Wireless Powering of Drone-Based MANETs for Disaster Zones

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***Abstract*—Since in emergency zones the communication network has to be rapidly established, the usage of autonomous drones, forming an ad-hoc network, is an interesting alternative. By using the mentioned drones, the main technical challenge to face is the difficulty of powering the drones for a long service time, having in mind that they are not wired to any infrastructure and the batteries are not designed for lasting the required period of time. To prolong the operating lifetime of such networks, we hence propose and investigate a new simultaneous wireless information and power transmission (SWIPT) scheme. We first study the optimal distribution of the harvested energy, that can be shared between data communication, drone movement, and battery charging. Then we optimize the positioning of the drones such that a line-of-sight situation is achieved as well as a minimum required signal-to-noise ratio is ensured at the receivers. Afterwards, the lobes of both transmitter and receiver antennas are optimally aligned to maximize the harvested energy. Finally, the proposed drone-based network is simulated by using realistic parameters to show its adequate performance in practice.**

***Index Terms*—autonomous drones, ad-hoc network, network optimization, wireless power transfer**

I. Introduction

Natural disasters, such as earthquake, flood, tornado, avalanche and forest fire, yearly impact the life of many people. Since everyday, we rely more in technology for our daily life, notwithstanding that the impact of these natural phenomena in the infrastructures is catastrophic. The critical infrastructures of our modern societies might overcome the damage created by the natural disaster, however, many of the communication infrastructures will be damaged, their functionality decreased, and in some cases completely destroyed. However, the emergency services must have a reliable communication network at the incident scene to rescue the endangered citizens, and at the same time, to coordinate their tasks.

In order to create this reliable infrastructure, different architectures have been proposed by the community. Among the proposed architectures, some communication schemes are based on movable road vehicles. In many cases, they are not adequate solutions due to the environment [1]. Other designs depend on satellite communications, that usually have high delays [2], making them infeasible for emergency communications. Furthermore, the research community has paid attention to Wireless Mesh Networks (WMN) [3] to provide a reliable network for disaster zones. The WMNs are multi-hop networks with a fixed backbone and stationary wireless Mesh Routers (MR), that provide high bandwidths. However, the usage of stationary nodes makes the deployment of WMNs relatively slow, which is a major drawback in emergency situations.

In our opinion, the proposed networks in the literature are not sufficiently fast deployed and do not have the capacity for adaptation in emergency situations [4]. Hence, in our proposed model, we opt to use drone-based Mobile Ad-Hoc Networks (MANET) to rapidly deploy a reliable system. Since recently a solar-energy propelled plane has been able to cross the entire globe [5] and with this achievement the gate for autonomous aviation by green energy is opened, the idea of supporting the aviation by Wireless Power Transfer (WPT) is near at hand. Thus, we aim at the usage of wireless powered drones for creating a reliable network at disaster zones. Although, a WPT by microwaves or lasers is relatively efficient over mid-range distances, it is sensitive due to its requirement of having a direct Line-of-Sight (LoS) connection between transmitter and receiver. However, the usage of self-propelled flying drones solves the problematic of obtaining a LoS situation between the transmitter and receiver, since an optimal positioning can be achieved, due to their mobility. In order to power the drones, a new Simultaneous Wireless Information and Power Transmission (SWIPT) scheme is developed in this paper. SWIPT has been studied for long by both academia and industry [6]–[8], but until now the efficiency of harvesting units has not been sufficient enough to power small devices for a long period of time [9]–[11]. This made it infeasible to develop a network based on this technology. By our approach, the drones can use the harvested energy for floating and holding their optimal position as well as for performing the data communication. Hence, it becomes feasible to build up a communication network based on drones which can have a long service lifetime.

Our work is organized as follows. We first describe the system model. Then the SWIPT cooperative scheme is introduced and the harvested energy is distributed optimally for different tasks. Afterwards the 3D-positioning of the drones is discussed and optimized. Finally, some simulation results are presented along with the conclusion.

