Coexistence of Terrestrial and HAP 3G Networks during Disaster Scenarios

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Abstract. *The aim of this paper is to show the possible coexistence of an HAP and a terrestrial component of 3G networks at a single carrier frequency. The main goal is to compare the basic parameters of terrestrial and HAP component 3G networks modeled in suburban (macrocell) and urban (macro/microcell) areas and to demonstrate the way they impact on each other. This study should present what we assume are the better capabilities of HAP 3G networks compared to their terrestrial counterparts. The parameters of the HAP and terrestrial component of 3G networks, were the terrestrial cells to be disabled during disasters, are also presented.*

Keywords

High altitude platforms (HAPs), UMTS, 3G, macro-, micro-cells.

1. Introduction

Cities worldwide are covered by 2G or 3G mobile network signals regardless of their location. A weak point of mobile networks is that they are relatively susceptible to easy disablement by natural disasters (earthquakes, tornados, floods, etc.) or terrorist attacks. A solution to these problems, or an alternative to the terrestrial provision of 3G mobile services, could be the application of High Altitude Platforms (HAPs). HAPs are quasi-stationary unmanned or manned vehicles (lighter-than-air vehicles, conventional aircraft or solar-powered aircraft) which are situated in the stratosphere at an altitude of between 17 and 22 km [1], [2]. HAPs can combine the benefits of terrestrial and satellite-based base stations. They have significantly lower Free Space Loss (FSL) than satellite links and do not suffer from shadowing at high elevation angles in dense urban areas, unlike terrestrial networks. A significant advantage of HAPs should also be the cost of their deployment and, especially in the case of disasters, the rapidity of their deployment – a matter of hours. This work is focused on the application of HAPs for 3G WCDMA systems only. The frequency spectrum for 3G mobile networks (around 2 GHz) has also been allocated to HAPs [3].

The first scenario under investigation focuses on the behavior of the independent HAP and independent terrestrial components of a 3G network and their system level parameters are compared. The second scenario, disaster, was modeled as follows. The two components overlap each other and the terrestrial cells were gradually disabled while the system level parameters were monitored at each stage. The terrestrial cells were disabled at random.

Fig. 1 shows the basic scenario, where part of the terrestrial network is disabled and the whole terrestrial network is overlapped by the HAP network.
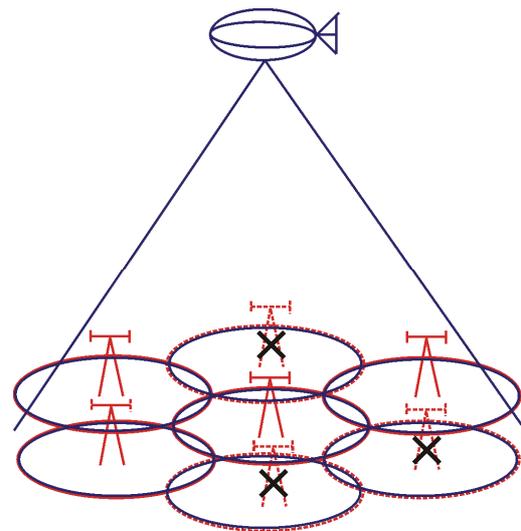

Fig. 1. The Composite Basic HAP and terrestrial network geometry.

The layout of this paper is based on the following format. The second section deals with selected simulation scenarios, propagation prediction methods and antenna models for both terrestrial and HAP networks. The third section provides the results of the simulation, where the HAP and terrestrial networks are analyzed independently. The parameters of the HAP and terrestrial networks are presented in different environments. The reciprocal impact of the terrestrial and HAP networks if the cells of the terrestrial network are gradually disabled is presented in the fourth section. Finally, the fifth section concludes the paper.

2.　General Simulation Parameters

The simulation scenarios were divided into three basic cases typical for radio network planning of 3G mobile networks. They are namely

- Suburban macrocellular environment
- Urban macrocellular environment
- Urban microcellular environment

The cells were arranged in hexagonal deployment. In the terrestrial urban environment the antennas were situated on the roofs of buildings in the case of macrocells or on the walls of buildings in the case of microcells, but still in an almost homogenous hexagonal deployment.

2.1　Propagation Prediction Model

2.1.1　Terrestrial Network

In the case of the terrestrial networks, the suburban macrocells were modeled using a COST 231 empirical model for suburban areas [4]. The Base Station's (BS) effective antenna height was assumed to be 35 m and the frequency of transmission was equal to 2.0 GHz. The standard deviation of the log-normal distribution of the shadowing margin was equal to 6 dB.

