Data Routing Challenges in UAV-assisted Vehicular Ad hoc Networks

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***Abstract*— Reliable and efficient transportation system in smart cities relies on effective integration of connected and autonomous vehicles. Although there has been a lot of improvements in this technology, additional support from the emerging unmanned aerial vehicles (UAVs) are needed to streamline the future transportation systems' capabilities. This paper investigates the problem of data routing in UAV-assisted vehicular ad hoc networks (VANETs) composed of multiple flying nodes and intelligent cars aiming at exchanging messages through the dynamic network topology. The introduction of UAVs can offer multiple advantages to the routing process thanks to their free mobility and enhanced channel quality but, at the same time, they are subject to many limitations including their limited batteries and positioning issues. This paper provides a comprehensive survey about the advantages and challenges related to the use of UAVs in data routing in VANETs. Then, it discusses some existing routing protocols for connected vehicles supported by UAVs. Finally, the paper introduces the idea of combining routing protocols with UAV locations and/or path adjustment solutions to enable efficient data routing for delay-tolerant applications.**

Keywords- Connected vehicles; data routing; intelligent transportation systems; unmanned aerial vehicle.

I. INTRODUCTION

Intelligent transportation system (ITS) constitutes one of the most important key components of future smart cities [1]. Reliable and efficient ITS is necessary to ensure safe and smarter transport networks. This requires the integration of multiple technologies, such as advanced wireless communication, computational, and sensing techniques to exchange and collect accurate and real-time information about the traffic and state of the transport network. Connected vehicles play an essential role in rendering the driving experience safer and more efficient. Using embedded communication capabilities, the vehicles can autonomously inform their neighbors about their status and motion parameters to mitigate any danger in the roads and avoid traffic jams [2]. The collected information can also be forward via cellular networks or deployed road side units (RSUs) to the traffic operator in order to monitor and control the transport networks.

Research in connected vehicles has witnessed significant advances over the last decade [3]-[5]. The most tackled issue in such scenarios is the mitigation of the instability of the wireless links connecting these mobile vehicles. Several routing algorithms have been proposed in the literature optimize the exchange and collection of data in these vehicular ad hoc networks (VANETs). However, the performances of connected vehicles remain limited due to the short ranges of the communication links, their random mobility, and fast dynamic topology change [6]. Therefore, there is still a need to support the intelligent vehicles with other road and transportation components. To this end, micro-unmanned aerial vehicles (micro-UAVs), aka drones, can be efficient candidates with great potentials to support the ground vehicles to overcome their limits and improve the quality of service of diverse ITS applications. Hence, UAV-assisted VANETs are henceforth the leading solution for data exchange and collection in ITS.

In this paper, we investigate the data routing process in UAV-assisted VANETs. In Section II, we will highlight the advantages and challenges related to the employment of UAVs in ITS. Afterwards, in Section III, a brief survey summarizing the developed data routing techniques with an emphasis on the UAV mobility impact is presented. Next, in Section IV, we investigate a particular scenario where we propose our joint routing path selection and UAV positioning solution. Finally, we conclude the paper in Section V.

II. ADVANTAGES AND CHALLENGES OF UAVS IN DATA ROUTING

Supporting connected vehicles by UAVs offer potential gains to enhance the performance of data exchange. UAVs can play an important role in routing the data between the different ground nodes due to the following advantages:

• **Channel Quality:** Thanks to their placement flexibility especially at high altitudes, UAVs can provide reliable line-of-sight (LoS) communication links with the ground vehicles [7]. Indeed, the higher the altitude is, the more the probability to establish LoS links occur. In this way, the system throughput of this air-to-ground (A2G) or ground-to-air (G2A) link is enhanced allowing the transmission of higher amount of data during the routing process. Moreover, transferring data from UAV to UAV is much more efficient than using traditional V2V communications through ground-to-ground (G2G) channels. Indeed, air-to-air (A2A) channels are subject to lower path loss and shadowing effects, which offer better channel quality. Hence, exchanging data between two ground nodes through multiple flying UAVs is much more efficient than using traditional methods. Mathematically, the free-space path losses in dB of A2A and G2G links corresponding to a LoS and non-LoS (NLoS) channels can be written as follows:

$$PL^{A2A} = PL^{LoS} = 10\gamma \log_{10}\left(\frac{4\pi f_c d}{C}\right) + L^{LoS}, \quad (1)$$

$$PL^{G2G} = PL^{NLoS} = 10\gamma \log_{10}\left(\frac{4\pi f_c d}{C}\right) + L^{NLoS}, \quad (2)$$

where γ is the path loss exponent, f_c is the carrier frequency, d is the Euclidean distance separating the two nodes, C is the speed of light, and L^{LoS} and L^{NLoS} are two additional attenuation terms for the LoS and NLoS environments, respectively, such that $L^{NLoS} \gg L^{LoS}$. It should be noted that other path loss models can be adopted.