II. System Model

In our proposed system model, we replace the malfunctioning communication equipments, e.g., base stations or data relays, by autonomous drones. These drones might have the capability of being configured as a communication node or relay. So they can be positioned in a three dimensional space to substitute the damaged communication equipments. The main advantage of a drone-based network is its ability to be self-configurable, provided by the high mobility of the nodes

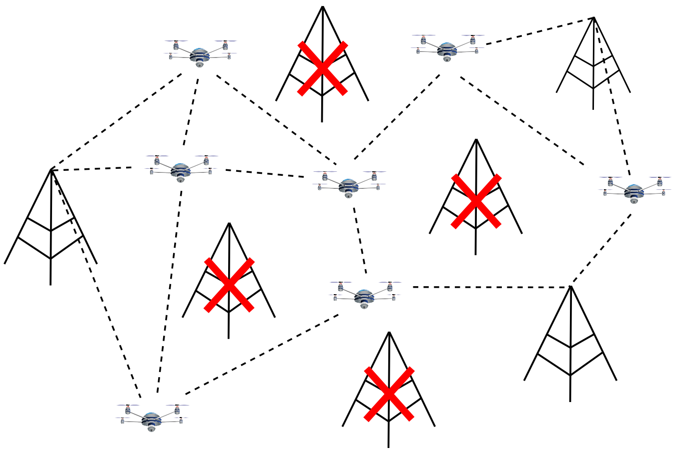

Fig. 1. Overview of the network architecture: drones are positioned to replace the damaged base stations and to cover the incident scene.

(drones). Since the drones are free-floating, in contrast to fixed structures of standard communication networks, they require to be powered by batteries or energy-harvesting units. Although the advances in solar-harvesting are considerable [5], installing solar panels onto the drones would make them extremely heavy, such that their power consumption increases. Due to this disadvantage, the drones should be powered by WPT based on electromagnetic waves. The main weakness of this technology is usually the requirement for a LoS situation between both communication ends. In our case, where drones are used, the LoS situation can easily be assumed or created due to the mobility of the nodes.

Fig. 1 shows a scenario in which several base stations do not work properly or are completely disabled. The communication network has only the remaining base stations available to provide services to users. Since the urban area will be in an emergency state, a priority is to establish communication facilities for emergency teams and to provide coverage to dense areas, i.e., stadiums or shelters where the population will be concentrated. To grant a reliable network for emergency communications, the goal is to deploy rapidly a wireless network by replacing the disabled stations by drones. In addition, the network should be self-powered and last long enough until the damaged infrastructures are repaired or substituted. The drones are used as communication nodes or relays while at the same time, they need to be powered using SWIPT technology. The block diagram of the communication modules is described

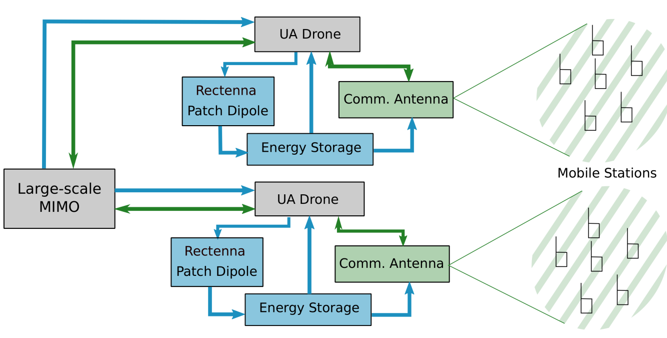

Fig. 2. Block diagram of the base station with drone connections.

in Fig. 2. Since the WPT scheme needs a high-power rate to power the drones, the transmission scheme is based on Large-Scale MIMO with a large number of antennas at the base station. Due to the collaborative scheme from the antennas, a spatial beamforming based on Channel State Information (CSI) can be performed to achieve a high gain for the harvested energy [12]. Moreover, thanks to the energy conservation law, the harvested energy is proportional to the received signal strength in high power regions [13]. The received power is transformed to DC using a rectenna (antenna + rectifier) in the range of 2.45 GHz, based on the design specifications [14].