The city model was based on the ITU-R P.1410 model [5]. A city with the following parameters - $\alpha = 0.46$, $\beta = 250$, and $\gamma = 16.9$ - was randomly generated for the simulations. Parameter α is the ratio of the land area covered by buildings to the total land area, β is the mean number of buildings per unit area, and γ is the parameter determining building height distribution. α and β can easily be determined from 2D city maps. The γ parameter models the Rayleigh statistic distribution of building heights [6], [7]. The path loss in the urban macrocellular environment was calculated based on a model for a vehicular environment suitable for an urban environment outside the high rise core [8]. A BS antenna height of 15 m was assumed. The penetration loss into the building was calculated based on [4] and an external wall attenuation of 15 dB was selected.

The Bergs recursive model was utilized for terrestrial propagation prediction in a microcellular environment [9]. The height of the base station antennas situated on the walls was assumed to be 5 m. The penetration loss was calculated in the same way as for macrocells [4].

The standard deviation of the log-normal distribution of the shadowing margin in urban environment was equal to 8 dB.

2.1.2　HAP Network

A FSL model is used in most of the existing works dealing with HAPs, including studies concerning the provision of 3G mobile services from HAPs. The FSL in dB is defined as

$$L_{FSL} = 20\log(d_{km}) + 20\log(f_{GHz}) + 92.4 \qquad (1)$$

where d_{km} is the distance between the transmitter and the receiver in km and f_{GHz} the frequency in GHz. However the FSL model is probably unrealistic for lower elevation angles in suburban environments and is totally unsuitable for studies of mobile systems provided via HAPs in urban areas.

An empirical fade margin model for a suburban environment [10] (developed for satellites) was used in order to achieve a more realistic approach to HAP propagation prediction. The fade margin (M) can be expressed in dB as

$$M = A \ln p + B \qquad (2)$$

where p is the outage probability in the range from 1 to 20%. Coefficients A and B are defined as follows

$$A = 0.002\theta^2 - 0.15\theta - 0.7 - 0.2f \qquad (3)$$

and

$$B = 27.2 + 1.5f - 0.33\theta \qquad (7)$$

where θ is the elevation angle in degrees and f is the frequency in GHz. An outage probability of 1% was used for the results presented here.

The shadowing effect of buildings was calculated based on the Uniform Theory of Diffraction. The propagation prediction model for HAP in different types of built-up areas and in the frequency band between 2.0 and 6.0 GHz was shown in [11] and the path loss L for an urban environment and a frequency of 2.0 GHz can be calculated based on

$$L = \begin{cases} 20\log(d_{km}) + 98.4 + normrnd(0,4) & \text{LOS} \\ 20\log(d_{km}) + 98.4 + \\ normrnd(\dfrac{-94.2 + \theta,}{-3.44 + 0.0318\theta}, \dfrac{-89.55 + \theta}{-8.87 + 0.0927\theta}) + \\ normrnd(0,10) & \text{NLOS} \end{cases} \qquad (5)$$

where d_{km} is the distance in km, θ is the elevation angle in degrees and the $normrnd(\mu, \sigma)$ generates random numbers using the Normal distribution with the mean μ and the standard deviation σ in dB. Normrnd() is a standard Matlab function.

Line of Sight (LOS) probability in the streets (in percentages) as a function of an elevation angle for urban environment is defined as

$$P_{LOS}(\theta) = 120.0 - \dfrac{120.0}{1 + (\dfrac{\theta}{24.3})^{1.229}} \qquad (6)$$

where θ is the elevation angle in degrees. HAP penetration loss into the building was calculated using an empirical model for high elevation angles. The building penetration loss in dB for elevation angle θ in the range from 55 to 90 degrees is defined as follows [12]

$$L(\theta) = -10\log\left[\int_0^{\pi/2} L^{-1}(\theta,\phi)d\phi\right] \tag{7}$$

where ϕ is the azimuth angle and $L^{-1}(\theta,\phi)$ is the weighted sum of the loss contributions of the walls and rooftop. The model works under perfect conditions – the building is rectangular in shape without projections. The sum of the loss contributions is then equal to

$$L^{-1}(\theta,\phi) = \frac{0.25}{10^{0.1[W_e + W_{GE}(1-\cos\theta\cos\phi)^2]}} + \frac{0.25}{10^{0.1[W_e + W_{GE}(1-\cos\theta\cos\phi)^2]}} + \frac{1.5}{10^{0.1(W_e + W_{GE})}} \tag{8}$$

where W_e is the loss in dB for an externally illuminated wall with perpendicular illumination (about 7 dB) and W_{GE} is the additional loss in dB, when illuminated under ideal conditions (about 20 dB). The standard deviation of the log-normal distribution of the shadowing margin was equal to 8 dB.

