A New Methodology for Estimating the Impact of Co-Channel Interference from High-Altitude Platforms to Terrestrial Systems

Vasilis F. Milas and Philip Constantinou

Abstract: **This paper addresses an in-depth analysis of the stratosphere-to-Earth co-channel interference produced by high-altitude platforms (HAPs) and proposes a new methodology for the evaluation of its impact to terrestrial systems in terms of fractional degradation in performance, taking into account parameters such as HAP's mobility, realistic distribution of azimuth and elevation angles of the terrestrial microwave links (TMLs), and gradual high-altitude platform network (HAPN) loading. Simulations performed for different HAPN configurations, prove that the implementation of the methodology proposed, may lead to a more efficient use of the spectrum shared between the two services.**

Index Terms: **Co-channel interference, frequency sharing criteria, high-altitude platform (HAP), terrestrial microwave link (TML).**

I. INTRODUCTION

Several high-altitude platform (HAP) systems have been recently proposed for the provision of fixed broadband services in the millimeter-wave frequency bands [1]–[3]. Flying in the stratosphere at altitudes between 15.5 and 30 km [4] HAPs could operate as a standalone or complementary network to satellite based and terrestrial communication systems, combining advantages of both such as large coverage area, low propagation delay, broadband capability, and clear line-of-sight signal paths offered by high elevation angles. However, there are still some critical issues for this new technology, relating to spectrum sharing conditions with other co-primary services and HAP station keeping, which are both studied in this paper.

The international telecommunication union (ITU) has allocated a pair of 300 MHz spectrum for HAP systems in the 47/48 GHz band shared on a non-harmful, non-protection basis with geostationary satellite and terrestrial services [3]. Up today there are not any applicable frequency sharing criteria concerning the stratosphere-to-Earth interference from HAPs to the reception of terrestrial microwave links (TMLs). Initial results [5] showed that an impractical separation distance is required for effective operation of HAP and terrestrial systems. ITU results [6] indicate that this scenario dominates and that it will only be possible to deploy terrestrial receivers outside the visible range of the HAP. Reference [7] proposes geometrical coordination distances ranging from 680 km to 880 km (measured from the sub-HAP point), to be adopted between HAPs and ground terminals of other systems. These distances could make coexistence of the two systems not feasible in real situations. This paper proposes a methodology for the evaluation of the impact of co-channel interference from HAP's stratosphere-to-Earth emissions to terrestrial receivers considering the HAP mobility models, realistic distribution of elevation, azimuth angles of typical urban point-to-point stations, and gradual loaded high-altitude platform network (HAPN) configurations.

This paper is structured as follows. Section II contains the operational and technical characteristics of the wireless communication network based on HAPs operating in the V-band. The three different HAP mobility models are given. Section III contains the general methodology for the evaluation of the impact of stratosphere-to-Earth interference into terrestrial systems. In order to assess the feasibility of frequency sharing in the practical operational environments, a stochastic distribution of typical terrestrial microwave links is proposed, based on their elevation, and azimuth angles. Preliminary interference results concerning HAP's instability are presented. Based on these results, the optimum platform in terms of interference levels to the terrestrial receiver is incorporated into the methodology proposed. The evaluation of the methodology and the derivation of initial frequency sharing criteria are studied in Section IV. Finally, our conclusions are drawn in Section V.

II. WIRELESS COMMUNICATION NETWORK BASED ON HAPS IN THE V-BAND

The typical parameters of a wireless communication network using high-altitude platforms for the provision of fixed services in the bands 47.2–47.5 GHz and 47.9–48.2 GHz are proposed in [3]. The system considered in our study comprises: a) A stratospheric platform placed in a fixed position at heights from 15.5 km to 30 km, able to stay aloft for long periods of time (up to 6 months-unmanned aircraft, up to 5 years-airships) [1], [2], [3], b) antenna installed on the bottom of the HAP transmitting multi-spot beams, providing broadband channels to ground stations within the HAP's visible range. This range varies for urban, suburban, and rural coverage areas, and is extended to a radius of 36 km, 76.5 km, and 203 km away from the HAP's nadir point below the platform, respectively, c) up to 2100 high-altitude platform user terminals (HAPUTs) arranged symmetrically in HAP's urban, suburban and rural coverage areas, and d) up to 80 high-altitude platform gateway stations (HAPGWs) in HAP's urban and suburban coverage areas, which provide interconnection with the fixed telecommunication network.

