A Flexible Communication System for High-Speed Broadband Wireless Access from High Altitude Platforms: a CAPANINA Candidate

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***Abstract*— This paper discusses the provision of broadband services from High Altitude Platforms (HAPs), and analyzes a flexible communication system for HAP-based multimedia communications. Particular attention is paid to the broadband connection to high-speed trains, as the primary reference scenario addressed in the CAPANINA project, which inspired this work. The high coding gain required by this high-mobility scenario is achieved through adaptive concatenated coding schemes, while smart antennas operating with adaptive beamforming algorithms are employed at the ground stations to cope with the fast relative movement of the end-point antennas. Simulated system performance based on a one-ray Ricean fading model of the stratospheric channel show the effectiveness of the proposed approach to achieve target QoS requirements.**

I. Introduction

EFFICIENT and reliable wireless solutions are becoming mandatory to respond to the market demand, which presses for communication service availability "anytime and anywhere," at high rate, with fast connections, and user-friendly personal terminals. This context has led to the huge worldwide development of cellular personal mobile telephony, which is nowadays evolving to a mobile multimedia and entertainment service, and to the growing deployment of wireless network segments that provide Internet, Intranet, and entertainment services and applications for their customers.

Broadband Wireless Access schemes (BWA), evolved from Fixed Wireless Access (FWA) paradigms, are intended to provide multimedia services to both personal and business users, at data rates typically beyond 2 Mbit/s. BWA should offer increased capacity with respect to common wireline high-rate schemes, such as ADSL and ISDN, with extremely low-cost and fast deployment characteristics, with the real medium-term possibility of reaching subscribing users practically anywhere.

Eight years after the publication of the paper by Djuknic, Freidenfelds and Okunev [1] in 1997, which for the first time clearly stated in the international community the idea of using HAPs for communication services, we can now mention High Altitude Platforms (HAPs) among the systems having the technological and commercial potential to offer wireless high-capacity services. The nature of these aerial vehicles, which fly in the stratosphere in the mild wind-speed zone between 17 and 22 km, can range from airplanes to airships and aerostats (balloons) [2].

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The interest in using these platforms for integrated communication services has been increasing in the past years, with the constantly increasing need for low-cost communication services, not only in highly populated areas, where communication infrastructures are generally present, but also in isolated or scarcely populated areas. However, HAPs can be seen not as competitors of previously existing communication systems, such as satellite and terrestrial systems, but as a novel, interesting and flexible element, namely the "stratospheric segment," which can be integrated with preexisting structures.

The European Community has funded, among others, two projects focused on the development of a network of HAPs integrated in the existing systems of personal communications, radio-location and navigation, and 4G broadband communication services. The HeliNet project [3], [4] was funded under the V Framework Programme initiative, to analyze the feasibility of a network of stratospheric platforms for traffic monitoring, environmental surveillance and broadband communications. It was followed by a second project, named CAPANINA, "Communications from Aerial Platform Networks delivering Broadband Communications for All" [5], funded under the European VI Framework Programme initiative and focused on the broadband communications aspects, including trials with aerial vehicles (tethered balloons and, possibly, an existing HAP). It started in November 2003 and has a three-years duration.

CAPANINA aims at answering to the demand of broadband communication services for "all potential users", also those located in hard-to-reach geographical areas and hard-to-manage conditions, such as high speed trains. Thanks to the high-capacity connectivity offered by HAPs (up to 120 Mbit/s), such users shall be seamlessly integrated into the wider broadband network, through a stratospheric network segment that complements both terrestrial and satellite infrastructures.

