Transfer and Management of Broadband Traffic in Wireless Telecommunication Networks

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Abstract. The present thesis aims to study resource allocation techniques in fixed wireless networks in order to optimize their spectral efficiency as well as to investigate alternative broadband transfer methods. A brief overview of broadband wireless access networks with their characteristics is given and the fundamental resource management techniques proposed in the open technical literature are also referred. Then, a typical wireless broadband network model is presented and a comprehensive review of the key resource management techniques proposed in the literature is given. Following this, the proposed resource management techniques are presented and compared using proper simulation results.

On the other hand, the analytical model of a wireless broadband traffic model over a terrestrial wireless optical link is analyzed. Its performance is extracted using analytical expressions of the average outage probability and the average error probability metrics. Appropriate simulation results are depicted as well. Furthermore, a network architecture comprising of several high amplitude platforms communicating with each other using optical links, is introduced in order to transfer broadband traffic over long distances. The outage probability performance is examined using either one-hop or multi-hop scenarios and suitable numerical results are provided. Finally, concluding remarks are summarized and suggestions for further research are indicated.

Keywords: Resource management, interference management, free space optics, fading, turbulence, pointing error.

1 Dissertation Summary

The vision of 'broadband to all' has necessitated the deployment of fixed wireless access (FWA) as an alternative technology in order to provide broadband access to geographical areas where the cost of wired infrastructure is extremely high. Such a technology is the Worldwide Interoperability for Microwave Access, commonly known as WiMAX, which is based on the IEEE 802.16 standard. The continuously

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growing demand for higher data rates and bandwidth-consuming services becomes a driving force toward larger channel widths and wider spectrum block allocation consequently. Traditional frequency planning with high reuse patterns wastes the limited available spectrum, especially in the lower regions of the WiMAX frequency operation band. Therefore a full frequency reuse in each sector of each cell is a very attractive alternative to fulfill this challenge.

However, such an approach results in high co-channel interference (CCI), which arises from concurrent intracell and intercell transmissions, and affects significantly the users' quality of service (QoS). Several approaches have been proposed in the literature for CCI reduction. An increased effort is focused on the corresponding time domain radio resource allocation techniques (RRA) [1–4] in order to organize the total amount of interference.

Another critical issue is the transfer of broadband traffic (e.g. WiMAX based traffic) in remote terminal stations in order to improve coverage, flexible access and reduce the cost of deployment. An effective solution is the transportation of radio signals between a central base station and multiple radio access units in optical form and the transmission through a fiber optic. Radio over Fiber (RoF) transmission [5] has a number of advantages but installation cost may be prohibited. Hence, it is not always feasible its deployment in practice. In this case, the transmission of radio signals on Free Space Optics (FSO) links combines the benefits for ease deployment in wireless links and high capacity enabled by fiber optic technologies. Several Radio over FSO (RoFSO) systems studies have been recently presented in the literature [6-9].

Obviously, as the terminal stations are located in increasingly greater distances satellite communications becomes a dominant alternative for broadband traffic transferring. Nevertheless, excessive high power requirements and high installation costs are serious disadvantages and an alternative high challenging solution is to employ a network consisting of high altitude platforms (HAPs). HAPs combine some of the most distinctive characteristics of terrestrial wireless and satellite communication systems, e.g., broad service areas, great capacity, low transmission delay, adequate power consumption, etc. They are located in the stratosphere, approximately 25km above the ground, and remain stationary, maintaining, thus, the same behavior as geostationary satellites. However, the short distance between HAPs and ground stations, lead to lesser power demands and much smaller round trip delays, making this technology quite attractive for broadband services in next-generation wireless communications [10].

