The Effects of a UAV on a Terrestrial MANET

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***Abstract*—Technological advances on Unmanned Aerial Vehicles (UAVs) and autonomous control could make UAVs useful for communication purposes, extending the range and increasing the performance of Mobile Ad-Hoc Networks (MANETs). However, how and whether the UAV should be deployed in an otherwise terrestrial MANET depends on multiple parameters and objectives. In this paper, we analyze the effect of a UAV as a traffic relay compared to terrestrial-bound forwarding in a connected CSMA/CA MANET with omnidirectional antennas. A UAV is superior to terrestrial nodes in terms of connectivity, due to the larger Line-of-Sight coverage. This also means that a UAV can reduce the average number of hops in a MANET, thus reducing the self-interference problem and improve the network resource use. However, there are also negative effects of a UAV. The potential for spatial reuse is reduced, and problems due to hidden nodes increase. The results show that the UAV's impact on throughput and fairness depends on the traffic patterns, the topology, and the traffic load.**

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) will be a key component in future mobile communication infrastructures, both in civilian crisis scenarios and for military use cases (Fig. 1). The development of new efficient UAV platforms has picked up speed in the last decade, due to a large civilian market. At the same time, developments in other research areas add to a convergence towards a UAV as an efficient airborne communications node. Lighter radio equipment can be elevated by low-cost UAVs, and new techniques in the area of Artificial Intelligence (AI) point towards more intelligent control of the UAVs, limiting the overhead costs of employing a communications UAV.

UAVs will in many situations be beneficial in a terrestrial Mobile Ad-Hoc Network (MANET). A MANET is a self-organizing and self-maintaining network that typically employs one channel for communication. The radio channel has a fixed capacity given static modulation and channel conditions. Nodes that communicate in interference range of each other can therefore be considered to share the same channel, and thus the same pool of network resources. A UAV will provide improved connectivity, due to a larger Line-of-Sight (LoS) coverage, improved network stability due to fewer relay hops between any two terrestrial nodes, and thus could improve network throughput. However, whether the UAV contributes to improved network throughput is not given. There will be less possibility for spatial reuse, due to the much larger interference range of the UAV. In addition, the UAV will suffer from collisions due to the terrestrial hidden node effects. The terrestrial nodes will have much smaller sensing ranges, compared to that of the UAV.

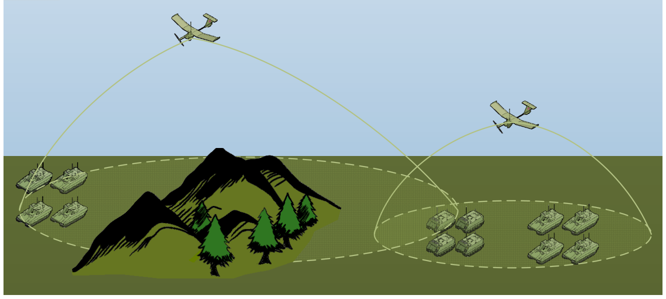

Fig. 1. Two UAVs providing connectivity (left) and improved coverage (right) for a terrestrial MANET.

In this paper, we show that depending on the scenario, employing a UAV as part of a MANET could either contribute to improved network resource use, or negatively affect the performance. We also show that higher fairness can be achieved by using a UAV compared to terrestrial forwarding, but there still is unfairness among nodes covered by a UAV. Through analysis and simulations, we develop arguments that we discuss with regards to scenarios where UAVs are useful, and how policing techniques need to be employed in order to ensure that using UAVs provides a positive effect in terrestrial MANETs.

The rest of the paper is structured as follows: First, related work is presented in Section II. Second, a discussion on factors affecting the network performance is presented in Section III. Third, simulations results showing the effects of traffic patterns on a deployed UAV are presented in Section IV. Finally, Section V concludes the paper.

II. RELATED WORK

There have been several works addressing the capacity of ad-hoc networks. Two main contributions are the works of Gupta and Kumar [1] and Li et al. [2], which show how the capacity of nodes in an ad-hoc network varies with the size of the network. However, these results are valid for networks where nodes have a homogeneous range, and must be adjusted when evaluating the impact of UAVs.