Regarding the A2G links, their path losses can be written as a linear function of the LoS and NLoS path losses weighted by the probability of having a path loss connection denoted by p_{LoS}. The A2G path loss is written as follows:

$$PL^{A2G} = P_{LoS}\, PL^{LoS} + (1 - p_{LoS})PL^{NLoS}. \quad (3)$$

An expression of the path loss probability p_{LoS} has been derived in [8] as follows:

$$p_{LoS} = \frac{1}{1+\alpha \exp\left(-\beta(\theta(h,d)-\alpha)\right)}, \quad (4)$$

where α and β are constants which depend on the environment and θ denotes the elevation angle and is given by $\theta = \frac{180}{pi} \sin^{-1}\left(\frac{h}{d}\right)$ where h is the UAV's altitude. From this expression, we can deduce that UAV placed at high altitude will increase the probability of having a LoS link and hence, improving the channel condition. At the same time, it may increase its distance with ground node. A tradeoff between the altitude and the distance separating the communicating has to be achieved to enhance the channel quality.

- **Free Mobility:** Thanks to their three dimension (3D) mobility, UAVs can offer additional degrees of freedom to enhance the data routing. Indeed, they can cover larger areas with the ability to transmit collected data in real-time or store it on-board for future use. Moreover, unlike vehicles that have to move according to road directions or fixed road side units (RSU), UAVs can be placed at any location in order to establish direct connectivity with other nodes. This flexibility allows these flying nodes to connect other out-of-range nodes and act as relays for their communications. Therefore, placing UAVs in optimized locations and/or efficiently planning their paths would contribute in enhancing the data routing process in UAV-supported VANETs. This constitutes one of the major challenges in data routing through the flying nodes. In addition, to the traditional path selection task that has to be performed in the VANET dynamic topology, placing and/or moving the UAVs to ensure better support to the routing path represents another objective that has to be jointly optimized. In such scenarios, balancing between path selection using traditional routing protocols and UAV positioning is a non-trivial task mainly for moving UAVs.

The free mobility can also be subject to certain limitations. First, UAVs are not necessarily employed to route data. In most of the cases, they are used for other tasks, such as traffic monitoring or collecting images or videos. Hence, they can participate in the data routing procedure, i.e., the secondary task, if the objective of the primary task is not affected. Therefore, the support offered by the UAVs might be limited in space and time. For instance, UAVs cannot freely move out of certain regions defined by the operator or related to the primary task. Moreover, relaying UAVs may not be always available due to their limited primary task engagement or allocated energy budget. Finally, the UAV mobility has a negative effect on the channel quality. Indeed, high Doppler spread can be observed when both the UAV and car are mobile. This may limit the performance of the routing process.

- **Battery-Limited Nodes:** Unlike vehicle nodes, UAVs are battery powered and require frequent to-and-fro trips to reload their batteries, which may affect their contributions in the data routing process [9]. Hence, the energy consumption of UAVs has to be taken into account during the data routing optimization procedure to ensure seamless communication between the nodes. In addition to the energy of the communication interface, additional and relatively more important energy is consumed to ensure the hovering and forward flight of the UAVs. Hence, the UAVs that are selected to participate in the routing procedure need to have sufficient energy to complete the data transfer. This may impact the transmit power level of the UAVs, affect their communication range, and limit their mobility.

III. Data Routing Techniques and Use-cases

In UAV-assisted VANET, UAVs and ground vehicles can contribute to the data routing procedure where messages can be exchanged through air, ground, or both. The path selection is dependent on the objective of the process, such as the reduction of the total transmission time or the conservation of the link stability. Some of the applications in ITS allow some delay in the data transfer. Hence, the data routing procedure can be adapted to the type of applications which can be classified to delay-intolerant applications and delay-tolerant applications. In the sequel, we briefly discuss the routing protocols that can be applied in UAV-assisted VANET and the challenges corresponding to the tolerance of applications.