The overall performance of outdoor FSO systems depends upon the climatological conditions and the general characteristics of the transmission paths. Furthermore, the transfer of broadband traffic over FSO links has not been adequately investigated in the literature. That was one of the motivations for this thesis and the contributions include detailed performance analysis of WiMAX RF signals transferring through two alternative FSO technologies. At first, an FSO terrestrial link is considered where turbulence effects for the FSO subchannel and composite fading effects for the RF subchannel are adopted [11,12]. Then, a multi-hop HAP network is examined [13]. These HAPs take the role of terrestrial base stations and collect the WiMAX traffic from the area they cover. They have transparent transponders that convert the WiMAX signals to optical ones and the reverse. The optical signals are transmitted from the source to the destination HAP through inter-HAP links and the traffic is delivered by this way to the end users after RF conversion. In addition, the optimization of spectral efficiency for the downlink segment of a FWA network is examined and three effective resource allocation methods are proposed and analyzed. The basic idea of the first proposed algorithm is the avoidance of the major interferers by using different allocation schemes for the even and odd sectors [14, 15]. This algorithm is enhanced with the adoption of multi-mode modulation schemes [16]. Finally, the use of alternate polarization allocation (PA), as a means to decrease the interference into the desired signal in conjunction with a time domain RRA technique is proposed in [17, 18]. The proposed architectures were evaluated with realistic sets of parameters and closed form expression and simulation results are presented.

2 Results and Discussion

2.1 A RRA scheme for FWA systems with avoidance of major interferers

As it has been proposed in [3], ESRA examines a packet switched broadband wireless network using time division multiple access (TDMA) technique and time division duplexing (TDD) with full frequency reuse. The service area is divided in hexagonal cells and sectors are labeled from 1 to 6, counter-clockwise, in such a way that there are no adjacent sectors bearing the same label (Fig. 1).

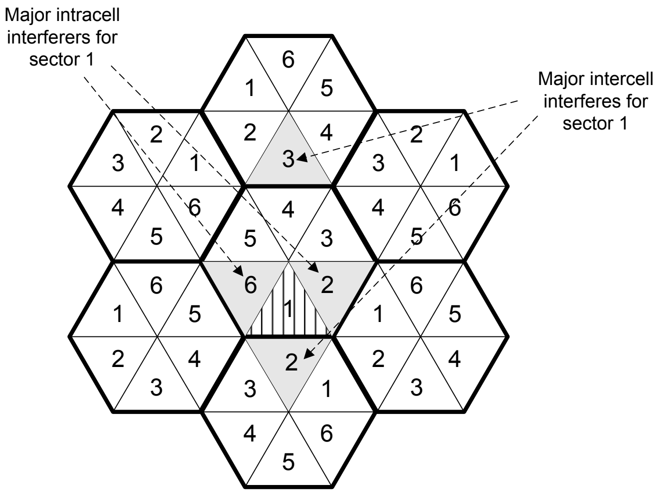

Fig. 1. Major interferers for the downlink direction of the hexagonal cell layout.

The frame is divided into six subframes (SBs), which are further divided into mini-frames (MF) labeled from 1 to 6. Each sector schedules packets for transmissions in available MFs of each SB following the staggered order of Fig. 2a.