Multiple works on UAVs and MANETs motivate their own proposals with the hidden node problem, which is very pronounced in CSMA/CA networks with UAVs and terrestrial network nodes. For instance, Alshbatat and Dong in [3] propose an adaptive Medium Access Control (MAC) to suit a directional antenna system for UAV communication. Another approach is Jiang et al. in [4] who propose a collision-free

MAC, based on Time Division Multiple Access (TDMA). However, we found no works that show how the impact of deploying a UAV could affect the resulting MANET performance for the common ad-hoc network setup of omnidirectional antennas and Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) MAC.

Earlier work has shown that employing a UAV as part of a CSMA/CA MANET can bring unexpected consequences. Larsen et al. in [5] show that the deployment of a UAV may yield non-intuitive optimal positions.

Although the problems may seem similar, work in topology control have little overlap with the effects addressed in this paper. Topology control mainly addresses heterogeneous sender power to limit interference. However, cross-overs to ad-hoc networking have been attempted. For instance, Baek et al. in [6] propose an algorithm to adapt the Request-to-Send/Clear-to-Send (RTS/CTS) range to address the hidden node problem, the MAC performance and the fairness problem when introducing mechanisms from topology control into ad-hoc networking.

Li et al. show in [7] that high data rate communication is not always the preferred solution in a MANET. They find that the network carrying capacity is dependent on the number of hops between the source and the destination. When the hop count exceeds 4 to 6 at 11 Mbps link rate (IEEE 802.11b), it is beneficial to reduce the link rate, thereby lowering the hop count. A high link data rate results in reduced transmission range, which leads to more hops. Given equal link break probability per hop, a path holding more hops is more error-prone. Hence, there is a trade-off between the link throughput and the network connectivity. A high network connectivity requires selecting a lower link data rate, at the cost of a lower rate.

Heusse et al. in [8] study a single-cell network with links at different rates. They show that fairness in capturing the media for transmission penalizes the high link rate users, limiting the throughput of the high link rate users to the level of the lower rate.

III. THE EFFECTS OF UAVS ON TERRESTRIAL MANETS

A UAV can be employed in a MANET for several different purposes. In this paper, the main goal of the UAV is not to connect otherwise partitioned network segments, but rather to improve the communication efficiency in an already connected terrestrial CSMA/CA MANET with omnidirectional antennas. Some general network characteristics must be established in order to evaluate and analyze the effect of a UAV as part of a MANET:

- The MANET is not partitioned without the UAV. I.e., the investigated gain of adding a UAV is not connectivity, but rather the optimization of the communication.
- The MANET is a non-hierarchical network, where the nodes in the network participate with a single radio sharing the same frequency. There is no clustering, which would steer some of the traffic onto longer than optimal paths.
- The traffic is network-internal, with all terrestrial nodes both generating and receiving traffic. It is not within the scope of this paper to examine network-external traffic and gateway challenges.

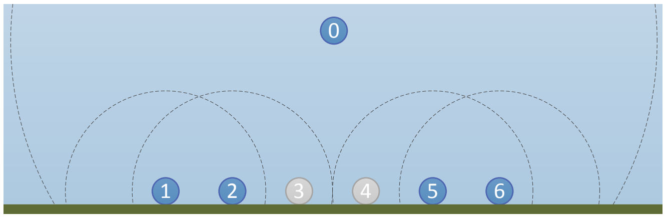

Fig. 2. Illustration of the interference ranges of the UAV (0) and the ground nodes (1,2 and 5,6).

With these network characteristics established, we now continue to address the effects of a UAV on a terrestrial MANET from two perspectives: *throughput* and *fairness*. We investigate the impact of a UAV on the MANET performance, first through an analytic approach, before we present simulations results that illustrate the analyzed effects.