A fully developed CAPANINA system must provide for bi-directional high-capacity links from the aerial platform to a number of ground stations, which can be either still (customer premises) or in fast movement (trains). Over those links, a variety of broadband traffic is expected, from video-on-demand and video streaming to community TV broadcasting and broadband Internet. The above applications require to define a communication framework able to handle high-capacity links which connect pools of end-users (e.g., the passengers of a train, the WLAN users in an enterprise campus) with an "intermediate flying gateway" to the Internet, through suitable wired or wireless access points in the vicinity of the users' equipment. In such a context, that includes fast mobility, high data rate and multimedia applications over bi-directional links, it is evident that providing Quality-of-Service-guaranteed services is a critical issues. Indeed, establishing high-capacity wireless links presents a variety of challenges, ranging from the extremely variable propagation conditions, the presence of Doppler and multipath fading for mobile links, the power efficiency of the non-linear amplifiers, the synchronization aspects, to the radio resource management issues, which must cope with limited spectrum availability, a variety of requirements for different kinds of supported traffic, and the interference with other existing or foreseen services. However, network level QoS requirements (e.g., bandwidth to be reserved, tolerable end-to-end delay and tolerable data loss rate) directly rely on physical layer performance, i.e., on the achieved signal-to-interference-and-noise ratio and bit error rate. Therefore, highly efficient signal processing solutions, able to increase the overall system reliability and spectral efficiency, and to cope with the fast mobility and variability of the addressed scenarios, become of primary interest.

These solutions are specifically the objective of the work reported in this paper, which investigates a flexible system architecture for high-mobility HAP-based communications. The proposed architecture is based on high-gain beamforming techniques based on smart antennas technology, and flexible channel coding schemes suitable for the stratospheric channel.

II. The HAP-based transmission system

The link from the HAP, acting as an "intermediate flying gateway", to the users' access point can represent a sort of "wireless last mile" of the network. This functional context suggested to look at a communication standard expressly intended to provide "last mile" communication services in wireless technology. The most promising proposal, at an early stage of the CAPANINA project, has been represented by the IEEE 802.16/802.16a standard, which addresses applications of wireless technology to link commercial and residential buildings to high-rate core networks [6]. Offered capacities and addressed frequency bands make 802.16 a very promising candidate for the CAPANINA communication services. Nonetheless, the IEEE 802.16 standard family has been initially developed for fixed BWA services; though recent works address mobility issues, the problem of handling fast mobility and non-LOS propagation conditions is still open and is object of deep investigations within the CAPANINA project.

Physical layer (PHY) specifications considered under CAPANINA have been related to the standards IEEE 802.16 (single carrier, SC) and IEEE 802.16a (OFDM). The work on this topic aimed at comparing system performance achievable with these standards. In this paper, the OFDM adopted by the standard IEEE 802.16a is investigated. Its main parameters are summarized in Table I [7].

The 47-48 GHz and 28 GHz bands assigned for HAP-based communications, determine propagation conditions in which large scale multipath effect, due to terrain, hills, buildings, other vehicles, is rarely an issue, at least for rural and suburban environments, since obstacle surfaces, rough with respect to the millimetric signal wavelength disperse the impinging energy instead of reflecting it back [8]. In this scenario, the large-scale channel structure includes a single propagation path along the ground-terminal-to-HAP link direction. On the other hand, in dense urban scenarios specular reflections are possible, due to the presence of building surfaces as glass and marble, smooth enough to generate multipath effects. In both cases, free-space attenuations and energy dispersion due to hydrometeors are the main source of signal deterioration, and suggest the use of high-gain antennas. Since we are dealing with mobile communications, it is not possible to employ directive high-gain fixed ground antennas, and it is therefore necessary to insert high-gain channel codes coupled with medium-gain antennas suitable for mobile applications. The use of concatenated channel codes and smart antennas seem a natural solution for the proposed scenario. Furthermore, the use of smart antennas and adaptive concatenated coding schemes improves the QoS performance at the physical layer, enhancing the received signal level with respect to noise and interference. Last but not least, the coupling of adaptive concatenated coding and smart antennas offers the flexibility required by a transmission system suitable for multimedia services.

No. of total OFDM carriers	256
No. of unused lower carriers	28
No. of unused higher carriers	27
Guard band ratio, G	$1/4,\ 1/8,\ 1/16,\ 1/32$
Bandwidths, B_w	$20,\ 25,\ 28$ MHz
Modulation schemes	BPSK, QPSK, 16QAM, 64QAM
OFDM symbol time	12.5μs @20MHz, 10μs @25MHz, 9μs @28MHz

TABLE I

Main physical layer parameters for the IEEE 802.16a standard.

