Network Architectures Exploiting Multiple HAP Constellations for Load Balancing

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Abstract: - This paper addresses network architectures in a constellation of high altitude platforms (HAPs) with overlapping coverage areas, focusing on the additional network elements/functionalities required to make use of load balancing mechanisms. According to the location within the network and the complexity of additional equipment/ functionality the paper proposes two different architectures. In the case of the basic utilisation of multiple HAPs a new equipment/functionality is installed only at the user premises, supporting load balancing only for the connections initialised from the HAP user network to the Internet (i.e. the outbound connections). In the case of advanced utilisation of multiple HAPs a new equipment/functionality is needed both at the user premises and in the HAP network, thus supporting load balancing in both directions. For the performance evaluation of load balancing mechanisms we built a simulation model supporting typical applications such as e-mail, file transfer, web browsing and IP telephony. Simulation results confirm that in the case of traffic load close to the congestion load balancing mechanism significantly improves the performance of selected reference applications. In order to asses the feasibility of the proposed network architectures in a multiple HAP system, and to confirm that carefully designed and pointed directional user antennas allow establishment of multiple access links for load balancing and to improve resilience of the network, we also investigate HAP visibility distribution across the coverage area for a single HAP system and a system comprising 4 HAPs.

Key-Words: - High Altitude Platforms, network architectures, load balancing, multiple HAP constellation

1 Introduction

In the last decade high altitude platforms (HAPs) have been extensively investigated as an alternative infrastructure for the provision of broadband wireless communications. Operating in a quasi-stationary position in lower stratosphere, typically at altitudes around 20 km, and capable of carrying communications payload, HAPs not only provide notably larger coverage areas compared to terrestrial systems, but also guarantee a predominant line-of-sight (LOS) communication. HAPs are seen as an attractive solution (i) for the provision of broadband wireless access (BWA) particularly to remote and sparsely populated areas [1, 2]; (ii) for on-demand establishment of wireless communication access in a specific geographical region, such as for disaster relief or special event servicing; as well as (iii) for the gradual service roll-out with incremental deployment of the network as the need emerges for larger coverage area and/or capacity. However, although HAP-based communication systems are mainly seen as alternative means for the provision of existing services and applications, they are also expected to play an important role in the Beyond 3G wireless infrastructure.

Multiple HAP constellations will typically be deployed by the same network operator to serve a common coverage area in order to increase the capacity provided and/or to improve the resilience of the system. In particular, constellations of multiple HAPs could enhance the overall system capacity in overlapping coverage areas by exploiting highly directional fixed user antennas used to discriminate spatially between different HAPs [3], essentially increasing the spectral efficiency of the system. Alternatively, they could increase the total link availability between the HAP and a user by exploiting the diversity gain in mobile user environment [4].

In this paper the network architecture implications of using multiple platforms with overlapping coverage areas are investigated. In particular, we investigate the load balancing in the multiple platform constellations by introducing additional network elements/functionalities. The multiple HAP system performance in real operating environment significantly depends on the constellation design, propagation channel characteristics and the configuration of the terrain. In order to validate and asses the feasibility of the proposed network architectures in a multiple HAP system, we also provide a comparison of HAP visibility distribution across the coverage area for a single HAP system and a system comprising 4 HAPs taking into account a representative hilly terrain configuration. The rest of the paper is organised as follows: in Section 2 we present a general multiple HAP system architecture, describe the multiple HAP constellation scenarios and introduce two multiple HAP utilization scenarios for load balancing. Basic utilisation of multiple HAPs for load balancing in outbound direction is described more in detail in Section 3, while in Section 4 we are discussing advanced utilisation of multiple HAPs, which extends the capabilities of load balancing to both inbound and outbound directions. Section 5 describes a simulation model used for performance evaluation of load balancing in multiple HAP constellation, and provides representative simulation results for per-flow load balancing in outbound direction. Section 6 introduces simulation model and provides simulation results for the visibility distribution across the reference terrain configuration for single and multiple HAP constellations, while Section 7 concludes the paper.

2 Multiple HAP System

From the system architecture point of view HAPs can be used in different configurations. A general HAP system architecture is depicted in Fig. 1.

The simplest HAP system configuration consists of standalone platform where the system coverage is limited to a single HAP cellular coverage. Only communication between fixed, portable and mobile user terminals within this coverage is enabled. Additionally, connection to other public and/or private networks via Gateway Station (GS) is foreseen. This scenario can be further divided into two distinct topologies according to where the switching is taking place [5]:

- Bent-pipe standalone platform (scenario with on ground switching), where the path between two users encompasses uplink (UL) from the user to the platform, feeder downlink (DL) to GS, where the switching is performed, feeder uplink from GS to the platform and downlink to the target user.
- Standalone platform with onboard switching, where the path between two users takes only uplink from the user to the platform, where switching is performed; and downlink from the platform to the target user. Standalone platform scenario with onboard switching is particularly suitable for temporary provision of basic or additional capacity required for the short term events with many participants, in case of natural disasters, or in areas where the fixed infrastructure has suffered a major failure.