III. SWIPT Cooperative Scheme

By using a SWIPT scheme it is possible to transmit information and power at the same time in order to extend the lifetime of the drone-based network. Different multiple access techniques can be considered. For example, a Time-Switching (TS) scheme for the SWIPT transmission [8] can be used in which each transmission block is divided into two orthogonal time slots: one for power transfer and one for data communication [15]. It is also possible to use a part of the data communication power as charging power whenever the Signal-to-Noise Ratio (SNR) is over-dimensioned. Hence, we can model all involved quantities abstractly. In this way, we define the harvested power at a node by P_{harvest}, the power consumption for flying by P_{fly}, the data communication power by P_{data}, and the available battery power of the node by P_{batt}. Since the most critical part of our design is the harvested power to maintain the network operation, an optimal trade-off between the required power by the drone to stay in steady flight mode and a communication power for an adequate data rate is pursued. Therefore, we can define the optimization problem

$$\begin{aligned}
\underset{\kappa, P_{\text{charge}_1}, P_{\text{charge}_2}}{\text{maximize}} \quad & P_{\text{charge}_1} + P_{\text{charge}_2} && \text{(1a)}\\
\text{s.t.} \quad & P_{\text{charge}_1} + P_{\text{fly}} \leq \kappa P_{\text{harvest}} + P_{\text{batt}} && \text{(1b)}\\
& P_{\text{charge}_2} + P_{\text{data}} \leq (1-\kappa) P_{\text{harvest}} && \text{(1c)}\\
& 0 \leq P_{\text{charge}_1} \leq \hat{P}_{\text{charge}_1} && \text{(1d)}\\
& 0 \leq P_{\text{charge}_2} \leq \hat{P}_{\text{charge}_2} && \text{(1e)}\\
& 0 \leq \kappa \leq 1\,, && \text{(1f)}
\end{aligned}$$

The optimization problem (1) is a linear program which can be solved by numerical tools or even in closed-form. The optimal solution describes how to split the harvested power in order to maximize the total charging power $P_{\text{charge}_1} + P_{\text{charge}_2}$ of the battery, where P_{charge_1} is the battery part for the flying mode and P_{charge_2} is the remaining part intended for the data mode in order to ensure both the flight and the data communication at each time instant. The charging powers are usually limited by hardware constraints $\hat{P}_{\text{charge}_1}$ and $\hat{P}_{\text{charge}_2}$, such that a balancing parameter κ is needed to adjust the power flow. In (1) we assume that battery power is only used for flight mode and not for the data communication task. A solution of (1) is described by $P^{\star}_{\text{charge}_1} = \hat{P}_{\text{charge}_1}$ and $P^{\star}_{\text{charge}_2} = \hat{P}_{\text{charge}_2}$ in case that the inequality $\hat{P}_{\text{charge}_1} + \hat{P}_{\text{charge}_2} + P_{\text{data}} + P_{\text{fly}} \leq P_{\text{harvest}} + P_{\text{batt}}$ holds. Another solution is given by $P^{\star}_{\text{charge}_1} + P^{\star}_{\text{charge}_2} = P_{\text{harvest}} + P_{\text{batt}} - P_{\text{data}} - P_{\text{fly}}$, whenever the reverse inequality $\hat{P}_{\text{charge}_1} +$

$\hat{P}_{\text{charge}_2} + P_{\text{data}} + P_{\text{fly}} \geq P_{\text{harvest}} + P_{\text{batt}}$ holds. Other closed-form solutions are neglected due to page limitations.

The SWIPT scheme can be summarized as follows:

- when the drone is in movement, the power P_{harvest} obtained from the base station and the battery power P_{batt} are used to fulfill the constraint P_{fly} while the exceeding power is stored by $P^{\star}_{\text{charge}_1}$.
- Once the drone is in a stationary position, i.e., floating at the desired location, the power consumption will rapidly sink [16], [17] and the harvested power can mostly be used for data communication to obtain a required bit-error rate while the remaining power is stored by $P^{\star}_{\text{charge}_2}$.