A. Routing Protocols

Several routing protocols involving UAVs have been discussed in literature [10]-[12]. Most of them are applied to Flying Ad hoc Networks (FANET) only. The routing protocols are classified as proactive, reactive, hybrid, and geographic routing protocols. The first protocol category assumes either fixed routing tables loaded to the UAVs before operation or periodically refreshed tables where the latest updates are considered to transfer the data. These protocols assume low topology variation even if the UAVs are in motion. The use of fixed routing tables requires a fixed topology. This can be applied for a group of nodes (UAVs

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and/or ground vehicles) having coordinated movement which is not the regular case in UAV-assisted VANET. For low frequencies of routing tables update, the protocols' performances can significantly degrade due to the very dynamic topology of the network and the distributed control of the nodes and their mobility. Optimized link state routing protocol (OLSR) is one of the prominent algorithms that are used in VANETs and FANETs. However, several extensions of OLSR have been presented in the literature to cope with the nodes mobility and high signaling overhead problems. In [13], directional antennas and cross-layer schemes based on flight information of UAVs have been added to the functionalities of the traditional OLSR in order to enhance its routing table's updates. A fast OLSR protocol has been proposed in [14] to meet the need of highly dynamic topology. This leads to a considerable increase in the signaling overhead especially for the in-motion node. The authors of [12] have proposed a predictive OLSR protocol using Global Positioning System (GPS) information to measure the quality of wireless links between nodes. The movement of UAVs are predicted based on their past mobility and speed. The routing tables are then pre-constructed based on these predictions. The performances of all these OLSR extensions remain dependent on the routing tables' accuracy and the stability of the links connecting the nodes.

The second routing protocol category known as reactive protocols proposes to discover paths for data transfer on demand. With such protocols, periodic messages are avoided but a delay has to be considered in order to establish the routing path before the data transmission. In addition to that, these protocols are designed for wireless mesh networks where a source needs to find a routing path to transfer its data to a target destination. Ad-hoc On-demand Distance Vector (AODV) is one of these reactive protocols where the source is aware about the next-hop information only [15]. Hybrid protocols represent a combination of proactive and reactive protocols. This protocol category will lead to more efficient performances but may cause additional delays in order to discover route in addition to extra signaling overhead.

The geographic routing protocol is a position-based routing protocol assuming that each node is aware of its neighbors' geographic locations [16]. The data transfer is performed such that each node selects its closest neighbor to the destination such that the distance to destination is reduced. In some cases, this greedy behavior of the algorithm fails to find a next hop closer to the destination. In such a scenario, face routing can be applied to help in finding another route to be followed by the geographic routing protocol. Although these greedy protocols do not require routing tables, their achieved routing paths remain suboptimal and may require higher number of hops before reaching destination compared to other categories.

B. *UAV Path and/or Location Adjustment for Data Routing*

The aforementioned algorithms, which are originally designed and applied to MANETs and VANETs, are applied for delay-intolerant applications where the objective is to find a route as fast as possible to deliver data. The total routing operation time, which is consisted of the route construction time and the data transfer time, is in the order of milliseconds. In such scenarios, the routing process requires the existence of communication links between some of the nodes such that the data can be routed. However, in many cases and especially in ITS, seamless routing paths might not be found due to deficient communication links between two or multiple nodes. Therefore, shifting the locations of some nodes can enhance the link quality and allow the discovery of routing paths. In UAV-assisted VANET, dedicated UAVs can be controlled by the operator to ensure connectivity. The operator may decide to place UAVs in precise locations to act as relays for other ground nodes. Another scenario could correspond to the case when relaying is not the principle task of UAVs. In such cases, UAVs can modify their current locations or their initial paths if they are in motion to support other nodes. For on-demand applications, the path or location adjustments of UAVs can lead to additional delay in the order of seconds and possibly minutes due to the flying time corresponding to the UAVs shift. Hence, such routing process involving UAVs path or location adjustment can be applied for delay-tolerant applications.