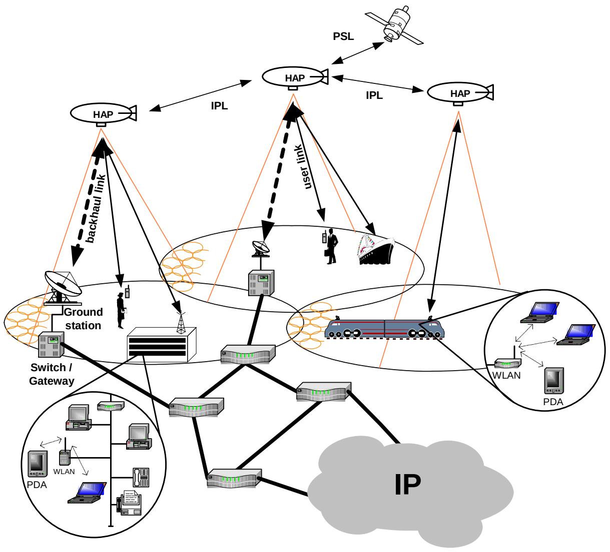

Fig. 1: General HAP system architecture.

In the case of multiple platform constellation HAPs can be interconnected via ground stations or with the interplatform links (IPL), essentially forming a network of HAPs, thus arbitrarily extending the system coverage.

The most extensive scenario, as depicted in Fig. 1, can also include platform to satellite links (PSL), which are particular useful if HAPs are placed above the areas with deficient (rural and remote areas) or non-existent terrestrial infrastructure. In this scenario HAPs can be connected to other remote public or private networks. Furthermore, PSLs could also be used as a backup solution in the case when the connection with the rest of the network via IPLs or GSs is disabled due to a failure or extreme rain fading on uplinks and/or downlinks.

The multiple HAP system architecture shown in Fig. 1 assumes partially overlapping coverage areas. In general, however, we distinguish four cases with regard to coverage areas of multiple platforms as depicted in Fig. 2:

- In Fig. 2(a) coverage areas of HAPs are not overlapping. This case is not interesting for further investigation as the user can only be in the coverage area of a single HAP and cannot exploit the benefits of multiple HAP visibility.
- In Fig. 2(b) coverage areas of HAPs in the system are partially overlapping. This is the most likely case in the network deployment as in the real HAP network the coverage areas will have to be partially overlapped to support a handover between different HAPs.
- Fig. 2(c) shows a multiple HAP system with largely/fully overlapping coverage areas. In this situation multiple HAPs are serving the same area to increase the overall capacity or improve resilience, or simply because of additional HAP network provider entering the market.
- Fig. 2(d) shows a mixed case of partially and fully overlapping coverage areas expected in the later phases of system deployment, when HAPs are added on demand to extend overall service area, to increase the system capacity and to improve the resilience of the network.

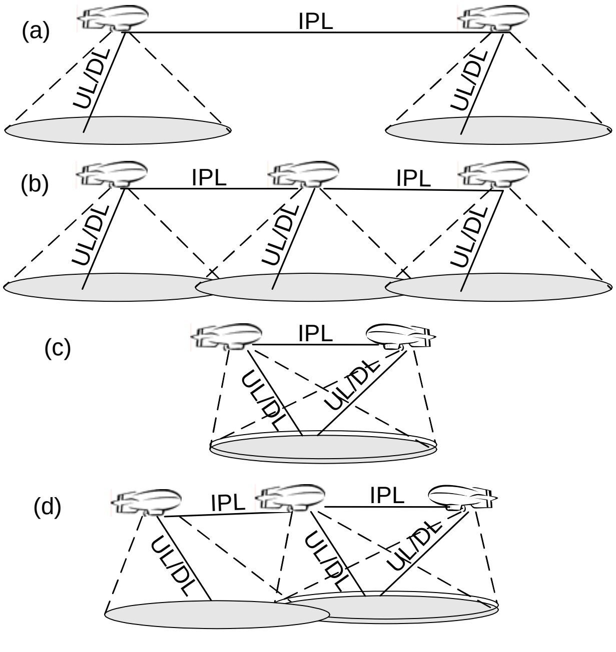

Fig. 2: Multiple-HAP constellations: (a) interconnection of service coverage area islands; (b) increasing service coverage area; (c) increasing the capacity; (d) improving resilience and capacity of the network.

