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Analysis and performance evaluation of integrated HAP/Satellite architectures

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***Abstract*— Both HAPS and satellite as stand alone systems represent a flexible infrastructure to provide telecommunication capabilities for a broad set of services. Nevertheless, each of the two technologies can greatly help the other to reduce the impact of some intrinsic limitation in performance. For example, the use of HAPS as intermediate point of access can greatly reduce physical layer requirements for the user terminal and can reduce the perceived latency while the satellite can be effectively used to interconnect HAPSs among one another in a cluster or to connect the HAPS with a very remote location, thus enhancing the actual coverage capability. For these and other reasons an integrated architecture looks very attractive even though complexity must be added on board the HAPS.**

The paper analyses advantages and disadvantages of the integrated HAPS/Satellite architecture both at system level and at service level. Moreover, the results of design activities at physical layer (link budget) and at transport layer (TCP protocol) will be shown.

Key Words: HAPS, Satellite, WiMax, transport protocols

1. INTRODUCTION

In recent years, broadband and ubiquitous access to communication services has become an established, worldwide diffused requirement for a growing percentage of the population. Anyway, in several scenarios (i.e. emergency, scarcely populated areas, oceans, special events, etc.) a fast to set up, efficient, and cost-effective provision of telecommunication capabilities requires the use of flexible and architectures independent on terrestrial infrastructures. In such a context HAPSs and satellite systems play a fundamental role thanks to their peculiar characteristics.

The concept of using unmanned flying (UAV) or stationary platform (HAPS) at relatively low altitudes to provide backup or support capacity to high traffic areas is now well assessed [1][2]. In general, such systems provide a number of potential advantages: low propagation delay, rapid deployment time, low maintenance costs, implementation of ad-hoc interfaces towards the user terminals.

A HAPS is intended to act as a relay station. A generic HAPS network can include a certain number of HAPS each one having a footprint of a radius more than 150 km. In general, the lower the minimum elevation angle for the HAP, the larger the coverage area but the propagation or blocking loss becomes high at the edge of the servicing area. A practical minimum elevation angle for Broadband Wireless implies that for a platform positioned at an altitude of 20 km the radius of the coverage area is approximately 200 km. HAPSs can intercommunicate through inter-HAP links and/or can be connected among one another by means of one or more satellites thus creating a hybrid HAPS-Satellite communication network. Ground stations such as the WiMax BSs, which connect the HAP network with other terrestrial networks, can be placed on roofs of buildings. For remote areas where there is no substantial terrestrial infrastructure, satellites can be used as backhaul.

On the other hand, satellite systems are intrinsically suitable to provide ubiquitously broadband services, not depending on ground situation. They offer large coverage areas ensuring also long range mobility, large bandwidth, cost-effectiveness to provide broadcast and multicast services, suitability to provide connectivity in emergency scenario and easiness to set up.

In this paper, we considered an integrated HAPS-satellite system as an even more suitable solution to guarantee the provision of broadband service everywhere [3] and in particular in emergency and critical scenario. In particular, two study cases are addressed: the extension of WiMax service and the impact of a hybrid space based architecture on transport protocols performance.

2. IDENTIFIED SCENARIOS

WiMax standard is proposed as last-mile solution for broadband wireless access. A space based infrastructure to support WiMax operation can greatly improve the performance in terms of coverage extension and service requirements satisfaction for both mobile and fixed users. A possible architecture is depicted in Figure 1. It envisages a direct interaction between HAPS and WiMax systems, in order to relax WiMax Subscriber Station (SS) or Base Station (BS) EIRP requirements, while the HAPS is connected to the satellite both to interconnect the cluster and to reach remote locations.

This paper presents the main results for the feasibility assessment of the considered integrated system architecture

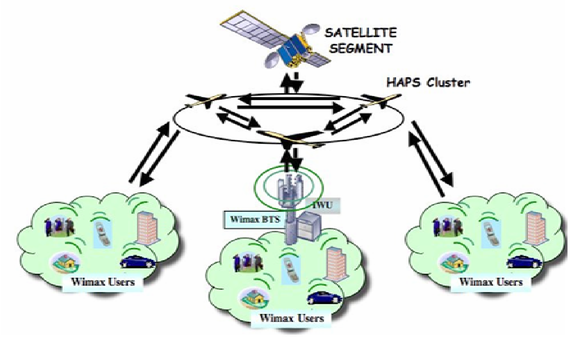

Figure 1: Proposed WiMax-Satellite-HAPS-WiMax solution

In addition, with classical satellite architectures, performance of the applications running on top of TCP (i.e. web traffic, FTP transfers, e-mails, etc.) are strongly affected by both the large propagation delay and random losses [6][7][8]. Also in this case, the insertion of a HAPS as intermediate node can improve performance. In particular, we investigate two different ways of maintaining TCP connections:

- *End to end connections, from ground user to Internet server.* We evaluate different TCP protocol choices including the legacy TCP New Reno [9] and the TCP Westwood [10] proposed by UCLA computer science department to improve performance over wireless links.
- *Proxy server on board of the HAPS and/or the satellite.* The idea is to split the TCP connection both on board the HAPS and on board the satellite thus reducing the problem into more tractable sub-problems [11].

This TCP performance analysis has been carried out by implementing a simplified model of the scenario depicted in Figure 2 in the Network Simulator Ns-2 [12]. Furthermore, without loss of generality, the following physical parameters have been considered:

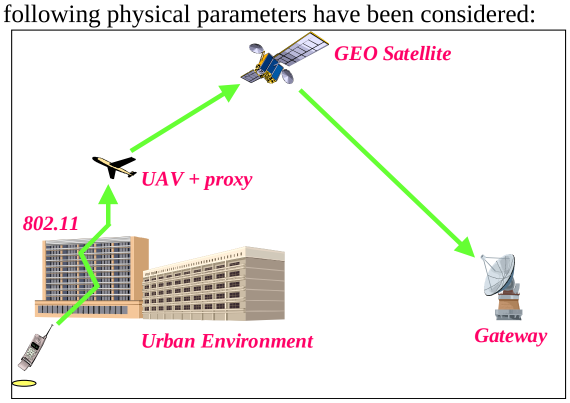

Figure 2: Identified scenario for transport protocol analysis

- Bandwidth: 1 Mbit/s;
- Round-Trip Time (RTT): 504 ms;
- Packet Error Rate (PER) over the HAPS-WiMax link varying between 0.1% and 1%;
- PER over satellite link: 0.1%.

3. WIMAX EXTENSION

3.1. Models and Assumptions

3.1.1. Satellite and HAPS characteristics

As concerns physical layer analysis, both satellite and HAPS payloads are assumed to be transparent. The Ka frequency band is used for satellite-HAPS communications while the band around 3.5 GHz (which represents the allocations for WiMax) is adopted for the HAPS-WiMax links. The scheme in Figure 3 illustrates a generic architecture of a single transponder of the satellite. In more details, the received signal (i.e. WiMax OFDM-256) from the common receiving antenna is first filtered by a band-pass filter (BPF) centered on the uplink transmitter frequency. Band-pass filtering is required to isolate the receiver low noise amplifier (LNA) from the transmitted downlink signals. The signal at the output of the LNA is (optionally) frequency converted to another band downlink transmission. The signal is then amplified by a high power amplifier (HPA) before retransmission. The HPA for a satellite can be a traveling wave tube (TWT) or a solid state power amplifier (SSPA). Additional AGC amplification (not shown in Figure 3) could be used to keep the signal to the required level. However, the gain adjustment is commonly controlled by ground commands and the use of an AGC would provide an additional element of uncertainty in the earth terminal transmitting power control commands. For this reason on-board AGC is commonly avoided.

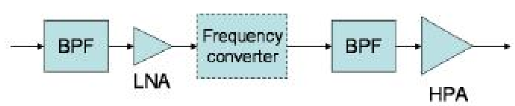

Figure 3: Generic payload architecture for transparent satellite or HAPS-single transponder

The transparent HAPS payload is similar to that presented in Figure 3.

3.1.2. WiMax Characteristics

WMAN based on WiMax is usually configured as a traditional cellular network with base stations (BS) using a point to multipoint (PMP) architecture to deliver communication services to subscriber stations (SS) over coverage radius up to several kilometers. The central BS can handle communications over multiple independent sectors simultaneously and transmits without having to coordinate with other stations, except when overall time division duplexing (TDD) is adopted.

In this paper, a WiMax radio interface based on the OFDM-256 modulation format [5] is considered. In particular, the number of the OFDM sub-carriers (N_{FFT}) is 256 and the number of used sub-carriers (N_{used}) is

200. Up to 8 pilot sub-carriers can be inserted in the signal. The guard band carriers are numbered from -128 to -101 and from 101 to 127. The guard time interval is Tg =1/4, 1/8, 1/16, 1/32 of T_b and T_b is the useful OFDM symbol time. For link budget purposes we assumed an OFDM signal bandwidth BW=5 MHz and the primary and secondary OFDM signal parameters obtained as in [5] have been indicated in Table 1.