The other HAP penetration loss model for a full elevation angle and for 3G and 4G mobile systems was published in [13].

2.2 Antenna Patterns

The antenna radiation pattern plays a very important role for HAP systems, because the cell shape is determined by the antenna radiation pattern more than by the terrain profile. The HAP radiation pattern also determines other cell interference and thereby cell isolation. The HAP antenna radiation pattern was modeled on ITU-R M. 1456 [14]. Fig. 2 shows the used antenna radiation patterns for different cell radii as a function of the angle from the antenna boresight ψ. The near-in-side-lobe level (dB) relative to the peak gain was equal to –30 dB and the far-side-lobe level (dB) relative to the peak gain was equal to –73 dB based on [14]. The antennas were modeled for different antenna power roll-off at the cell edge (the roll-off means the difference between peak antenna gain and antenna gain at the cell edge). The antenna power roll-off was equal to –15 dB for a suburban cell, -25 dB for an urban macrocell and –30 dB for an urban microcell. The methods used for HAP ITU-R HAP antenna modeling based on antenna power roll-off are shown in [15]. A steep roll-off can increase the inter-cell isolation but at the expense of the quality of coverage at the cell edge. The smaller cells can be modeled by antennas with a steeper roll-off.

The terrestrial base station used the realistic antenna mask for OMNI directional antenna (in one cut). The gain

of this antenna was assumed to be 11 dBi – the OMNI directional antennas for the terrestrial base stations were chosen in order to compare the 3G system-level parameters of terrestrial and HAP networks. In a real-life situation the terrestrial macrocellular base station mainly utilizes three-sectored antennas with an antenna beamwidth of 65 degrees, but the system level parameters of the OMNI and three-sectored antennas are almost the same [16] (the capacity is naturally almost three times larger than in sites with one OMNI directional antenna).
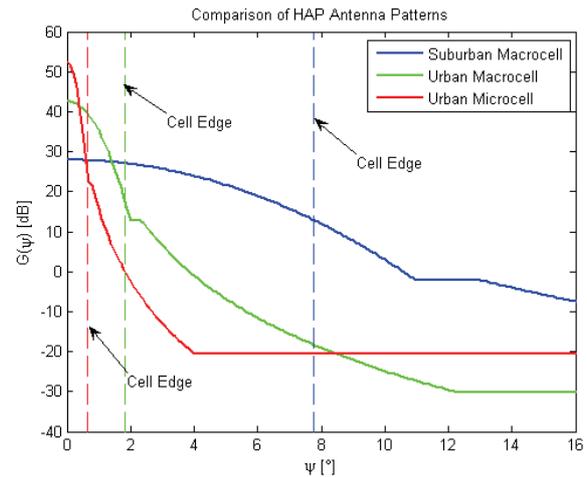

Fig. 2. ITU-R radiation patterns for different cell radii used in different environments.

2.3 Parameters of System Level Simulation

As was mentioned above, third-generation mobile systems (UMTS) are among the applications currently proposed for HAPs. Problems of capacity and coverage are inseparable in the radio network planning of third-generation mobile networks. UMTS coverage planning using HAPs scenarios has already received the attention of researchers in the literature, e.g. [17], but these studies are mostly empirically based on a number of very simplistic assumptions. In 3G mobile networks base station sensitivity is not constant, but is closely related to the number of users and the total bit rate used in each cell. The coverage area of a 3G cell is determined by the level of interference and interference cancellation methods. A number of iterations may be required. To obtain realistic results that show the quality of coverage and cell capacity analysis in real-life scenarios, an iterative simulation approach can give a better insight into performance than an analytical one. The principles of this simulation approach are described in detail in [16], [18].

The general simulation parameters are summarized in Tab. 1.

