Satellite Downlink Reception through Intermediate Module Repeaters: Power Delay Profile Analysis

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ABSTRACT

The introduction of Intermediate Module Repeaters (IMRs) in a satellite network architecture aims at improving the coverage of densely populated area, where the presence of buildings renders the link obstruction probability excessively high. This is particularly true when the satellite elevation angle is low. IMRs provide boosted replicas of the satellite signals, enabling the satellite signal reception, but also introducing a considerable amount of "artificial" multipath, especially when multiple IMRs are considered for outdoor coverage. The use of a Direct Sequence Spread Spectrum and a rake receiver makes it possible to collect the energy of the multipath components. For proper receiver design, it is necessary to characterize the overall received signal power delay profile, which is the aim of the present work.

I. INTRODUCTION

Satellite systems are promising candidates in the provisioning of digital multimedia broadcast services (DMB), as well as of a fast downlink channel for the download of Internet content. The main reason to support the use of satellite for these services is the better efficiency of satellites in the delivery of the same content to several users over a vast area. In fact, a number of users may be reached by means of a single-point to multi-point connection, while in a terrestrial system that would require the set up of a large number of point-to-point links, with a consequent waste of network resources. However, for the economical success of these services, it is essential that the most of potential users can be reached, i.e. that the satellite signal reception be possible even in large cities and densely populated areas, where the presence of buildings greatly increases the link obstruction probability, i.e. the absence of a LOS (Line Of Sight) link between the satellite and the User Equipment (UE). This problem is exacerbated in the case of GEO satellites (usually preferred for economical reasons too). To this regard, it is worth reminding that at high latitudes, such as in central Europe as well as in North America where most of potential users are located, the elevation angle of GEO satellites is quite low, increasing the probability of satellite link obstruction in presence of buildings other obstacles. To overcome this problem, the introduction of Intermediate Module Repeaters (IMRs), or Gap Fillers, seem a viable and effective choice (Fig.1). By providing the user equipments (UEs) with boosted local replicas of the satellite signal, IMRs can improve the coverage of densely populated areas [1], [2]. In addition, IMRs are indispensable to permit the satellite signal reception inside buildings, cars, ships and other means of transport.

By no means can the use of IMRs be considered a new concept. However, usually the emphasis is on the fact that IMR help the reception by strengthening the satellite signal, while the "side effect" of a significant modification of the characteristics of the received signal has not received great attention in the literature. A remarkable exception is given by [3], where an interesting study on the power delay profile resulting from direct and indirect reception through IMR is presented, considering a terrestrial system and a single IMR. However, satellite systems present peculiar characteristics and pose additional problems that deserve to be carefully investigated (for example, the influence of the service area latitude). Moreover, if the coverage of a densely populated area is envisaged, it is more likely that the signal is received through multiple IMRs, especially when outdoor coverage is concerned. As multiple IMRs and terrestrial multipath introduce many replicas of the satellite signal, the use of a Direct Sequence Spread Spectrum and a rake receiver to collect the energy of the strongest signal components should be considered preferential. To this regard, note that the "artificial" multipath introduced by IMRs largely increases the number of signal components and the amount of delay spread. If these multipath components are resolvable and there are enough fingers in the rake receiver to collect them, an increased level of diversity is obtained. In the opposite case, multipath components result in an additional interference, with detrimental effects.

The link between the introduction of indirect reception and the characteristics of the received signal mentioned before has a significant impact on the rake receiver design and therefore deserves to be thoroughly investigated. This is the aim of the work, where GEO satellite reception through multiple IMR is studied, focusing on the characteristics of the power delay profile. The analysis begins with a comprehensive description of the reference coverage layout (i.e. IMRs coverage areas, relative locations of GEO satellite, IMRs and UE). Then, an appropriate propagation model is defined for every link involved; namely, the satellite-to-UE link for the direct reception, and the satellite-to-IMR and the IMR-to-the UE links for the indirect components. Finally, by combining the geometry of the problem with the propagation assumptions, the wanted power delay profiles of the received signal are derived. Note that the complexity of the problem requires a 3D geometrical representation, in order to achieve accurate results, while for characterizing the terrestrial propagation some widely adopted ETSI model can be suitably exploited [4]. Other parameters considered in the analysis, such as the carrier frequency and the chip rate, refer to an S-UMTS system [5]. Numerical results, pictorially represented by some power delay profile snapshots, highlight the influence on the received signal of the many factors considered in the analysis.