A. HAP Mobility Models

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One critical aspect in HAP operation is its station's position keeping when flying in the stratosphere. There are three types of platforms considered in the literature as potential HAPs as described below:

1. *Unmanned airships*: Unmanned airships are semi-rigid or non rigid structures, helium filled, deriving power from solar cells on their upper surface, which is used for propulsion and payload operations [3]. These platforms appear to be very large up to 200 m in length and more effective in maintaining station keeping. The ITU considers such a structure which uses a differential GPS sensor for closed loop control of its spatial location to a 400 m radius circle and a vertical dimension to ±700 m (nominal height 21–25 km) at altitude.
2. *Solar-powered unmanned aircraft*: Unmanned solar-powered aircraft are best represented by HELIPLAT [1] and HELIOS [4]. They are expected to maintain their stability within a position cylinder that is sized depending on the service availability. The target figures for this category are based on HELINET results [1], which indicated ±4 km laterally and ±1500 m altitude for 99·9% of the time and ±2.5 km laterally and ±500 m altitude for 99%. Along with airships, unmanned aircraft appear to grapple with high-altitudes of 21 km.
3. *Circling manned aircraft*: Circling aircraft are best represented by HALO platform [2]. They keep a quasi-stationary position above the Earth by flying in a toroidal volume of airspace with a diameter of about 9.3 km to 14.8 km and heights between 15.5 km and 18.3 km.

III. METHODOLOGY

The methodology described in this section provides a model for the evaluation of the impact of co-channel interference from the downlink (stratosphere-to-Earth) emissions of HAPs to the reception of terrestrial point-to-point (P-P) systems. The methodology comprises the following basic concepts: a) Evaluation of fractional degradation in performance, b) consideration of high-altitude platform's mobility, c) consideration of realistic distribution of azimuth and elevation angles of the terrestrial microwave links, and d) consideration of gradual high-altitude platform network loading.

A. Fractional Degradation in Performance

Most common approaches for frequency sharing studies [6], [7] for this scenario (HAP-to-terrestrial), consider *station-by-station* analysis and conclude that interference from HAP into fixed service will exceed the interference criterion as long as the terrestrial stations are deployed within the visible range of the HAP.

However spectrum sharing between high-altitude platform networks and terrestrial systems involves time-varying phenomena such as HAP's movement, interference geometry, propagation conditions, and HAPN varying traffic allocation during day and night. In such cases it is appropriate to model the effects of interference in terms of *fractional degradation in performance* (FDP) [8]. The FDP is the fractional increase in the percentage of time that the controlling performance criterion will not be met because of the presence of interference.

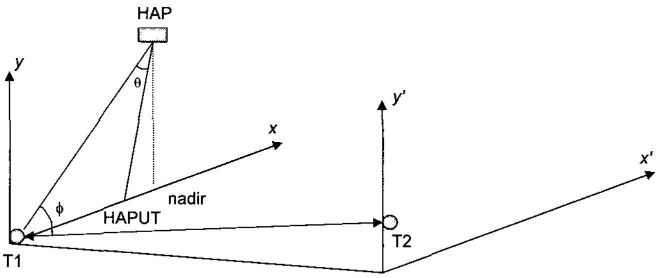

Fig. 1. Geometry of interference between HAP and TML.