IV. 3D Optimal Drone Deployment

The drone deployment is different to the typical cellular mobile stations. The drones can move in three dimensional patterns, i.e., latitude, longitude and altitude. Using a GPS system, the drones can move to the dense areas where a number of them are required. Moreover, the adjustment of drone altitude helps to increase the coverage area, i.e., more altitude implies a bigger footprint, but at the same time the signal strength is reduced. On the contrary, if the drones are positioned low, the coverage area decreases while the received signal is amplified. To ensure a minimum required SNR at the receiver and to provide LoS between the base station and the drones, maximum and minimum altitudes are considered by z_{max} and z_{min}, respectively. Assuming circle-shaped coverage areas A_i to cover the emergency area A described by its radius r_{max}, we consider the following optimization problem to maximize the sum area with a certain number of drones:

$$
\begin{aligned}
\underset{x_i,y_i,z_i,u_i}{\text{maximize}} \quad & \sum_i u_i A_i && \text{(2a)}\\
\text{s.t.} \quad & A_i = \pi r_i^2 && \text{(2b)}\\
& r_i = (z_i - z_A)\tan\phi && \text{(2c)}\\
& (x_i - x_A)^2 + (y_i - y_A)^2 \leq r_{\text{max}}^2 && \text{(2d)}\\
& (x_i - x_j)^2 + (y_i - y_j)^2 \leq (r_i + r_j)^2 && \text{(2e)}\\
& z_{\text{min}} \leq z_i - z_A \leq z_{\text{max}} && \text{(2f)}\\
& r_i \leq r_{\text{max}} && \text{(2g)}\\
& z_A \leq z_i && \text{(2h)}\\
& u_i \in \{0,1\} && \text{(2i)}
\end{aligned}
$$

In (2), the aperture angle ϕ of the drone antenna is assumed to be the same for all drones. The optimal solution of (2) describes the optimal positions $(x_i^\star, y_i^\star, z_i^\star)$ of the drones which are positioned over the emergency region with its center position at (x_A, y_A, z_A). Furthermore, the solution specifies the optimal number $\sum_i u_i^\star$ of drones for covering a maximum area of $\sum_i u_i^\star A_i^\star$. Note that (2) is a non-convex and very hard optimization problem. Fortunately, it can be solved by specialized algorithms in a short time. The complication in solving (2) emerges from the constraint (2e), that ensures overlapping-free coverage areas. Furthermore, note that the solution of (2) is not unique in general. To overcome these difficulties, specialized solutions can be determined for particular scenarios. For example, whenever the emergency area is sufficiently small, such that $6(z_{\text{max}} - z_A)\tan\phi \leq r_{\text{max}}$ holds, we can use the method of close-packing of spheres (here circles) to obtain large coverage regions. This method is used in Sec. V-A to show its practical relevance.

It is also critical to consider the energy consumption of the drones in terms of altitude and mobility [18]. Since our transmitter is equipped with a large number of antennas, using a spatial beamforming according to the channel state information (CSI), it is possible to generate a high power at each node [6], [7]. Therefore, we assume that the transmitter has N_t antennas, enough to perform spatial beamforming, while the receivers have N_r antennas. The harvested power at each receiver node can be modeled by

$$P_{\text{harvest}} = \eta \alpha_i P_{\text{TX}} |\mathbf{h}^H \mathbf{w}(\theta_i, \theta_j, \phi_i, \phi_j)|^2 , \tag{3}$$

where P_{TX} is the transmit power from the transmitter and η is the efficiency ratio obtained from the conversion of RF to electrical energy. Moreover, $\mathbf{w}$ describes the antenna beamforming based on the CSI which depends on the pair of parameters (θ_j, ϕ_j) and (θ_i, ϕ_i). These pairs are the angles of transmission from the base station and the reception angle at the drone, respectively. The channel impulse response is given by $\mathbf{h}$ while $\alpha_i = \text{PL}(d_0) + 10 \cdot \beta \log_{10} \frac{d_i}{d_0}$ is the frequency-distance dependent path loss for LoS. Furthermore, $d_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2}$ is the distance between the transmitter at position (x_0, y_0, z_0) and the nodes at any position (x_i, y_i, z_i) in Cartesian coordinates. $\text{PL}(d_0)$ is the path loss at the reference distance d_0 while β is the path loss exponent. In this way, the harvested power at each node can be maximized by optimizing the beamforming angles. The corresponding optimization problem reads