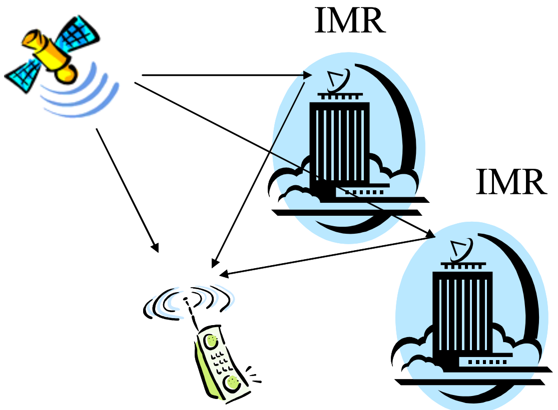

Fig.1. Direct and indirect (through IMRs) satellite reception

II. COVERAGE LAYOUT

Low Power and High Powers IMRs cell radius

IMRs can be classified in two categories, depending on the use, or not, of the same frequency for the signal reception and transmission. In the former case, the signal is simply retransmitted in the same frequency band, without any processing but an analog amplification. As the use of the same frequency sets strict constraints on the maximum transmitted power (because of the limited isolation between the Tx and Rx antennas), they are identified as Low Power IMR. On the contrary, if two different frequencies are used for transmitting and receiving, these power limitations do not apply and they are consequently identified as High Power IMRs. As neither power control is implemented nor additional scrambling codes are superimposed on the signal, both high and low power IMRs act as plain signal repeaters. We assume, following [6], that IMRs make use of omni directional antennas and assure a coverage radius of about 400m or 2 km for low power and High Power IMRs, respectively.

Cellular layout

As every IMR is supposed to transmit with the same fixed power, with a coverage radius that ranges from a few hundred meters to a few kilometres, the adoption of a regular hexagonal cellular layout model, of the kind usually considered in the study of cellular terrestrial systems, seems the most appropriate choice. The adopted cellular layout is reported in Fig.2. The UE (indicated by a star) is located inside the “reference” IMR cell, i.e. the cell covered by the closest IMR. The six neighbouring cells of the first tier are also reported, as their IMRs provide the most significant signal replicas. In the numerical results, the UE will be moved along a straight line from the proximity of the cell centre (a tenth of the cell radius) to a corner (a cell radius). Note that IMRs are not strictly synchronous, i.e. they do not transmit the same signal at exactly the same time, as a consequence of their different distances from the satellite (small, but not irrelevant as far as chip times delays are concerned). The corresponding relative delays change with the elevation angle of the GEO satellite, that is to say with the latitude of the coverage area; the higher the latitude, the greater the relative delays. Cells are assumed to be oriented to North, in such a way that the reference IMR and the IMR1 and IMR4 lie on the same meridian. For symmetry, the GEO satellite is supposed to be at the same longitude.

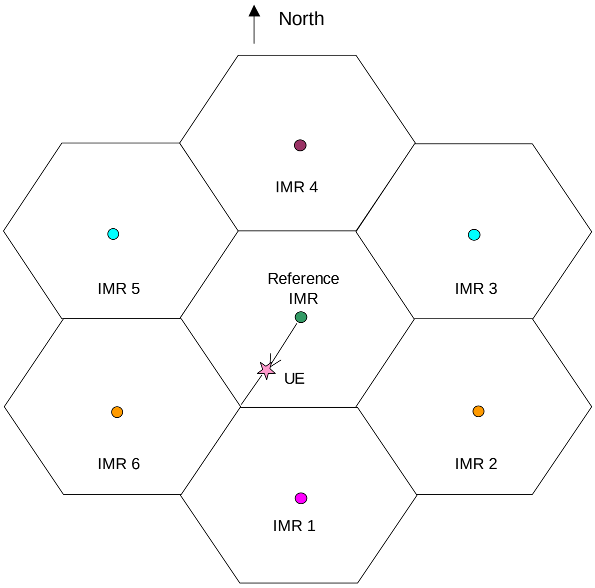

Fig.2. IMR cellular layout

III. LINKS AND PROPAGATION MODELS

The signal received by the user equipment (UE) is composed by different replicas of the satellite signal. We can distinguish between a “direct” component, and many “indirect” components (Fig.1). The direct component is received directly from the satellite (satellite-to-UE link) and is present only in case of no link obstruction. The many indirect components are received through the IMRs and involve two radio legs (satellite-to-IMR link, IMR-to-UE link). They are assumed to be always present, as IMRs are supposed to be located in favourable positions (e.g. at the top of buildings). To carry out the analysis, it is necessary to describe with a suitable propagation model every radio link involved in the satellite signal reception. We distinguish between satellite and terrestrial propagation.

