propagation, and communication challenges. These are the specific considerations that also motivate our own work.

III. Resilient Routing Protocol Framework

The proposed routing framework resides at the software controller and consists of four different modules: (i) data acquisition, (ii) estimate transmission time (ETT) calculation, (iii) graph modeling, and (iv) multi-path determination as shown in Fig. 1.

A. Data Acquisition via OpenFlow

We assume that each UAV forms a packet which holds its location information $[X, Y, Z]$ and its available radio interfaces $[I_l, I_{ac}, I_{ad}]$ and, forwards this packet using flooding through a dedicated control channel over the network. Thus, the software controller acquires necessary information in order to model the dynamic data plane. This module creates distance matrix (D) which holds the distance between every UAV pairs in the network and forwards this matrix to the next module. Here, we assume data plane at software controller periodically collect information through a dedicated control channel and do not create an extra flooding overhead within the routing algorithm.

OpenFlow v1.5 is used as south-bound API of SD-UAV network and OpenDayLight is used as the main controller. Experimenter messages are utilized to forward the location and active RAT information from SD-UAVs to the controller and group table capabilities are utilized for implementing multi-path routing protocols to orchestrate flow entries over OpenFlow capable SD-UAVs. The flow tables and the related group action buckets are configured by Modify_State messages from the controller. A flow entry is implemented for each e2e connection and their actions are set as "go_to_group_table" where groups tables hold the information of multi-path routing configuration. To this end, Mininet v2.1.0 is used to validate the flow table entries and the matching mechanism. Since Mininet does not support various RATs, the performance of the proposed framework is evaluated with a specific software written in Java. Further detail about the simulation is given in Section IV. OpenFlow group tables support set of actions for multipath forwarding. Hence, the calculated multi-path routes are implemented by using fast failure recovery group tables in which each diverse route is defined as a action bucket. Thus, when a link fails in an e2e connection, a UAV is capable of choosing an alternative route that is already defined as a different action bucket without consulting the controller to avoid outage.

B. Estimated Transmission Time Calculation

ETT is a function of packet error rate (PER) and data rate of radio access technology. First, the expected transmission count (ETX) is calculated as $\text{ETX} = 1/(1 - \text{PER})$. This is used as an input in the calculation of ETT as: $\text{ETT} = \text{ETX}(L/R)$, where L is the size of the packet and R is the data rate [6]. Following list explains the methodology to calculate the ETT for each RAT:

- **802.11ad**: We estimate bit error rate (BER) as well as data rate using Modulation Coding Scheme (MCS) and SNR for IEEE 802.11ad as shown in [7] to calculate ETT. Given the BER, we estimate PER and then ETX. Furthermore, we consider 802.11ad with a single carrier modulation (CS) and OFDM modulation. The OFDM modulation and coding schemes that are used are SQPSK, QPSK, and 16-QAM. The 64-QAM ranging is from MCS 13 to MCS 24, which are supposed to allow very high throughput and reach the maximum announced data rate of 6.76 Gbps [8].

- **LTE**: First, the Block Error Rate (BLER) is calculated based on SNR, modulation and coding rate to determine the ETT in LTE. [9]. The multipath fading channel is used for a vehicle scenario, which is called extended vehicular a model (EVA) with the 2x2 MIMO configuration. Since data rate impacts the ETT, we choose the approach in [10] to do calculations according to the MCS and bits per symbol. Since release 8, LTE supports the QPSK, 16-QAM, and 64-QAM modulation schemes. We determine the bits carrying capacity per symbol for each modulation. The throughput of LTE is calculated as the resulting symbols per second. Thus, depending on a number of bits represented by the symbol, the data rate in bits per second is obtained [11].
- **802.11ac**: We perform simulations in MATLAB to calculate ETT for 802.11ac with 8 spatial streams and 160 MHz channel bandwidth. The simulation covers SNR values from 11 to 50. PER is calculated for different MCSs based on SNR. Lastly, the data rate is calculated accordingly MCS index for 802.11ac[1].