$$
\begin{aligned}
\underset{\theta_i,\theta_j,\phi_i,\phi_j}{\text{maximize}} \quad & \eta \alpha_i P_{\text{TX}} |\mathbf{h}^H \mathbf{w}(\theta_i, \theta_j, \phi_i, \phi_j)|^2 && \text{(4a)}\\
\text{s.t.} \quad & \theta_i + \theta_j = \pi && \text{(4b)}\\
& \phi_i + \phi_j = \frac{\pi}{2} && \text{(4c)}
\end{aligned}
$$

Since we aim to obtain the maximum possible gain from the spatial beamforming, ϕ_i and ϕ_j are defined as complementary angles. The assumption of LoS is in general reasonable due to the spatial mobility of the drones, i.e., we can position the drones such that LoS situation is ensured.

V. Simulation Results

In this section, a realistic simulation is implemented and the results are analyzed. The first part of the simulations deals with the optimal positioning of the drones in order to obtain a maximum coverage at the desired area. The transmitter is placed at the coordinates $(x_0, y_0, z_0) = (0, 0, 50)$. The simulation parameters are defined in the Table I.

TABLE I
Simulation Parameters

Symbol	Description
$f = 2.45$ GHz	radiowave frequency
$P_{\text{TX}} = 46$ dBm	power of the base station using LTE standard
$G_{\text{TX}} = 26$ dB	gain at the transmitter
$G_{\text{RX}} = 3$ dB	gain at the receiver
$\eta = 0.8$	RF-DC conversion efficiency

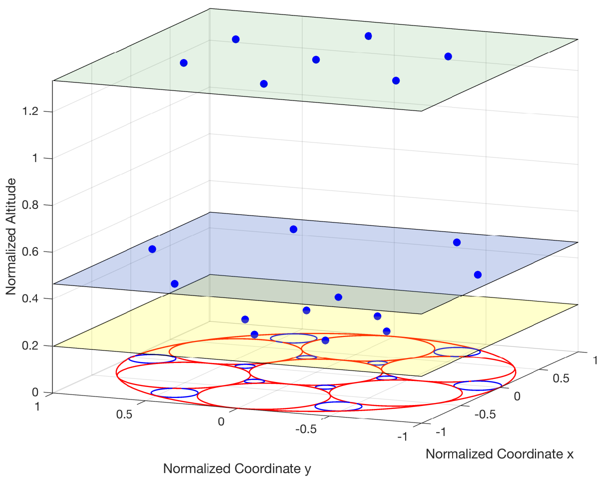

Fig. 3. Optimal drone positions in 3D.

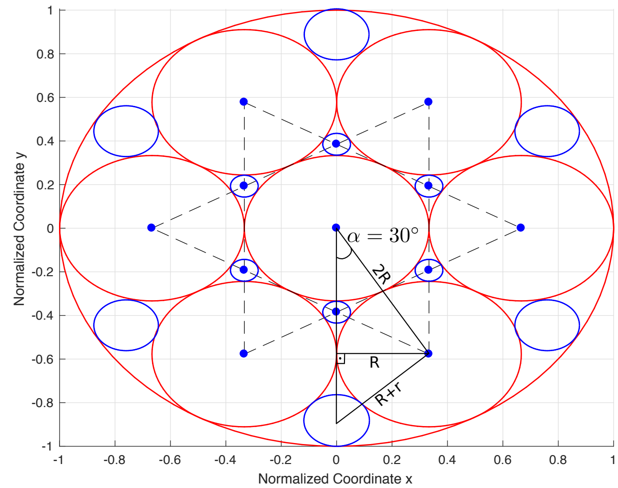

Fig. 4. Footprint of the optimal drone positions.