Satellite propagation

Free space propagation is assumed for the satellite-to-UE and the satellite to IMR links. On the satellite-to-UE link non-selective Rice fading is superimposed.

Terrestrial propagation

From a propagation point of view, the IMR-to-UE links present the same characteristics of a terrestrial cellular system downlink: high distance attenuation, shadowing and multipath fading. Therefore, they can be conveniently described by the model proposed by ETSI in [4]. In this document several “environments” are considered to account for different outdoor and indoor propagation conditions. Here, we will focus on the “Vehicular” environment as it seems the most appropriate for the coverage layout considered in this study. The main characteristics of the associated path loss and channel impulse response models reported here for the reader’s convenience:

Path loss model

We refer to the ETSI path loss model for Vehicular Test Environment (B.1.4.1.3 [4]). Assuming an IMR antenna height of 15 metres above the average rooftop we have:

$$L = 58.8 + 21\log_{10}(f) + 37.6\log_{10}(R) \tag{1}$$

where L is the attenuation in dB, f the carrier frequency in MHz and R the IMR to UE distance in Km. The ETSI model considers also the presence of a lognormal shadowing with a variance of 10 dB.

Channel impulse response model

The channel impulse response is described by means of a tapped delay line model. Two variants are presented, depending on the amount of delay spread. Here we consider the ETSI Channel Impulse Response model for Vehicular Test Environment Channel A (i.e. low delay spread) (B.1.4.2 [4]). The corresponding parameters are reported in Table 1. The intensity of every path is the average over the independent Rayleigh fading that is superimposed on each path. The fading correlation in time depends on the Doppler spread, i.e. on the UE speed.

Table 1. Channel impulse response model

ETSI Vehicular High Antenna Channel A		
Tap	Intensity (dB)	Delay (s)
1	0	0.00E+00
2	-1	3.10E-07
3	-9	7.10E-07
4	-10	1.09E-06
5	-15	1.73E-06
6	-20	2.51E-06

IV. ANALYSIS OF THE DELAY SPREAD

For the purpose of determining the channel impulse response of the *overall* received signal (i.e. direct and indirect components) it is convenient to analyze the delays and the powers of the signal components separately. Thus, let us start the delay analysis by distinguishing between the delays due to the terrestrial and the satellite propagation (more complex).

Delays due to Terrestrial Propagation

It is assumed that for every IMR-to-UE link, the six components of the power delay profile of the ETSI channel model are all delayed according to the corresponding IMR to UE distance.

Delays due to Satellite to Earth Propagation

The IMRs are not perfectly synchronous transmitters, as they receive and retransmit the satellite signal with different delays, being their distances from the satellite not exactly the same. The higher the latitude of the coverage areas, the higher the relative time delays, because the GEO satellite is seen at a lower elevation angle. As the distance variation is limited to hundreds of metres, it does not influence the power loss from the satellite to the IMRs. However, being the chip time very short, small differences in space may easily result in relative delays of several chip times, increasing the power delay spread of the overall signal received by the UE.

For the sake of simplicity, in this study the serving satellite has been located at the same longitude of the reference IMR, minimizing the differential delays due to different IMR longitudes. Basically, signals transmitted by the IMRs located at North of the reference one are delayed (IMR 3, 4, 5), while the others (IMR 1, 2, 6) are in advance. Obviously, these time misalignments sum up to the delays due to the terrestrial propagation from the IMR to the UE. Finally, note that the signal received by the UE directly from the satellite (in case of no link obstruction) is moderately influenced by the UE location too. As it is always received by first, its arrival time can be conveniently considered as the time origin.