Parameter	Suburban - macrocell	Urban - macrocell	Urban - microcell
Mobile station maximal transmission power	21 dBm	21 dBm	21 dBm
Base station maximal transmission power per link	40 dBm	40 dBm	34 dBm
Overall base station transmission power	43 dBm	43 dBm	37 dBm
Uplink loading limit	0.5	0.5	0.8
Mobile/Base station noise figure	8 dB/5 dB	8 dB/5 dB	8 dB/5 dB
Uplink/Downlink Eb/N0 for speech service	5.5 dB/8.5 dB	4.0 dB/11.0 dB	4.0 dB/11.0 dB
Platform height	22 km	22 km	22 km
Cell Radius	3000 m	700 m	250 m
Number of cells	37	19	19
Orthogonality	0.5	0.5	0.5
Activity factor (Speech Service)	0.67	0.67	0.67
HAP antenna max gain/ter. BS antenna gain	27.9dBi /11.0 dBi	42.7dBi /11.0 dBi	52.4dBi /11.0 dBi
Mobile station - body loss	2 dB	2 dB	2 dB
Mobile station antennas	Omni (0 dBi)	Omni (0 dBi)	Omni (0 dBi)

Tab. 1. The general simulation parameters.

3. Comparison of HAP and Terrestrial Network

The system level parameters of identical HAP and terrestrial networks in three different environments are presented in this section. Fig. 3 shows the quality of coverage in the uplink (UL) for four different data rates (speech service 12.2 kbps and three different data services – 64, 128 and 384 kbps).

In the urban environment there was a problem with the coverage of indoor areas. In the case of HAP, the quality of coverage is primarily determined by the antenna radiation profile. The final antenna pattern has to be a compromise between the quality of coverage and the inter-cell interference. Anyway, from Fig. 3 it is obvious that the HAP network offers better quality of coverage than the terrestrial one.
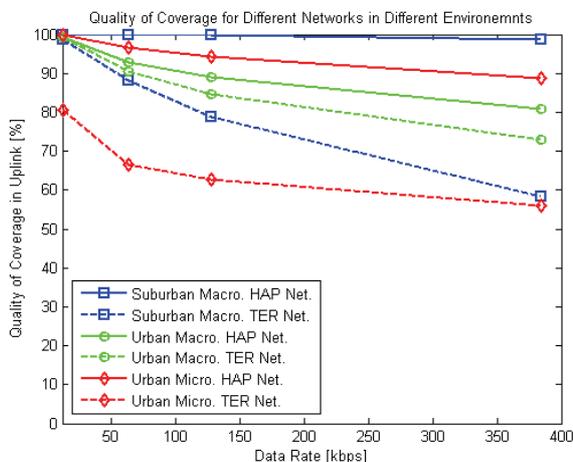

Fig. 3. The probability of uplink quality of coverage in different environments.

The next parameter under investigation was cell capacity. The cell capacity is presented as an average number of served users per cell. It is important to point out that the macro- and microcells were allowed different loadings in the UL (see Tab. 1). The cell capacity - presented as an average number of served users using speech service per cell – was simulated as follows

- Sub. macrocell. $C_{HAP} = 65 / C_{TER} = 45$
- Urb. macrocell. $C_{HAP} = 93 / C_{TER} = 49$
- Urb. microcell. $C_{HAP} = 121 / C_{TER} = 102$

The speech service is probably the most demanding service during disasters and in addition, for the speech service, the iteration based simulation approach is almost independent of coincidental user distribution in the target area – due to the large numbers of served users in different areas of the cell.

It is obvious from the results presented above that the HAP network offers noticeably better parameters than the terrestrial one.

Fig. 4 illustrates CDF (Cumulative Distribution Function) of other-to-own cell interference ratio in the uplink i. Only in the case of microcells does the terrestrial network offer higher performance of this parameter than the HAP networks. This is because the terrestrial microcells can use the neighboring buildings to the inter-cell isolation. In any event, the quality of coverage was the lowest in the terrestrial microcellular network.

CDF of other cell interference in the downlink (DL) (I_{other}) are depicted in Fig.5. The better isolation of HAP cells compared to their macrocellular terrestrial counterparts is evident from this figure.
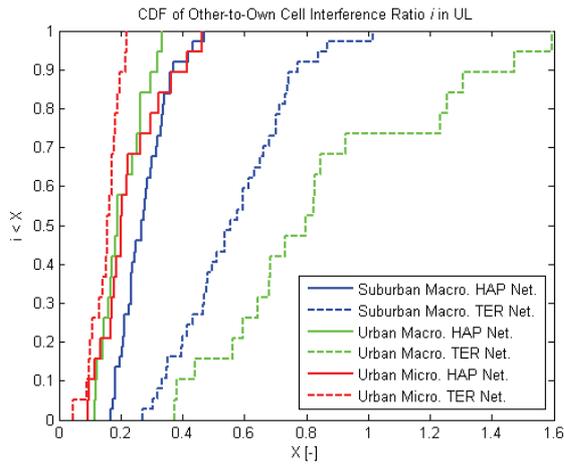
Fig. 4. CDF of other-to own cell interference ratio in UL for different networks in different environments.