The scenario used in this paper for investigation of network architectures supporting load balancing in a multiple HAP system represents a subset of the general HAP system architecture shown in Fig. 1. In particular we are focusing on fixed users in the overlapping area of at least two HAPs, regardless whether they form fully or partially overlaid coverage areas. We are only focusing on solutions which in general do not need changes at the application level. Thus from the users' perspective the usage of more than one HAP is transparent resulting only in better performance and/or better reliability/availability of services. The reference network architecture, which is investigated in this paper, is depicted in Fig. 3. We assume there are one or more users which are connected to the HAP network via router (i.e. LB Router) using wired or wireless access (e.g. WLAN). In the original scenario depicted in Fig. 3 with different shades of gray representing different flows, these users are utilizing only one HAP (i.e. HAP A), although they are also within the coverage area of HAP B. All users (and applications) are accessing internet via the same HAP access terminal (HAT) and access link, which can cause the congestion in the access segment and/or backhaul link.

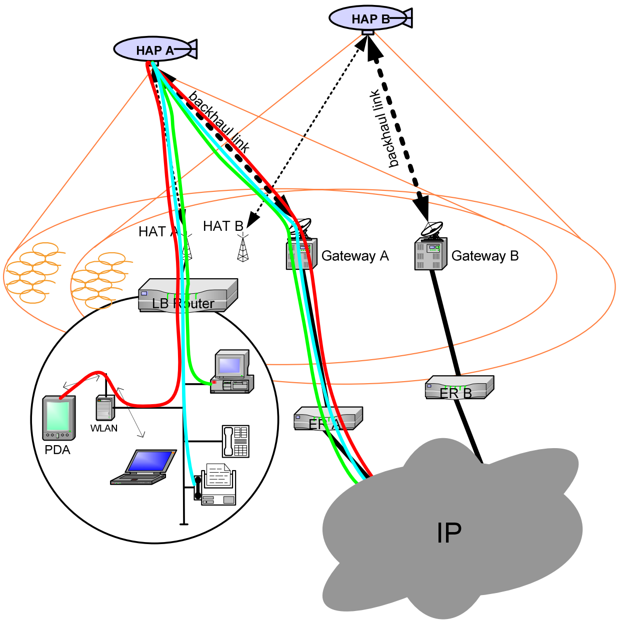

Fig. 3: Traffic flows if only one HAP is utilized.

In order to utilize also the second HAP (i.e. HAP B) we need to introduce additional equipment and/or functionality in the network. In this respect we distinguish two scenarios:

- Basic utilisation of multiple HAPs – in this scenario a new equipment/functionality is installed only at user premises.
- Advanced utilisation of multiple HAPs – in this scenario a new equipment/functionality is needed at user premises and also in the HAP network between the Gateway and Edge Router (ER).

3 Basic Utilisation of Multiple HAPs for Load Balancing

Basic utilisation of multiple HAPs is based on installing a router with load balancing capabilities at user premises. The router can combine two or more broadband connections, at least summing up the amount of bandwidth which is available to users and at the same time creating a more resilient solution. In this solution the load balancing works only when connections are initialised from the HAP user network to the Internet (i.e. outbound direction). Typically, the load balancing can work in per-packet, per-destination or per-flow fashion.

Per-packet load-balancing means that the router sends one packet for destination d_1 over the first path, the second packet for (the same) destination d_1 over the second path, and so on [6]. Typically the round robin scheduling policy is applied. Per-packet load balancing guarantees equal load across all links. However, packets may arrive at the destination out of order because different delays may exist within the network. Graphical representation of the per-packet load balancing is depicted in Fig. 4, where different shades of gray represent different packet flows. Packets belonging to the same flow are split at LB router, thus utilizing both HAPs and increasing the overall throughput. From the user perspective the overall capacity a single application can achieve is the sum of the capacities of each particular connection.

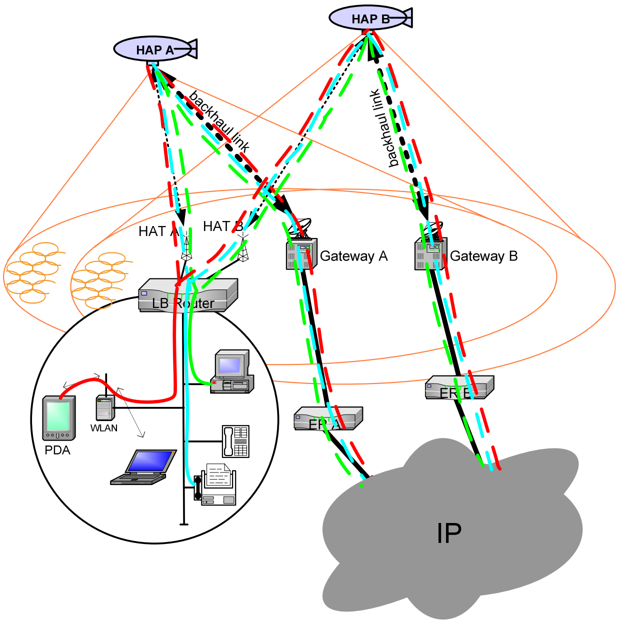

Fig. 4: HAP architecture for basic utilisation of multiple HAPs: per-packet load balancing.