A. *Throughput*

The combination of UAV and MANET can affect the resulting network throughput through several effects. A UAV can reduce the average path length in the network. Due to *self-interference*, the throughput in a MANET is dependent on the number of hops between the source and the destination. A UAV will reduce the hop count for long flows, increasing the efficiency of packet forwarding, allowing for improved network throughput. On the other hand, the potential for channel reuse, also called *spatial reuse* [9] is reduced when using a UAV. Spatial reuse occurs when one radio channel can be utilized simultaneously by multiple senders successfully. In practice, spatial reuse depends on the two transmissions not interfering with each other. The interference range for the UAV will be much larger than for the terrestrial nodes. A further consequence of this mismatch in interference range between the UAV and its terrestrial counterparts is a high likelihood of hidden node effects, since the terrestrial nodes are outside of each others' sensing range. The virtual channel sensing for IEEE 802.11, RTS/CTS, is able to improve the efficiency to some degree, but only for large packets.

1) Self-interference: A packet forwarding transmission is the basis for multi-hop communication, an important feature of MANETs. The forwarding transmission causes self-interference for the traffic flow, meaning that a forwarding transmission will compete with the previous node's transmission of new packets and expend of the common channel resources. As the packet is forwarded towards the destination, each new forwarding node's transmission will interfere *at least* with the previous node (Fig. 2). As observed by Li et al. [2], the capacity for a flow in a chain topology is $\frac{1}{4}$ of the link capacity, given that the input data rate is controlled and the traffic path distance surpasses 3. With a data rate increasing beyond the maximum achievable, the capacity is shown to fall to $\frac{1}{7}$, due to the sub-optimal multi-hop characteristics of IEEE 802.11. Li et al. further show that in a grid topology the capacity ($\frac{1}{12}$) is even lower than in a chain topology, due to the reduced possibility for spatial reuse.

2) Spatial reuse: Spatial reuse occurs when two nodes can transmit data simultaneously on the same frequency due to the nodes being outside interference range of each other. The capacity of a MANET node in one cell is $\frac{1}{n}$, where n is the number of nodes in the cell. As the area increases, the network expands beyond interference range, and Gupta and Kumar in [1] define the upper bound of the per node throughput of a MANET as $\Theta\left(\frac{W}{\sqrt{n}}\right)$, where W is the transmission capability per node in bits per second and n is the number of nodes in the network.

As discussed in [2], the traffic pattern has a great impact on the performance of the network. Local traffic limits the expended resources, as the number of transmissions per packet is low, reducing the number of interfering transmissions. The local traffic also enables spatial reuse, since multiple forwarded flows can be transmitted independently and simultaneously, given that the traffic flows forwarding occurs outside of each other's interference range.

A ground node's interference range will be low, compared with that of a UAV. In a network without the UAV, the spatial reuse will benefit the network, and make it scale with an increasing network diameter. In our scenario, the UAV will hear all transmitting nodes, and will be unable to transmit at the same time as any other node in the network. This leaves no possibility for spatial reuse, so the capacity for the UAV will be $\frac{1}{n}$, which does not scale. Thus, if most traffic is local, introducing a UAV will not improve the communication performance.

B. Fairness

Network fairness is an unresolved problem in mobile wireless networks, and the concept can span several different definitions of fairness, from node channel access to user level experience. In this paper, we consider fairness to be the equal performance of traffic from any node, regardless of the distance to the destination. We compare fairness when traffic is forwarded terrestrially and via a UAV. Clearly, as long the total traffic load is below congestion, each node will fairly get similar access to the wireless channel and the traffic will be forwarded to the destination without queue loss skewing the results according to the distance between the source and the destination. However, when the traffic increases, the channel access probability will typically be skewed by a number of reasons, such as the node's location in the network.

A node's position in the network is also critical in terms of fairness. A node located on the network edge will typically have fewer competing terrestrial nodes, but at the same time, it will be more exposed to the hidden node problem when using the UAV. A node that experiences the hidden or exposed node problem is less likely to get access to the wireless medium due to a larger share of its time in backoff. In case of a UAV used as a relay for a convoy of ground vehicles, the relative position of the vehicle will impact the probability to get access to send data. A vehicle positioned in the center of a convoy with a UAV directly above will have a higher likelihood of channel access than vehicles located on the edge of the convoy. The reasons are sensing and the hidden node problem. The vehicle in the center will sense more vehicles, and thus will have an improved likelihood of a successful transmission up to the UAV. Clearly, the fairness is better if the UAV is the source, due to superior sensing. I.e., the UAV hears all the vehicles. On the other hand, the fairness is skewed for the terrestrial nodes. Fig. 2 shows that the nodes on the network edge are more prone to the hidden node problem, as they can not sense each others' transmissions.