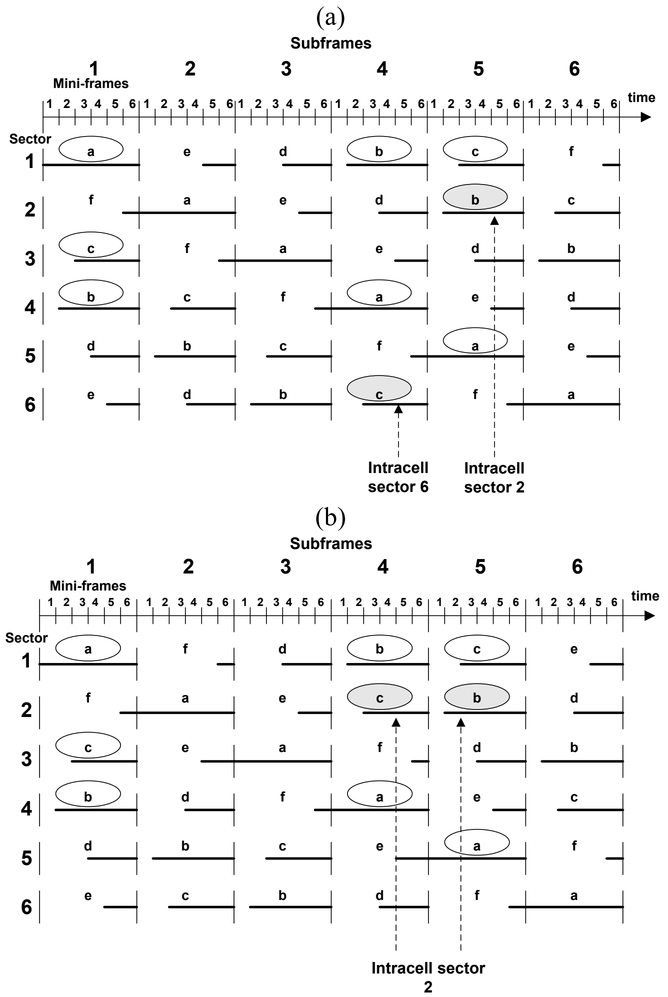

Fig. 2. Three concurrent transmissions for sector 1 according to (a) ESRA and (b) proposed method.

According to this order, sector 1 schedules packets for transmissions in SB 1 (denoted by a). For further packet transmissions, exploiting Base Station (BS) directional antennas, it uses SB 4, which is the first SB of the opposite sector. The next options for sector 1 will be the available MFs of the first SBs of the other two opposite sectors (i.e. sectors 5 and 3) clockwise and the last two options will be the available MFs of the first SBs of the adjacent intracell sectors (i.e. sectors 2 and 6) clockwise too. The same procedure is applied to the other sectors. Terminals are classified into six classes according to the number of maximum tolerable concurrent transmissions following the staggered order of Figure 2a. For example, a class 3 terminal of sector 1 tolerates the following three concurrent transmissions: sectors 1-4-3 in SB 1, sectors 4-1-6 in

SB 4 and sectors 5-2-1 in SB 5 (Fig. 2a). The degree of concurrent transmissions of each MF is defined on its label. More precisely, MF 1 allows only 1 packet transmission; MF 2 allows 2 concurrent packet transmissions and so on. Terminal classification is based on the reception quality of their location that depends on antenna characteristics (3dB beamwidth and Front-To-Back (FTB) ratio), shadowing and distance from serving BS. The reception quality may be improved through a macrodiversity procedure (i.e. selection of serving sector). Each MF with the same label has the same number of timeslots in each SB (MF i has n_i , $i = 1, 2,\ldots,6$ timeslots in each SB). The size of MFs is chosen to match the expected traffic load and is a mechanism to increase the overall throughput.

For a typical FWA system, throughput enhancement is achieved by upgrading the number of higher classes' terminals through advanced methods of major intercell and intracell interferers' avoidance. As shown in Fig 1, the major interferers for sector 1, under a simple path loss model, comes from the shadowed intracell sectors 2 and 6 (due to overlapping sector antenna patterns) as well as from shadowed intercell sector 3 (because of the front lobe of sector antenna 3 that point directly to the terminals of the tagged sector) and the opposite shadowed sector 2. Following the ESRA staggered order (Figure 2a) for higher terminal classes (i.e. classes 4, 5 and 6) the major intracell interferers are appearing not only solely but also together.