Summarizing, given the regular hexagonal layout previously considered, we have the following four contributions to the delay spread:

- the terrestrial differential delays due to the different distances between the user equipment and the IMRs (dependent only on the UE location);
- the satellite differential delays due to the different distances between the satellite and the IMRs (basically dependent only on the satellite elevation angle);
- the multipath on every terrestrial link (dependent on the delay spread of the channel impulse response);
- only in case of satellite visibility, the satellite differential delay between the signal received directly from the satellite and that received by the reference IMR (dependent on both the user equipment location and the elevation angle).

A quantitative assessment of satellite and terrestrial delays can be derived by inspection of Table 2. In the first column we report the delays due to the terrestrial propagation from the IMRs to the UE. In the second, are report the delays at which the satellite signal is received by IMRs, with respect to the UE reception of the direct component. The sums are reported in column three, and represent the delay of the first terrestrial component of each IMR signal. It is evident that satellite delays, which depend on latitude, cannot be neglected.

Table 2: Terrestrial and Satellite delays. Latitude=51° north (central Europe); d=0.86

	terrestrial delay (s)	satellite delay (s)	first path delay (s)
REF IMR	1.15E-06	8.45E-07	1.99E-06
IMR1	1.44E-06	-1.12E-06	3.17E-07
IMR2	2.58E-06	-1.37E-07	2.44E-06
IMR3	3.35E-06	1.83E-06	5.18E-06
IMR4	3.35E-06	2.81E-06	6.16E-06
IMR5	2.58E-06	1.83E-06	4.41E-06
IMR6	1.44E-06	-1.37E-07	1.30E-06

V. POWER ANALYSIS (LINK BUDGETS)

The link budget data necessary to the calculation of the signal power received by the UE, both directly from the satellite and indirectly through an IMR, are summarized in table 2 (from [1]. Both the direct and the indirect component share the same 2 GHz band. Note that while the path gain from the GEO satellite and the UE can be considered independent of the UE position, given the high distance of the satellite from the Earth, the path gain from the IMR and the UE depends on their relative locations. To provide a significant example, the value reported in Tab.2 has been calculated by assuming an IMR-to-UE distance equal to the apothem the hexagonal cell (i.e. 0.86◦cell radius), corresponding to 346m and 1732m for low power and high power IMRs, respectively. Of course, in the numerical results calculation, the path gains will be calculated taking into account the effective UE distances from the reference and the six first tier IMRs.

Table 3. Link budget data

Sat-to-UE link (direct component)		IMR-to-UE link (indirect components)	Low Power	High Power
EIRP/Traffic code (dBW)	57	EIRP/Traffic code (dBW)	-19	10
Path Gain (dB) (free space)	192.5	Path Gain (dB) (ETSI, d=0.86)	-112.8	-139.2
Polarization Gain (dB)	-1	Polarization Gain (dB)	-1	-1
UE Antenna gain (dB)	2	UE Antenna gain (dB)	2	2
Received Power (dBW)	134.5	Received Power (dBW)	-130.8	-128.2

It is now possible to evaluate the intensities of the many power delay profile elements. The intensity of the direct component (if present) is simply given by the received power value reported in Table. The calculation of the indirect components is relatively more complex. For every IMR-to-UE link, the corresponding received power is calculated taking into account the effective IMR-to-UE distance, by making use of the path loss formula of the ETSI Vehicular model. Then it is assumed that the six components of the power delay profile of the ETSI Vehicular channel model are all scaled by this calculated value. Summarizing, given the regular hexagonal layout previously considered, the power delay profile will be given by the following elements:

- a direct component (if present, it is not necessarily the strongest);
- six components for each IMR; their relative intensities are given by the tapped delay coefficients reported in table 1; their absolute intensities depend on the IMR to UE distance.

Finally, it should be reminded that shadowing and fading should be superimposed over the deterministic values reported in the power delay profiles. In particular, according to the ETSI model, the terrestrial links are affected by shadowing, modelled as a log-normal r.v. (m_{dB}=0, σ_{dB} =10). All the signal replicas coming from the same IMR are obviously affected by the same shadowing level. Moreover, every terrestrial path is affected by independent Rayleigh fading, which again must be superimposed over the average power values reported in the tables. The fading correlation in time depends on the Doppler spread, i.e. on the UE speed.

