Flying Relays for 4G Service-on-Demand Applications

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***Abstract*— Network providers around the world have deployed 4G LTE technology in most of the major cities, providing the consumers with 4G services. However, a lot of remote areas still suffer from coverage holes and lack high speed connectivity that is crucial in emerging traffic hotspots e.g. emergency situations or mobile crowds. This paper discusses the use of small unmanned aerial vehicles that act as wireless flying relays, in order to offer 4G services on demand and assist the network performance. The presented analysis shows that for line of sight scenarios, an aerial vehicle with antenna gain no more than ~18dB can support 10Mbps, for a user as far as 100Km. It is also demonstrated how the directional elevation antenna pattern of a typical 4G base station affects the link performance when the unmanned aerial vehicle flies close to the base station.**

***Index Terms*—UAV, LTE, 4G, Flying Relays**

I. Introduction

Most of the mobile operators have already deployed 4G networks in urban areas, promising extreme fast and reliable connectivity and new services. Not only individual consumers can experience high download and upload speeds, but other parts of the society, like health organizations (e.g. hospitals, clinics etc.), businesses (e.g. content broadcasters) and academia can benefit from this new emerging technology.

But what about the people living away from the major cities? Mobile network providers seem to hesitate expanding their 4G networks to rural areas, providing mostly GSM/2G coverage to the majority of the remote places. Even though, there are still blind spots where the user cannot establish even a low rate voice call. The complexity but mainly the cost of covering such huge and remote areas, have been discouraging the big network providers to implement high speed connectivity.

One can argue that there is no great need of offering 4G services in rural areas, as the population is low compared to the big cities, but apart from being unfair, there are often emergency situations (e.g. network failure from natural disasters, big events, health issues, etc.) that a high speed connectivity is demanded. So, how can these areas be served even in a temporary basis and with affordable cost?

Unmanned aerial vehicles (UAVs) [1] have recently received great attention because they could be the answer to these problems. UAVs loaded with telecommunications equipment could fly close to the area of interest and acting as flying relays, could offer network coverage for as long as it needed. Due to the relative small size of the aircrafts, several issues need to be taken into account. Moreover, since this deployment applies mostly to emergency situations, it is expected that the uplink will be the limiting factor.

The following sections describe the system architecture (section II), the scenario and the simulation setup that was used for the analysis (section III), along with the corresponding results (section IV). Finally, the paper concludes in section V.

II. System Architecture

A. Scenario

Let's assume the following realistic scenario: An accident has happened at a distant underserved area and the local clinic or the emergency rescue staff needs a high speed connection, in order to pass telemedicine services (e.g. real time diagnostic sound and video and other data exchange). The emergency unit makes a request through the existing GSM system for a temporary 4G coverage and a UAV takes off and flies to the emergency site. The unmanned aircraft follows a pre-designed procedure to find the optimized position, establishing a connection between the emergency unit and the appropriate 4G Base Station (BS) (Fig. 1).

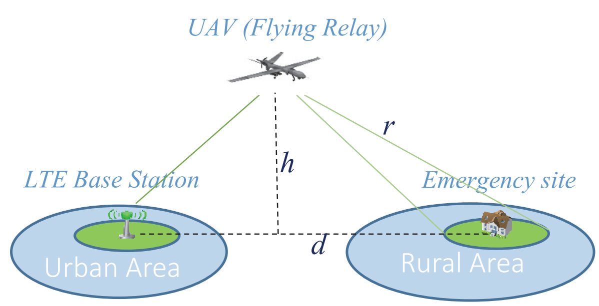

Fig. 1. Flying Relay concept

B. Why UAV?

The primary goal of this system is to provide immediate communication in every area that temporary 4G coverage is required.

For a ground relay station to be set, fixed or mobile, a number of certain requirements must be applied. The terrain must be flat and clear (in order for the tower to be deployed) and roads must be available, in order the technicians to approach the installation area. Furthermore, a network planning study is needed, prior to the tower installation, in order to find the appropriate position of the relay, for achieving high speed connectivity between both paths (i.e. emergency unit-relay and relay-BS). Even if the right position is already known and the installation unit approaches it in time, the height of the tower will be limited, resulting to severe losses, if no Line of Sight (LoS) exists (Fig. 2).