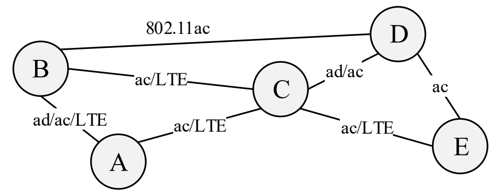
TABLE I: ETT/ETX for wireless standards at distance 0.5km and coding rate of 3/4 and target SNR = 22

Standard	Freq. (GHz)	Mod.	Rate (Mbps)	ETX	ETT (µs)
802.11ad	60	64QAM	6237	1.06	5.4697
LTE	2.69	64QAM	302.4	1.01	26.69
802.11ac	5	QPSK	1404	1.08	20.05

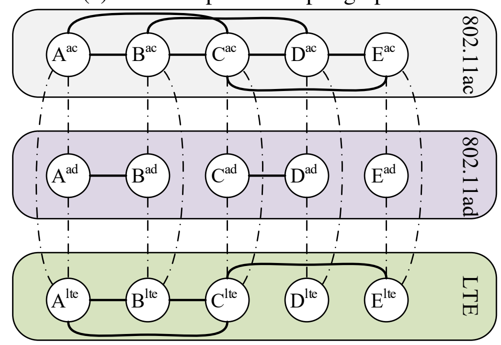
Table I represents the ETT/ETX for a scenario where the distance and the noise level for each of RATs is assumed to equal to 0.5 Km, -93 dB respectively. First, the free space path loss is calculated, and then the tx power is set to achieve the required SNR. Finally, ETX and ETX is calculated according to the modulation and the coding rate of each technology with respect to the defined SNR.

C. Multi-layer Graph Modeling

This module first creates a simple graph $G(V, E)$ where vertices (V) and edge (E) represent UAVs and the connections between UAVs respectively, as shown in Fig. 2a. Then, this graph is transformed into a multi-layered graph [12] $G'(V', E')$ where each layer represents radio interfaces and links between UAVs in the specific RAT. The layered graph contains horizontal and vertical edges. The horizontal edges represent the physical data-link of a given UAV with others in the same RAT and shows the reachability between UAVs using that RAT. The vertical edges belonging to the same physical UAV represent



(a) An example of simple graph G



(b) The representation of graph G' after transformation [12]

Fig. 2: Illustration of an exemplary graph transformation.

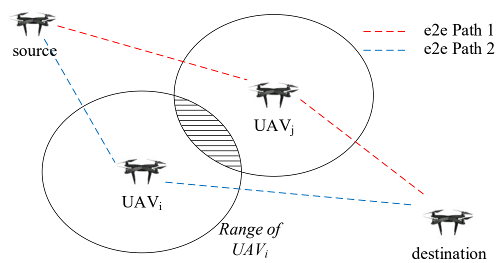


Fig. 3: End-to-end connectivity problem.

delay caused by the switching radio interfaces. Thus, formally, sets V' and E' are[2]:

$$V' = \left\{v_i^l, v_i^{ac}, v_i^{ad} | \forall v_i \in V\right\} \tag{1}$$

$$\begin{aligned} E' = &\left\{e_{ij}^l{:}<v_i^l, v_j^l> | \forall e_{ij}{:}<v_i, v_j> \in E \wedge l_{ij} = 1\right\} \\ &\cup \left\{e_{ij}^{ac}{:}<v_i^{ac}, v_j^{ac}> | \forall e_{ij}{:}<v_i, v_j> \in E \wedge ac_{ij} = 1\right\} \\ &\cup \left\{e_{ij}^{ad}{:}<v_i^{ad}, v_j^{ad}> | \forall e_{ij}{:}<v_i, v_j> \in E \wedge ad_{ij} = 1\right\} \\ \cup &\left\{e_i^d{:}<v_i^l, v_i^{ac}>, e_i^d{:}<v_i^l, v_i^{ad}>, e_i^d{:}<v_i^{ad}, v_i^{ac}> | \forall v_i \in V\right\} \end{aligned} \tag{2}$$

In the graph $G'(V', E')$, the weight of every horizontal edge is defined with their ETT. A graph transformation example is given in Fig. 2 for a network that contains 5 UAVs with three different RATs. The uncoupled representation of links that connect the same UAV with different wireless access technologies provides an important advantage while calculating diverse multi-path routes as explained in the following subsection.