Before presenting some preliminary results of the research activity developed within CAPANINA in the field of advanced smart antennas and channel coding solutions, it is interesting to observe a link budget evaluated for one of the most critical applications, which is the transmission from HAP to high-speed trains.

III. Link budget evaluation

In Table II the link budget for the HAP-to-train downlink is reported. Considering the system constraints previously described, the use of a high-gain multi-beam on-board antenna in conjunction with a smart ground antenna has been considered. The HAP is assumed to fly at an altitude of 20 km and to provide broadband services over a region of about 35 km radius on the ground. The region covered by the HAP is divided into cells and frequency reuse is adopted to avoid inter-cell interference. A uniform cellular structure is obtained by illuminating the covered area with multiple antenna elliptic beams, to give circular footprints on the ground. Each HAP antenna is supposed to provide 22 dB gain. Within each cell a communication link compliant with the IEEE 802.16a standard is established. For the link-budget considered here, a 20 MHz system bandwidth has been assumed, along with a medium-length guard interval (1/8 of the total symbol period), resulting in a coded bit-rate of 61.44 Mbps, provided via a 16-QAM modulation scheme. The channel code is assumed to provide a coding gain of 6 dB.

Parameter	**Value**
Transmitter	
Modulation Scheme	16-QAM
Code-Rate	1/2
Code Gain [dB]	6
Uncoded Bit-Rate [Mbps]	30.7
Coded Bit-Rate [Mbps]	61.44
Number of Spot Beams	37
System Bandwidth [MHz]	20
Carrier Frequency [GHz]	28
HAP Antenna Gain [dB]	22
Transmitted Power per Spot [dBW]	15.2
Total Transmitted Power [dBW]	30.9
Channel	
Worst Case HAP-Train Distance [km]	40
Free-Space Attenuation [dB]	153.4
Atmospheric Attenuation [dB]	4.5
Outage Probability	1e-3
Fading Margin [dB]	10
Receiver	
Implementation Loss [dB]	2
Number of Train Array Sensors	16
Train Antenna Gain [dB]	17
Receiver Operative Temperature [°K]	1000
N_0 [dB]	-199
BER	1e-6
E_b/N_0 [dB]	14.45

TABLE II

LINK BUDGET FOR THE HAP-TO-TRAIN SCENARIO.

In order to guarantee a bit error rate of 10^{-6} over the whole covered area, the link budget has been evaluated by considering a user located at the edge of the region. The power received at the ground terminal is affected by atmospheric attenuation effects, evaluated as 4.5 dB, essentially due to oxygen and water vapors, and by Ricean fading, with 20 dB Rice factor as in a rural environment [9]. To ensure an outage probability of 10^{-3}, the fading margin has been set to 10 dB. Finally, an implementation loss of 2 dB has been included, accounting for both physical and algorithmic loss effects.

The train receiver is equipped with an array of sensors, controlled by an adaptive algorithm whose main role is to keep the receiver antenna steered toward the direction of the HAP, despite the possible rapid relative movement of both end-points of the link. By adopting a 16 sensor smart antenna, the theoretical receiver antenna gain is 17 dB.

With these assumptions, the platform is required to transmit a power of 15.2 dBW per spot beam, resulting in a total power required for broadband communications of 30.9 dBW.

IV. ADVANCES ON SMART ANTENNAS TECHNOLOGY FOR HIGH-SPEED TRAINS

It is recognized that smart antennas play a key role as a new technological tool to enhance efficiency of radio resource allocation plans, thanks to their capability of reducing co-channel interference, mitigating multipath fading, and overcoming some critical aspects of other system components, such as equalizers and power controllers. In the CAPANINA context, the antennas at the end-points of the stratospheric link always have a non-zero relative velocity, which can be even very high in case of a ground terminal placed on board of a train. For the flying antenna it may be preferable, in some cases, to implement a fixed spot-beam coverage of the ground area, where the relative movement of the end-point antennas is managed by hand-over [10]. Otherwise, the antenna must be able to track the position of the other end-point transceiver, to steer its main beam toward the link direction; this solution is always mandatory for the ground terminal. Therefore, *adaptive* beamforming approaches are necessary for the connection from the ground terminal to the HAP. Besides, it is desirable to avoid the continuous transmission of training sequences, used as synchronized reference signals, and to avoid the real-time estimation of both HAP and ground terminal locations. Therefore, the suitable solution is represented by *blind* algorithms, which exploit just inherent properties of the received signal, without the need of data demodulation and synchronization.