Per-destination load balancing means that the router distributes the packets based on the destination address [7]. Given two paths to the same network, all packets for destination d_1 on that network go over the first path, while all packets for destination d_2 on that network go over the second path. Also in this case the round robin scheduling policy is typically applied. This solution preserves the packet order, yet potentially yields unequal utilisation of the links. If one host receives the majority of the traffic all packets use a single link, leaving bandwidth on other links unused. A larger number of destination addresses leads to more equally used links. To achieve more equal link utilisation a route-cache entry has to be built for every destination address, instead of every destination network, as is the case when only a single path exists. Therefore traffic for different hosts on the same destination network can use different paths. The downside of this approach is that for the core backbone routers, carrying traffic for thousands of destination hosts, memory and processing requirements for maintaining the cache become very demanding. From the user perspective the overall capacity a single application can achieve is the same as the capacity of each particular connection. However the overall capacity for all applications/users is increased.

Per-flow load balancing means that connections or flows are shared between users [7]. Thus, whilst a single flow cannot use more bandwidth than provided by a single link, multiple users/ applications balance across multiple links. Graphical representation of the per-flow load balancing is depicted in Fig. 5. Two flows are using the first broadband connection via HAT A, while the third flow is utilizing the second HAP (HAP B) via HAT B, thus not utilising the first HAP at all.

Routers with load balancing capabilities have a range of methods by which they balance traffic between the broadband links. Typical criteria, which are used by the router when deciding which connection to use, include:

- Round robin – every new flow is using different link from the previous one.
- Least connections – a new flow is established via the broadband connection with less active connections.
- Traffic load – a new flow is established via the broadband connection with less traffic load.
- Best quality – a new flow is established via the broadband connection with better quality.

- Least hops – a new flow is established via the broadband connection with less hops to the final destination.
- Scheduled – a new flow is established according to the predefined time schedule.
- Traffic type – particular traffic classes are utilizing always the same HAP.

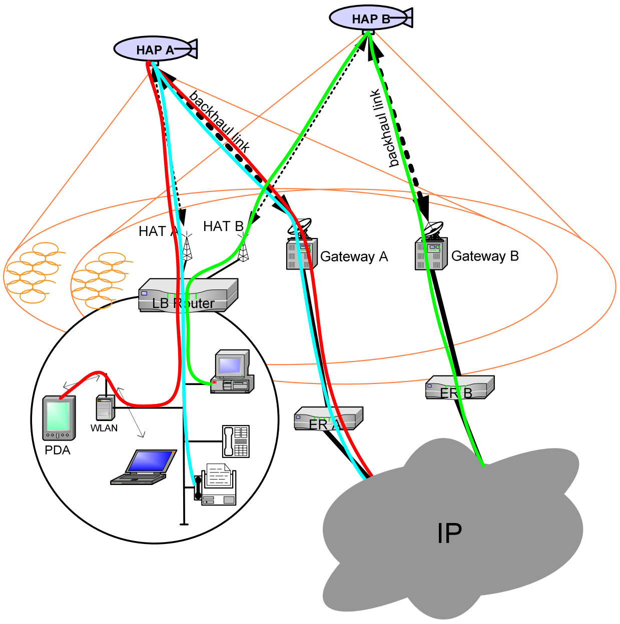

Fig. 5: HAP architecture for basic utilization of multiple HAPs: per-flow load balancing.

Advantages and disadvantages of per-packet, per-destination and per-flow load balancing are summarised in Table 1. The presented solution is independent of HAP network operator (i.e. each HAP can belong to different network domain / ISP). The capacity can be increased also if HAPs are operated by two different providers. The main disadvantage of the basic utilisation of multiple HAPs is that it is outbound only, which means that inbound traffic is forced to traverse the dedicated connection (link).

4 Advanced Utilization of Multiple HAPs for Load Balancing

As mentioned in previous chapter basic utilisation of multiple HAPs, can be used only in outbound direction. In order to provide load balancing in outbound and inbound directions, additional router with load-balancing capability should be added to the network architecture. The proposed architecture for advanced per-packet load balancing is depicted in Fig. 6. The main difference compared to the basic utilization of multiple HAPs is that the traffic load can be split also in the inbound direction in LB router 2. In this case both HAPs should be operated by the same network operator.

The advanced load balancing can be performed also with per-destination and per-flow load balancing mechanism, the latter shown in Fig. 7, using the mechanism of equal cost routes in router LB and router LB-2 for the routes over both HAPs. The same advantages/disadvantages for per-packet, per-flow and per-destination load balancing apply as described in Table 1 for basic utilisation of multiple HAPs.

Table 1: Advantages and disadvantages of different load balancing mechanisms.