As we will see, the fairness is mainly affected by the network traffic load, the topology and thus the path length, and also the positions of the senders.

TABLE I
DEFAULT SIMULATION PARAMETER SETTINGS

Parameter	**Setting**
Communication frequency	2.4 GHz
Ground nodes antenna altitude	2 m
Ground nodes separation	1200 m
Propagation model	Two-ray-ground
UAV antenna altitude	600 m
Control rate	1 Mbps
Data rate	1 Mbps
MAC protocol	IEEE 802.11b
RTS/CTS	Always enabled
Data packet size	1500 bytes
Traffic start	50 s
Measurement start	60 s
Confidence interval	95%
Simulation time per run	360 s
Number of runs per data point	10

IV. SIMULATIONS

The analysis in Section III emphasizes two different mechanisms that contribute to the effects that a UAV has on the network throughput: self-interference and spatial reuse. Further, the fairness analysis describes the sender sensing range as an important factor for achieving node fairness, along with achieving a more equal path length for all traffic flows. To evaluate and illustrate these effects, we have performed simulations using a terrestrial chain topology and a centered UAV. With this topology, we can observe self-interference, spatial reuse, and the reduced hop-count using a UAV. Several different traffic patterns were selected to emphasize the studied effects.

A. Simulation setup

The simulations were performed using ns-3.26 [10]. The simulations have been run using the default settings of ns-3 if nothing else is specified. Simulation parameters are also listed in Table I. The topology is shown in Fig. 3. All traffic flows were set up with the source to the left and the destination(s) to the right. Static routing was used to direct the traffic along

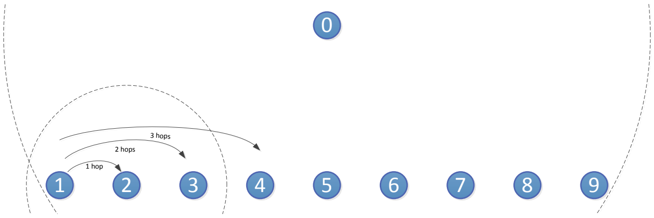

Fig. 3. Simulated topology with UAV (0) and the ground nodes (1-9). Communication ranges for UAV and node 2 shown.

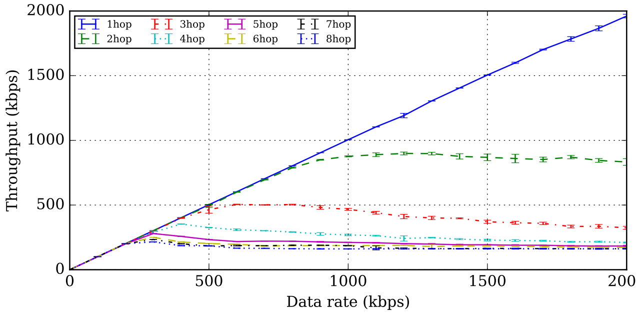

Fig. 4. The throughput performance for terrestrial forwarded traffic (no traffic forwarded via the UAV), where there is a strong correlation between traffic path length and the resulting performance.

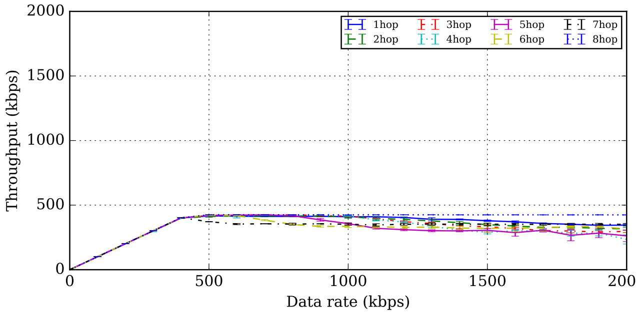

Fig. 5. The throughput performance for UAV-forwarded traffic. Regardless of the terrestrial distance, all traffic is forwarded over the UAV, and have the same 2-hop performance without spatial reuse.

the ground or over the UAV. The results are evaluated with respect to the achieved network throughput and fairness.

