Interference Aware Positioning of Aerial Relays for Cell Overload and Outage Compensation

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***Abstract*—Compensating temporary overload or site outage in cellular mobile networks is still an unsolved problem in order to avoid situations where services are unavailable. For this objective, we propose to use a swarm of Unmanned Aerial Vehicles (UAVs) equipped with cellular technology to temporarily offload traffic into neighbouring cells in LTE/4G networks. We discuss relay placement, amount of relays and relay transmit power for overload and outage compensation and provide an analytical model for evaluating system performance in the downlink. We assume that the spatial separation between the aerial service provider, users, and offload eNodeB is beneficial for temporarily increasing spectral efficiency. Our results give evidence, that aerial network provisioning can be used for optimizing mobile networks in overload and outage scenarios.**

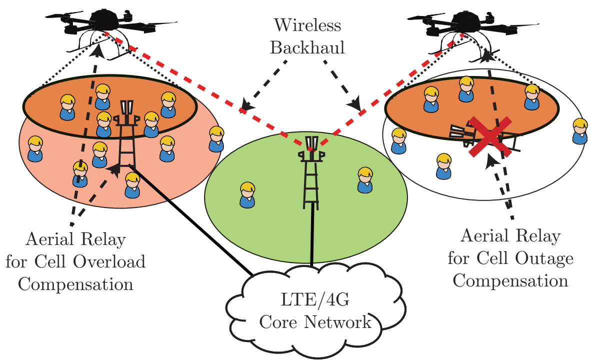

Fig. 1: Cell Overload Compensation Concept

I. Introduction

Cell overload (see Fig. 1) typically appears in areas with a temporary traffic advent that heavily exceeds the expected average traffic load. If network traffic is magnitudes above the average load the capacity reserve will not be sufficient as network providers have to take economic considerations into account during the network planning process. The actual problem emerges for example during large events where a potentially moving crowd of people needs cellular network availability with a high total capacity demand. This problem could be addressed by ground based mobile relays but these relays suffer from limited mobility, long deployment times, and high total cost. Consequently, aerial cell overload compensation can – due to the mobility of the relays – in particular handle moving overload situations (e.g. a parade) while being very quickly deployed. This quick deployment particularly qualifies aerial relays for compensating macrocell outage. This even allows them to be used in emergency scenarios when there is a quick need for reestablishing communication capabilities.

Recent advances in Unmanned Aerial Vehicles (UAVs) and mobile networking technology make aerial relays [1] feasible for using them in 4G/LTE networks. Small scale UAVs can nowadays carry a variety of sensors, actuators and communication equipment. Depending on the platform even affordable off-the-shelf quadrotor UAVs are able to carry >1 kg and Helium driven aerostats can exceed this limit. The ongoing miniaturization in commercial femto cells has at the same time proven that network equipment like base stations can be made much more lightweight and inexpensive than in the past. This enables the combination of cellular network provisioning equipment and UAVs.

The proposed concept involves a UAV equipped with eNodeB and User Equipment (UE) technology. The UE allows to take advantage of unused capacity in neighboring mobile network cells while the eNodeB enables the UAV to provide cellular services to the ground. Despite our focus on the upcoming Long Term Evolution (LTE) next generation mobile network the proposed strategies can easily be adopted for backhauling using other all-IP cellular networks like WiMAX or satellite connectivity.

In our previous work we focused on agent based mobility [2]. As for traffic offloading continuous network connectivity is inherently necessary, we now assume a central planning instance for decision making and relay node placement. In [1] we proposed the system concept for a UAV based service platform on which the concepts in this paper are based upon.

Hence, we propose a system concept for UAV driven aerial cell overload and outage compensation in LTE networks. We consider aspects of frequency planning, relay node placement and communication capabilities. We then show the feasibility of the proposed concept through an analytical model.