Primary OFDM parameters			
OFDM signal bandwidth	BW	5	MHz
Normalization factor	n	1,152	
Sampling frequency	*Fs*	5760000	Hz
N. of OFDM sub-carriers	N_{FFT}	256	
N. of used sub-carriers	N_{used}	200	
Secondary OFDM parameters			
OFDM Carrier spacing	_f	22500	Hz
Equivalent noise bandwidth	*Beq*	4500000	Hz
Useful OFDM symbol time	T_b	0,000044	s
OFDM guard time	T_g	0,000003	s
OFDM symbol time	T_s	0,000047	s

Table 1: OFDM-256 signal parameters

3.2. Link Budget Analysis

To calculate the overall signal to noise ratio at the end of the multi-hop transmitter-receiver chain, without loss of generality we consider the three-hops communication scheme indicated in Figure 4. L_{mn} represents the overall loss on the link connecting the *m*-th transmitter with the *n*-th receiver. For simplicity of notation, we assume that L_{mn} includes the *m*-th transmitting antenna gain and the *n*-th receiver antenna gain. The $N^{(n)}=kT_{sys}^{(n)}$ is the overall noise power added to the received signal in the *n*-th repeater stage and $T_{sys}^{(n)}$ is the corresponding system temperature and *k* is the Boltzmann's constant. The I_n indicates the power of the intermodulation at the output of the *n*-th transmitter. We assume that the disturb due to intermodulation $i_n(t)$ at the output of the *n*-th HPA is orthogonal with the signal $as_n(t)$ where *a* is a (complex) coefficient and $s_n(t)$ is the input signal (possibly including noise).

From the scheme in Figure 4 the carrier to interference plus noise ratio at the receiver input is:

$$\frac{C}{N+I}=\frac{1}{\sum_{n=1}^{n_h}SNR_n^{-1}+\sum_{n=1}^{n_h-1}SIR_n^{-1}} \tag{1}$$

where n_h is the number of hops and SNR_n is the useful signal power to noise ratio at the input of the *n*-th receiver; for example:

$$SNR_n=\frac{L_{(n-1)n}P_T^{(n-1)}}{N^{(n)}} \tag{2}$$

where $P_T^{(n-1)}$ is the (maximum) useful transmitted power at the output of the *(n-1)*-th transmitter. In presence of non-linearities the output power is reduced by the output back-off (OBO), defined as:

$$OBO=10\log_{10}\left(\frac{P_{max,OUT}}{P_{OUT}}\right) \tag{3}$$

The SIR_n accounts for non-linear effects and it is the useful signal power to intermodulation ratio measured at the output of the *n*-th transmitter in the chain.

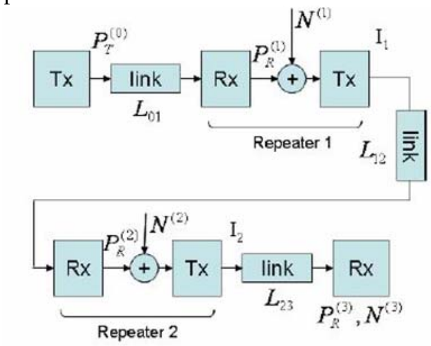

Figure 4: Multiple hop communication scheme (3-hops case)

To perform link budget analysis we made the following assumptions:

1) the maximum value of the output power level that can be transmitted from the satellite or from the HAPS is fixed;
2) we assume that the transmitter-receiver amplifier chain of the repeater (satellite or HAPS) is a design parameter to be determined in order to provide the maximum output power;
3) intermodulation effects are neglected;
4) the free space propagation model is considered; WIMAX and the Satellite or the HAPS are always in line of sight; rain margin and additional losses due to atmospheric effects are included in the calculations when applicable;
5) interference and shadowing are not considered.
6) the WIMAX to HAPS link uses the frequency of 3.5 GHz while the HAPS to WIMAX link uses the frequency 3.0 GHz. Transmissions of the HAPS to the satellite use the Ka band.

In the next section, we provide the link budget result for the considered architecture by considering link budget parameters used for the calculations in Ka band and summarized in [14].

3.3. Feasibility Assessment

In Table 2 an example of link budget corresponding to the network architecture WiMAX-HAPS-SAT-HAPS-WiMAX, is reported. As a first advantage, no rain margin has been considered since the first and the last hop operate around 3 GHz and HAPS are positioned at 20 km from the Earth so that the link with the satellite is out of the troposphere.