The proposed method [14, 15] is based on a different allocation scheme for odd and even sectors, which is examined and proposed as follows. The sector 1 schedules packets for transmission in SB 1, as shown in Fig. 2b. If there are more packets for transmission, it uses the available MFs of SB 4, which are the first SB of the opposite sector, in order to exploit the BS directional antennas and the low level of interference. All sectors follow this procedure for the first two SBs. However, the next two options for sector 1, according to the staggered order will be the available MFs of the first SBs of the other two opposite sectors (i.e. sectors 5 and 3) clockwise and the last two options will be the available MFs of the first SBs of the two adjacent intracell sectors (i.e. sectors 6 and 2) counter-clockwise. This concept is applied to the odd labeled sectors (i.e. sectors 3 and 5). On the contrary, for sector 2, the next two options will be the available MFs of the first SBs of the other two opposite sectors (i.e. sectors 4 and 6) counter-clockwise while the last two resorts will be the available MFs of the first SBs of the two adjacent intracell sectors (i.e. sectors 3 and 1) clockwise. This procedure is repeated for the even labeled sectors (i.e. sectors 4 and 6). This situation is exploited by the proposed method in order to increase the number of class 3 terminals due to the fact that each sector is interfered only by one adjacent intracell sector in contrast with ESRA where each sector is interfered by both adjacent intracell sectors one after the other. More explicitly, in the case of three concurrent transmissions (class 3 terminals) of sector 1, Fig. 2a presents the allocation scheme based on ESRA and Fig. 2b the proposed scheme. Sector 1, following the ESRA staggered order, is interfered in SB 4 by sector 6 (one dominant intracell interferer) and in SB 5 by sector 2 (the other dominant intracell interferer). On the other hand, following the proposed staggered order, sector 1 is interfered in SBs 4 and 5 by sector 2 (i.e. the same dominant intracell interferer). As a result, the proposed method upgrades the fraction of terminals that tolerate three concurrent transmissions enhancing the maximum throughput per sector.

2.2 Performance improvement of FWA systems using multi-mode modulation schemes

The classification procedure presented in the previous section is based on the worst case scenario, so that all users are guaranteed a minimum QoS for a given signal to interference ratio threshold (SIR_{thr}). However, this procedure produces a different signal to interference ratio (SIR) for each terminal in each SB. Indeed, each class-*i* terminal has *i* respective SIRs in *i* different SBs. Therefore, a SIR margin becomes available for each terminal and i different SIR margins may be expected from SB to SB. It is well known that a higher SIR supports a higher modulation mode and therefore a larger number of bits per symbol. Approaches proposed in [3,14,15] ignore these SIR margins and adopt a single modulation mode according to the specific SIR_{thr} used in the classification procedure. The motivation of [16] is to examine the possibility of utilizing the above SIR margins by adopting higher modulation modes. A performance enhancement in each sector is then expected.

The adoption of different modulation modes affects the TDMA frame structure (Fig. 3). The time sharing of MF among terminals using the same modulation mode induces its further partition into N_{modes} micro-frames, where N_{modes} is the number of the adopted modulation modes. It is noticed that one mode is assigned to each micro-frame. In [16] it is shown that the adoption of multiple modulation modes induces a maximum throughput per sector enhancement exceeding 50%.

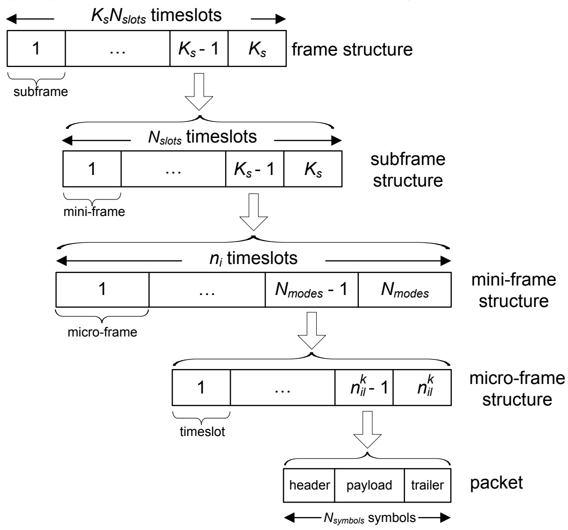

Fig. 3. TDMA frame and proposed MF structures.

2.3 Performance improvement of FWA systems by conjunction of dual polarization and time domain RRA technique

The CCI reduction is a major challenge and the proposed RRA algorithms significantly improve the maximum throughput per sector. However, a further improvement would be achieved by jointly utilizing a scheduling algorithm and an alternate polarization allocation (PA) scheme as presented in [17, 18].