The better parameters of HAP networks compared to the terrestrial can be explained by comparing transmission power per link (see Fig. 6). The mobile stations transmit at higher power in the case of a terrestrial network than in a HAP network. This is caused by the higher path loss in terrestrial networks than in the case of HAPs.
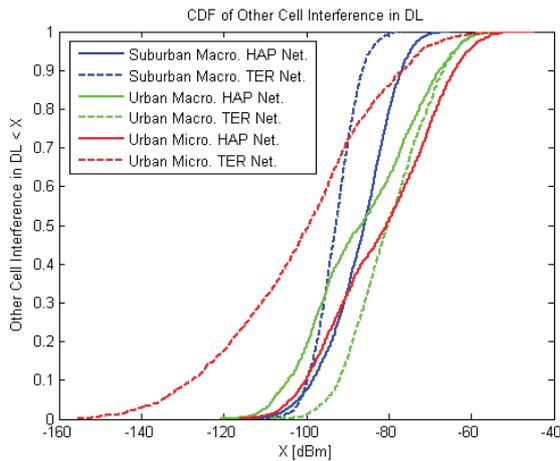

Fig. 5. CDF of other cell interference in DL for different networks in different environments.
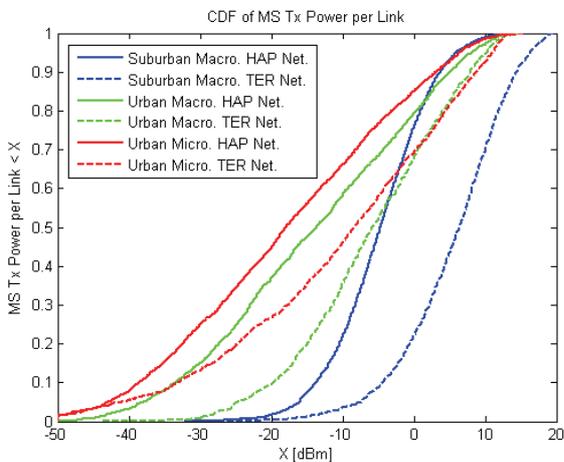

Fig. 6. CDF of MS transmission power per link for different networks in different environments.

4. Disaster Scenario

The disaster simulating scenario was modeled as follows. The terrestrial cells were gradually disabled and the system level parameters were monitored at each stage. The terrestrial cells were disabled at random. The reciprocal impact of both the HAP and terrestrial component of the 3G network was studied. The results of the system level simulation are presented on average normalized cell capacity.

4.1 Suburban Macrocellular Environment

Fig. 7 illustrates the normalized number of served users in an area served by 37 HAP base stations when the number of 37 terrestrial BS with OMNI directional antennas is gradually decreased. From Fig. 7 it is obvious that in a situation where the terrestrial and HAP component overlap completely, the capacity of the HAP network is almost ten times larger than the terrestrial component. In addition, the benefit of the terrestrial component to the total capacity is minimal in comparison with the HAP component in the case of full cell overlapping. The terrestrial component of the 3G network might perform better in the event of disaster in the suburban environment should the HAP network be switched off. The explanation of this effect is in the propagation condition for HAP and terrestrial links. For example, in the DL, the interfering signal from the terrestrial BS is far more attenuated than from terrestrial base station, which means that the interference level for terrestrial network users is at a higher level than for HAP network users.
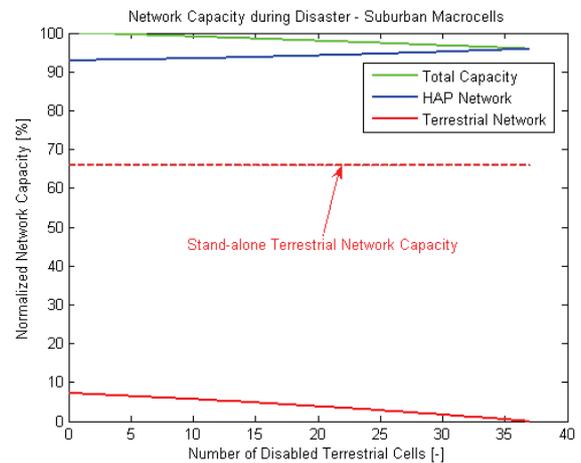

Fig. 7. Cell capacity as a function of the number of disabled terrestrial cells – suburban macrocellular environment.