VI. SNAPSHOT EXEMPLES

Some power delay snapshots are reported in Fig.3-Fig.7, to give a pictorial view of the obtained results. First, we have studied the influence of the UE distance from the reference IMR, considering low power IMRs and latitude 51° north, typical of central Europe. Delays are reported in chip times, having assumed a chip rate of 3.84 Mchip/s, while the UE-to-IMR distance, *d*, is normalized to the cell radius. In Fig.3 the UE is very close to the reference IMR (*d*=0.1). As a result, the six corresponding multipath components (triangle markers) are several tenth of dBs stronger than the others, including the direct component (at delay=0). Moving towards the cell border (*d*=0.86, Fig.4), the reference IMR components decrease, while the signals coming from IMR1 and IMR6 become stronger.

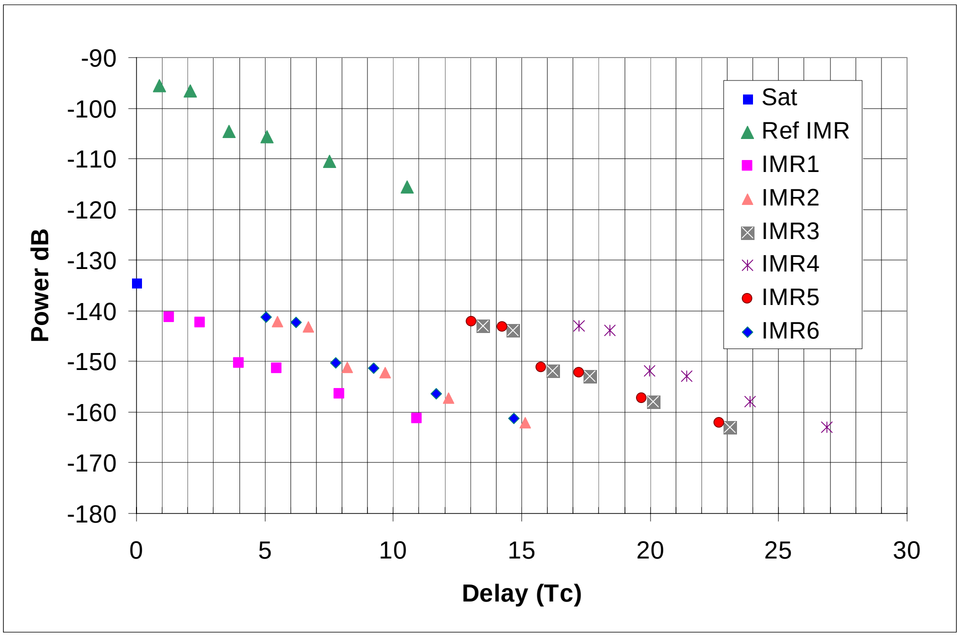

Fig.3. Power delay profile for Low Power IMR coverage (Lat. 51 North, *d*=0.1)

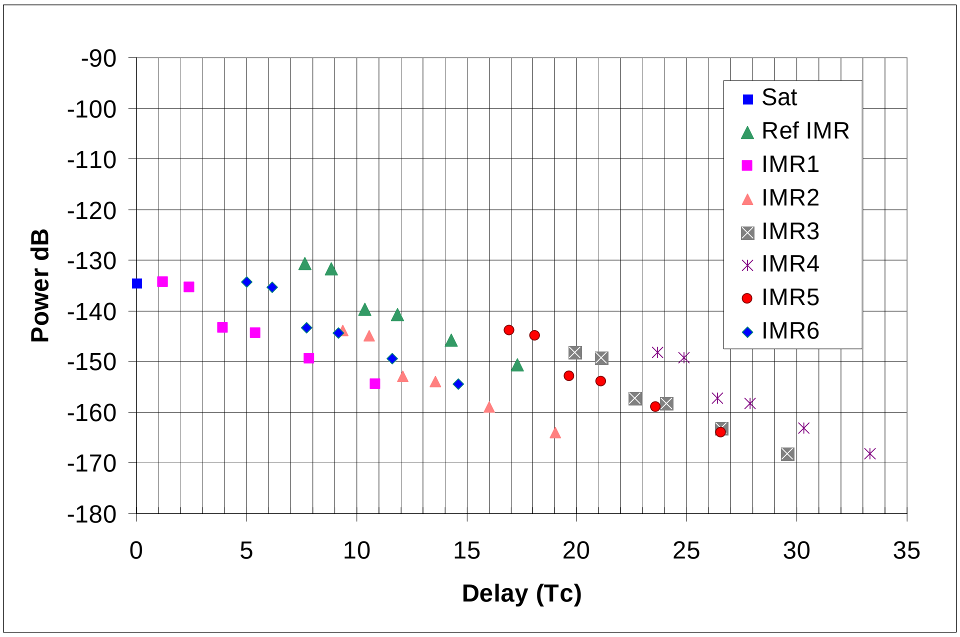

Fig.4. Power delay profile for Low Power IMR coverage (Lat. 51 North, *d*=0.86)

