Propagation Impairment Countermeasures in Mobile Stratospheric Operating Environment

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Abstract—The efficiency of wireless communication systems largely depends on proper understanding of propagation impairments and the design of suitable countermeasures, taking into account physical causes and time-scales of propagation phenomena. The primary focus of this paper is the link between High Altitude Platform (HAP) and a collective mobile terminal onboard high speed train. The paper characterizes the temporal behavior of the propagation channel on this link by means of first- and second-order statistics, presents a QoS framework based on IP architecture, and discusses potential propagation impairment countermeasures from the perspective of their usage in the provision of different services.

Keywords—High Altitude Platform (HAP); Channel modelling; Applied statistics; Quality of Service (QoS); Propagation Impairment Countermeasures

I. INTRODUCTION

Nowadays, the design of communication systems is faced with ever increasing and principally contradicting challenges such as anytime and anywhere connectivity, growing capacity demands, scarcity of the regulated spectrum, stringent Quality of Service (QoS) requirements, etc. that need to be addressed and fulfilled simultaneously. Consideration of these challenges depends also on the segment the communication system is being designed for. In this respect, High Altitude Platforms (HAPs) [1] have emerged as an alternative or complementary solution to terrestrial and satellite communication systems, representing a promising new way to satisfy users’ needs on one side, and address system design challenges on the other.

During recent years we have witnessed a tremendous growth of new applications, provided using different connection configurations and having diverse QoS requirements. This has influenced the development of the Internet service model, in order to support scalability and integration of heterogeneous networks and provide means for end-to-end QoS management [2]. Such a model in turn requires differentiation of transport services also in the lower layers of the protocol stack, to provide the most suitable link level support for the transmission of services with respect to delay, errors and required connection configurations.

The primary focus of this paper is the link between a HAP and a collective mobile terminal onboard a high speed train [3].

In particular, the paper characterizes the temporal behavior of the propagation channel on this link, classifies potential propagation impairment countermeasures or their combinations, and proposes their usage for a reliable, yet efficient provision of various services. To this end we take into account characteristics and behavior of the HAP-train operating environment described in terms of channel traces and a set of specific types of services and applications along with their requirements, taking into account two main railway lines in Slovenia as a reference. We show how link attenuation levels and outages/availabilities can be used to acquire system operation boundaries and the approach to the design of propagation impairment countermeasures for different scenarios. This framework is discussed from the perspective of connection configuration, QoS provisioning, and the operating environment characteristics.

The rest of the paper is organized as follows. Section II summarizes the investigated HAP-train architecture and the assumptions that were taken into account. A hybrid HAP propagation channel model used to generate channel traces is described in Section III, while its first- and second-order statistical properties are analyzed in Section IV, providing link attenuation levels and outages/availabilities. Next, Section V presents the adopted QoS framework, and Section VI discusses the role and the design of propagation impairment countermeasures. Finally, Section VII concludes the paper and gives some directions for future work.
II. SYSTEM ARCHITECTURE

HAPs combine some of the best features of terrestrial and satellite communication systems, so they have generally been seen either as an alternative or a complementary communication system, but they can be also used as an integral part of a hybrid architecture. Compared to satellites they have similar general system architecture and power constraints, elevation angles like LEO satellites, and due to their close proximity to the ground characterized by significantly smaller propagation delays (in the range of few ms compared to 250 ms delay from gateway to mobile terminal in the case of GEO satellite). In contrast to terrestrial systems, HAPs can more easily guarantee Line-of-Sight link provisioning with a comparable free space loss and require less ground infrastructure.

In this study, no particular link budget and antenna patterns are considered, meaning the system is analyzed only from the perspectives of the propagation properties. The system architecture investigated in this study is depicted in Figure 1. It is composed of a gateway connected to the core network, a HAP equipped with a communication payload at an altitude of 22 km above Ljubljana, the capital of Slovenia, and a collective mobile terminal onboard a train travelling on either of two major railway lines, one running between South-West and North-East (SW-NE) and the other between North-West and South-East (NW-SE). The link between HAP and MT is assumed to be established in the 28-31 GHz frequency band, assigned for the operation over HAPs by the International Telecommunications Union (ITU), but it is not yet available in Europe.