Two promising blind adaptive beamforming techniques have been selected as suitable approaches for the CAPANINA context: PAST (Projection Approximation Subspace Tracking) [11] and MP (Maximum Power) [12]. They are based on the estimation of the dominant eigenvector of the received signal spatial correlation matrix. Indeed, in a rural or suburban propagation scenario where just the direct signal path is likely present, the optimal choice for the beamformer weight vector $\mathbf{w}[n]$, which maximizes the gain of the equivalent array radiation pattern along the link direction at the time instant n, is the steering vector in that direction [12], which also coincides with the dominant eigenvector of the correlation matrix.

The iterative adaptive equation implementing PAST assumes the form

$$\mathbf{w}_{\mathrm{P}}[n+1] = \mathbf{w}_{\mathrm{P}}[n] + (\mathbf{x}[n] - \mathbf{w}_{\mathrm{P}}[n]y[n])\,\frac{y^*[n]}{\mu[n]} \qquad (1)$$

where $\mathbf{w}_{\mathrm{P}}[n]$ is the estimated beamformer weight vector, $\mathbf{x}[n]$ is the received signal snapshot and $y[n] \triangleq \mathbf{w}_{\mathrm{P}}^H[n]\mathbf{x}[n]$ is the spatially-filtered signal sample. The variable adaptation step $1/\mu[n]$ allows high convergence speed.

The Maximum Power (MP) algorithm obtains the optimum signal-to-noise ratio of the spatially-filtered signal, employing the classic "power method" to estimate the dominant eigenvector of a correlation matrix, with quadratic complexity in the number of weights. Nonetheless, a simple modification makes it possible to estimate the dominant eigenvector of the correlation matrix in an adaptive way, with linear computational complexity, at the expense of a slight performance deterioration. Then, the beamformer weight vector for the MP method can be obtained through the following recursion

$$\begin{aligned} \mathbf{p}[n+1] &= \beta\mathbf{p}[n] + \mathbf{x}[n]y^*[n] \\ \mathbf{w}_{\mathrm{M}}[n+1] &= \tfrac{\mathbf{p}[n+1]}{\|\mathbf{p}[n+1]\|_2}, \end{aligned} \qquad (2)$$

with $\mathbf{p}[0] = \mathbf{0}$ and $|\mathbf{w}_{\mathrm{M}}[0]| = 1$. It is worth to notice that

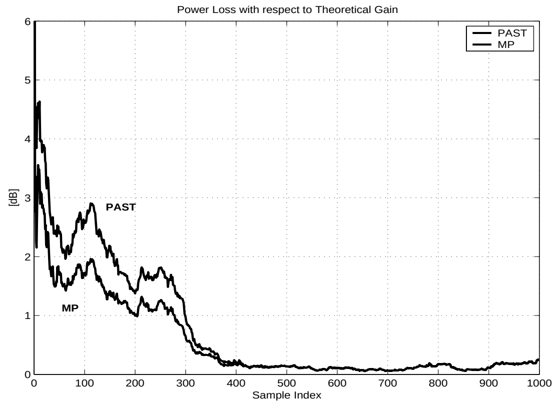

Fig. 1. Comparison of the beamformer power loss with respect to the theoretical gain, achieved by the PAST and MP algorithms, as a function of time.

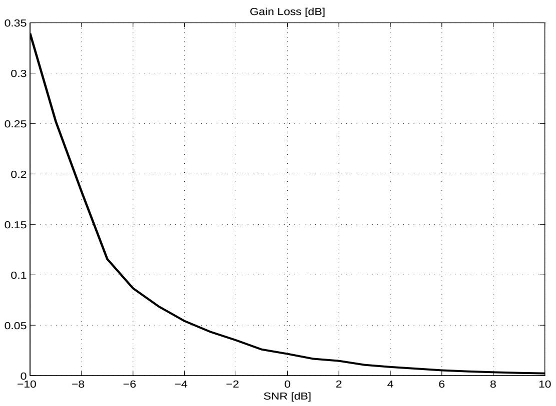

Fig. 2. Comparison of the beamformer gain loss achieved by the PAST and MP algorithms, as a function of the SNR at the receiver.

the computational complexity of (1) and (2) is linear in the number of sensors, and the explicit calculation and storage of the spatial correlation matrix is avoided in both cases.