The service area is divided in hexagonal cells and triangular sectors. Each sector is equipped with its own directional antenna and labeled from 1 to 6 counter-clockwise, in such a way that there are no adjacent sectors bearing the same label (Fig. 4). Each sector is connected with the IP backbone network through a switching module. The labels of three adjacent cells are rotated by 120°, in respect one another, creating a cluster (contained in the heavy line in Fig. 4) whose pattern is repeated across the entire service area. Adjacent sector antennas use alternate polarization so as to maximize isolation among them and increase the communication quality. Users use rooftop directional antennas pointing to their respective sector antenna following the polarization pattern. The beamwidth of a sector antenna has to be wide enough in order to serve the entire sector, whereas the beamwidth of each terminal antenna must be more directional to lower interference.

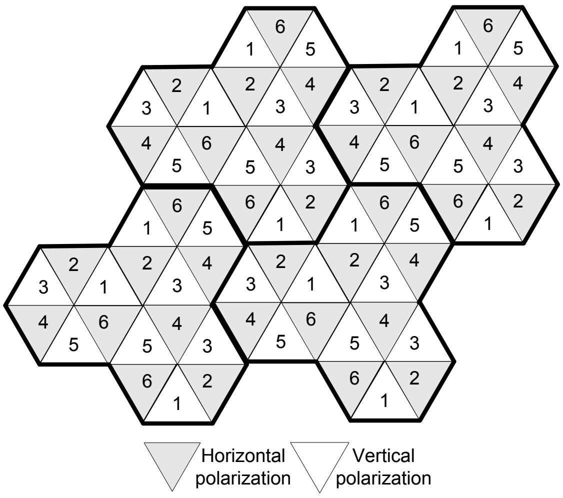

Fig. 4. A representative part of the hexagonal cell layout consisting of 4 clusters.

Considering an FWA network without a PA pattern, it is clear that the most significant amount of intracell interference, for each sector, is originating from its two adjacent sectors due to the overlapping sector antenna patterns. However, under the proposed framework, each sector antenna is transmitting with orthogonal polarization with respect to its adjacent sector antennas. Hence, the amount of intracell interference is significantly reduced and the maximum throughput per sector is further increased.

2.4 Transfer WiMAX signals via terrestrial optical wireless links

In [11, 12] we consider a terrestrial FSO link which is used to deliver WiMAX traffic from one geographic region to another. The overall system configuration is composed of the optical and the wireless subsystems. We assume that the WiMAX traffic from heterogeneous networks reaches the optical transmitter through an access gateway. The transmitter (Fig. 5b) converts the electrical signal to laser. It is composed of a modulator, a laser driver, a light-emitting diode (LED) or laser, and a telescope as a whole. The laser propagates through the atmosphere to the receiver assuming a Gaussian beam wave model.

The receiver (Fig. 5b) uses a direct detection scheme and includes a telescope, a filter, a positive–intrinsic–negative (PIN) photodetector, and a trans-impedance amplifier. Depending on cost restrictions and reliability requirements, a tracking and pointing subsystem may be implemented in both sides of the communication link to maintain transmitter–receiver alignment.

The electrical signal is guided to a WiMAX base station and delivered to the users located there. The WiMAX standard is based on the OFDM standard utilizing a large number of closely spaced orthogonal subcarriers.