	Load Balancing Mechanism		
	Per-packet	Per-destination	Per-flow
Advantages	Per-packet load balancing allows the router to send successive data packets over paths without regard to individual hosts or user sessions. Allows more evenly loaded links.	Packets for a given destination / source-destination host pair are guaranteed to take the same path, even if multiple paths are available. Traffic destined for different pairs tend to take different paths.	Packets for a given flow are guaranteed to take the same path, even if multiple paths are available. Traffic destined for different flows tend to take different paths.
Disadvantages	Packets for a given source-destination host pair take different paths, which could introduce reordering of packets. This is not recommended for Voice over IP (VoIP) and other flows that require in-sequence delivery.	It may result in unequal distribution with a small number of destination / source-destination pairs. Per-destination load balancing depends on the statistical distribution of traffic; load sharing becomes more effective as the number of destinations / source-destination pairs increases.	It may result in unequal distribution with a small number of flows. Per-flow load balancing depends on the statistical distribution of traffic; load sharing becomes more effective as the number of flows increases.

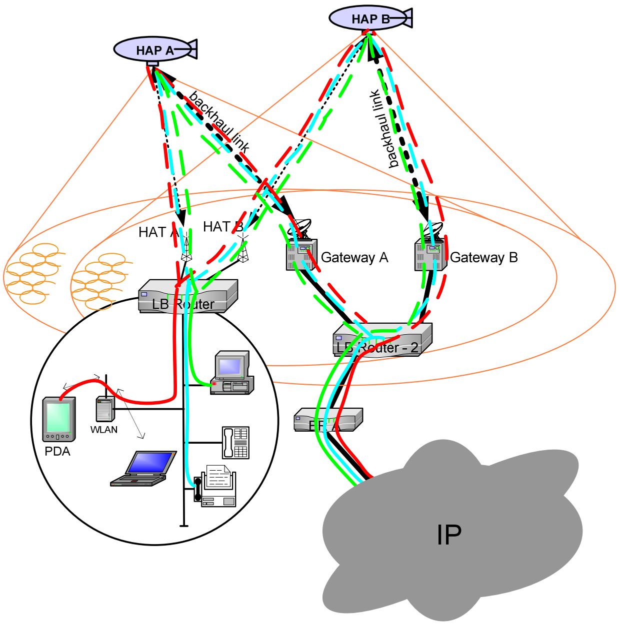

Fig. 6: HAP architecture for advanced utilization of multiple HAPs: per-packet load balancing.

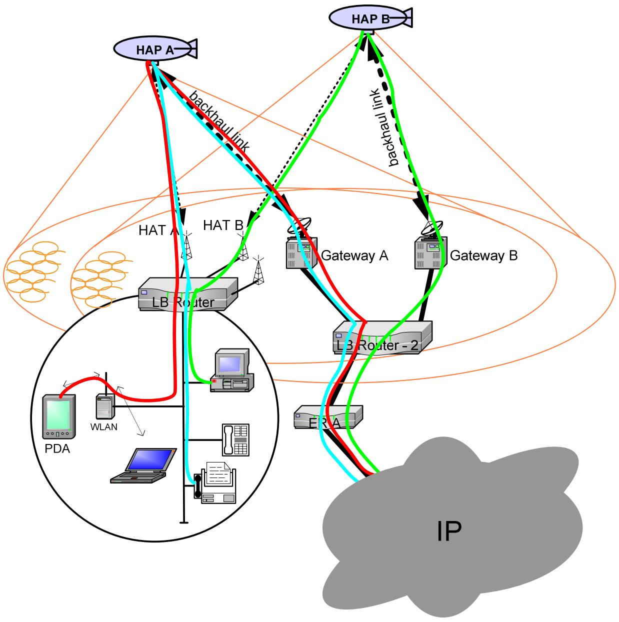

Fig. 7: HAP architecture for advanced utilization of multiple HAPs: per-flow load balancing.

5 Performance Evaluation of Load Balancing

5.1 Simulation model

In order to evaluate the impact of load balancing on the set of representative applications, we built the simulation model using OPNET Modeler simulation tool. The simulation model corresponds to per-flow load balancing assuming basic utilization of multiple HAPs as depicted in Fig. 5, and allows performance comparison with the system without load balancing mechanism. In case that traffic flows are uniformly distributed among destinations the results obtained for per-flow load balancing could be generalised also to per-destination load balancing. Per-packet load balancing, on the other hand, was intentionally not considered in the simulation model, since it is not suitable for the real-time applications (e.g. IP telephony) that are sensitive to the order in which packets arrive to the destination node.

For the purpose of this study, the simulation model consists of 100 MBit/s LAN connected to the LB router, which can establish an access link via two HAPs. The capacity of the fronthaul link between the LB router and HAPs was set to 2Mbit/s, while the backhaul link between HAPs and the gateways was set to 10 Mbit/s, thus resembling possible real scenario. In order to omit the influence of the IP backbone on the performance of load balancing, we also set the links from Gateways to ER routers and further towards servers in the IP cloud to 100 Mbit/s. The simulating scenario consists of 100 users in the LAN network using the following applications: e-mail, file transfer (FTP), web browsing (HTTP), and IP telephony (VoIP). All corresponding servers (e-mail, FTP and HTTP) are connected to the backbone, thus all the traffic goes via HAP segment, neglecting the communications between the users within the same LAN. In addition, all VoIP connections are also established with peers connected to the backbone network, again neglecting the voice communication between users within the same LAN.