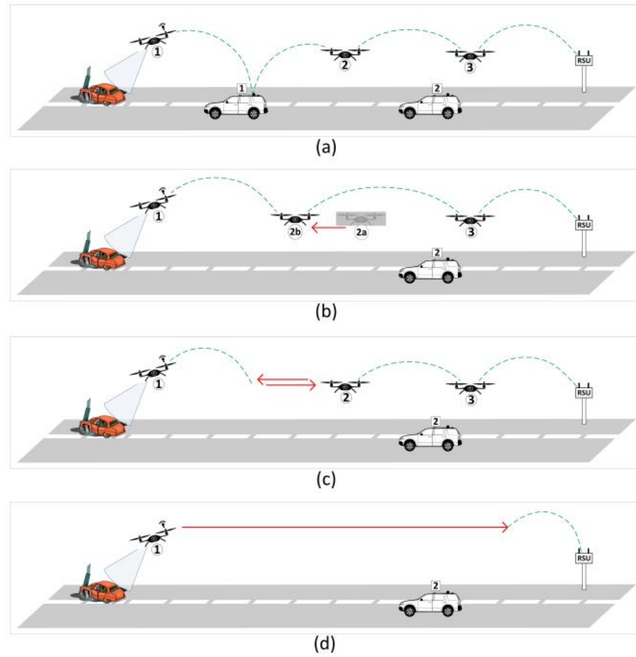

Figure 1. Examples of routing scenarios in UAV-assisted VANETs.

In Figure 1, we illustrate examples of some routing scenarios involving UAVs. In Figure 1(a), the UAV collects information about a particular event in the transport network. The data is routed through flying and ground vehicles already deployed in the area as direct communication links exist. Delay-intolerant applications require the existence of such topology to enable successful routing. Notice that the absence of ground vehicle 1 causes the failure of the routing process due to long distance separating UAV 1 and UAV 2. Hence, in order to overcome this issue and enable successful routing, one possibility based on location adjustment is shown in Figure 1(b). In this case, UAV 2 shifts its location

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from position (2a) to position (2b) in order to establish a direct link with UAV 1 without breaking up its link with UAV 3. This location adjustment will certainly cause certain delay in the routing due to the motion of the UAV but remain a good solution for applications tolerating a certain delay. If the distance separating UAV 1 and UAV 3 is very long such that it is not possible to find a location for UAV 2 where it can establish direct communication links with its peers, UAV 2 seeks close location to UAV 1 to collect the data and then, return next to UAV 3 to forward it as shown in Figure 1(c). Finally, another special case of routing is given in Figure 1(d). One or multiple UAVs act as data collectors where each UAV has to follow a particular path to collect and store necessary information from various locations then, go back and send the data to the sink. Many use-cases related to this type of applications exist in ITS. In the following, we cite few of them:

- **Flying Accident Report Agent:** In this case, one or a set of UAVs fly to the accident's location to get a detailed report about the accident. The collected information need to be sent to the related authorities. When reaching the accident's location, the UAV can exploit the ground vehicles to transfer the data. Other UAVs can also support the ground nodes in the routing process. They UAVs can be partially shifted to be located between out-of-range nodes to allow them transfer their data.
- **Flying Road Side Unit:** Enabled with Dedicated Short Range Communications (DSRC), the UAV will be used as a flying road side unit that can fly to a specific location to act as a V2X RSU (e.g., extend communication link at corners) or to broadcast useful information, such as traffic situation in the surrounding area, and suggest alternative detours. In this case, UAV path planning approaches can be developed to determine the locations of UAVs through which it has to pass by to collect the data from ground vehicles. Data routing approaches and clustering algorithms can be combined together to find how data can be efficiently collected in traffic network using UAVs.
- **Flying Police Eye:** The UAV will provides the police agent with a top view video streaming to better assess the traffic around and easily detect specific traffic violations. If the UAV is not directly communicating with police vehicle then, data routing is required through the UAV-assisted VANET.

Joint optimization of the data routing procedure in UAV-assisted VANET using traditional routing protocols and UAV path and/or location adjustments is a new trend research direction that has to be investigated in academia and industry. The mobility of UAVs represents, at the same time, an advantage and a challenge that has to be well studied. Mechanisms enabling efficient coordination and routing among UAVs and close ground vehicles need to be developed while taking into account the specific characteristics of 3D mobile environment, the energy limitation, and the application objective. In the following section, we investigate an example of data routing in UAV-assisted VANET involving the adjustment of some UAVs' locations to ensure an efficient data routing for delay-tolerant application.

IV. Selected Example and Simulation Results

In this section, we provide an example of data routing involving location adjustments of UAVs for delay-tolerant applications. In the framework, we consider a multiple-UAV network where each UAV is executing a certain task related to a primary application. Some of the UAVs are selected to participate to a secondary task, i.e., data routing, in order to transfer data from a source to a destination. In case of the absence of direct communication link, some UAVs are shifted to ensure seamless transmission. The participating UAVs are chosen according to their battery state, mobility range tolerated by the primary application, and the channel quality. The objective is to minimize the data transfer time, denoted by T^{tr}, from the source to the destination which is the sum of the total transmission time in addition to the mobility time denoted by T_n^f. To this end, the following mixed integer nonlinear programming problem is formulated:

$$\underset{\boldsymbol{\epsilon},\boldsymbol{\pi},\boldsymbol{X}^f}{\text{minimize}} \quad T^{tr} = \max_n \pi_n T_n^f + \sum_{n=1}^{N} \epsilon_{sn} T_{sn}^c(X_s, X_n^f)$$
$$+ \sum_{n=1}^{N} \sum_{\substack{m=1\\ m\neq n}}^{N} \epsilon_{nm} T_{nm}^c(X_n^f, X_m^f) + \sum_{n=1}^{N} \epsilon_{nd} T_{nd}^c(X_n^f, X_d) \quad (5)$$

subject to

$$\sum_{\substack{m=1\\ m=s}}^{N} \epsilon_{mn} E_{nm}^r + \sum_{\substack{m=1\\ m=d}}^{N} \epsilon_{nm}\left(E_{nm}^c\right) + \pi_n E_n^f \leq \bar{E}_n,$$
$$\forall n = 1, \dots, N, \quad (6)$$
$$\pi_n D_n(X_n^0, X_n^f) \leq \bar{D}_n, \quad \forall n = 1, \dots, N, \quad (7)$$
$$\sum_{m=1}^{N} \epsilon_{mn} = \sum_{n=1}^{N} \epsilon_{nm}, \quad \forall n = 1, \dots, N, \quad (8)$$
$$\sum_{m=1}^{N} \epsilon_{nm} \leq 1, \quad \forall n = 1, \dots, N, \quad (9)$$
$$\epsilon_{nm} + \epsilon_{mn} \leq 1, \quad \forall n, m \in \{1, \dots, N\}, \quad (10)$$
$$\sum_{n=1}^{N} \epsilon_{sn} = 1, \text{ and } \sum_{n=1}^{N} \epsilon_{nd} = 1, \quad (11)$$
$$\epsilon_{nm} \leq \Phi_{nm}, \quad \forall n, m \in \{1, \dots, N\}, \quad (12)$$

The decision variables of the optimization problem given in (5)-(6) are the binary matrix $\boldsymbol{\epsilon}$, the binary vector $\boldsymbol{\pi}$, and the matrix $\boldsymbol{X^f}$. The entries ϵ_{nm} of the matrix $\boldsymbol{\epsilon}$ denote the states of the links between UAV n and UAV $m, \forall n, m \in \{1, \dots, N\}$ where N is the number of UAVs in the network. The parameters ϵ_{sn} and ϵ_{nd} indicate the states of the link between the source and a UAV n and the UAV n and the destination, respectively. The entries of $\boldsymbol{\pi}$ are binary variables indicating whether the UAV n is moving from an initial location to another to support the data transfer. If yes, π_n =1. Finally, the entries of the matrix $\boldsymbol{X^f}$ correspond to the coordinates of the new locations of N UAVs. Note that $X_n^f = X_n^0$ where X_n^0 are the initial locations of the UAV n. In (5), the first term indicates that the data transmission begins when all the UAVs have reached their new locations. The other terms correspond to the transmission time over the selected path where T_c^{xy} is the communication time needed to send the message from node x to node y. The communication time depends on the size of the message and the achieved throughput per each selected link.

Constraint (6) indicates that the total energy consumed by the UAV during the shifting (E_n^f), the data transmission (E_{nm}^c), and the reception (E_{nm}^r) has to be less than the available energy in its battery allocated to the secondary task. In other words, we assume that, for each UAV, the operator assigns a certain amount of energy for the secondary task that we denote by $\bar{E}_n$. Constraint (7) indicates that, a UAV cannot be shifted with a distance D_n higher than $\bar{D}_n$ in order to guarantee the safe operation of the primary task. The data flow conservation is guaranteed by constraint (8), which forces a UAV that received a data to forward it to other UAVs. Constraint (9) ensures that a data is transmitted to only one UAV and, with constraint (10), cyclic transmission within a single link is disabled. Cyclic data routing over the whole network is avoided by jointly imposing the constraints (8)-(10). Hence, a UAV will not receive the message twice or more during the routing. The equality constraints in (11) force the source to transmit the data and the destination to receive it. Finally, constraint (12) indicates that the data transfer can only be possible over seamless links defined by the binary parameter $\Phi_{nm} = 1$.