The outage probability of a digital system can be written in the following form

$$P_0 = C\left[10^{-DFM/10} + 10^{-TFM/10} + 10^{-(C/I-CNC)/10}\right] \quad (1)$$

where C is a constant depending on climate, terrain and link parameters, DFM is the dispersive fade margin in dB, TFM is the thermal fade margin in dB, C/I is the ratio of unfaded signal power to the noise-equivalent value of interference power in dB, and CNC the value of carrier-to-noise ratio at which the performance criterion is just met in dB. Considering that: a) Modern digital systems usually have dispersive fade margins larger than their thermal fade margins, the first term in (1) can be ignored for interference, and b) since the difference in decibels between the unfaded carrier-to-noise ratio and the critical carrier-to-noise ratio (CNC) is the thermal noise fade margin (TFM), the fractional increase in P_0, the probability of exceeding the performance objective, is equal to the ratio of the interference power I to the noise power N_T, we conclude that the fractional increase is equal to I/N_T, for a constant interference power I. Such an increase in P_0 will be designated as a fractional degradation in performance (FDP). If an interferer caused an interference power I_i for a fraction of reference period f_i, and was absent for the remainder of the period, the incremental FDP due to this interference is given by

$$\Delta P_{O,i} = \frac{I_i f_i}{N_T}. \quad (2)$$

The FDP due to a set of events, where the i-th event consists of the fraction of time that the interference had a power I_i is given as

$$FDP = \sum \Delta P_{0,i} = \sum \frac{I_i f_i}{N_T} \quad (3)$$

where the summation is taken over all interference events.

Considering the interference geometry, depicted in Fig. 1 where θ is the discrimination angle between the direction of the main beam of HAP towards the HAPUT and the direction of the interfered terrestrial station, ϕ is the discrimination angle between the azimuth of the TML (T1-T2) and the direction towards the HAP, the interference power from the HAP to the terrestrial receiver is obtained by

$$I_{(\mathrm{H-T})} = P_H + G_H(\theta) + G_T(\phi) - FSL_{(H-T)} - L_{feeder} - L_{Atmospheric} \quad (4)$$

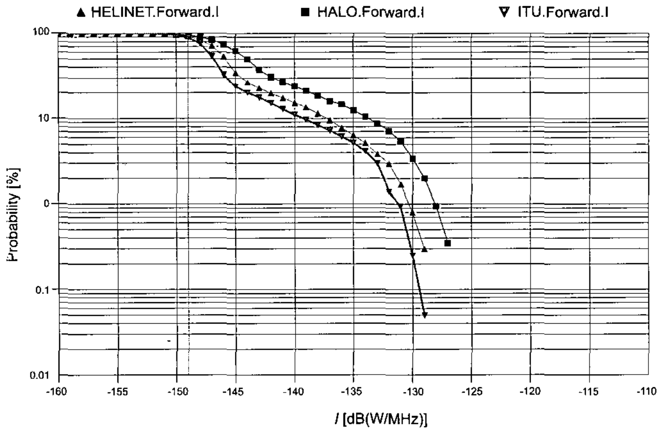

Fig. 2. CDFs of Interference density—60 km.

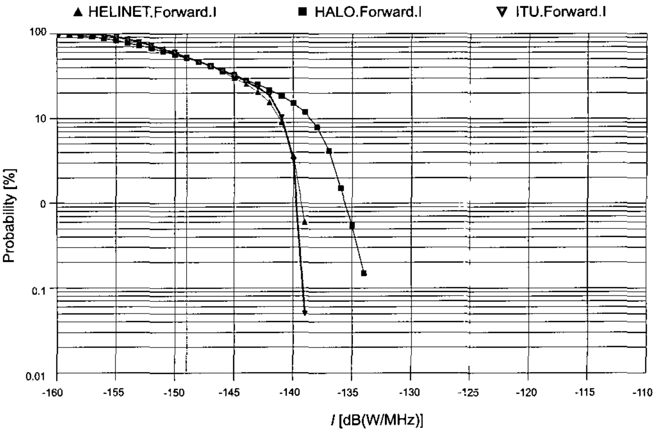

Fig. 3. CDFs of Interference density—135 km.