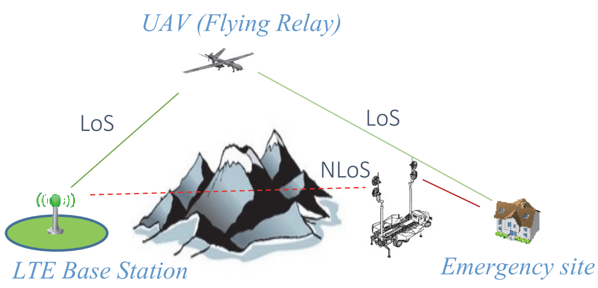

Fig. 2. UAVs can ensure LoS.

UAVs can overcome these limiting factors. A UAV can fly directly to the emergency site (even above the sea), as no road infrastructure is needed, in much shorter time than a ground unit would need. It can move fast into a wide area, searching for the best position in order to establish the connection. And as soon as it gets there, it can start relaying traffic immediately, without any need of equipment installation. Also, it can fly as high as necessary, in order to achieve a LoS connection with the BS and the emergency unit (Fig. 2).

In the case that one UAV cannot establish the required connection, due to the landscape and the distance between the user and the possible BS, multi-hop UAVs could be used to relay the data to the BS. The UAVs could communicate between them and dynamically change their position, for optimizing the transmission link. The SMAVNET I and II project [2] deploys a flying ad-hoc network (FANET) [3] composed of small UAVs, in order to pass data from one side to the other. The swarm of flying robots is autonomous, self-organizing and easily and fast deployed.

The UAV could also have the capability of using alternative backhaul options. Satellite links and other technologies like High Altitude Platform Systems (HAPS) [4], could be a choice for the backup backhaul connection.

Regarding the access link (i.e. user-UAV), a multi-UAV deployment could be a solution for special service needs and terrains (e.g. coverage in canyons etc.). A main unmanned aircraft could fly at a high altitude establishing the backhaul connection and a swarm of small UAVs could be released for accessing the user.

C. System requirements and restrictions

UAV Payload: These flying machines are relatively small in size (e.g. 1-2 meters), so the weight they can lift is limited. As a result, there is a restriction on the weight and the volume of the onboard radio equipment.

Available Power: UAVs usually employ Lithium-Polymer (Lipo) batteries to provide the motors and the rest of the UAV systems with the required power. So, the transmitting power heavily depends on the characteristics of the batteries.

UAV Endurance: The time that a UAV can stay in the air is limited and it depends on many factors, like the battery type, payload, electric consumption, wind, altitude and type of the UAV (e.g. multirotor, fixed-wing etc.). More than one or larger UAVs might be needed for longer coverage time.

UAV range: Complementary to the limited UAV endurance is also the limited operational range. A typical speed for a small UAV is 12m/sec, hence for a remote destination several kilometers away battery consumption needs to be considered.

Other considerations: Except from the above restrictions, there is a number of other issues that must be considered, like public safety (e.g. a UAV falls or is hacked), interference, and flight regulations.

III. SIMULATION SETUP AND APPROACH

A. The scope

Since every user, in every remote area, might ask for a temporary 4G coverage, it is obvious that the only part of the system that is adjustable is the UAV radio equipment, as the user and the BS locations are not known a priori. The UAV must transparently [6] receive and forward the user's data to the base station and vice versa. It should be able to "hear" the remote user's transmission and to reach the BS. As a consequence, one of the radio components that is of a great importance is its antenna. Since high gain antennas (especially adaptive beamforming antenna arrays) are heavy and bulky in the 4G frequency band, compared to the UAV size, there is a trade-off between the efficiency of the antenna and the endurance of the UAV. The aim of the simulations presented in the following section is calculate the required UAV antenna gain, for the access and backhaul links (i.e. user-UAV and UAV-BS) in relation to the UAV position.

B. SINR requirement

In the context of this work, rate calculations are based on LTE [6] system. All system Resource Blocks (RBs), are available to the remote user of our scenario. Following the reverse process described in [7] and the calculations of LTE overhead for uplink [8] we associate the user's requested rate, i.e. Transport Block size, to the CQI value, i.e. modulation and code rate. Finally, we use the work in [9] to map this CQI to a minimum SINR requirement.

C. User to UAV link

The user antenna radiation pattern is assumed to be close to isotropic and the path loss depends only on the distance r between the user and the UAV, which depends on the UAV altitude h and the distance d between the user and the UAV altitude trace (Fig. 1). It is also assumed that the UAV can steer its main lobe towards the user and/or the BS.