The achieved gain at the receiver is due to the use of LS-MIMO at the transmitter, while the frequency is selected for the design of our rectenna [14]. Using the equation stated in [19], the power consumption of the drone in flight mode and floating mode can be obtained as

$$P_{\text{drone}} = \frac{(m_p + m_v)v_{drone}}{370\hat{\eta}r} + p \tag{5}$$

where m_p is the payload mass, e.g., the communication equipment, m_v is the drone mass, $\hat{\eta}$ is the efficiency between the motor and the propellers, r is the lift-to-drag ratio, and p is the power consumption of the electronics. Since all the drones are of the same model the following parameters are used. Therefore, the power consumption of the drone in flight mode

TABLE II
DRONE PARAMETERS

Symbol	Value
m_p	500 g
m_v	700 g
v_{drone}	12 m/s
p	1.6 Wh
$\hat{\eta}$	0.8
r	3

is $P_{\text{fly}} = 122.6$ while in floating mode $P_{\text{fly}} = 1.6$ considering a stable wind gradient. Using the simulations in [20], the parameters in Table I are sufficient to fulfill the requirements of the drones in floating state, due to the gains obtained from the spatial beamforming. In the flight mode case, the battery capacity should be adequate for movements.

A. Drone Positioning

Using the optimization problem stated in (2) for sufficiently small emergency areas is too complicated. Here, we use the method of close-packing of circles to obtain a fast optimal solution, which is depicted in Fig. 3 and Fig. 4.

For our simulation, it is assumed that there are no obstacles between the transmitter and the receivers which corresponds with a LoS situation. Moreover, a perfect matching between the parameters θ_i, θ_j, ϕ_i and ϕ_j is also assumed in the simulation. The drones cover an area $\sum_i u_i^\star A_i^\star$ of approximately 0.1 squared kilometers and for that purpose $n = 19$ drones have been deployed. The sum coverage region of the drones is $D = 0.8612$ times of the total emergency area. It is noteworthy that a guard distance between the drones can be incorporated as a constraint into the optimization problem (2) in order to reduce interferences between the drones. So the drones can be positioned at different altitudes obtaining a trade-off between coverage area, received SNR, and interference between the nodes.

In order to obtain the position of the 7 big circles, the solution from [21] has been used providing a coverage of 77.77%. However, this coverage value is not enough for our application, and hence, two different methods have been used to add more coverage areas by using 12 extra drones in total. For the first 6, we use simple trigonometry to obtain the center positions, that are equidistantly arranged around the emergency area, with a circle radius of $r = (1-\sqrt{3}R)^2/\big(2(1+R-\sqrt{3}R)\big)$. The radius R of the big circles along with other relations are shown in Fig. 4. Since the area close to the center of the emergency zone is more important than the areas at the border, the gaps between the big circles can be covered by additional smaller coverage circles. Again by simple trigonometry, we obtain the radius $r' = R/\sqrt{12}$ of the smallest circles, where their location is obtained by the intersection of the lines connecting the center of the big circles, as shown in Fig. 4. It is interesting to observe the received SNR in each coverage region. As shown in Fig. 5, the SNR at the center of the areas is obviously higher than those at the edge of the areas. Moreover, it is reasonable to assume that a higher density of users are located next to the central area of the emergency zone. Hence, in our positioning scheme a higher number of drones is placed next to the central area providing a better mobility and a faster reposition of the drones.