The links HAPS-Satellite and Satellite-HAPS, as expected, are critical and the overall C/N results are practically independent on the WiMAX transmitter characteristics i.e. transmitter power and antenna size. This is further confirmed by the data in Table 3 where the overall C/N has been evaluated considering different values of the WiMAX antenna diameter and transmitter power.

Uplink - Wimax BS to HAPS			
Effective Isotropic Radiated Power	EIRP	54.8	dBW
Uplink propagation loss	Lup	129.4	dB
Additional losses	Ladd	4.0	dB
G/T	G/T	21.7	dB/K
Noise eq. bandwidth x k	kBeq	-162.1	dBJHz/K
Received power	C	-19.9	dBW
Overall HAPS Gain	GHaps	32.9	dB
Uplink C/N	C/N up	105.3	dB
Uplink - HAPS to Satellite			
Effective Isotropic Radiated Power	EIRP	74.7	dBW
Uplink propagation loss	Lup	214.1	dB
Additional losses	Ladd	2.0	dB
G/T	G/T	39.9	dB/K
Noise eq. bandwidth x k	kBeq	-162.1	dBJHz/K
Received power	C	-77.6	dBW
Overall Satellite Gain	Gsat	90.6	dB
Uplink C/N	C/N up	60.7	dB
Downlink - Satellite to HAPS			
Effective Isotropic Radiated Power	EIRP	72.8	dBW
Downlink propagation loss	Ldl	210.5	dB
Additional losses	Ladd	2.0	dB
G/T	G/T	38.6	dB/K
Noise eq. bandwidth x k	kBeq	-162.1	dBJHz/K
Received power	C	-109.7	dBW
Overall HAPS Gain	GHaps	114.5	dB
Downlink C/N	C/N d	61.0	dB
Downlink - HAPS to WiMAX BS			
Effective Isotropic Radiated Power	EIRP	46.5	dBW
Downlink propagation loss	Ldl	128.0	dB
Additional losses	Ladd	4.0	dB
G/T	G/T	19.1	dB/K
Noise eq. bandwidth x k	kBeq	-162.1	dBJHz/K
Received power	C	-43.8	dBW
Downlink C/N	C/Nd	95.7	dB
Overall SNR			
Sum of the inverse of C/N	C/N T	57.8	dB
Ref. SNR (BPSK rate 1/2)		6.4	dB
Ref. SNR (QPSK rate 1/2)		9.4	dB
Ref. SNR (16QAM rate 1/2)		16.4	dB
Ref SNR (64QAM rate 1/2)		22.7	dB

Table 2: Example of link budget calculation for WiMAX-HAPS-SAT-HAPS-WiMAX link

The HAPS and Satellite Tx/Rx antenna parameters used to obtain data in Table 3, Table 4 and in Table 5 have been shown in Table 6.

Since the Satellite-HAP gain and the WiMAX-gain are independent on the WiMAX transmitter characteristics, the required overall satellite gain is constant and it is equal to 90.6 dB while the HAP gain for maximum output power on the HAP-WiMAX link is 122 dB.

As shown in Table 2 the availability of two HAPS acting as repeaters to/from the satellite allows to achieve WiMAX transmitter-receiver requirements in terms of transmitter power and, most important, on the antenna size of the same order of the terrestrial systems and, more important, significant improvement is also obtained if compared with the case of WiMax terminals directly connected to the satellite, as shown in [14]. As concerns the space segment (satellite and HAPS) the achieved figures looks realistic compared to real system implementation. Nevertheless, to pursue the practical feasibility of this architecture optimizing space resources, accurate trade off analysis must be performed between overall satellite gain and HAPS parameters.

	WiMax Transmitter power (W)								
D (m)	**0.5**	**1**	**2**	**3**	**4**	**5**	**10**	**12**	**15**
0.1	53.4	54.6	55.4	55.7	55.8	55.9	56.1	56.2	56.2
0.5	57.5	57.6	57.7	57.7	57.7	57.7	57.7	57.7	57.7
1	57.7	57.8	57.8	57.8	57.8	57.8	57.8	57.8	57.8
1.5	57.8	57.8	57.8	57.8	57.8	57.8	57.8	57.8	57.8
2	57.8	57.8	57.8	57.8	57.8	57.8	57.8	57.8	57.8
2.5	57.8	57.8	57.8	57.8	57.8	57.8	57.8	57.8	57.8
3	57.8	57.8	57.8	57.8	57.8	57.8	57.8	57.8	57.8
5	57.8	57.8	57.8	57.8	57.8	57.8	57.8	57.8	57.8

Table 3: Overall C/N as a function of the WiMAX transmitter power and antenna diameter

In Table 4 we show the HAP overall gain required to polarize the high power amplifier so to provide the maximum output power on the HAP-Satellite link.