where P_H is the transmission power density from HAP to the ground station in dB(W/MHz), $G_H(\theta)$ is the transmitting antenna gain of HAP at the angle θ in dBi, $G_T(\phi)$ is the receiving antenna gain of terrestrial station at the angle ϕ in dBi. $FLS_{(H-T)}$ are the free space losses in the channel between the HAP and the terrestrial station, L_{feeder} are the feeder losses of the HAP and the terrestrial station in dB.

$L_{Atmospheric}$ are the losses due to atmospheric absorption. In the path between a HAP and terrestrial terminals, atmospheric gases including water vapour cause attenuation, which depends on the distribution along the path of meteorological parameters such as temperature, pressure and humidity, and thus varies with the geographic location of the site, the month of the year, the height of a ground terminal above sea level, and the elevation angle of the slant path and the operating frequency. According to [7], the following numerical formulae can be used for estimating minimum slant path attenuation in the 47 GHz band:

$$\begin{aligned} A_L(h,\theta) &= 52.43/[1+0.7364\theta+0.036010\theta^2-0.0010990\theta^3 \\ &\quad +0.8024\times10^{-5}\theta^4+h(0.264+0.2479\theta)+h^2(0.08130 \\ &\quad +0.026370\theta)] \quad (5) \end{aligned}$$

$$\begin{aligned} A_M(h,\theta) &= 47.00/[1+0.70040\theta+0.035680\theta^2-0.0010810\theta^3 \\ &\quad +0.7878\times10^{-5}\theta^4+h(0.2527+0.19700\theta)+h^2(0.05539 \\ &\quad +0.032390\theta)] \quad (6) \end{aligned}$$

$$\begin{aligned} A_H(h,\theta) &= 46.70/[1+0.68720\theta+0.036370\theta^2-0.0011050\theta^3 \\ &\quad +0.8087\times10^{-5}\theta^4+h(0.2472+0.18190\theta)+h^2(0.04858 \\ &\quad +0.032210\theta)] \quad (7) \end{aligned}$$

where $A_L(h,\theta)$, $A_M(h,\theta)$, and $A_H(h,\theta)$ denote total atmospheric absorption loss (dB) for the low-latitude (within 22.5° of the Equator), mid-latitude (greater than 22.5°, but less than 45° from the Equator), and high-latitude (45° or more from the Equator) areas, respectively, and h and θ denotes ground terminal antenna altitude above sea level (km) and elevation angle (degrees), respectively.

The thermal noise of the terrestrial station is obtained by $N_T = 10\log(kTB) + NF \quad (dB)$ where k is the Boltzmann's constant ($1.38 \times 10^{-23}(J/K)$), T is the temperature (K), B the bandwidth (Hz), and NF the noise figure of the terrestrial receiver (dB).

B. Evaluation of HAP Mobility Models

The evaluation of the statistical behavior of interference variations due to platform's movement was based on a Monte-Carlo approach, in which every trial corresponds to a different random position of the HAP inside the edge area of each mobility model described in Section II-A. The cumulative distribution functions (CDFs) of interference density are generated corresponding to the probability that a certain amount of interference may be experienced. The analysis was performed with a HAP serving 50 user terminals in the rural area coverage. The rural area is the worst frequency sharing area for this interference propagation path [5]. In the first case studied (Fig. 2), the terrestrial receiver was deployed 60 km away from the nadir point underneath the HAP, while in the second case (Fig. 3), the receiver was deployed 135 km away from the border of HAP coverage area.

The results of Figs. 2 and 3 demonstrate that co-channel interference levels depend on the HAP mobility model used. In both cases, HALO model appear to have the strongest effect on the interference levels, with the HELINET an ITU models subsequent. ITU model proves to be the optimum model in frequency sharing criteria and thus it will be the one to be incorporated in the general methodology and to be used in the analysis presented in Section IV.

