Performance Analysis of Throughput Efficient Switch-over between FSO and mmW Links

F. Nadeem, M. Gebhart, E. Leitgeb, M. S. Awan, B. Geiger, M. Henkel, G. Kandus

Abstract: **Free Space Optics (FSO) links provide usage of high bandwidth and the flexibility of wireless communication links. However, weather patterns like fog and heavy snow fall limit the availability of FSO. Another technology providing similar properties regarding offered data rates and flexibility of setup is Millimeter Wave Technology (mmW), operating at several tens of GHz. In this case, heavy rain limits mmW link availability. A combination of both technologies had been proved to be very effective to achieve very high availability. Different hybrid architectures of these two links and switch-over techniques had been proposed in the recent years. All of these techniques require redundant transmission on either both transmission links or waste bandwidth of backup link when main FSO link is operational. In this paper, a switch-over between these technologies is proposed, to maintain high availability without the loss of transmission bandwidth. The performance of this switch-over has been simulated for more than one year measured availability data for hybrid network of mmW link and FSO link The switch over behavior has also been simulated for fog, rain and snow events. It has been shown that the availability with switch-over reaches the redundant link availability but switch-over can save more than 90% redundant transmission and increase the hybrid network throughput significantly.**

Index terms: **Availability, FSO, Hybrid network, mmW, Switch-over**

I. Introduction

Free space optics (FSO) communication due to its high carrier frequency in the range of 300 THz, enables transmission of high data rate demanding applications like audio and video streaming, video on demand, video teleconferencing, real time medical imaging transfer, enterprise networking and work sharing capabilities. These optical wireless links are greatly influenced by the transmission media which in most cases is the earth atmosphere for terrestrial and ground-space communication applications. Among the various attenuating factors, fog is the most deterrent of all because the size of fog droplets is comparable with the optical wavelengths used; however the attenuation due to rain is comparatively less important for the optical wireless links. Similarly, comparable data rates can be achieved using millimeter Wave (mmW) based communication networks operating at very high carrier frequencies of the order of 30-300 GHz. The main limiting factors for the mmW links are rain, hail and wet snow, which limit the link power margin. Importantly, for these mmW links fog is not a major concern since increased humidity causes attenuations less than 5 dB/km [1].

Different combinations of FSO and mmW transmission links had been proposed for various application scenarios like hybrid link for airborne applications [2], ad-hoc mobile networks [3, 4] and terrestrial and space applications [5, 6, 7, 8] etc. A measurement campaign was carried out using redundant FSO and mmW links in Graz for more than 14 months starting from 01.12.2001 to 01.01.2003 during the years 2001 and 2003. Same data was simultaneously sent over two such parallel links and the availability was measured over 14 months for each individual link and for the hybrid combination of both links. An availability of 99.93% was achieved for the hybrid combination at Graz [1].

Two approaches are generally considered for implementing a hybrid system either by using two different link technologies operating in parallel for all the time thus resulting in loss of almost 50% available bandwidth for redundant transmission or it can be implemented by a kind of switch-over so that only one technology has to be operational most of the time. The second approach saves redundant transmission of the data and use back up link only if it is needed in case of main link failure. Switch-over employing the second approach for these hybrid links were previously discussed in [9, 10, 11], but all these proposed switch-over techniques do not utilize transmission bandwidth of back up links when main link is operational.

In this paper, the switch-over is proposed that improves the bandwidth utilisation by employing load sharing when both links are operational. Moreover, when any link is not operational, it monitors that link for its recovery. The switch-over to any of the link is based on the idea of monitoring received signal strength against a threshold level [9]. The performance of proposed switch-over is simulated for the measured availability data of 14 months for these links.

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II. Free Space Optics (FSO) Communication Links

Based upon line-of-sight connections through the air, FSO technology can provide broadband outdoor communication links for company intra-networking or serve as an alternative, flexible access technology to a network backbone. In general, the technology is an alternative for conventional wireless radio links in the 2.5 and 5.6 GHz frequency range, and to fibre optic cable links. FSO systems can be installed very quickly, if a network connection, supply power and an option to mount the system stable on ground is available, allowing also temporary short-term installations or "nomadic" use for events and meetings at dislocated places. But they can also be used for permanent short distance links in urban areas in Point-to-Point or Point-to-Multipoint configurations.