III. HYBRID HAP PROPAGATION CHANNEL MODEL

The availability of a simple but accurate propagation model is of paramount importance for the design of any wireless communication system and especially its radio interface. In general, communications in the mm-wave band are adversely affected by rain attenuation, scintillation due to atmospheric turbulence and scattering from trees foliage. All these effects need to be properly taken into account in a propagation model. However, a statistical mm-wave band HAP propagation channel model cannot be built due to insufficient propagation measurement results obtained to date in the stratosphere. On the other hand, a relatively large number of terrestrial and satellite channel models have been proposed and can potentially be adjusted to model HAP propagation effects. As the propagation aspects of HAPs are in general more similar to those in satellite systems, two HAP channel models have been proposed in [4] and [5] built upon generally established satellite models. The first HAP channel model [4] is used for fixed conditions, where the channel is affected by atmospheric effects, whereas the second model [5] is suitable for mobile conditions, and is based on the land mobile satellite (LMS) channel. The mobile HAP channel proposed in [5] is a three state channel model, with the states representing Line-of-Sight (LOS), partially shadowed, and completely blocked conditions. In LOS and partially shadowed states different probability density functions are used to model slow and fast channel variation (e.g. lognormal, Rice, Rayleigh, Loo distributions).

In order to enable a complete insight into the behavior of a HAP communication link at the considered mm-wave frequency band, this paper investigates a hybrid HAP channel model. The latter is a combination of channel models presented above and it allows joint analysis of fading caused by mobility and atmospheric effects. The modeled effects thus range over a set of different timescales, from extremely slow fading caused mostly by rain attenuation, through slow channel variations caused by transitions among channel states with different statistical properties, to fast fading caused by scintillation, multipath and/or scattering due to mobility. A sample generated trace for atmospheric fading (i.e. rain fading plus scintillation) over one month is depicted in Figure 2a, while Figure 2b presents mobile fading on SW-NE and Figure 2c on NW-SE railway lines. The sample traces represent a single train journey, taking into account free space loss and mobile fading LOS and shadowed states, and characterizing blocked state with 240 dB attenuation.

To investigate whether and how much a particular propagation impairment is correlated to the user location and thus being deterministic, the ray tracing part of the hybrid model allows also simulations of random HAP motion, train speed and acceleration variation, and different halt durations. In general, different railway lines in the same region have similar location-independent properties (i.e. result of small obstacles such as trees or buildings, scintillation, HAP motion, multipath signal transmission, etc.) and different location-dependent properties (i.e. caused by tunnels, bridges or other superstructures, and even power supply arches), which allows efficient general architecture design and a particular environmental system optimization.
IV. STATISTICAL ANALYSIS OF CHANNEL TRACES

In this section we provide a statistical analysis of the channel traces generated by the hybrid HAP propagation channel model described above, with the main objective to characterize the high speed railway environment, analyze its impact on the overall link performance and aid the design of a robust radio interface. For this purpose we generated hybrid traces for both reference railway lines over one month, from periodic end-to-end train journeys. This resulted in 182 traces for the SW-NE railway line and 200 traces for the NW-SE railway line. First-order statistical analysis shows that on average over all journeys, the link of SW-NE railway line is in LOS state for 63 % of the time, 20 % of the time the signal is partially shadowed, and 17 % of the time the channel is completely blocked (2 % of the time due to tunnels and 15 % of the time due to other blockages). Similarly, for the traces of NW-SE railway line, the link exhibits LOS state for 74 % of the time, the shadowed state for 9 % of the time and blocked conditions for 17 % of the time (1 % due to the tunnels and 16 % because of other blockages).

By means of second-order statistics, we analyzed both railway lines in terms of link attenuation levels, availability timeshare intervals and blockage timeshare intervals.

A. Link Attenuation

The principal behavior of propagation channel along SW-NE and NW-SE railway lines over one month period is presented with link attenuation Probability Density Function (PDF) in Figure 3a and with Cumulative Density Function (CDF) in Figure 3b. The similar geographical environment of the railway lines causes the results to have very similar characteristics. By inspecting the CDF it can be noticed that approximately 65 % of link availability (i.e. only LOS state representing link closure) can be obtained with a 30 dB margin, while for the 83 % of link availability (i.e. for link closure in LOS and shadowed) the margin increases to nearly 50 dB. In both cases, around 12 dB is due to the variable free space loss.