D. End-to-End Resilient Multi-path Routing

In the last module, physically diverse paths are calculated within the graph G' to provide resilient e2e communication. The modified Dijkstra algorithm with

[1]http://mcsindex.com/ accessed on Apr, 2017

[2]l, ac and ad stand for LTE-direct, 802.11ac and 802.11ad resp.

vertex splitting method [13] is utilized to determine various diverse paths between any pair. While this algorithm is able to determine optimal disjoint multi-paths between two nodes, spatially distributed interference may still disrupt the communication of the vertices on disjoint paths. An example scenario for two disjoint routes is given in figure 3. While these routes do not share common a vertex/UAV, when the communication ranges of the UAVs are taken into consideration, there can be still intersecting volumes in the actual 3D-space. Any unexpected interferer or other noise source which resides or is effective in the intersecting volume is capable of disrupting the communication for both routes concurrently. Thus, e2e communication may fail even when it contains disjoint multi-path routes. To address this concern, we refine our formulation to include an additional constraint beyond solely minimizing the path delay to determine optimal disjoint routes. Specifically, we aim to provide disjoint paths where even spherical volumes representing the transmission range of the nodes on these paths preferably do not intersect or at least are kept below a defined threshold (T_r). The following equation defines the optimization problem that captures the aforementioned constraint:

$$\min\Big(\sum_{k\in[1,K]}\sum_{i=1}^{i<|p_k|} w(<p_k(i), p_k(i+1)>)\Big)$$

$$\text{s.t.}\begin{cases}\forall k\in[1,K],\quad p_k\in P_{ij}\\ \left[\sum_{m,n\in[1,K]}^{m\neq n}\ \sum_{\substack{i\in[1,|p_m|]\\ j\in[1,|p_n|]}} V(p_m(i),p_n(j))\right]\le T_r\\ \forall m,n\in[1,K],\quad m\neq n\Rightarrow p_m\cap p_n=\emptyset\end{cases}\tag{3}$$

where T_r is the pre-defined threshold for intersecting volumes between paths, P_{ij} is the set of possible paths between UAV_i and UAV_j, function w states the weight of the edge between two vertices, function V represents the intersecting volume between two UAVs and K is the number of paths defined between each pair within the data plane. Lastly, p_i defines the ordered set of vertices for a path and $p_i(u)$ gives the u^{th} vertex on the path. Since the behavior of the objective function significantly varies based on the random attributes of the data plane such as 3D coordinates and active RATs of UAVs, the solution space of the given problem grows exponentially with the number of UAVs. Hence, a heuristic approach is proposed to achieve suboptimal solutions by utilizing scalable algorithms. This heuristic is used to multiply the weight of the edges which have intersecting volumes with the ones on the shortest path (or a different chosen path) before calculating an additional e2e route. Thus, the heuristic forces the algorithm to choose distant edges without intersection.

$$DM_{ij} = 1 + \gamma e^{1-\frac{V}{V_{jk}}} \tag{4}$$

Algorithm 1 Multi-path Routing Algorithm

function CALCULATEMULTIPATH(Graph G', K, **UAV** *source*,*destination*)
    Define an empty List *Paths* to store result
    for (i=1; i≤K; i++) **do**
        Calculate shortest path btwn *source* and *destination* with Dijkstra[3]
        if List *Paths* is not empty **then** ▷ Check T_r constraint
            Calculate overall intersection volume with the Path p
            if calculated volume $> T_r$ **then**
                Re-initiate the algorithm with greater γ coefficient
        Include the calculated Path p to List *Paths*
        Replace all edges on p with arcs of negative weight and direction ▷ Vertex Splitting Method [13]
        Replace vertices on p with two and connect with 0-weighted arc
        for all $UAV \in Path \quad p$ **do** ▷ apply heuristic
            if There is intersecting volume in range with another UAV **then**
                Update the weight of edges for the specific RAT on the p
    Post-process List *Paths* to acquire disjoint paths

where V_{jk} is the intersecting volume of ranges between UAV_j and UAV_k, V is the maximum volume of the spherical range of an UAV, γ is a coefficient to tune the Delay Multiplier (DM) in the algorithm (see Alg. 1). The algorithm calculates K number of disjoint paths within the given graph G' for a pair of UAVs. Thus, the given algorithm runs for every UAV pair in the data-plane individually. In this manner, the shortest path is calculated first between pre-defined source and destination UAVs. Then, the vertex splitting method is applied [13] before rerunning the shortest path algorithm to determine an additional path. After the updating the graph with vertex splitting, we apply the heuristic to multiply the weight of the other links that have intersection volumes with the ones already in the path. Then, the algorithm repeats the steps explained above to calculate an additional path. Lastly, the algorithm controls the volume constraint defined in the second constraint in (3) after a new path is calculated. If the calculated paths do not satisfy the constraint, the algorithm re-initiates itself with a greater γ variable to boost the effect of the heuristic in (4).