D. *UAV to Base Station link*

The BS antenna is a Kathrein 742215 [10], a commonly deployed antenna, with a highly directional radiation pattern [Fig. 3]. Simulating a realistic scenario, a total of 10 degrees electrical and mechanical tilt (i.e. 5 degrees electrical and 5 degrees mechanical tilt) is considered. It is clear that every change to the direction, especially in the elevation plane (where the antenna is highly directional), has a significant impact to the system. For this reason, both the azimuth and the elevation planes are taken into account.

E. *Simulation Parameters*

The UAV antenna gain calculation is done with the help to a link budget for both links (user-UAV and UAV-BS). The following setup is considered:

- **Path loss model:** The UAV flies high enough to avoid any obstacle and to ensure Line of Sight (LOS) both with the user and the BS. Thus free space path loss is considered.
- **User EIRP:** Since any user might ask for a temporary 4G service, it is assumed that every handset supports LTE with a 0dB gain antenna and 23dBm transmit power.
- **User frequency:** Since the user operates an LTE capable handset and asks for a 4G service, a frequency of 2 GHz is considered.
- **Service:** According to the scenario, the user needs to send a real time high quality diagnostic video, so it is assumed that at least a bit rate of 10Mbps is demanded [11].
- **UAV transmit power:** The UAV is a small aerial vehicle, so a transmit power equal to a mobile handset transmit power is considered (i.e. 23 dBm).
- **UAV altitude (h):** It is considered that the UAV flies above 100 meters, in order to avoid any low obstacles (e.g. trees, buildings, electricity wires, etc.) and up to 4 Km. So, the simulation runs for a UAV altitude range of 0.1 Km to 4 Km.

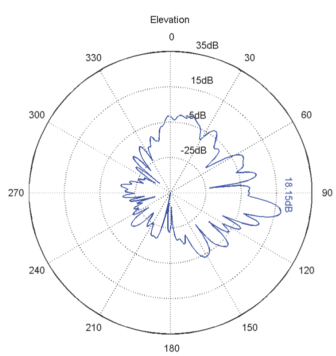

Fig. 3. The BS antenna pattern in the elevation plane, as derived by the Kathrein 742215 information sheet [10].

IV. Simulation Results

A. *UAV antenna gain requirements*

Let's consider a hypothetical scenario of a remote user at 100Km distance from the nearest BS, who requires a 4G service with 10Mbps uplink throughput. Our goal is to estimate the required UAV antenna gain toward both the user and the BS, when the UAV covers the entire distance between the BS and the user.

This step is necessary, in order to explore how the UAV antenna gain requirement depends on the UAV flight altitude and on the azimuthal distance between the UAV and the transmitter, i.e. the user.

1) *User to UAV link*

Calculating the link budget for the user-to-UAV link, the required UAV antenna gain toward the user is derived in (1)

$$G_{UAV}^{user} = \frac{\text{SINR} \cdot P_N}{P_{tx}^{user} \cdot G_{tx}^{user} \cdot G_{ch}}, \quad (1)$$

where SINR is calculated according to the procedure of section III.B., P_N is the noise power at the UAV, P_{tx}^{user} and G_{tx}^{user} is the user's transmit power and antenna gain respectively, while G_{ch} is the channel gain between the UAV and the user.

Fig. 4 depicts the UAV antenna gain, for five different flight altitudes, as the UAV flies away from the user. For instance, when the UAV is just above the user (the distance *d* from the user equals zero), the UAV antenna gain is negative for all the simulated altitudes, but as the UAV travels toward the BS, the antenna gain requirement increases.

Specifically, when the UAV flies above or close to the user (for distance *d* up to 10 Km), the required UAV gain ranges from -15 to 5 dB, depending on the altitude *h* and on the distance *d*. For distances more than 10Km, the required gain climbs up to 25 dB, depending mainly on the distance *d* and not on the UAV altitude. This is geometrically justified since when the UAV flies away from the user, the distance *r* approximates *d*, as the altitude *h* is very small relatively to the distance *d* (Fig. 1).