At the cell radius (*d*=1, Fig.5), the three group of components have the same power, as the UE is at the same distance from the three IMRs considered (see Fig.2). Note, however, that the delays are not the same because of the different latitudes of the three IMRs. Then, focusing on the intermediate case of *d*=0.86, a lower latitude (42 north, Rome) has been considered (Fig.6). Comparing the power delay profile with the corresponding results for 51° North (Central Europe, Fig.4) only limited differences can be perceived (in particular the delay spread is reduced by a chip time). Finally, we have considered the use of high power instead of low power IMR (Fig.7). In this case, the differences are really apparent, and of great impact. Due to the large distances involved, the satellite replicas coming from different IMRs are separated in time. The delay spread introduced by the terrestrial multipath on the signal transmitted by a given IMR is much less than the delays introduced by the delays due to the different path lengths. As a result, the overall delay spread is increased by a factor of ten with respect to a plain terrestrial transmission.

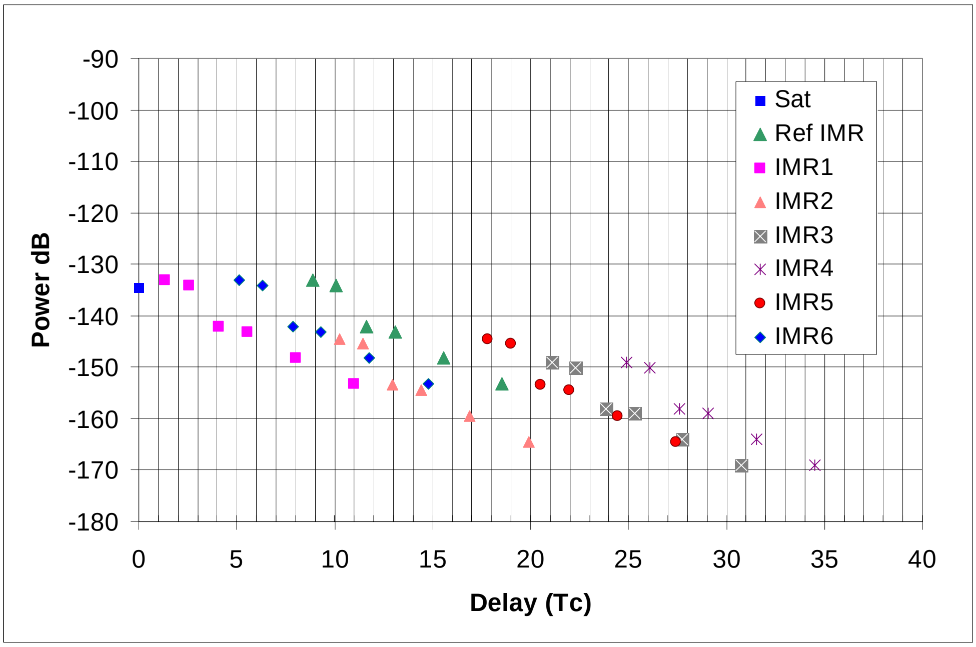

Fig.5. Power delay profile for Low Power IMR coverage (Lat. 51 North, *d*=1)