The remainder of this paper is organized as follows. After considering related work in section II we will describe our system concept concerning aerial network provisioning in section III. In section IV we will shortly present our methodology, followed by elaborating on our analytical

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model for evaluating relaying scenarios in section V. Consequently, we present our results in section VI and draw conclusions in section VII.

II. Related Work

In [3] the outage probability of communication links using relay UAVs in a rician fading environment is analyzed analytically. [4] presents a methodology for minimizing the amount of relay UAVs in order to connect multiple clusters and provide a fully connected mobile ad hoc network that is failure resilient and provides some throughput guarantees. [5] deals with an extension of a Wireless Sensor Network (WSN) with a UAV based aerial relay network in order to reduce sensor data packet loss. None of those solutions targets to offload cellular network traffic to other eNodeBs. However, they provide valuable input to node positioning considerations. [6] contains interesting thoughts on ground relay node placement for 4G networks while considering the link used to offload data. At the same time neither aerial relays, nor specifics of 4G network integration have been provided. In [7] an approach for outage compensation through LTE control parameter tuning has been proposed. However, the suggested methodology does not address the problem of overload compensation. An analytical model for evaluating network performance when using LTE-relaying was given in [8] and allows to estimate spectral efficiency of classical LTE relaying. Vertical Sectorization has been analyzed in [9]. The authors provided simulation studies for multiple antenna configurations. In [10] aerial wireless relays have been introduced but neither interference, nor cellular network were addressed specifically. To the best of our knowledge no prior publication considered the multilateral problem of temporary aerial overload compensation in existing commercial cellular networks.

III. A System Concept for Aerial Overload Compensation

We propose the use of aerial eNodeBs equipped with a second UE alike LTE radio unit working in client mode associated to a remote macro eNodeB. Consequently, femto-cell technology could be used in order to realize a decode-and-forward relaying using the UE as the backhaul. We suggest to use a blimp or quadrotor UAV for scenarios where mobility of the aerial relay is needed. In fixed scenarios a temporary offload can also be achieved by aerostats. Quadrotor UAVs are limited in operational time and replacement strategies must be developed for a continuous service. However, they offer a high degree of mobility. Blimps are almost in an aerostatic equilibrium and need only a small amount of energy for flying. They are more sensitive to environmental effects and can only be used in good weather conditions. Aerial relays can help to use bandwidth more efficiently through exploiting unused local capacities of nearby macro cells which – due to fading – cannot be used for connectivity by UEs or ground based relays when no line of sight conditions are available. The relays are considered to have antennas with a hemispheric downwards characteristic and 7dBi antenna gain. The aerial relays can use directional antennas for up- and downlink to the eNodeB. These optimizations allow the UE to have good connectivity to the corresponding eNodeB despite a larger than usual distance. However, in [11] it is experimentally shown that aerial connectivity to remote cellular network base stations is surprisingly good due to the line of sight to the base station and the first reflected transmission from the ground.

IV. Methodology for Validating the Aerial Relay Concept

In order to validate the system concept a combination of traffic and analytical interference modeling has been used to evaluate the downlink case of system configurations that vary in aerial relay positioning and aerial relay transmit power. In addition, the effects of macrocell outage have been analyzed. As a basis for evaluating the benefit of