Figures 1 and 2 compare the performance of PAST and MP, in terms of beamformer gain loss with respect to the optimum weight vector solution. Figure 1 plots the power loss with respect to the theoretical beamformer gain of both PAST and MP as a function of the time (discrete time steps taken at the baud rate), for a random initialization assigned to both weight vectors; it is possible to see that, though a slightly better behavior of MP in the first adaptation phase, the algorithms show the same steady-state performance. Figure 2, on the other hand, analyzes the steady-state gain losses (ratio between the measured and theoretical beamformer gain) as a function of the signal-to-noise ratio (SNR) at the receiver; again, the two algorithms have the same steady-state performance, for the whole range of SNR. It is worth to notice that the gain loss is always less than 0.35 dB. It represents a (quite small) portion of the “implementation loss” entry of the link budget.

V. ADVANCES ON FLEXIBLE CHANNEL CODING FOR HAP-BASED COMMUNICATIONS

One of the potential candidates for adaptive high-gain coding scheme in the CAPANINA context is represented

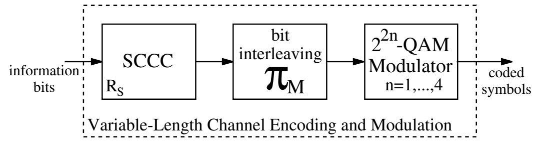

Fig. 3. Block diagram of the variable-length bit-interleaved coded modulation.

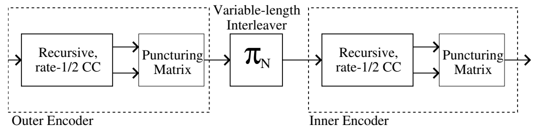

Fig. 4. Block diagram of the SCCC encoder. The overall code rate is $R_s \approx R_o \cdot R_i$ (by neglecting the effects of code terminations), whereby R_o is the rate of the outer code, while R_i is the rate of the inner code.

by the family of the variable-rate, variable-length Serially Concatenated Convolutional Codes (SCCCs).

The architecture of the considered variable-rate, variable-length bit-interleaved modulation and channel coding scheme is shown in Figure 3. Data bits are channel encoded through a variable-rate, variable-length SCCC with overall rate R_s. The encoded bits are first interleaved through a random permutation Π_M of length M, and then modulated through a Gray-mapped 2^{2n}-QAM modulator with $n = 1, \ldots 3$, so that all the IEEE 802.16a modulation formats are considered. The size M of the random permutation can be selected in order counteract the effects of multipath fading. Modulated symbols are fed to an OFDM modulator with $N_u = 256$ carriers, according to the IEEE 802.16a standard. The theoretical bit rates R_b achievable with code rates $R_s = 2/3$ and $R_s = 3/4$ are shown in Table III, for different values of the system bandwidth B_w.

The considered SCCC scheme is shown in Figure 4 along with the variable-length interleaver Π_N used in the serial concatenation. The interleaver length N can be selected in order to guarantee the required QoS, given possible constraints on the amount of delay introduced by the serial concatenation. The interleaver has been optimized according to the method proposed in [13], a design technique for variable-length, prunable interleavers that guarantees optimal BER/FER performance for any interleaver size between 1 and the target maximal length N. The convolutional encoders, along with

B_w, $R_S = \frac{2}{3}$	BPSK	QPSK	16QAM	64QAM
20MHz	10.24	20.48	40.96	61.44
25MHz	12.80	25.60	51.20	76.80
28MHz	14.22	28.44	56.88	85.33
B_w, $R_S = \frac{3}{4}$	BPSK	QPSK	16QAM	64QAM
20MHz	11.52	23.04	46.08	69.12
25MHz	14.40	28.80	57.60	86.40
28MHz	15.99	32.00	63.99	96.00

TABLE III
THEORETICAL BIT RATE, R_b, AS A FUNCTION OF THE SCCC CODE RATE R_s AND THE SYSTEM BANDWIDTH B_w.