B. SWIPT Scheme Analysis

In this section, the performance of the SWIPT scheme is analyzed in two different scenarios: an ideal scenario where

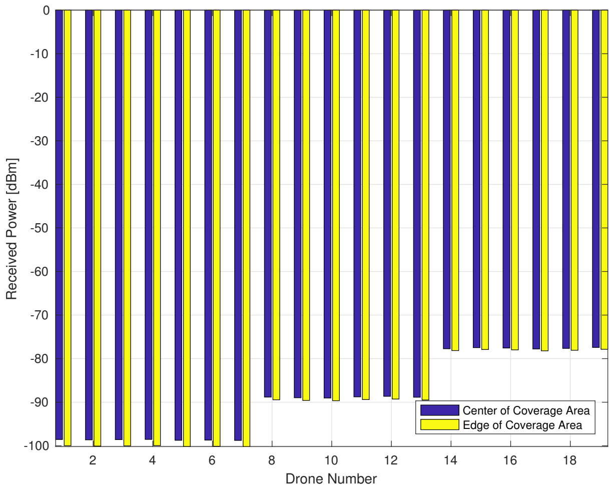

Fig. 5. SNR at the center and at the edge of each coverage region.

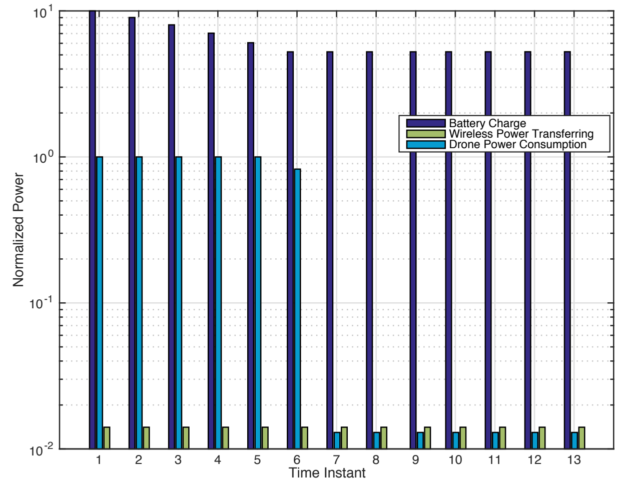

Fig. 6. Power consumption and power transfer for a single drone.

no external factors affect the environment and a scenario where the wind influences the drone performance. Note that for comparing the simulation results, one time instant corresponds to 5 seconds.

1) Ideal Scenario: The power consumption of a drone, the harvested energy, and the battery power obtained from the SWIPT scheme in (1) are shown in Fig. 6. In the first time instant, the drone consumes a high amount of power mainly from its battery, since it is moving to its optimal position (flight mode). During the flight mode, the drone uses in combination the harvested energy to charge the battery and to support the flight. Once the drone reaches its optimal position, the energy consumption decreases drastically. It can be observed that the harvested power exceeds the one consumed by the drone. Due to this extra power, the drone can perform its communication task and further charge the battery. As depicted in Fig. 2, the drones have a feedback link to the base station to feedback the current battery level. When the battery level goes under a pre-specified threshold, the drone can fly back and be exchanged by another one with full battery power. It is also possible to change the charging strategy based on the environment by adjusting the parameter κ as used in (1) in order to prolong the lifetime of the drone.

2) Windy Scenario: The studied wind conditions, based on the Beaufort scale [22], are a moderate breeze with a speed of 6 m/s and a strong breeze which can reach a speed up to 14 m/s. For the case of our commercial drones, the maximum achievable drone speed is 12 m/s, hence, this is the maximum considered airspeed. Assuming a constant airflow in the opposite direction to the drone flight, the drone power consumption is

$$\hat{P}_{\text{drone}} = \frac{(m_p + m_v)\hat{v}}{370\hat{\eta}r} + p \tag{6}$$

where $\hat{v} = v_{drone} + v_{wind}$. Therefore, the travel time to the destination and the battery consumption are both greatly increased due to the effect of the wind. The simulation results for windy conditions are displayed in Fig. 7, where the distance to the desired position for the drone is 60 meters. It is assumed that the wind-speed is constant and in the opposite direction to the drone trajectory. It is shown in Fig. 7 that the power consumption is highly influenced by the wind factor, i.e., the flying time is increased as well as the power consumption per second. It is noteworthy that even in a steady position, the power consumption is higher, since the drone has to maintain its position against the wind guts.