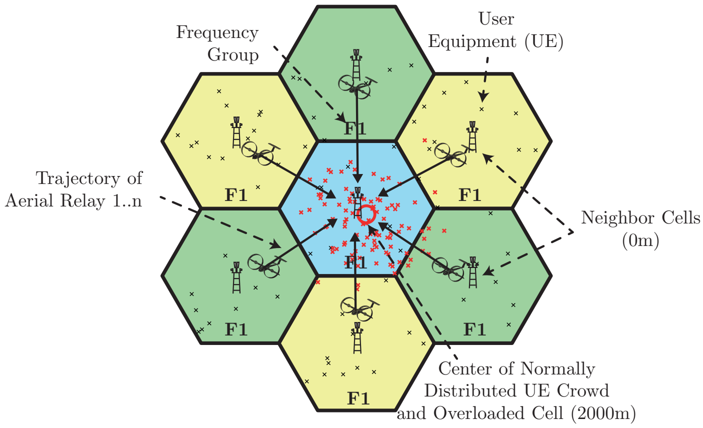

Fig. 2: Evaluation Scenario with 6 Simultaneously Moving Aerial Relays

aerial relays, we chose a scenario based on an reuse-1 frequency allocation scheme using no sectorization. The eNodeBs are always in the center of the cell. There are two groups of users in the evaluation scenario. The distribution of group A is uniform over all cell areas while group B is normally distributed around a supposed center of interest (i.e. a large event, see Fig. 2). The users are assumed to request a constant bit rate downstream of t_{req} of 300 kBit/s per user. This corresponds to a video download. Higher quality video with higher bit rate would reduce the amount of users that can be handled by the system. The evaluation in this paper concentrates on the downstream. One BS (LTE eNodeB) is supposed to provide a maximum data rate T_{bs} of 150 MBit/s using 20 MHz bandwidth. In the evaluation scenario we simulate the aerial relays' simultaneous movement from neighboring cells towards the overloaded cell as shown in Fig. 2. At each position the analytical model is used to evaluate the overall situation and provide throughput, load and system loss estimations.

V. Analytical Model for Performance Evaluation

A. Channel Model

For the channel model we assume free space path loss (formula 1). The resulting path loss in dB is used in the *Friis* equation by adding sender/receiver antenna gain and transmit power.

$$\Gamma^{l}_{ij} = 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10\gamma\log_{10}|x_i - x_j| \tag{1}$$

The propagation coefficient is denoted with γ. In our analysis we use $\gamma = 3.3$ for Macro2UE communication with no additional fading.

We use a simplified model for modulation and coding scheme (MCS) and resource allocation. In equation (2) T_{ue} denotes the maximum throughput that one UE could theoretically achieve if it was using all resources of the cell. This maximum throughput has been derived from its current signal to noise ratio SNR_{ue}. Link level throughput curves in [12] indicate that the achievable throughput is proportional to the SNR in dB up to SNR_{opt} when always selecting the optimal MCS. The corresponding signal level is calculated using equation (1).

$$T_{ue} = min(T_{bs}, T_{bs}\frac{SNR_{ue}}{SNR_{opt}}) \tag{2}$$

B. Resource Usage

In equation (3) it is assumed that the UE allocates resources proportionally to it's relative use of link resources. Hence, the relative workload of the cell R_{bs} equals the sum of all bs-associated UE's resource allocations.

$$R_{bs} = \sum_{ue\in UE_{bs}} \frac{t_{ue}}{E[T_{ue}]} \tag{3}$$

In LTE this corresponds to the relative usage of Resource Blocks (RBs). The instantaneous throughput figures t_{ue} must therefore be chosen in way that $R_{bs} \leq 1$ and $t_{ue} \leq t_{req}$ with t_{ue} being maximized in order to fulfill traffic model and resource constraints. $E[T_{ue}]$ is described in the next section.

C. Interference and Load Aware Throughput Estimation

In [13] and [8] a probabilistic methodology for estimating cellular network system performance has been proposed. We adapted in 4 and 5 the idea of calculating the expectation for the cell throughput from the published models and integrated them into the framework of scenario, resource and channel model described in the previous sections.

The basic idea is to consider each cell individually with the load vector π (consisting of the R_{bs} of all surrounding cells) assumed to be fixed. Through continuous iteration over all cells the load vectors R_{bs} converge.

$$E[T_{ue}] = \sum_{\chi\in X} T_{ue}(\chi)Pr(\chi) \tag{4}$$

Formula 4 is used to calculate the expectation of T_{ue} with $|\pi|$ as the number of possibly interfering cells, $X = \{0,1\}^{|\pi|}$ being the bitwise set of all possible combinations of interferers. $Pr(\chi)$ (formula 5) describes the probability that the interference situation specified by χ occurs, while $T_{ue}(\chi)$ denominates the estimated throughput for the corresponding ue. Therefore it is necessary to slightly modify formula 2 as $SNR_{ue}(\chi)$ can be exactly calculated using formula 1 for signal and interference levels between sender and receiver using the information which sender is interfering(χ).