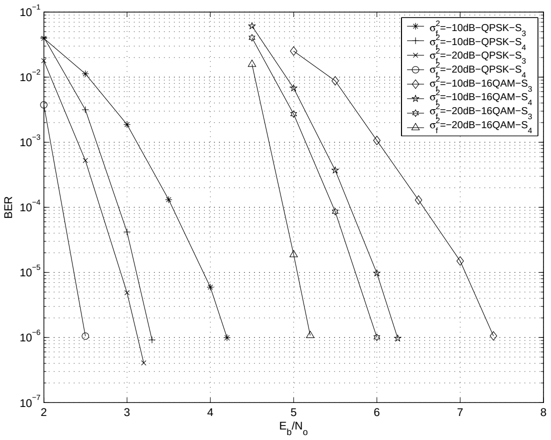

Fig. 5. Bit error rate performance of the SCCC schemes with rate $R_s = 2/3$.

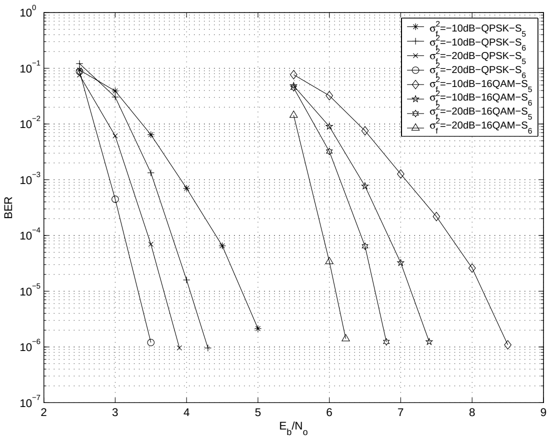

Fig. 6. Bit error rate performance of the SCCC schemes with rate $R_s = 3/4$.

the Puncturing Patterns (PP) applied, have been chosen in order to maximize the interleaver gain produced by the serial concatenation [14], [15]. In particular, the Outer Encoder (OE) polynomial generators are $G_o(D) = [1, 35/23]$, while the Inner Encoder (IE) polynomial generators are $G_o(D) = [1, 7/5]$.

BER performance are shown in Figures 5-6, for QPSK and 16-QAM modulations. The system parameters are summarized in Tables I, III and IV. In particular, Table IV shows the OE code rate R_o, the PP of the OE in octal notation PP_o, the IE code rate R_i, the PP of the IE in octal notation PP_i, the SCCC code rate R_s, the SCCC interleaver size N and the number of decoding iterations, N_{it}. As far as the channel model is concerned, Rice fading with Rice factor $1/\sigma_f^2$ equal to 10 dB and 20 dB has been considered [9]. Because of the practically negligible delay spread shown by the rural channel considered in these simulations, no guard interval has been inserted in the simulated system.

VI. CONCLUSIONS

In this paper the provision of high-speed broadband services from high altitude platforms has been discussed, suggesting the need for a flexible and adaptive transmission system, based, at the physical level, on the use of concatenated codes and smart antennas. Simulated system performance based on a one-ray Ricean fading model of the stratospheric propagation channel show the effectiveness of the proposed solutions to improve system performance, in order to achieve target QoS levels.

	R_o	PP_o	R_i	PP_i	R_s	N	N_{it}
S_3	$4/5$	266	$5/6$	527	$2/3$	1331	15
S_4	$4/5$	266	$5/6$	527	$2/3$	5331	15
S_5	$7/8$	15532	$6/7$	2627	$3/4$	1369	15
S_6	$7/8$	15532	$6/7$	2627	$3/4$	4798	15

TABLE IV

PARAMETERS OF THE DESIGNED SCCCS. THE LABELS S_3–S_6 IDENTIFY FOUR DIFFERENT CODING SCHEMES WHOSE PERFORMANCES ARE SHOWN IN FIGURES 5 AND 6.

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