B. Link Availability/Outage Timeshares

The second important aspect of the channel is its temporal behavior. We investigate this behavior in terms of timeshares of link availability and link outage. The link availability timeshare is defined as the time interval the state of the channel was either only LOS or only shadowed. Similarly, the link outage timeshare represents a time interval in which the channel was blocked due to either tunnels or other obstacles.

Figure 4a and Figure 4b depict PDF and CDF functions for link availability timeshare. One can see that NW-SE railway line has a lower probability for very short link availability timeshares than the SW-NE railway line. Thus, for the NW-SE railway line about 85 % and for the SW-NE line around 70 % of link availability timeshares are shorter than 100 s. For both lines, less than 10 % of link availability timeshares are longer than 600 s and range up to 2200 s for the SW-NE line and to 4500 s for the NW-SE line.

The PDF and CDF functions for link blockage timeshares are provided in Figure 5a and Figure 5b. As it can be noted, the characteristics of both railway lines are practically identical, with a high probability of very short blockage timeshares (shorter than 10 s), and 95 % of the blockage timeshares shorter than 100 s.

Based on the analysis of channel traces belonging to two railway lines of the same geographical region, the conclusion is that the communications over the HAP are highly dynamic in terms of channel state transitions, representing a major concern regarding the design of the radio interface and calling for careful use of propagation impairment countermeasures.

V. QOS FRAMEWORK

In the classical IP architecture, without any connection setups and all with the traffic handled in a best-effort manner, the QoS is subject to the statistical nature of the network traffic. Avoiding the congestion and satisfying application requirements can thus only be achieved by increasing the bandwidth and consequentially minimizing delays and avoiding packet drops. In order to provide service guarantees in a more efficient manner, the IP architecture requires incorporation of additional features, supported by all network elements and all layers of the protocol stack. Aiming to enable QoS management, two architectures have been proposed by the Internet Engineering Task Force (IETF), i.e. Integrated Services (IntServ) [6] and Differentiated Services (DiffServ) [7], with different and somewhat contradicting features and objectives. Thus, interworking approaches have also been proposed, with the IntServ principles used to guarantee end-to-end service and the DiffServ mechanisms introduced where absolute guarantees are not required or where scalability is an issue [2, 8].

There are a number of documents describing the IP-based network QoS parameters, but in this paper we take as reference those provided by the ITU-T in the recommendations G.1010 [9] and Y.1541 [10]. The recommendation G.1010 discusses key parameters affecting the QoS and provides requirements classification for different applications. The key QoS parameters are: (i) bandwidth, giving the maximal data transfer rate between end points; (ii) delay, describing the time of packet transfer from the sender to the receiver; (iii) delay
variation (jitter), representing the variation of the end-to-end delay; and (iv) error rate, being a consequence of lost or corrupted packets. Considering the application characteristics, queuing mechanisms and routing types, the recommendation Y.1541 defines six QoS classes, reflecting the application layer requirements in the recommended network objectives (delay, jitter and error tolerance). In particular, regarding the delay, services can be classified into delay-tolerant (elastic) and delay sensitive (real-time) ones. Error rates can be error-tolerant or error-intolerant. Finally, with respect to the connection configuration transport services, they can be seen as point-to-point (unicast), point-to-multipoint (multicast), point-to-allpoint (broadcast), point-to-anypoint (anycast), and multipoint-to-multipoint (mesh). For any combination of this three-fold service characterization, advanced approaches of QoS provisioning may be applied, whereas we focus in the next section on the error control techniques to be used in the mobile HAP access segment.

VI. PROPAGATION IMPAIRMENT COUNTERMEASURES

Although mm-wave frequency bands assigned for communications over HAPs are attractive from the perspective of available bandwidth, important limitations must be taken into consideration and specific techniques should be used in order to translate these potential resources into actual system capacity, link availability and provided QoS levels. To fulfill at the same time also the cost per bit requirements, the techniques to compensate for propagation impairments in real-time should be pushed forward where possible, instead of applying fixed static margins. Following the analysis of channel traces and respecting the considered QoS framework, the aim of this section is to discuss the suitability of numerous propagation impairment countermeasures in the mobile access segment of HAP-based communication system.