$$Pr(\chi) = \prod_{i=1}^{|\pi|} \pi(i)^{\chi(i)}(1-\pi(i))^{1-\chi(i)} \tag{5}$$

Fig. 3 shows T_{ue} after the system has converged towards a stable load situation. Note that the maximum throughput at a given location indicates mostly how much resources a UE consumes for transferring data (cf. formula 2) while the actual available traffic (and overload) can only be seen indirectly as it influences the level of interference. The figure shows visibly the amount of traffic that the best-server base station could handle if the UE at the given location was the only one being served by the respective base station.

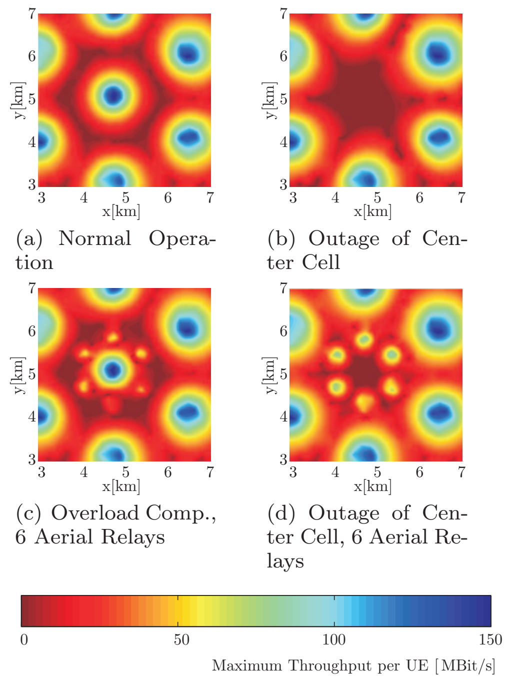

Fig. 3: Expectation of Maximum Analytical Downlink Throughput at Different Locations (T_{ue})