The evaluation is based on two distinct traffic flow setups. In the first setup, each simulation is run with only one traffic flow, testing the achieved throughput for varying length from one to eight hops. In the one-hop traffic case, node 1 transmits traffic destined to node 2, node 2 transmits traffic destined to node 3, etc. Node 9 does not transmit anything, since it has no right-hand neighbor. In the two-hop traffic case, node 1 transmits traffic destined to node 3, node 2 transmits traffic destined to node 4, etc. Node 8 and 9 do not transmit anything, since they have no right-hand two-hop neighbors. Thus, for each increase in traffic hops, the number of senders is reduced with one, from the right. For the results figures, the X-axis 'Data rate' is the total offered network load. Each flow data rate is the total network load divided by the number of nodes generating traffic.

In the second setup, all traffic flows are simulated simultaneously. We have run two different flow patterns in this setup: one-sender and multi-sender. In the one-sender pattern, the sender node is node 1. It transmits one flow to each of the other ground nodes. The flows are named according to the path length along the ground, i.e., *1-hop* for the flow between nodes 1 and 2, *2-hop* for the flow between 1 and 3, and so forth. In the multi-sender pattern, all ground nodes generate traffic destined to node 9. Here, the one-hop flow is the flow from node 8 to node 9, while the flow from node 1 to node 9 is the *8-hop* flow.

B. Throughput - flow length performance

The throughput results for terrestrial forwarding for 1-8 hops traffic (Fig. 4) show that the throughput decreases as the required number of hops increases. The effect is caused both by self-interference within one flow and interference between flows, in addition to the reduced potential for spatial reuse. The results clearly show the effect of spatial reuse for the *1-hop* traffic. As shown in [11], the Theoretical Maximum Throughput (TMT) with 1 Mbps data rate, 1500 bytes packets and RTS/CTS is around 850 kbps. For the *2-hop* traffic, the throughput levels out at around 900 kbps. Since all traffic is relayed, requiring two transmissions for every packet, this represents a full channel spatial reuse as the spent capacity is 1800 kbps. As the hop count increases, the number of senders in our topology decreases. Thus, while the increased number of forwarding transmissions continues to be the main factor for limited throughput, the effect of spatial reuse is reduced with the increasing hop count.

Employing a UAV for all forwarding of the 1-8 hops traffic (Fig. 5) shows that as anticipated, there is no channel reuse when using a UAV. One channel is shared among all nodes, and hence they all achieve similar throughput. The traffic flows are identical to Fig. 4, but as they are forwarded over the UAV, all flows have the same path length.

C. Throughput - accumulated flows performance

The previous subsection looked at the performance for flows of different lengths. In this subsection, we look at the accumulated performance of simultaneously transmitted flows with lengths varying from one to eight hops, to study the achieved network throughput with a more complex traffic pattern.

The accumulated results for multiple flows (Fig. 6) show that the best performance is achieved using the UAV to forward traffic (*air_one* and *air_multi*). However, as the data rate increases beyond congestion for some flows, the results for ground forwarded traffic generated by multiple senders (gnd_multi) push past the UAV results. The reason is that the data rate is equally divided among the flows. Thus, only when the loads for the 1-hop and 2-hop traffic flows are high enough do the results for the ground traffic with multiple senders

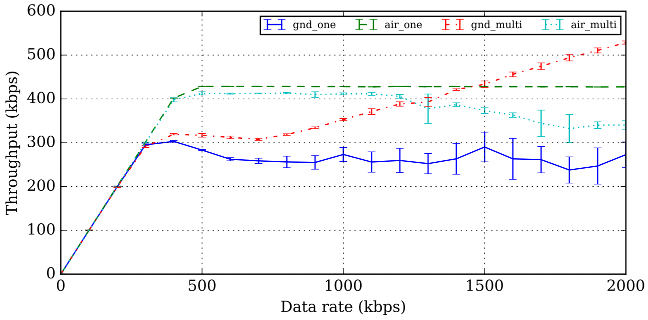

Fig. 6. Accumulated results for traffic forwarded either terrestrially (gnd) or via UAV (air), from a single (one) and multiple (multi) senders, showing better performance until congestion for the UAV-forwarded traffic.