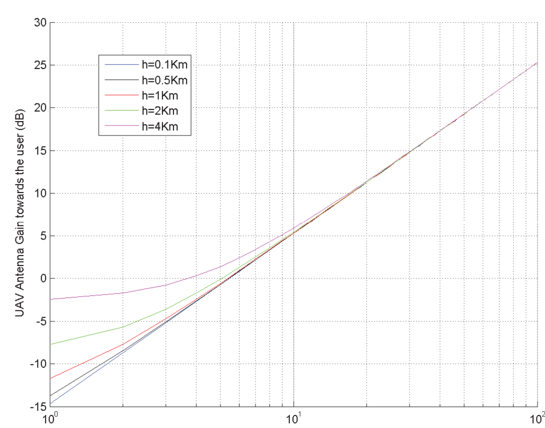

Fig. 4. UAV antenna again for different altitudes – user to UAV link

2) UAV to Base Station link

The UAV antenna gain toward the BS is derived in (2).

$$G_{UAV}^{BS} = \frac{\text{SINR} \cdot P_N}{P_{tx}^{UAV} \cdot G_{rx}^{BS} \cdot G_{ch}} \quad (2)$$

Fig. 5 shows the G_{UAV}^{BS} as the UAV moves in the X, Y axes, in an area of 100X100 Km. The BS is located at the axes origin (0,0) and the color map represents the different required gains of the UAV antenna.

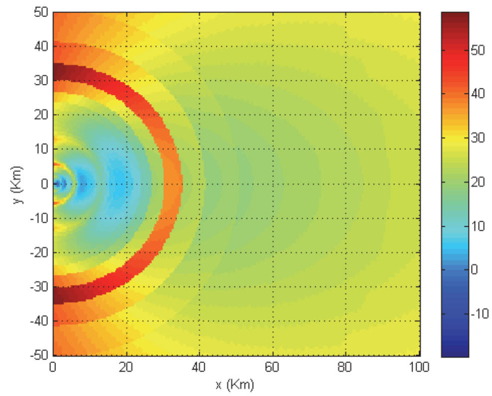

Fig. 5. UAV antenna gain for an altitude *h* of 4 Km – UAV to BS link

When the UAV flies away from the BS - more than 40 Km for an altitude of 4 Km (Fig. 5) – the required antenna gain changes smoothly up to almost 30dB. However, close to the base station, the required antenna gain changes rapidly, as "high gain" zones are present. When the UAV moves outside of these zones and in a good proximity to the BS (up to 27Km and close to the x-axis), the required gain ranges from -10dB to 10dB. But as soon as it enters a "high gain" zone, the gain requirement climbs to very high values, even at 50dB.

The high gain zones are a result of the BS highly directional radiation pattern, in the elevation plane (see Fig. 3). As the UAV moves toward the BS the angle that it "sees" the BS changes, moving out of the BS main lobe and falling into a null or a side lobe. The more the UAV altitude, the worse the fluctuations.

Fig. 4 shows that for an altitude of 4Km several "high gain" zones are present, with the larger expanding at a radius of 30 Km with almost 6 Km width. This means that the UAV needs to cover a distance up to 6 Km in order to avoid these zones. It is evident from this analysis that the UAV position greatly affects the antenna gain requirement, and hence, it is studied in greater detail in the following section.

B. UAV Antenna Gain Optimization

Fig. 3 and 4 show that when the UAV flies close to the user or the BS, its antenna gain requirement is relatively low, depending on its position. However, since the UAV must support the requested service on both parts of the uplink, at the same time, the gain requirement of both links must be considered. The UAV, at every possible position, must utilize a certain antenna gain for each link i.e. one toward the BS (G_{UAV}^{BS}) and one toward the user (G_{UAV}^{user}), as calculated in section IV. The UAV antenna must be able to support the maximum of (G_{UAV}^{BS}) and (G_{UAV}^{user}) at every location. So, in order the UAV antenna gain to be optimized, the optimum UAV position must be derived, where the maximum of all the G_{UAV}^{BS} and G_{UAV}^{user} pairs is minimized according to (3).

$$G_{UAV}^{\min}(h) = \min_{d_{BS}\in\{0,..,100\}}\max\{G_{UAV}^{BS}(h,d_{BS}), G_{UAV}^{user}(h,d_{BS})\}, \forall h \in \{0,..,4\} \quad (3)$$

In (3) h is the UAV flight altitude, and d_{BS} is the azimuthal distance between the UAV and the BS, ranging from 0 to 100Km, in the context of the scenario. Fig. 6 shows the optimized required UAV antenna gains as calculated with (3), for altitudes as high as 4Km.