Another important factor affected under wind conditions is the stability of the drone. However, assuming a maximum airspeed of 12 m/s, the drone's stability is not notably affected due to the stability methods equipped in it. These methods vary from back-stepping controls to non-linear controllers or the vastly extended PID controllers [23], [24]. The stability methods require information from the position and the attitude of each individual drone which are available owing to the base station link. Nonetheless, in order to show the worst case scenario, we assume a variation in the pitch angle, ϕ, of the drone in the range of $[0, 40]$ degrees. Therefore, considering the worst-case scenario in terms of external factors, i.e., maximum opposite wind-speed and maximum variation of the drone attitude, the SWIPT graph is illustrated as follows.

In Fig. 8, the battery charge is completely drained before

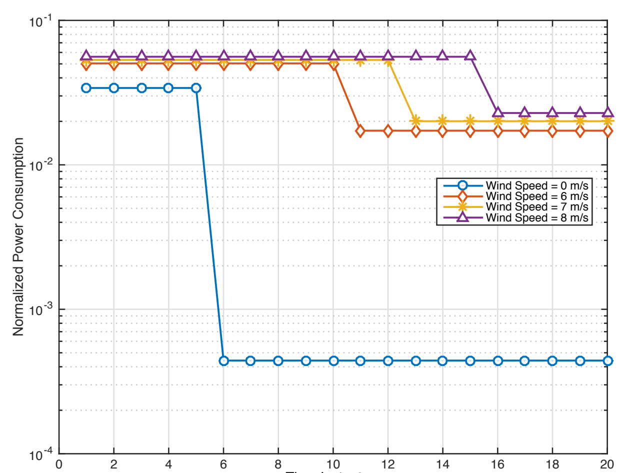

Fig. 7. Power consumption in function of wind speed.

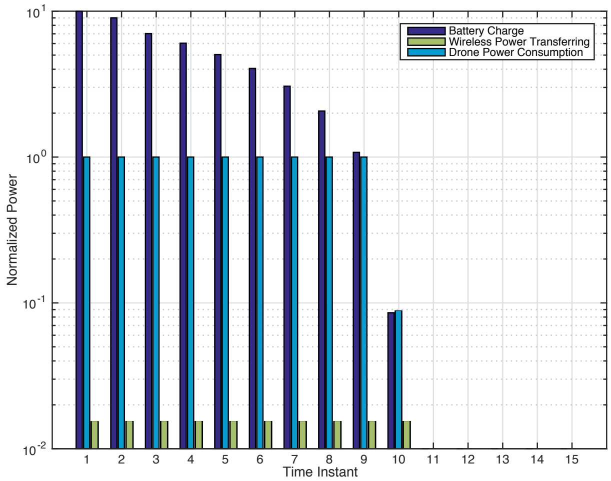

Fig. 8. Power consumption and power transfer for a single drone in windy conditions.

the drone reaches the desired destination with maximum wind in the opposite direction. Since the battery drains its charge so fast, these conditions are not suitable for the proposed network with the considered drone types. To improve the results for power transfer in windy scenarios, one has to use more powerful batteries.

VI. Conclusion

In this paper, a drone-based ad-hoc network has been investigated which uses wireless power transfer technology. The drone-based network is intended to provide a communication network for emergency areas after natural disasters or in areas that are disconnected from the rest. The proposed system uses autonomous flying drones for building up a communication network rapidly and using the flexibility of the drones to achieve a line-of-sight environment thanks to the 3D spatial mobility of the drones. We have investigated the optimal positioning of the drones to ensure for a minimum required SNR on the emergency area. The optimal positioning in addition leads to the maximum coverage area, that can be spanned by the least possible number of drones. Furthermore, we have aligned the antenna lobes of both the base station and the drones in order to obtain a maximum power transfer between the transmitter and receivers. Moreover, we have described an optimal method to split the harvested energy between data communication, drone movement, and battery charging. Finally, we have reinforced our investigations by numerical results, which confirm the practical usage of wireless energy transfer.

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