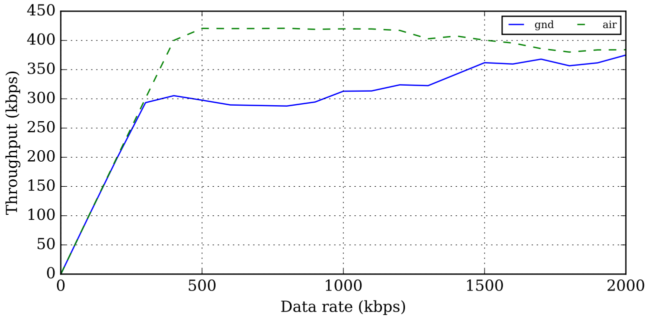

Fig. 7. Average single and multiple sender results for UAV and terrestrial-forwarded traffic, emphasizing further the benefit of the UAV-forwarding in our 9 terrestrial nodes scenario.

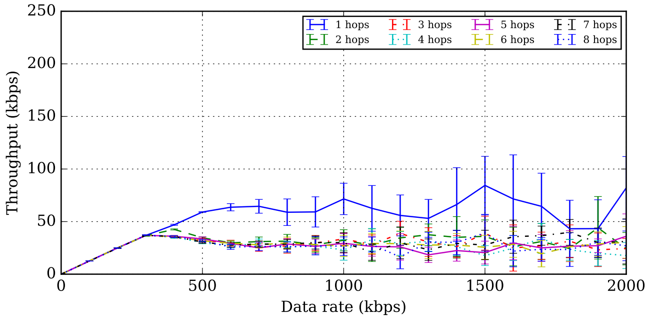

Fig. 8. Throughput for terrestrial-forwarded flows from one sender, showing unfair advantage for the 1-hop traffic.

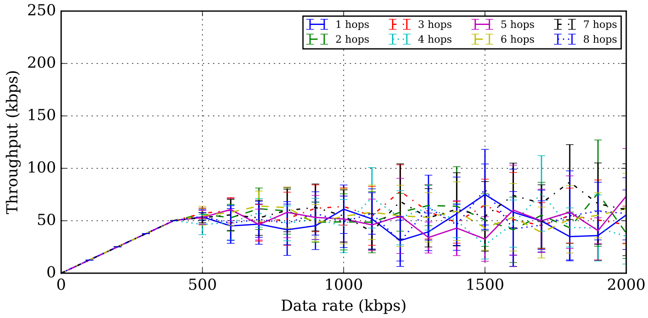

Fig. 9. Throughput for UAV-forwarded flows from one sender, showing equal performance for flows of all lengths.

push beyond the UAV relay results. Do note, however, that the packet loss rate is very high at this point. Notice also that the ground results for a single sender (*gnd_one*) are devoid of the increase that is prominent for the multi-sender results. With only one sender, i.e., one transmission queue, the longer path flows limit the performance of the shorter path flows, due to the shared transmission queue.

To examine the difference between the terrestrial and UAV forwarded traffic scenarios closer, we have averaged the results for one and multiple senders for each of the two scenarios. The Fig. 7 shows the results averaged for one and multiple senders from Fig. 6. Here, it is clear that the UAV is able to ensure a higher performance as the load increases until the packet loss rate is close to 80%.

D. *Fairness*

1) One sender: In this test, we evaluate fairness among destinations when only one sender sends concurrent traffic to multiple destinations at different distances. We have used the same traffic patterns as in Section IV-C.

Fig. 8 and Fig. 9 show the difference in achieved throughput for terrestrial and UAV-based forwarding. For terrestrial forwarding, the *1-hop* flow obtains a higher throughput than the more distant flows. Flows with a destination distance of more than two hops all receive similar throughput and see a decrease when the data rate exceeds 300 kbps. This is caused by interference and self-interference. The achieved throughput levels out due to a congested channel at the source and spatial reuse without concurrent flows. When all traffic is sent over one UAV, there is only one relay and thus similar conditions for all flows. In our test, all traffic flows were sent over the UAV, although in real deployments, 1-hop traffic would preferably being sent directly, at the cost of fairness.

2) Multiple senders: Fig. 10 and Fig. 11 show the difference in achieved throughput when multiple senders send traffic to one destination, following the setup from Section IV-C.