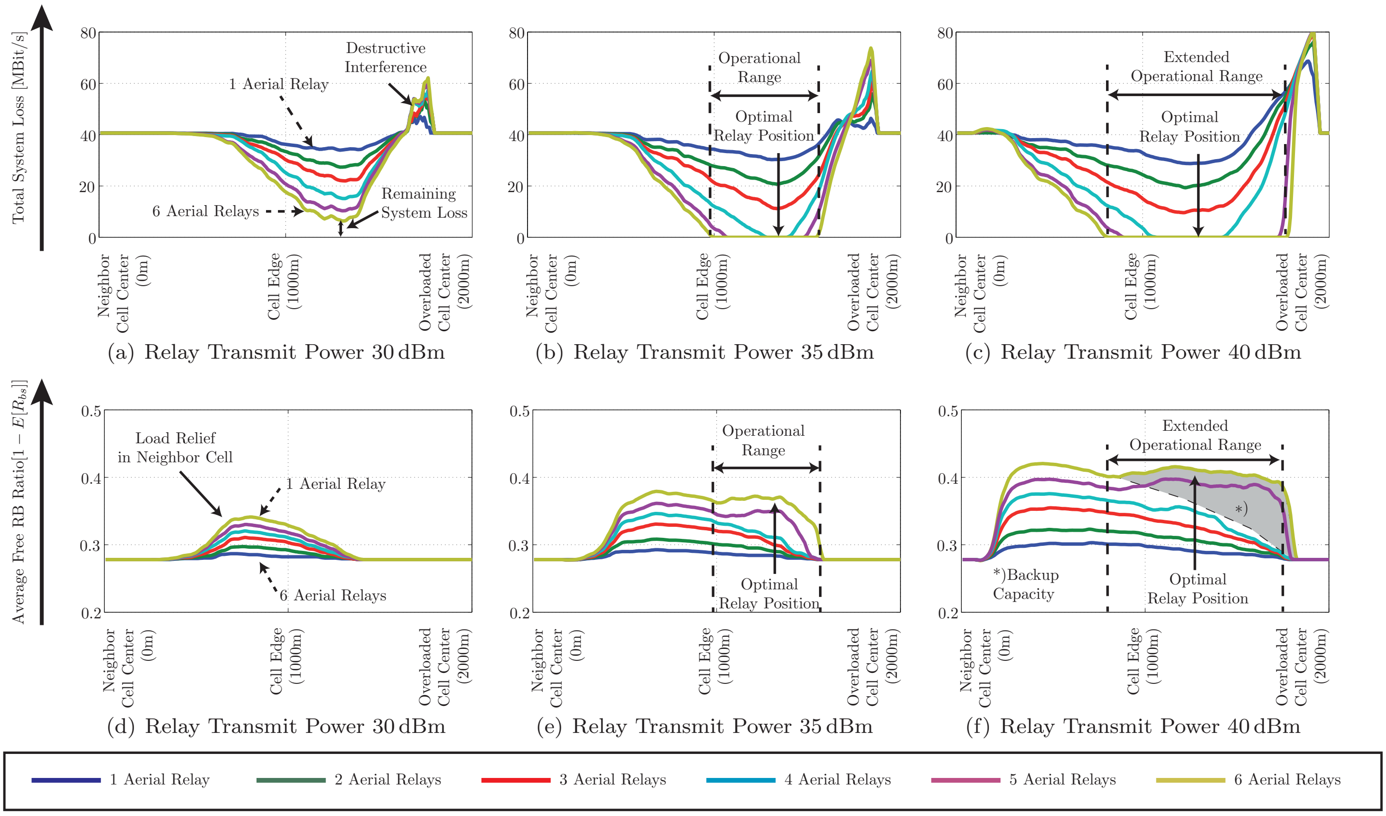

Fig. 4: Results for Overload Compensation for Different Relay Power Values and Different Number of Aerial Relays

D. System Performance Metrics

If t_{ue} is below the desired bit rate t_{req} the difference is considered to be data loss. This system overload must be avoided. The total loss of the system can be calculated as $\sum_{ue \in UE} t_{req} - t_{ue}$. In general, the second minimization goal is to reduce the number of aerial relay stations necessary for compensating cell overload situations in order to save operational cost. The average of free resource blocks $(1 - E[R_{bs}])$ for all macrocells is used for evaluating the overall system load. It indicates the level of interference that is introduced by the current load situation.

VI. Effects of Aerial Relay Placement on System Performance

The analytical model was configured using the system parameters specified in Table I. We analyzed up to 6 aerial relays which have the same varying distance towards the overload cell (cf. Fig. 2). All relays are considered to use different neighboring cells for offloading. Consequently, they are positioned on the connecting line between a neighboring cell and the center of the overloaded cell.

A. Impact of Aerial Relay Transmit Power Variations

In Fig. 4 we show the effect of varying relay transmit power on system loss and on the proportion of unused resource blocks as explained in section V. Fig. 4(a) and Fig. 4(d) show that the use of aerial relays in an overload scenario can significantly reduce the system loss that is mainly caused by the overload situation in the cell of interest. The peak in Fig. 4(d) shows that a considerable relief of relative cell resource usage takes place when the relay is next the neighboring cell. This is due to better connectivity of former cell-edge users. It does not influence the system loss, as this loss is primarily induced in the overloaded cell. When the relays reach proximity of the overloaded cell, the loss is being reduced as the traffic can be offloaded towards neighboring cells. The free Resource Block ratio is being reduced in that case as only the loss of the overloaded cell is compensated without freeing any