Before discussing some of the promising techniques [11, 12, 13] or their combinations more in detail, a perspective of their usage and optimization should be stated. From the link perspective the propagation impairment countermeasures may be pre-estimated, i.e. being defined during the link setup, or may allow adaptive optimization, i.e. being optimized with respect to instantaneous link (propagation) conditions. The adaptive techniques additionally imply the existence of a return communication link to perform link state information signaling and can be further divided into techniques acting on a link state change with or without respect to other coexisting links. It should also be noted that the latter techniques greatly rely and depend on the accuracy of the link state information. In other words, the techniques’ performances are subject to errors caused by the estimation algorithms and/or errors introduced by the obsolescence of information due to feedback and processing delays. The framework for the design of propagation impairments countermeasures for different scenarios and connection configurations, taking into account requirements on one side and external effects on the other, is illustrated in Figure 6.

Using propagation impairment countermeasures means adapting the link budget to changing propagation conditions so as to best satisfy the QoS requirement. Many countermeasures have been proposed in the literature for Layer 1 and 2, and also some for the layers above. When speaking of Layer 1 countermeasures, typically referred to as Fade Mitigation Techniques (FMT), it should be noted that their usage might have direct impact on Signal-to-Noise ratio (SNR) and/or Signal-to-Interference ration (SIR). A widely used technique in this respect is power control (PC), where transmitting power is adjusted to propagation impairments. Next a strictly Layer 1 technique is adaptive modulation (AM), where the order of modulation (bits per symbol) is set according to the energy per bit requirement. A technique generally used together with AM is adaptive coding (AC). Its objective is to introduce redundant bits to the information bits to allow error detection and/or offer error-correcting capability. The latter technique is more commonly called Forward Error Correction (FEC), with its objective being the reduction of required energy per transmitted bit. It can be applied on different layers, but most often on Layer 1 (i.e. channel coding) or Layer 2 (i.e. upper-layer FEC). FEC might also be optimized together with other techniques not directly intended to countermeasure propagation impairments, such as application coding (i.e. used to compress the information), in order to provide optimal balance or enable
efficient resource utilization (e.g. unequal protection of diversely important data). Upper-layer FEC is usually introduced to cope with temporal propagation impairments (i.e. burst errors) and it can be used in addition to classically applied interleaving, to dispose errors over several codewords. A group of techniques applied on different layers, not having the aim to act on a particular link, but instead improve the transmission by using least impaired link or multiple links, is known as diversity techniques. These include frequency diversity, where the link is established on a less occupied or a frequency less susceptible to impairment; site diversity, where the connection is rerouted through an alternative network element; space diversity, with the signal being received from different paths; and time diversity, where the signal is received in different time instances. Special cases of time diversity techniques are also periodic retransmissions and Automatic Repeat Request (ARQ). Another set of countermeasures not intended to adapt a particular link are gap filler and buffers, having similar objectives and ability of being introduced on different layers, but suitable for different types of services.

It is obvious from the above that different propagation impairment countermeasures are applicable in different combinations, on different timescales and on different layers of the protocol stack. Consequently they have different impact on the overall communication system and are appropriate to compensate for different effects that could degrade QoS. This implies that there may be existing different optimal combinations of countermeasures for the provision of different services through different connection configurations. Our future work will thus first focus on the investigation of estimation and prediction techniques for the propagation phenomena distinction and joint design of propagation impairment countermeasures. In other words, by bringing into the system environmental-awareness [14], we will try to aid system design and operation for the seamless QoS provision and efficient resource utilization.

VII. CONCLUSION

This paper addresses the design of propagation impairment countermeasures for the specific stratospheric environment. In particular, it focuses on the mobile access segment for the HAP-train operating environment, represented by channel traces incorporating atmospheric and mobility fading effects along two representative railway lines in Slovenia. Channel traces were analyzed by means of first- and second-order statistics and characterized in terms of link attenuation level probabilities and link availability/outage probabilities. The statistical analysis confirmed the HAP-train operating environment as being highly dynamic, thus requiring estimation and prediction techniques for the propagation phenomena distinction and joint design of propagation impairment countermeasures, paying particular attention to the timescales of impairment effects to be compensated for and to the actual QoS levels different services need to deliver to applications.

ACKNOWLEDGMENT

Part of this work has been carried out during the lead author's Short Term Scientific Mission at the University of York supported by the COST 297 Action - HAPCOS.

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