C. Terrestrial Microwave Links in Urban Environment

The technical characteristics of typical terrestrial systems in the 47–50.2 GHz band are specified in [9] and are outlined in Table 1. We have selected to perform our simulations based on the characteristics of a sensitive to interference system (system 3). In this way, the results and the conclusions of this study can be a guide for all the terrestrial systems proposed in the recommendation. The position of terrestrial stations was obtained from databases that provide specifications of the existing links in the geographic region of Attiki (Greece). The terrestrial microwave links in our analysis are deployed in a typical urban environment covering an area of 11300 km^2 with the centre of the area having the following coordinates: Latitude: N 38:8°, longitude: E

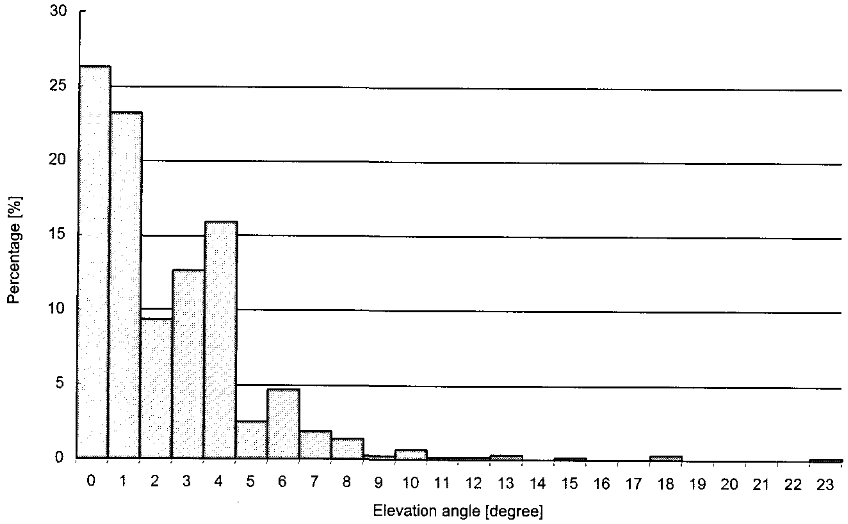

Fig. 4. Antennas' elevation angle distribution of terrestrial microwave links in urban environment [mean = 4.17, standard error = 1.56, median = 0.29, standard deviation = 7.65].

Table 1. Technical characteristics of wireless terrestrial systems in the V-band.

System	1	2	3	4
Modulation	2-FSK	4-QAM	16-QAM	256-QAM
Capacity (Mbit/s)	1.544	44.736	90	310
Channel spacing (MHz)	5	50	50	50
Antenna gain (maximun) (dBi)	46	46	46	46
Antenna type	Dish	Dish	Dish	Dish
Max. Tx output power (dBW)	−11	−12	−2	−2
E.I.R.P. (maximum) (dBW)	35	34	44	44
Receiver thermal noise (dBW)	−130	−114	−122	−122
Rx input level for 1×10^{-3} BER (dBW)	−122	−105	−106	−94
Nominal long-term interference (dBW)	−140	−124	−132	−132
Spectral density (dB(W/MHz))	−143	−143	−147	−147

23:40°.

In most studies up today, the worst case regarding the elevation angle of the terrestrial stations was considered. In this paper, we propose a realistic stochastic distribution of terrestrial station antenna elevation angle derived from databases that provide specifications of the existing links in the geographic region of Attiki, which can be useful for frequency sharing studies in urban environment (Fig. 4). As can be seen from the distribution, 49.51% of the elevation angles are in the range of 0–1 degrees, 37.87% are in the range of 2–4 degrees while the rest are in the range of 5–23 degrees.