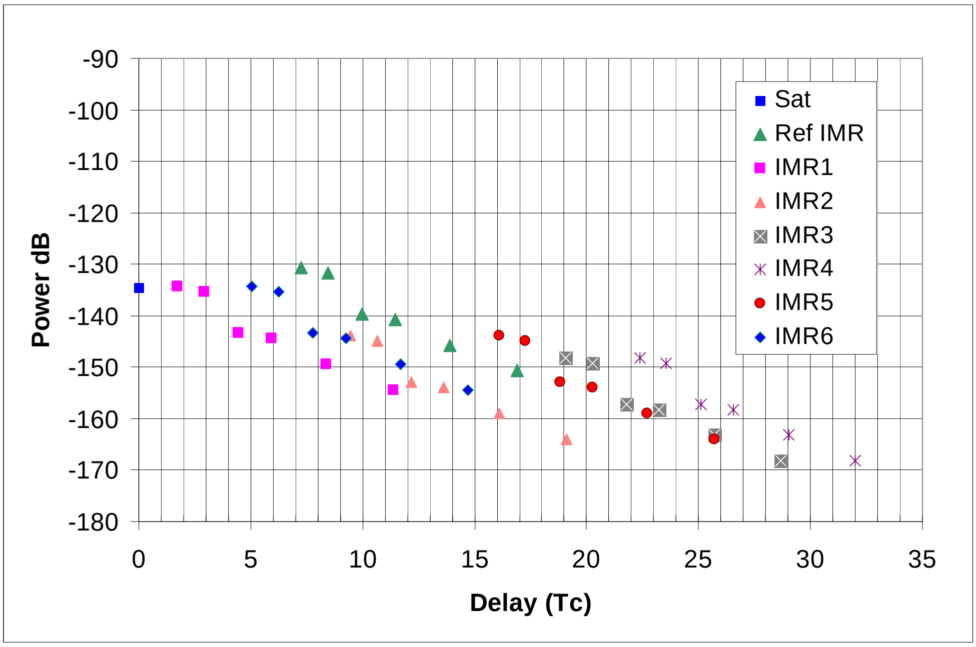

Fig.6. Power delay profile for Low Power IMR coverage (Lat. 42 North, *d*=0.86)

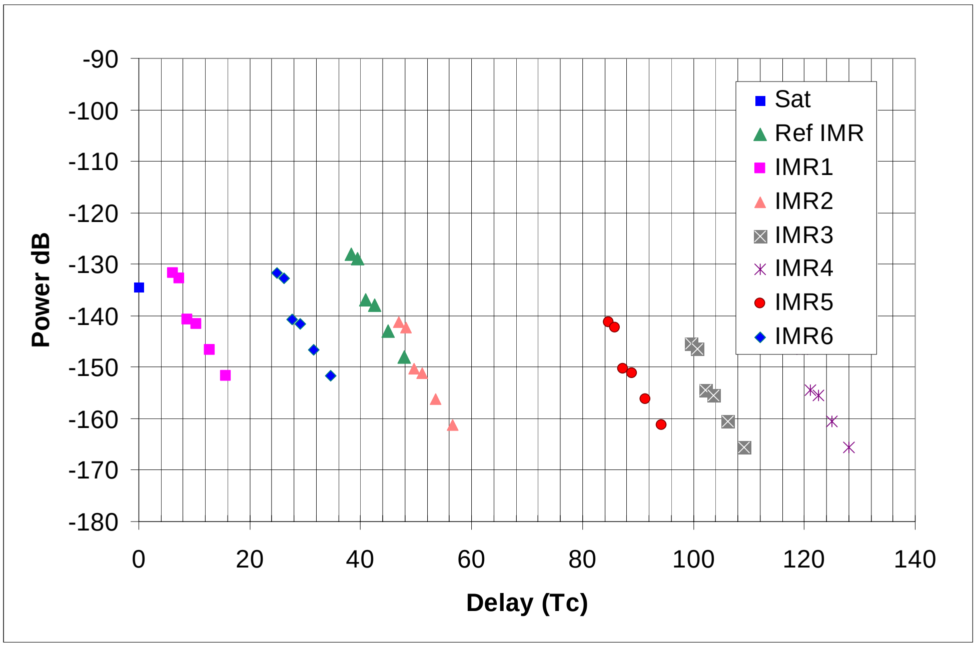

Fig.7. Power delay profile for High Power IMR coverage (Lat. 51 North, *d*=0.86)

VII. CONCLUSIONS

On the basis of the results presented in the previous sections, some conclusions can be drawn. First, the presence of multiple IMRs results into a much wider delay spread with respect to a terrestrial transmission, or a single IMR reception (from a factor of three to a factor of ten, depending on the IMR power). Second, the number of resolvable components is generally much higher. In other words, the rake receiver design seems to be more challenging than in the terrestrial case, requiring a large number of fingers and multiple tracking devices.

ACKNOWLEDGEMENTS

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