IV. PERFORMANCE EVALUATION

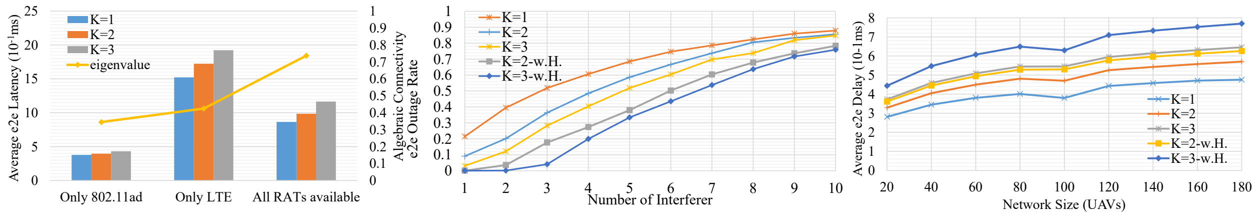
The routing algorithm and the simulation are written in Java by using JDK version 1.8 and Graphstream library v1.3[4]. With K as the number of diverse paths between UAV pairs, the traditional shortest-path algorithm K=1, and optimal multi-path algorithms for K=2 and K=3 are compared with the proposed routing framework, K=2-w.H. and K=3-w.H. where the postfix $w.H.$ specifies the use of our heuristic.

A. Network Connectivity Evaluation

We conduct a simple analysis to demonstrate the advantages of utilizing multiple RATs. The e2e latency and network connectivity are measured under three different RAT configurations, such as using only 802.11ad, using only LTE and randomly selecting access technology, where all RATs available. (K=1), (K=2) and (K=3) methods are used to determine average e2e latency

[3]Simple variation of Dijkstra algorithm that work with graphs that include arcs with negative weights [13].

[4]http://graphstream-project.org/ accessed on Apr, 2017



(a) e2e latency and network connectivity (b) e2e outage w.r.t. random interferer (c) e2e delay w.r.t. network size.

Fig. 4: Evaluation results of the proposed SD-UAV network and multi-path routing algorithm

in a static network topology with 30-UAVs. Algebraic connectivity [14], i.e., the second smallest eigenvalue of the Laplacian matrix, is utilized to measure the connectivity of the graph. As seen in Fig. 4a, using *only* 802.11ad offers best e2e latency performance while providing the least network connectivity. On the other hand, utilizing all possible RATs drastically improves the network connectivity while reduction in the e2e latency as a result of its random RAT selection policy.

B. End-to-End Resiliency Evaluation

In this evaluation, a UAV-network is created with uniformly distributed 100 UAVs within 1 km^3 space. According to this data plane configuration, e2e routes are determined and set for every-pair of UAVs in the network. Then, an interferer is created with a random coordination and its effect on the e2e connections is evaluated to measure the resiliency of the network. Fig. 4b shows the comparison of the proposed routing algorithm with traditional shortest-path routing algorithms. 200-trails are run for each scenario with various number of interfering sources on the x-axis and the average e2e outage rates are given on y-axis. We observe that the utilization of the proposed heuristic improves the performance in terms of e2e outage ratio when there are various interferers in the data plane. However, since the number of interferers increases, the routing algorithms converge to a state where all e2e connections fail.

C. End-to-End Delay Evaluation

Here, we analyze how average e2e delays of the determined routes change based on the number of UAVs in the network. Nine different topologies are created, of sizes varying from 20 UAVs to 180 UAVs . Topologies consisting of increasing number of UAVs are composed as super-sets of the previous ones. As seen in Fig. 4c, the best performance is achieved by the traditional shortest path algorithm, since it only focuses on calculating optimal paths in terms of e2e delay. Moreover, the calculated routes with the use of our heuristic performs slightly worse in terms of delay contributed by lines (13-14) in Algorithm 1. In these lines, weights of adjacent links to the shortest path are multiplied to avoid their selection in the path, thereby trading off latency with the goal of improving resiliency.