D. Gradual Development of High-Altitude Platform Network

Frequency sharing studies made so far related to HAP interference were focusing either on single interferer or on worst-case scenarios such as a fully deployed network. A more realistic approach is introduced in this paper considering the impact of gradual development of high-altitude platform network on co-channel interference levels.

The scenarios considered in this study associate the percentage of high-altitude platform network load with the number of high-altitude platform user terminals in urban, suburban and rural areas, as well as the number of gateway stations in urban and suburban areas. The different HAPN configurations studied in this paper are shown in Table 2.

IV. STATISTICAL ANALYSIS

Initial simulations were performed between a high-altitude platform network and terrestrial microwave links with the scope of evaluating the fractional degradation in the performance of all the terrestrial links using the model introduced in Section III.

First, we focused on the effect of the orientation of a possible HAPN deployment towards the TMLs area. After that we studied gradually developed high-altitude platform networks at different geographical separation distances from the terrestrial service area as specified in the preceding section.

Table 2. HAPN configurations.

HAPN	HAPUTs in UAC/SAC/RAC	HAPGWs in UAC	HAPGWs in SAC
10% loaded	210	4	4
25% loaded	525	10	10
50% loaded	1050	20	20
75% loaded	1575	30	30
100% loaded	2100	40	40

Preliminary results indicated that the coexistence of the two services in the same geographical areas is not feasible. Therefore we have focused our analysis on deriving a geographical separation distance d_{sep} between the HAP coverage area and the TMLs deployment area taking into consideration that a HAPN will be gradually deployed.

In our analysis, we assume the required protection level of FDP = 10%. Reference [9] states that, in principle, the interference level relative to receiver thermal noise should not exceed -10 dB (or -6 dB). In the case of digital terrestrial systems, these values correspond to an FDP value of 10% (or 25%), respectively.

A. *Impact of the Orientation*

The first step of our analysis was to identify the worst possible orientation of the HAPN coverage area with respect to the deployment area of the terrestrial stations. We considered a 10% loaded HAPN, providing services westwards to the terrestrial service area and another one northwards to the TMLs area, based on the possible deployment strategies defined by the specific geographic environment around the area of Attiki (Greece). The HAPN and the TMLs areas are adjacent ($d_{sep} = 0$ km).

By comparing the statistics presented in Fig. 5, we focus our analysis on the westwards placed HAPN which appear to produce the worst FDP levels in the TMLs with an average value of 9.6% and a deviation of around 24%.

In addition one of the two directions of the links, return direction, is selected for our study for the reason that it appears to be more degraded than forward links. Adjacent operation of the two services seems difficult even for a low loaded HAPN.

However, it should be mentioned that the average values of FDP, for this case, as can be seen in Table 3 are below the criterion of 10% (3.19% for the north HAPN, 9.62% for the east HAPN).

B. *Separation Distance*

Initial results presented in Fig. 6 and Table 3 demonstrate that a d_{sep} of 130 km proves to be adequate for the protection of terrestrial receivers from the aggregate interference from a 10% loaded HAPN with respect to the criterion value of FDP = 10%. For the scenarios with the 25%, 50%, 75% loaded HAPN, the interference criterion is exceeded.

However, the average values of FDP are very low (<2%) which is an indication that by adopting the appropriate interference mitigation technique for this scenario, separation distance in the range of 130 km could be used for the protection of terrestrial receivers.

Table 3. FDP statistics.

Interferer HAPN		FDP statistics		
Configuration	d_{sep}	Worst	Average	Standard deviation
10% loaded [a]	0 km	129.17%	3.19%	14.58%
10% loaded [b]	0 km	134.05%	9.62%	23.98%
10% loaded	130 km	6.34%	0.22%	0.89%
25% loaded	130 km	14.45%	0.53%	2.17%
50% loaded	130 km	29.09%	1.07%	4.38%
75% loaded	130 km	41.25%	1.55%	6.32%

[a] northwards

[b] westwards

V. CONCLUSION

This paper has described a methodology for estimating the impact of stratosphere-to-Earth co-channel interference from high-altitude platforms to terrestrial systems. This methodology is based on the evaluation of fractional degradation in performance of terrestrial systems considering parameters such as high-altitude platform's movement, different high-altitude platform network configurations and realistic allocation of azimuth and elevation angles of the terrestrial microwave links.