The average cumulative generated traffic of all users (each user uses all applications in parallel, according to statistical distribution) is about 1.78 Mbit/s and 1.84 Mbit/s on the uplink and downlink, respectively. The simulation time was set to 120 minutes, but taking into account the simulation warm up time we calculated all average values reported in the following by eliminating the results for the first 5 minutes.

5.2 Simulation results for load balancing

In the first set of simulation results we show the impact of LB mechanism on the most congested link, i.e. the uplink between the LB router and HAP A and HAP B. If there is no LB mechanism all traffic traverses the link between the LB router and HAP A, yielding very high utilization (89 % on the uplink and 92 % on the downlink) close to the congestion. It is worth noting that we on purpose dimensioned the traffic load so that we were close to the congestion without LB mechanism. Thus, in the case of using LB mechanism the utilisation of the link from LB router to HAP A is decreased to 44 % on the uplink and 46 % on the downlink, evenly distributing the traffic load also on the link between the LB router and HAP B, resulting in the same link utilisation, i.e. 44 % on the uplink and 46 % on the downlink.

In the second set of simulation results, which are summarised in Table 2, we are investigating the impact of LB mechanism on the performance of selected reference applications. The results for average response times of non-real time applications show that all of them are significantly improved. HTTP average page response time and e-mail average download response time are decreased for nearly 300 ms, while FTP average download and upload response times are improved for approximately 1 second.

Although the above results for non-real-time traffic are important for user experience, the performance of VoIP application has even stronger impact on user experience, especially since in the case without LB mechanism the average packet end-to-end delay even exceeds the ITU recommended value for voice communications (i.e. 100 ms for packet end-to-end delay for QoS class 0) [8]. Although the average value of 104 ms is only slightly above the recommended value, the occurrence of larger deviations due to the dynamics of traffic load is quite frequent (see Fig. 8). In the case of utilising load balancing the average packet end-to-end delay is decreased for approximately 40 ms; perhaps even more important is that variation of average packet end-to-end delay is significantly reduced with respect to results obtained without load balancing. Average jitter, which is one of the important performance measures for voice traffic, is also significantly improved from 59 µs in the case without LB mechanism to 2 µs, if the LB is employed as depicted in Table 2.

Table 2: Performance of representative applications with out and with load balancing.

Application	Performance measure	no LB	LB
e-mail	Average download response time	340 ms	50 ms
FTP	Average download response time Average upload response time	1453 ms 1313 ms	425 ms 395 ms
HTTP	Average object response time Average page response time	120 ms 353 ms	57 ms 57 ms
VoIP	Average packet end-to-end delay Average jitter	104 ms 59 µs	62 ms 2 µs

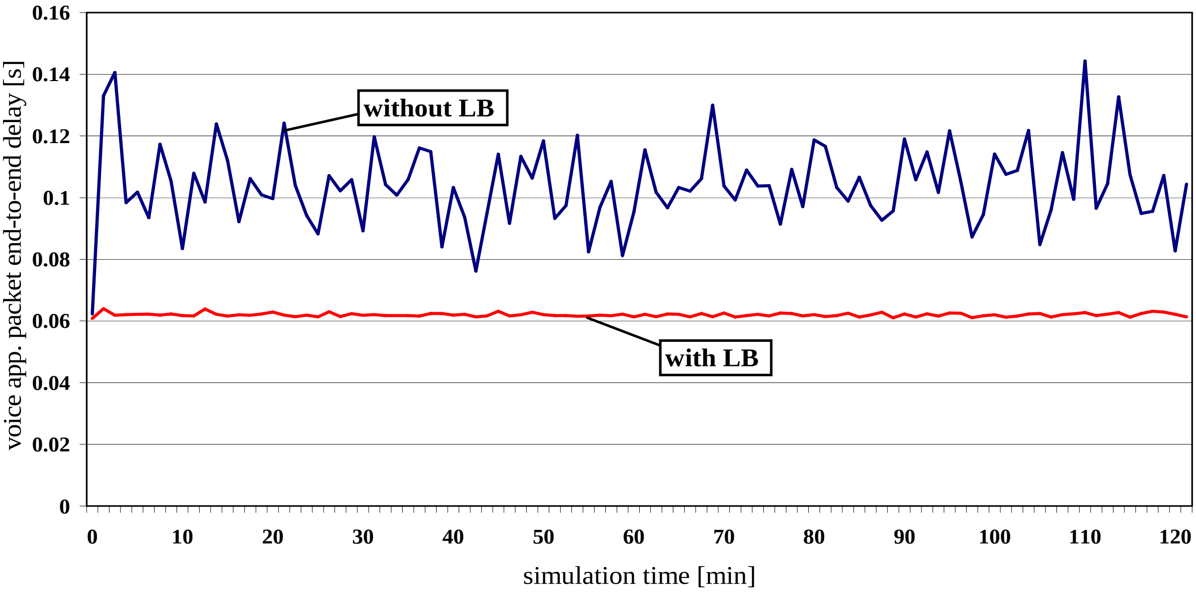

Fig. 8: Voice application packet end-to-end delay

In summary, the simulation results presented in this section confirm that the utilisation of load balancing mechanism in the case of high traffic loads significantly improves the performance of selected representative non-real-time and real-time applications.