The formulated optimization problem given in (5)-(12) is a mixed integer non-linear programming (MINLP) problem. It is difficult and complex to reach the optimal solution of these non-convex problems due to the existence of combinatorial decision variables. Therefore, to solve it, sub-optimal deterministic or meta-heuristic algorithms can be implemented. In the following simulation results, we employ an exploratory search strategy to solve the MINLP problem. Inspired from the Hooke-Jeeves search method applied for multimodal functions, the proposed algorithm tries to find the best directions and distances according to which the UAVs will move in order to establish seamless links for data routing. The objective is to find the best shift combinations for the UAVs that do not affect their energy budgets and do not lead to a high delay. Notice that, for fixed UAV positions, the optimization problem is transformed to an integer linear programming problem that can be optimally solved using CPLEX optimizer.

Four different scenarios are studied in Figure (2). The UAVs' speed are set to 10 m/s and the size of the transmitted message is 10 kilobyte. Figures 2(a), 2(b), and 2(c) investigates the same network topology but for different energy budget distributions. Figure 2(d) illustrates another network topology. Figure 2(a) assumes the absence of energy constraints of all UAVs. The obtained routing path is directly obtained without the need to shift the UAVs with a total transmission time equal to 0.18 s. In Figure 2(b), UAV 4 and UAV 11 are not able to participate in the routing process due

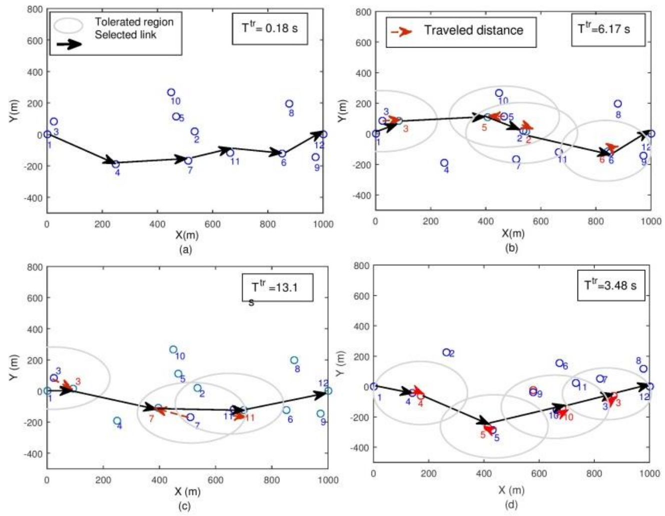

Figure 2. Example of joint location adjustments using an exploratory search strategy (a) scenario 1: no energy limit, (b) scenario 1: $\bar{E}_4 = \bar{E}_{11} = 0$, (c) scenario 1: $\bar{E}_2 = \bar{E}_4 = \bar{E}_5 = \bar{E}_6 = \bar{E}_8 = \bar{E}_8 = \bar{E}_9 = 0$, and (d) scenario 2: no energy limit.

to their limited energy budgets ($\bar{E}_4 = \bar{E}_{11} = 0$). Hence, some direct links are degraded and a shifting operation is needed by some of the remaining UAVs. To this end, the exploratory approach shifts UAV 3 and UAV 2 and accordingly, UAV 5 and UAV 6 to establish direct link between the different nodes. Then, instead of transmitting the message to UAV 7, UAV 5 decides to forward it to UAV 2 and UAV 2 skips UAV 11 and sends the message to UAV 6. The total transmission time is equal to 6.17 seconds due to the shifting operation.

In Figure 2(c), we disable the contributions of all UAVs except UAVs 3, 7, 10, and 11. In this case, the approach decides to shift UAV 7 and UAV 3 in addition to UAV 11. The obtained transmission time is 13.1 seconds due to the high shifted distance (UAV 7).

In Figure 2(d), the initial topology created by the 10 UAVs imposes the execution of a shifting process in order to find a routing path over the FANET. In this scenario, we notice that four UAVs are slightly shifted: UAV 4, UAV 5, UAV 10, and UAV 3. These minor location adjustments result in a low total transmission time of 3.48 seconds.

V. CONCLUSION

In this paper, we investigated the data routing process in UAV-assisted VANETs. We started by highlighting the advantages of using relays in ITS and the challenges that have to be addressed to ensure efficient data routing. Afterwards, we surveyed the data routing techniques that can be implemented in such scenarios by describing some interesting use-cases. Finally, we highlighted the need to proceed with location and/or path adjustments of UAVs in order to obtain direct communication links and seamless routing process. A particular scenario involving UAV location adjustment is finally investigated. The joint optimization of the routing process along with the location and path modifications remain a challenging research direction especially for delay-tolerant applications.

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