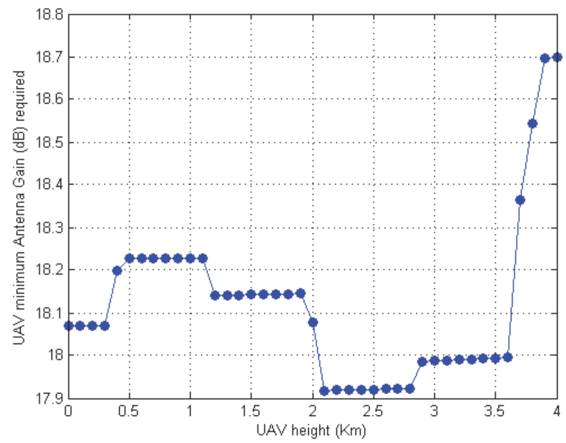

Fig. 6. Minimum UAV antenna gain values as a function of the altitude

The minimum gain requirement is 17.9dB and occurs at an altitude of 2.1 Km. However, due to the landscape and other factors (e.g. weather conditions, flight regulations etc.), the UAV might not be able to fly at this altitude, so it must move to the next better choice of Fig. 6.

As the UAV is ascending or descending, it falls into the nulls or the side lobes of the BS, so the minimum gain for each altitude occurs at a different azimuth position. According to the simulation, all the minimum gain values of Fig. 6 are achieved, when the UAV flies at a distance of 35-46 Km away from the BS. The best value of 17.9dB is achieved when the UAV is located at 46 Km and 54 Km away from the user and the BS, respectively.

In spite of the fact that a specific scenario, with specific parameters was considered, the geometry of the system doesn't change, when the service requirements change. For Fig. 7 the UAV is placed at 2.1Km altitude and at 46Km from the BS. The goal is to calculate the required minimum antenna gain $\max\{G_{UAV}^{BS}, G_{UAV}^{user}\}$ of the UAV in order to support different services. For instance, when the user requests 15Mbps and 5MHz are available by the system, the UAV needs 27dB antenna gain. If higher bandwidth is available, i.e. more RBs, the same rate can be supported with lower SINR leading to reduced UAV antenna gains (e.g. 17dB for 20MHz). With a 35dB antenna gain the UAV can take advantage of the peak uplink throughput that LTE can offer.

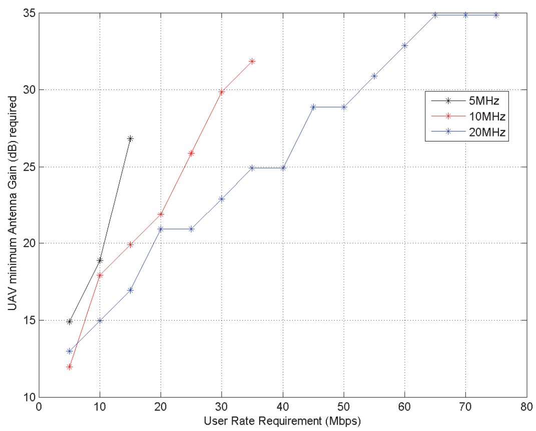

Fig. 7. Minimum UAV antenna gain values for different bit rates and available bandwidths

V. Conclusions

The scenario of a UAV acting as a relay station between a BS and a distant user requesting 4G service is discussed in this paper.

The presented analysis shows that when the UAV flies in the simulated area and out of the high gain zones, it can support 10Mbps in the uplink, with less than 30dB antenna gain. Optimizing the UAV position, the minimum antenna gain requirement of ~18dB is achieved at 2.1 Km altitude and 46 Km distance from the BS. However, since the UAV might not be able always to fly to this position, alternative locations with different gain requirements can be chosen.

Additionally, when the UAV hovers at the optimized position, the UAV utilizing a 35dB antenna gain can fully exploit the LTE rate capabilities, offering up to 75 Mbps in the uplink, even for users that are located 100 Km away from the BS (when 20MHz are available).

It is also noted that flying closer to the user, the required antenna gain changes slowly and smoothly (Fig. 5). Hence, the UAV has the option of optimizing its location, without been affected by the severe gain fluctuations of to the BS antenna.

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