New concepts which could be used in spectrum sharing studies between HAPs and terrestrial systems operating in adjacent geographical areas in the millimeter-wave bands were presented. Recapitulating these are:

1. Evaluation of the co-channel interference levels produced by HAPs downlink (stratosphere-to-Earth) emissions considering the platform's instability. Comparison of existing mobility models (ITU, HELINET, HALO) showed that ITU model behaves better in terms of interference levels produced to the direction of terrestrial receivers.
2. Derivation of d_{sep} (separation distance), should be based on calculations of fractional degradation in the performance of multiple terrestrial links in their deployment area, taking into account aggregate interference from HAPs.
3. High-altitude platform systems will be gradually deployed and different loaded network configurations should be considered in frequency sharing studies.

Initial simulations were performed and the results indicate that the application of the methodology leads to the determination of applicable frequency sharing criteria between the two services. The comparison with the coordination distances proposed by ITU shows that by using the proposed methodology a more efficient use of the spectrum in the V-band is obtained. The proposed methodology can constitute the basis for the development of realistic coordination distances around areas with terrestrial stations.

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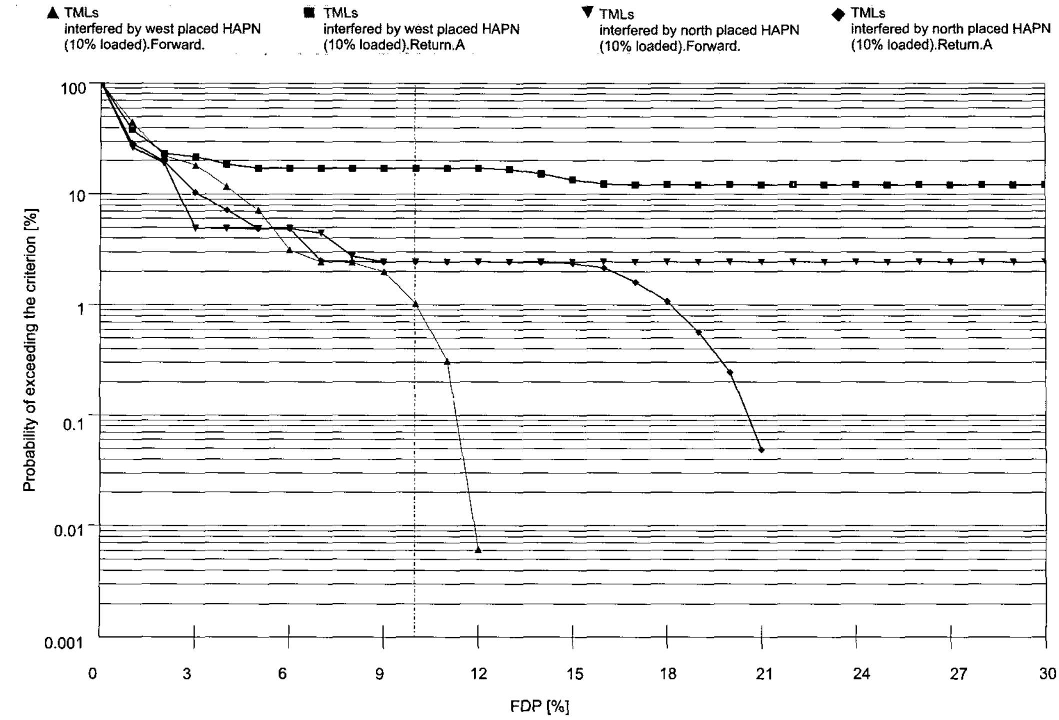

Fig. 5. FDP statistics for a 10% loaded HAPN (north and west oriented) adjacent to the TMLs area.