	WiMax Transmitter power (W)								
D (m)	**0,5**	**1**	**2**	**3**	**4**	**5**	**10**	**12**	**15**
0,1	66,9	66,9	66,9	66,9	66,9	66,9	66,9	66,9	66,9
0,5	52,9	52,9	52,9	52,9	52,9	52,9	52,9	52,9	52,9
1	46,9	46,9	46,9	46,9	46,9	46,9	46,9	46,9	46,9
1,5	43,4	43,4	43,4	43,4	43,4	43,4	43,4	43,4	43,4
2	40,9	40,9	40,9	40,9	40,9	40,9	40,9	40,9	40,9
2,5	38,9	38,9	38,9	38,9	38,9	38,9	38,9	38,9	38,9
3	37,4	37,4	37,4	37,4	37,4	37,4	37,4	37,4	37,4
5	32,9	32,9	32,9	32,9	32,9	32,9	32,9	32,9	32,9

Table 4: Required WiMAX – HAP - Satellite gain

	WiMax Transmitter power (W)								
D(m)	**0,5**	**1**	**2**	**3**	**4**	**5**	**10**	**12**	**15**
0,1	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5
0,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5
1	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5
1,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5
2	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5
2,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5
3	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5
5	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5	114,5

Table 5: Required Satellite – HAP - WiMAX gain

Diameter of HAPS Tx-Rx antenna to SAT (m)	**5**
Diameter of HAPS Tx-Rx antenna to WiMAX (m)	**5**
Diameter of SAT Tx antenna	**6**
Diameter of SAT Rx antenna	**6**

Table 6: Antenna parameters for HAPS and satellite

4. TCP PERFORMANCE EVALUATION

4.1. Network Simulator Platform

NS-2 is one of the most powerful general purpose platforms to perform simulation analysis at network level [12]. It provides substantial support for discrete event driven simulations at various network levels. One of the main characteristic of NS-2 is its extensibility that allows inserting new functionalities and models, to investigate different scenarios and new protocols.

In the frame of the TCP performance analysis carried out in this paper, we have added the code to simulate the behavior of TCP Westwood [10] and a splitting [11] scheme at the HAPS. In fact, as discussed in [3], both TCP Westwood and TCP splitting represent suitable solution to enhance transport layer performance. Of course, TCP splitting requires the installation of a proxy, and then not transparent payloads on the HAPS/satellite. Moreover, we have written the OTcl scripts to configure the scenario depicted in Figure 1. This allowed to obtain meaningful and fully understandable results by precisely configuring various network parameters:

- TCP packet size
- queue size at nodes and cache size at the proxy (when present)
- Location of the proxy (when present)
- Propagation delay of each link
- capacity of each link
- TCP Packet Error Rate on each link
- Number of flows present at on the channel
- Involved TCP/IP protocols.

4.2. Simulation configurations

In particular, the following parameters are assumed in our analysis. The bandwidth available on each link is 1 Mb/s and the packet size is 1500 bytes, thus having a pipe capacity of about 42 packets on the round trip connection. The buffer available between each couple of adjacent nodes is 50 packets, while a cache of 200 packets have been utilized by each proxy, if not differently specified, when splitting mechanism is enabled. Furthermore, each simulation has been run utilizing different combinations of transport protocol, various PER on the ground to Haps link, presence or absence of a proxy on the ground satellite station and on the satellite, diverse dimensioning of the cache in the proxy, and alternate direction of the data flow. Summarizing the various alternatively chosen features:

- transport protocol: TCP New Reno [9], TCP Westwood [10]
- PER on the ground-Haps link: 0.1%, 0.5%, 1.0%
- proxy on board
  - on the ground satellite station: split enabled, split disabled
  - on satellite: split enabled, split disabled
- Traffic direction: UT-Sat-Haps-UT, UT-Haps-Sat-UT.