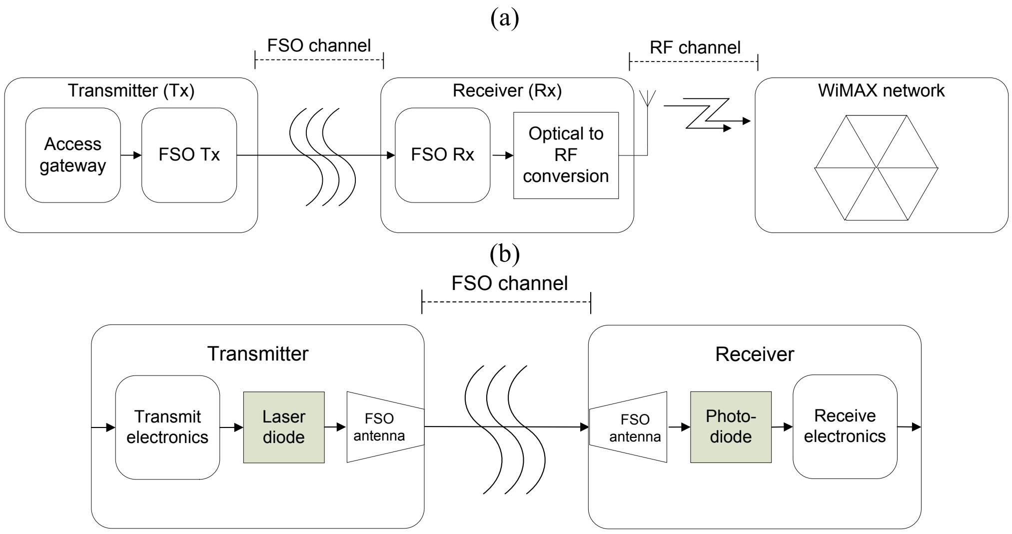

Fig. 5. (a) Optical and RF subsystem (b) Optical subsystem.

An appropriate channel model is adopted, which entails some of the most critical impairments of the optical channel, i.e., attenuation, turbulence, pointing error effects, as well as of the RF channel, i.e., path loss, shadowing, and fast fading, is taken into account. The overall link budget and a closed-form of the outage probability of the system are deduced. Several analytical results are depicted using a realistic set of parameter values, to lend a helpful insight to the performance of the proposed architecture.

2.5 Transfer WiMAX signals using an FSO multi-hop HAP network

In [13], we present a novel HAP network architecture which aims at delivering WiMAX services to extremely far distances on Earth using multi-hop routing. HAPs in the network take the role of terrestrial base stations and collect the WiMAX traffic from the area they cover. They have transparent transponders that convert the WiMAX signals to optical ones and the reverse. The optical signals are transmitted from the source to the destination HAP through inter-HAP links and the traffic is delivered by this way to the end users after RF conversion. In such an architecture, we determine the WiMAX quality of service (QoS) by minimizing the outage probability for the network configuration.

The source HAP (Tx HAP in Fig. 6) communicates with the destination HAP through R_i, i=1,2,…,N -1 optical transceivers, which act as relays-nodes all being in equidistance d_O, i.e., there are N point-to-point propagation links before the laser signals arrive to the destination. Relay assisted transmission is a common technique in wireless RF communication systems since it provides a broader and more efficient coverage and can be used as a fading mitigation tool. Every intermediate node in a multi-hop network acts as a router that forwards traffic towards its destination. In [13], we consider N-1 relays where each one has knowledge of the channel state of the previous hop. We assume the use of amplify-and-forward (AF) relays which just amplify and forward the incoming signal without performing any sort of decoding. These relays use less complex circuitry compared to decode and forward (DF) ones, which decode the signal and then transmit the detected version to the destination ones.

The destination HAP (Rx HAP in Fig. 6) receives the optical power using a telescope. Optical light can be concentrated by using lenses and mirrors, or any combination of them. A filter helps to remove the background radiation from entering the Rx which generally creates shot noise and saturates the detector. The optical signal from the output of the filter propagates to the detector, which converts it to an RF electrical signal using a photodetector [19]. Finally, the RF electrical signals are delivered to the end users located in the HAP Rx area.

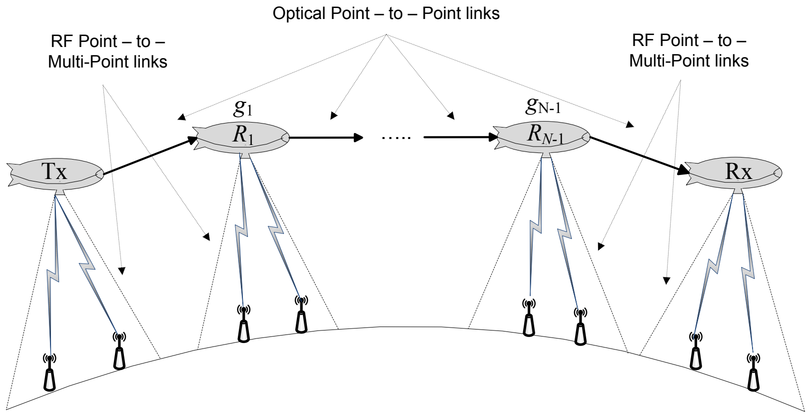

Fig. 6. HAP network configuration.