TABLE I: Analytical Model Parameters

Property	Setting
Inter-Site-Distance	2000 m
Macro2UE TX-Power	40 dBm
Macro2UE Antenna Gain	10 dB
Macro2UE Pathloss Coefficient	3.3
Relay2UE TX-Power	30|35|40 dBm
Relay2UE Antenna Gain	7 dB
Relay2UE Pathloss Coefficient	3.3
Macro2Relay TX-Power	40 dBm
Macro2Relay Antenna Gain	15 dB
Macro2Relay Pathloss Coefficient	2.6
Center Frequency	2100 MHz
Amount Users	1900
Amount of HotSpot Users	200
Bandwidth	20 MHz
MaxDataRate (T_{bs})	150 MBit/s
SNR_{opt}	33 dB
Requested CBR Downstream (t_{req})	300 kBit/s per User

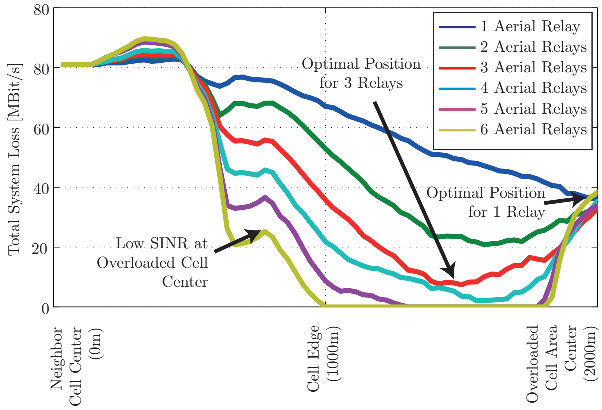

Fig. 5: Outage Compensation for Overloaded Cell using Aerial Relays: System Loss (35 dBm Relay Transmit Power)

resource blocks. The cell remains overloaded. By looking at Fig. 4(b) it can be perceived that the increased transmit power of the aerial relays has a notable effect on their offload capabilities and even 3 aerial relays can compensate the induced system loss. Additional aerial relays therefore yield an extra backup capacity which can be used to increase positional freedom. Fig. 4(e) and Fig. 4(f) visibly show this extra capacity as the previously overloaded cell now has some free resources in case the loss has been totally eliminated due to an appropriate amount of aerial relays. Fig. 4(c) and Fig. 4(f) show that by further increasing the transmit power the operational range for total loss compensation can be increased. The maximum amount of compensated loss remains almost the same.

B. *Aerial Relay Placement in Cell Outage Situations*

In Fig. 5 we show the effect of cell outage. Whereas in the non-outage case the optimal position is quite far away from the overloaded cell center due to the macrocell interference, in the outage case the optimal position of the aerial relays depends on the amount of relays due to their interference between each other. Two relays with 35 dBm transmit power already yield better overall system performance than no relays in the non-outage situation. 3 aerial relays in the outage case outperform 3 aerial relays with a functional macrocell. From a downlink perspective, it would then be better to switch off the macrocell in that case and relocate the aerial relay. However, it must be noted that these effects are related to the normal distribution of additional users around the overloaded cell center. The spike in the curves is caused by a low SINR at the center of the crowd distribution when the relays are at the respective position.

VII. Conclusion and Future Work

In this paper we have shown that the use of aerial relays can significantly reduce the downlink system loss of the given scenario. It is further demonstrated that the deployment of aerial vehicles can be particularly effective in outage situations. We showed through the proposed evaluation framework the effects of interference in an irregularly loaded system that is induced by aerial relay deployment in reuse 1 cellular networks. Consequently, relay deployment decisions in overload and outage scenarios can be derived from the causal relationships that were shown in this paper. In our example 4 aerial relays were used to increase the total system capacity by 40 MBit/s. Our next steps will be to perform automatic positioning of aerial relays while considering heterogeneous network layouts, antenna characteristics, channel models and sectorization. In addition, an uplink analysis will be conducted for an analytical evaluation of the entire system situation.

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