4.2 Urban Macrocellular Environment

The urban macrocellular environment was modeled more realistically than the suburban areas – including the buildings. The normalized number of served users in the area served by 19 HAP cells and then when the number of terrestrial base stations with OMNI directional antennas is

gradually decreased, is presented in Fig. 8. From Fig. 8 it is obvious that where the terrestrial and HAP components of macrocells in the urban area overlap totally, the capacity of the HAP network is approximately four times greater than the cell capacity of the terrestrial networks. The relatively smaller impact of the HAP and terrestrial networks compared to suburban areas is caused by the more complicated propagation condition. In any event, the HAP provide much better conditions for propagation, because the number of LOS connections from the HAP to the street is huge for an HAP situated above the city [11], [19]. The additional penetration loss in case of HAP for high elevation angles about 90 degrees is also larger than in the case of terrestrial networks [12], [13].
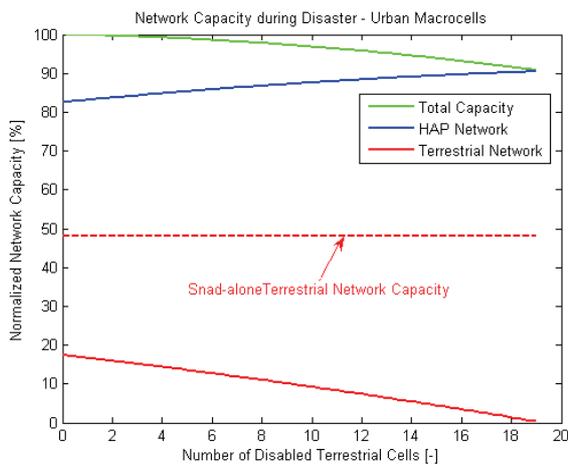
urban macrocellular environments, due to their propagation effects. Small (micro, hot-spot) cells in urban areas provide similar capacity for terrestrial and HAP components of the 3G network. The simultaneous application of HAP and terrestrial networks in the same place particularly impacts the terrestrial signal in a suburban and urban macrocellular area, while the reciprocal impact, although similar, is not so crucial in an urban microcellular environment. Anyway, the terrestrial network could be switched off after its replacement by HAP network. It was shown that in disaster scenarios, when the terrestrial network is partially or completely disabled, the overlaid HAP 3G network is able to provide a more than adequate service in both coverage and capacity.
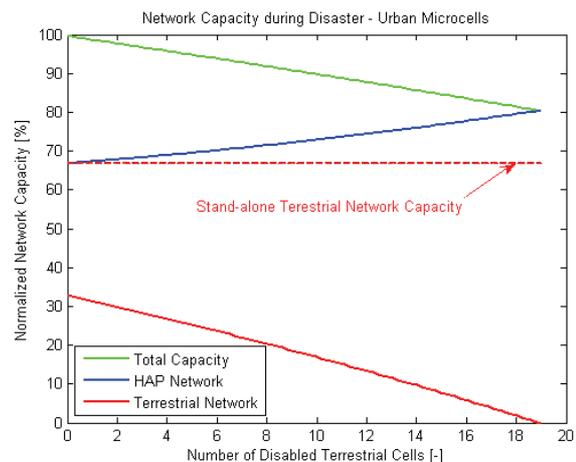

Fig. 8. Cell capacity as a function of the number of disabled terrestrial cells – urban macrocellular environment.

Fig. 9. Cell capacity as a function of the number of disabled terrestrial cells – urban microcellular environment. .

4.3 Urban Microcellular Environment

Finally, the normalized capacity of HAP and terrestrial microcells is depicted in Fig. 9, which shows the normalized number of served users in the area served by 19 HAP BS and by gradually decreasing the number of terrestrial microcellular base stations. From Fig. 9 it is obvious that where the terrestrial and HAP components of micro- or small cells in the urban area overlap totally, the capacity of the HAP network is twice as large as the cell capacity of the terrestrial networks. The increase in the HAP component capacity is not as considerable as in the macrocellular models, because the overlapping of the HAP and terrestrial components in a microcellular environment do not affect each others networks so crucially as in the case of the suburban area.

5. Conclusion

The coexistence of terrestrial macro- in suburban and urban areas and microcells in the urban area with an HAP component of the 3G network was presented in this paper. It was shown that HAP 3G networks offer a higher capacity than terrestrial networks, especially in suburban and

Acknowledgements

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