V. Conclusion

In this paper, we proposed a novel routing framework for SD-UAV networks that determines multiple disjoint routes for a given source-destination pair in order to improve resiliency of the network. To this end, our proposed resiliency metric combined with the heuristic method reduced the outage rate of end-to-end connections in the presence of interferers. Finally, we showed that the proposed framework performs better in terms of end-to-end outage with slight degradation in end-to-end delay, when compared to traditional algorithms.

Acknowledgement

This work was supported by the U.S. Office of Naval Research under grant number N000014-17-1-20416.

References

[1] J. P. Sterbenz, E. K. Çetinkaya, M. A. Hameed, A. Jabbar, S. Qian, and J. P. Rohrer, “Evaluation of network resilience, survivability, and disruption tolerance: Analysis, topology generation, simulation, and experimentation,” *Telecommun. Syst.*, vol. 52, no. 2, pp. 705–736, Feb. 2013.

[2] L. Gupta, R. Jain, and G. Vaszkun, “Survey of important issues in uav commun. networks,” *IEEE Commun. Surveys Tutorials*, vol. 18, no. 2, pp. 1123–1152, 2016.

[3] S. Rosati, K. Kruelecki, L. Traynard, and B. R. Mobile, “Speed-aware routing for uav ad-hoc networks,” in *2013 IEEE Globecom Workshops (GC Wkshps)*, Dec 2013, pp. 1367–1373.

[4] A. Puri, “A survey of unmanned aerial vehicles (uav) for traffic surveillance,” Ph.D. dissertation, Dept. of Comput. Sci. and Eng., University of South Florida, Florida, USA, 2005.

[5] I. Bekmezci, O. K. Sahingoz, and Ş. Temel, “Flying ad-hoc networks (FANETs): A survey,” *Ad Hoc Networks*, vol. 11, no. 3, pp. 1254–1270, 2013.

[6] R. Draves, J. Padhye, and B. Zill, “Routing in multi-radio, multi-hop wireless mesh networks,” in *10th Annu. Int. Conf. on Mobile Computing and Networking*. ACM, 2004, pp. 114–128.

[7] M. Zaaimia, R. Touhami, A. Hamza, and M. Yagoub, “Design and performance evaluation of 802.11 ad phys in 60 ghz multipath fading channel,” in *IEEE Int. Workshop on Systems, Signal Processing and their Applications (WoSSPA)*, 2013, pp. 521–525.

[8] E. Perahia and M. X. Gong, “Gigabit wireless lans: an overview of ieee 802.11 ac and 802.11 ad,” *ACM SIGMOBILE Mobile Computing and Commun. Review*, vol. 15, no. 3, pp. 23–33, 2011.

[9] W.-B. Yang and M. Souryal, “Lte physical layer performance analysis,” *National Institute of Standards and Technology US Department of Commerce*, 2014.

[10] P. K. Rekhi, M. Luthra, S. Malik, and R. Atri, “Throughput calculation for lte tdd and fdd systems,” *White Paper*, 2012.

[11] M. T. Kawser, N. I. B. Hamid, M. N. Hasan, M. S. Alam, and M. M. Rahman, “Downlink snr to cqi mapping for different multipleantenna techniques in lte,” *Int. Journal of Information and Electronics Engineering*, vol. 2, no. 5, p. 757, 2012.

[12] C. Xin, L. Ma, and C.-C. Shen, “A path-centric channel assignment framework for cognitive radio wireless networks,” *Mobile Networks and Applications*, vol. 13, no. 5, pp. 463–476, 2008.

[13] R. Bhandari, *Survivable Networks: Algorithms for Diverse Routing*. Norwell, MA, USA: Kluwer Academic Publishers, 1998.

[14] A. Abbagnale and F. Cuomo, “Leveraging the algebraic connectivity of a cognitive network for routing design,” *IEEE Trans. on Mobile Computing*, vol. 11, no. 7, pp. 1163–1178, July 2012.