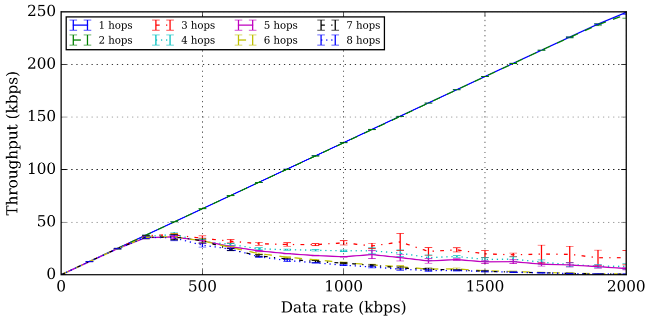

Fig. 10. Throughput for terrestrial-forwarded flows to one receiver. Both 1-hop and 2-hop flows receive unfair advantage compared to the other flows.

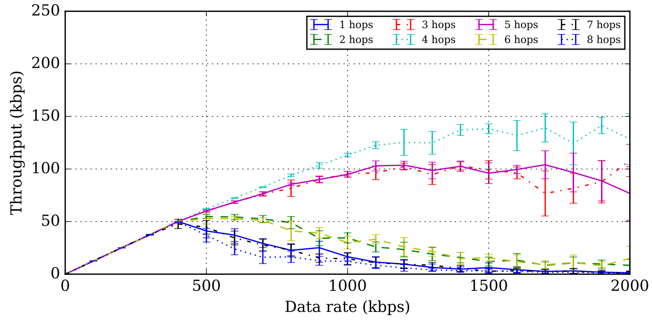

Fig. 11. Throughput for UAV-forwarded flows to one receiver. Evident unfair advantage to the sender nodes closer to the UAV.

Similarly to the test with one source, the test with multiple sources sending to one receiver is dominated by short distance flows for the terrestrial forwarding. In our example, the 1-hop flow achieves the highest throughput, and the fairness compared with the more distant flows is very low.

In the previous tests (one sender), the more distant flows leveled out after the offered data rate exceeded 600 kbps. When multiple senders are sending to one destination, the more distant flows steadily decrease their achieved throughput after reaching congestion at approximately 300 kbps. The reason is that, as documented in [2], the 802.11 MAC is not able to maintain optimal rate under congestion in a multi-hop environment.

Fig. 11 clearly shows that nodes achieve different throughput based on their ground position. There are three main levels of throughput. The highest throughput is achieved for the node centered below the UAV, while the throughput decreases with the ground distance to the UAV. Nodes located at the edge of the network are not able to sense ongoing transmissions at the other edge up to the UAV, and hence they are all exposed to the hidden node problem. The problem is much less pronounced for the nodes closer to the ground center of the UAV.

V. CONCLUSIONS AND FUTURE WORK

In this paper, the effect of a UAV on a terrestrial MANET has been analyzed. Based on capacity measurements from [2], an analysis of the effect of a UAV on the network throughput has been performed. Several impact factors that affect the outcome have been identified in the analysis. These have also been supported by the presented ns-3 simulations results.

The performance comparison for terrestrial-only communication and communication over a UAV shows different advantages and disadvantages. A UAV has larger ground coverage, thus it is able to connect more nodes via the UAV. Due to a reduced number of hops required to connect any two nodes, fewer transmissions are required, at the cost of more nodes competing for the same channel. Hence, the benefit of a large UAV channel results in an increased hidden node problem.

As a consequence of the increased hidden node problem, employing a UAV also introduces unfairness for the terrestrial nodes, depending on their ground location. Nodes positioned at the edge of the network will have less likelihood of accessing the UAV, due to the hidden node problem and achieve less throughput, compared to more central ground nodes.

Future work based on the results presented in this paper includes developing control mechanisms to select whether to utilize a UAV for forwarding, given the known state of the network, with regards to the topology, traffic patterns, and the required fairness. Other aspects more fundamental to the challenges of hidden node and interference should be addressed through work on physical layer and MAC layer solutions, such as MIMO, smart antennas (e.g., phased arrays), and adaptive transmission power.

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