6 Feasibility of Load Balancing in Real HAP Operating Environment

Multiple HAP systems are typically investigated in order to increase the overall system capacity by exploiting highly directional fixed user antennas [3] or to improve the total link availability between HAP and a user by exploiting the diversity gain in mobile user environment [4]. In the following we show how the same or similar multiple HAP constellation as the one used for the capacity increase can be used also for the implementation of load balancing mechanisms. In particular, we provide a thorough study of multiple HAP system comprising 4 HAPs taking into account a representative terrain configuration and compare it to the performance of a single HAP system, thus confirming the feasibility of the proposed network architectures for load balancing.

6.1 Simulation setup

The investigated multiple HAP constellation layout and the representative hilly terrain configuration (extracted from the digital relief of Slovenia) are shown in Fig. 9. In the simulation the coverage area with the radius of 30 km is selected based on the assumption that the elevation angle in the system should be equal or larger than 20 degrees. The four HAPs comprising the multiple HAP network are arranged in a circle with a spacing radius of 16 km. The antenna boresight direction is set to one half of the spacing radius, which is at 8 km, towards the centre of the coverage area. Platforms are positioned at the altitude of 17 km. The performance of this system is evaluated relative to a basic single HAP system with a platform positioned above the centre of the coverage area, with a boresight direction perpendicular to the coverage area.

The basic idea for multiple HAP constellations with fully overlaid coverage areas is based on making use of highly directional antennas, capable of discriminating spatially between different HAPs. This approach can significantly increase the system capacity by improving spectrum utilization, allowing users to share a common spectrum [5]. Careful antenna radiation pattern planning needs to be applied, in particular the planning of user antenna sidelobe levels, as this is the main factor for the efficiency of such system.

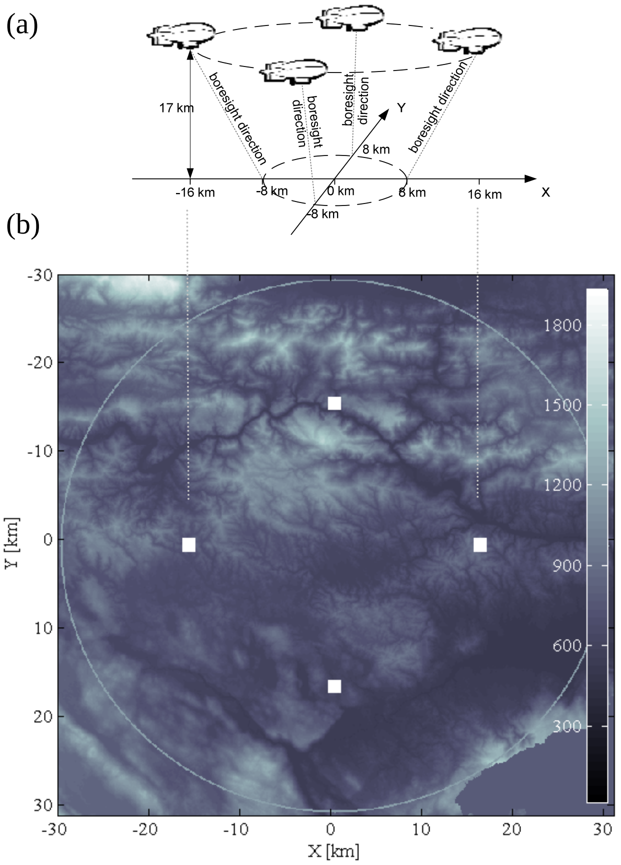

Fig. 9: The 4-HAP constellation layout (a) and the coverage area with the representative hilly terrain configuration (b).

In the following we provide visibility simulation results for the multiple HAP constellation with respect to the single HAP system. These visibility simulation results demonstrate that carefully chosen and mounted user antennas not only increase the overall system capacity within the coverage area [3] but can be also used for load balancing and to improve resilience of the network simply by using multiple antennas at user premises. Simulation results for HAP visibility have been obtained by a simulation tool developed in MATLAB using a ray tracing approach [9]. In this context the visibility means that respective HAP is above the minimum elevation angle and in the line-of-sight from the position of the user antenna. When considering such multi-HAP network architecture, the interference from adjacent non-serving HAPs can become a significant factor affecting the reception of the desired signal. In order to reduce this interference and increase the received signal level, highly directional antennas, with a 3 dB beamwidth set to 5 degrees, are assumed at user premises.