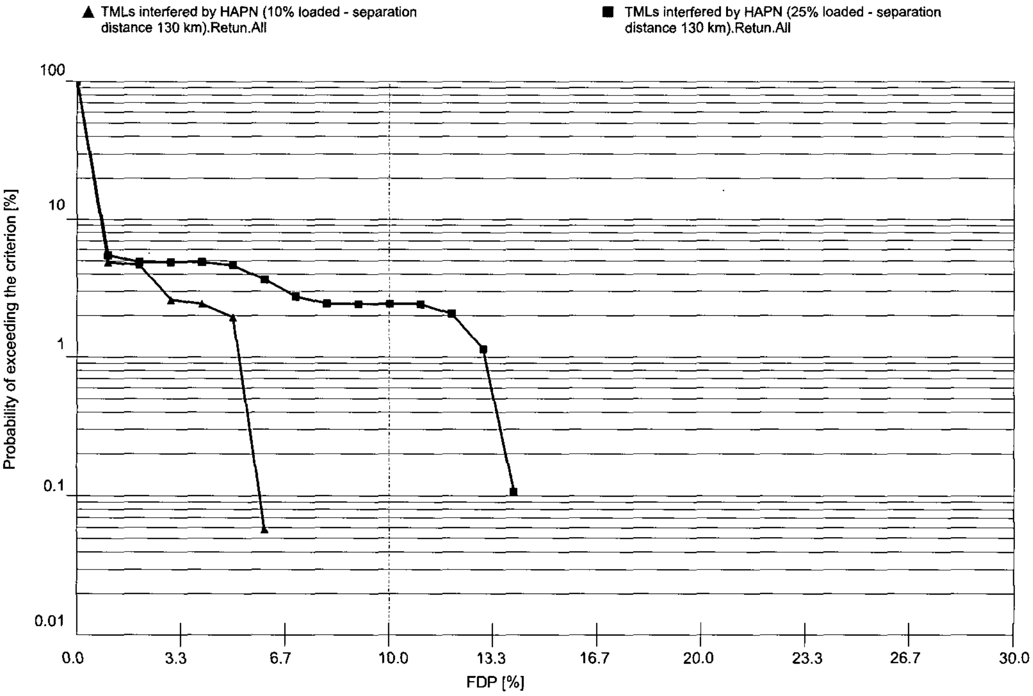

Fig. 6. FDP statistics for a 10% loaded HAPN and a 25% loaded HAPN (130 km away from the TMLs area) adjacent to the TMLs area.

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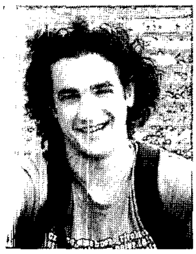

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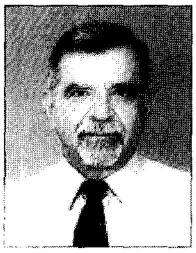

Philip Constantinou received the diploma in Physics from the National University of Athens in 1972, the master of Applied Science in Electrical Engineering from the University of Ottawa, Ontario, Canada in 1976 and the Ph.D. degree in Electrical Engineering in 1983 from Carleton University, Ottawa, Ontario, Canada. From 1976 to 1979, he was with Telesat Canada. In 1980, he joined the Ministry of Communications in Ottawa, Canada. From 1984 to 1989, he was with the National Research Centre Demokritos in Athens, Greece were he was involved on several research projects in the area of Mobile Communications. In 1989, he joined NTUA where he is currently professor. His current research interests include High-altitude Platform Communication Systems, Mobile Satellite Communications and Interference Problems on Digital Communications Systems. He is the Vice-Chair of COST Action 297 "High Altitude Platforms for Communications and Other Services."