The overall performance is examined by using a channel model which incorporates laser path loss as well as pointing error effects. A closed-form of the outage probability of the system is extracted and several analytical results are depicted adopting a realistic set of parameter values.

3 Conclusions

In the context of this dissertation we examined advanced RRA methods for the downlink of a FWA network as well as the transfer of broadband traffic via optical wireless links.

More precisely, we presented a RRA which improves the ESRA method in terms of throughput per sector by increasing the number of terminals that tolerate more concurrent transmissions. For a typical radio environment, a 10% increment of the maximum throughput per sector with respect to ESRA method is achieved. It’s worth mentioning that the proposed RRA scheme performs better under realistic transmission conditions and with various types of antennas and exploits better low performance antennas, which present large beamwidths and FTB ratios.

Furthermore, the SIR margin, induced by the terminal classification procedure, in a TDMA FWA system is examined and analyzed. An advanced frame structure is proposed, facilitating the utilization of multiple modulation mode schemes. It has been shown that a significant throughput improvement is achieved, for various SIR_{thr} values, used in terminal classification procedure.

The third contribution includes an integrated time domain RRA technique of concurrent transmissions and polarization alternation pattern for the downlink direction of an FWA system. The proposed scheme presents an enhanced performance since the PA pattern incorporation reduces significantly the impact of dominant interferers. It must be noticed that the proposed scheme performs better under worst propagation conditions and exploits better low-performance antennas, which present large beamwidths and small FTB ratios.

Moreover, we constructed a simple but adequate architecture to investigate WiMAX transmission over terrestrial FSO channels. The channel model considers the laser link and the WiMAX communication system parameters used in practice. Specifically, some of the most critical impairments of the optical channel, i.e., path loss, turbulence, pointing error effects, as well as of the RF channel, i.e., path loss, shadowing, and fast fading were taken into account, and an analytical derivation of the outage probability was obtained. The feasibility of the proposed architecture was further evaluated with a realistic set of parameter values and depicted using proper graphs. The present architecture may constitute the outset of adopting and evaluating more complicated and, at the same time, more realistic RoFSO deployment scenarios. In this vein, the incorporation of forward error correction schemes in order to increase the overall performance seems to be quite challenging and such an extension is a subject of ongoing research.

Finally, we presented an alternative method to deliver WiMAX services at extremely far distances on Earth by using a HAP network. A source HAP collects the traffic from the multi-hop routing through a number of intermediate HAPs. HAPs communicate with each other using laser links. After reaching the destination HAP, the traffic is transformed in RF form and delivered to the end users on Earth. The optical HAP transceiver and the laser inter-HAP channel, that takes account of the pointing error statistics, were analytically described. At first, we considered the case where the source directly communicates with the destination and then we generalized to a relayed scenario. We particularly focused on the outage probability at the ground users and presented proper graphical results for the performance evaluation of the network. The obtained results can serve as a guideline for designers to predict and evaluate a HAP network ability to deliver broadband services in practice. The analysis conducted assuming a typical parameter set mainly used in practical systems. However, a thorough investigation is necessary in order to find the appropriate set for better performance. The choice for example of optimum gains and the beam divergence angle is a crucial point before the implementation process. Random angular jitter affects the overall performance and therefore proper tracking systems need to be considered. The present analysis can be extended in a number of ways. For instance, it would be interesting to consider nonlinear laser diodes and examine the effect of intermodulation distortion which is often present in practical laser links. Another extension is the consideration of turbulence in optical links for large inter-HAP distances. Fading may also be included in the RF downlink link. These additions would increase the mathematical complexity of the model but on the other hand make it much more reliable. Since practical HAP networks are currently working using microwave links, the idea of evaluating the performance of RF multi-hop links would be of particular help for comparison reasons. Moreover, different types of relays may be used, e.g., DF, all-optical relays, etc. Finally, the investigation of a coexistence scenario between heterogeneous HAP and satellite networks for increased overall performance appears quite challenging.

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