4.3. Simulation results

A first point of interest is undoubtedly the performance benefits achievable combining the use of TCP Westwood and a splitting proxy. In Figure 5 we compare the average throughput achieved in the WHSW traffic direction for different combinations of transport protocol, eventual utilization of a splitting proxy on HAPS, and various PER in the ground-Haps links. For each configuration we have run 20 simulations averaging the number of bytes sent in 230 seconds to calculate the average throughput achieved. Again, TCP Westwood coupled with a proxy attain the best results, with an average throughput that reaches 923.53 kbit/s (with a PER of 1.0%) to 961.18 kbit/s (with a PER of 0.1%). The ability of the splitting mechanism to hide the frequent errors on the shortest wireless link from the rest of the connection is confirmed: once chosen a transport protocol, the average throughput achieved remains almost constant, independently from the PER present.

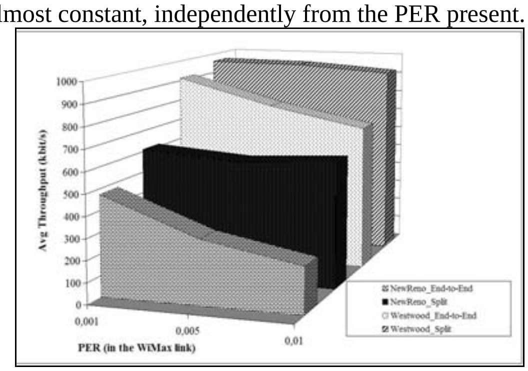

Figure 5: Average throughput over a 230 seconds transmission in UT-Haps-Sat-UT direction

For the sake of completeness, a set of simulations which considers the reverse data flow (UT-Sat-Haps-UT) has also been performed and corresponding results are shown in Figure 6. The outcomes closely match the previous results. In fact, even in this case performance increases as a result of the ability of TCP Westwood in dealing with wireless links, while the splitting scheme again protects the whole connection from the frequent errors in the ground-Haps link.

The performance advantage in using the splitting technique comes from the ability of this scheme in locally circumscribing wireless problems. Moreover, since proxies along the path generate TCP acks faster than a ~500ms (of RTT) far receiver, the congestion window at the sender can increase faster and thus speeding up the transmission rate.

Specifically, the higher the overall PER, the greater the TCP splitting benefits. To enforce such evidence, we have compared the pure end-to-end case with those involving the utilization of one (S-split) or two proxies

(D-split) located (a further TCP proxy on satellite). The final result presented in Figure 7 concerns a 5 MByte file download in the UT-Haps-Sat-UT direction and y-axis reports the average time required by the various configurations. As it is easy to see, TCP NewReno takes great benefit from the ability of proxies present on the path in dealing with wireless losses: deleterious shrinkage of the sending windows are avoided when not necessary, thus reaching a very high utilization of the channel (about 91% of the capacity in case of double split) and equaling TCP Westwood performance.

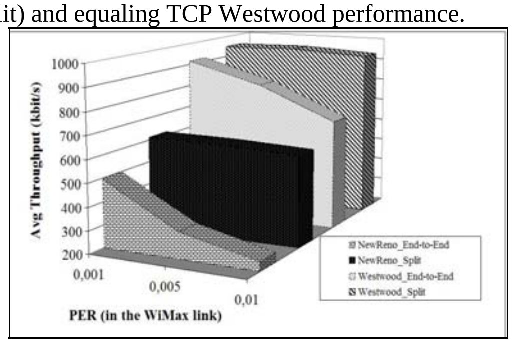

Figure 6: Average throughput over a 230 seconds transmission in WSHW direction

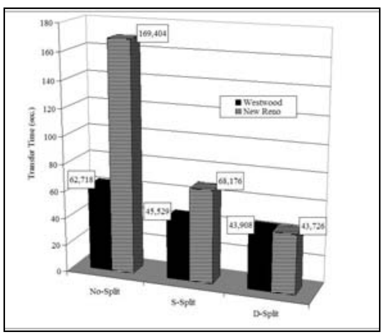

Figure 7: Transfer Time measurement for different TCP splitting configurations

5. CONCLUSIONS

We presented feasibility analysis for a communication architecture based on the integration of three different systems: WiMax, HAPS and satellite. In particular, we observed the fundamental role of HAPS that located at approximately 20 km of altitude can be helpful to relax the WiMax transmitter requirements. This allows achieving very high link budget margins on both the WiMax-HAPS and HAPS-satellite links. Moreover, it was observed that also the direct connection between WiMax and satellite by providing a large satellite receiver gain.

Finally, we proposed some solutions enhancing TCP performance, when the proposed systems is used to access to TCP-based services. In particular, we demonstrated that both TCP Westwood and TCP splitting greatly improve performance perceived at the end-points.

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