6.2 Simulation results

Representative simulation results in terms of distribution of the number of visible HAPs across the coverage area for single and multiple HAP constellations are depicted in different shades of grey in Fig. 10 and Fig. 11, respectively. These results are summarized in Table 3 giving the share of the coverage area without HAP visibility, with single HAP visibility (i.e. the case not supporting any capacity increase or load balancing) and with two or more visible HAPs.

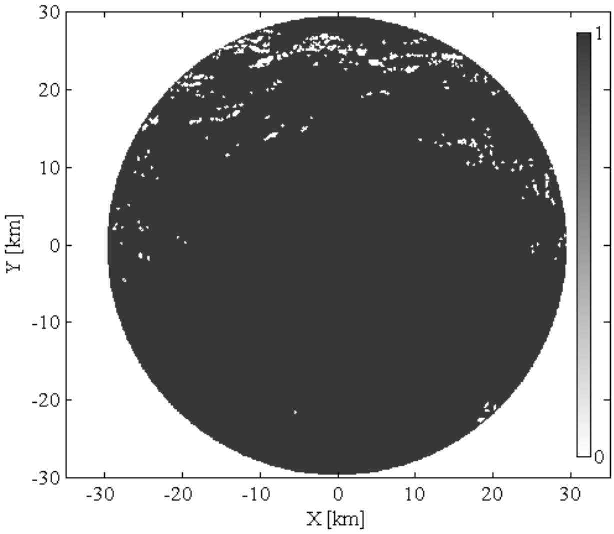

Fig. 10: Visibility distribution in the hilly terrain configuration: single HAP constellation.

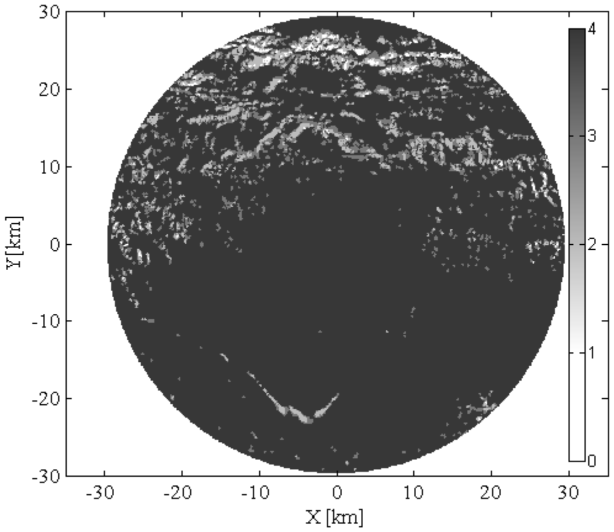

Fig. 11: Visibility distribution in the hilly terrain configuration: 4-HAP constellation.

Table 3: HAP visibility share in the coverage area.

	Visibility		
Constellation	Blocked	Single	Multiple
1 HAP	0.44 %	99.56 %	0 %
4 HAPs	0 %	0.19 %	99.81 %

Fig. 10 confirms that the elevated position of HAP guarantees very good visibility and thus access to the network practically from any position within the coverage area. In fact, according to Table 3 the wireless access via HAP cannot be provided with the assumed antenna characteristics only to 0.44 % of the coverage area. Nevertheless, Fig. 11 shows that a constellation of 4 HAPs already guarantees access from any position within the coverage area and that multiple HAP connections can be exploited for load balancing or improved access reliability from most of the locations. More precisely, there are only 0.19 % of locations within the coverage area that provide a single HAP visibility, while vast majority of locations provide access to all 4 HAPs.

7 Conclusions

In this paper we investigated the network architecture implications of introducing additional network elements/functionality for the support of load balancing in the network with multiple platforms with partially or completely overlaid coverage areas. We proposed two different architectures with regard to the complexity of additional elements/functionality, which should be installed in the system. For the basic utilisation of multiple HAPs an additional network element is added at user's premises, allowing the capacity increase on outbound connections only. The advanced utilisation of multiple HAPs is more complex and requires also the load balancing router at the gateway, allowing the load balancing in both directions, outbound and inbound. In order to be able to evaluate the performance of different services using basic utilization of multiple HAPs and per-flow load balancing we developed a simulation model in OPNET Modeler simulation tool. The results show that the performance of observed applications, and in particular the VoIP application, is significantly improved when load balancing is applied. Finally we also provided HAP visibility distribution across the coverage area for single and multiple HAP constellations, thus confirming that in multiple HAP constellation several HAPs are visible instantly from vast majority of locations in real HAP operating environments, making use of load balancing a feasible solution. In the future work we plan to investigate the impact of different scheduling policies in load balancing mechanism.

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