As the air has good transmittance in the same "windows" as used for fiber optic links, mainly at 850 nm and at 1550 nm wavelengths, the FSO systems can use the same component technology which allows very high bit rates for a wireless system, up to several Gbit/s, based on qualified technology today. Moreover, due to the linear channel characteristics, this can be achieved with serial line codes used in cable networks on the physical layer, so there is no need for a code conversion like to OFDM or Spread Spectrum technology. Also, there is no requirement for "Listen before Talk" at the air interface. In addition it allows similar high data throughput as in cable networks. The systems can be operated license-free all over the world, and in case the Laser Safety regulations are met, which means, the system should be certified to Class 1, 1M or Class 2, there are no further restrictions on the use of the technology. For the 850 nm technology, less output power is allowed, but receivers can be built more sensitive, while for 1550 nm more output power is allowed in eye-safe Laser Classes, but the receivers are a bit less sensitive. So a sufficient total power margin can be achieved for both types of systems for quasi bit-error free operation. Also, due to the high carrier frequencies of about 200 and 350 THz, the directivity is very high even with small optics diameter, which results in a small illuminated beam and gives a security benefit on the physical layer, in addition to any encryption that may be applied by the application.

The main challenge for FSO is variable attenuation in the air which depends very much on the local climate (seasonal and diurnal) and weather situation. Fog attenuation has the most critical impact on the optical signal propagation in the free space. As the water droplets have the same order of size than the wavelength of the infrared light, this causes Mie scattering, which mainly means more directivity loss than power loss of the light beam. Rain causes less attenuation, but as the droplets have much larger dimensions compared to the carrier wavelength, they cause geometrical scattering, which is less critical. Snow flakes can also have high attenuation as they are opaque, their effect depends on the relation between the diameter of the light beam and the diameter of the flakes. Further effects for reduced transmission quality or link failures are direct sunlight at the receiver, turbulences in the air, beam misalignment or soiled optical components (like mirrors, glasses and lenses).

III. Millimeter Wave (mmW) System

Due to their high carrier frequencies ranging from several tens of GHz up to more than 100 GHz Millimeter Wave communication systems also offer very high data rates comparable to FSO. Operated at the diffraction limit, high directivity can be achieved even with small antenna dishes in the range of 20 cm. Although the frequency range up to 375 GHz is governed by Frequency Control Commissions worldwide, there are some license-free bands available like 77 GHz with limitations in power and other properties.

The most promising technology for a cost-effective market solution is based on integrated semiconductor amplifiers. For this new technology however, several technical challenges exist. Temperature drift of oscillators and filter stages, noise , low available output power and device aging under thermal stress are critical points today. As the price increases much for Millimeter Wave semiconductor amplifiers, system costs would increase much with link distance, for a given bit rate and availability.

The channel for terrestrial outdoor mmW communication links has different characteristics as compared to wireless optical communication. Rain causes the main attenuation contribution. Fog on the other hand is less important (except for wavelengths which are absorbed by water vapours, as in the 22 GHz range). This complementary behaviour gives rise to the concept of a hybrid system, combining advantages of FSO and mmW to a wireless communication link offering high data rates and high availability at reasonable costs.

IV. The Hybrid System – mmW and FSO Ccombined

Experimental transmission measurements on two such links over a distance of 2.7 km in Graz were made over 15 months for mmW and FSO in parallel (2001-2002), and for more than 4 years for a FSO system over the same link distance (2000 – 2004). The FSO equipment was a commercial GoC MultiLink system with 156 Mbit/s bit rate (STM-1) with multiple beam technology for transmitter and receiver optics. The mmW equipment was a prototype designed for an LMDS experimental setup operating at 10 - 100 Mbit/s (depending on modulation scheme and symbol rate) at a carrier frequency in the 40.5 – 43.5 GHz band.

For a stand-alone FSO system, fog can cause specific attenuation up to 120-130 dB/km in the climate around Graz [12], while a specific attenuation up to 25 dB/km in a thunderstorm can be caused at a rain rate of 150 mm/h [13], which is less critical as compared to fog. The attenuation for the same rain rate in a mmW link can be up to 50 dB/km [14] (up to 35 dB/km for 40 GHz). For a mmW link fog does not particularly matter, and attenuation caused by increased humidity is less than 5 dB/km [1]. A high link margin is required to achieve high availability. It limits FSO applications to less than 0.7 km distance and for a longer range mmW system it poses the requirement of high output power. In the hybrid system, the problem of attenuation can be tackled in this way that FSO only needs to overcome rain attenuation and the mmW system needs to overcome attenuation due to increased humidity. That eliminates the requirement of operating both systems at high margin or at less distance. For the data transmission measurements over 2.7 km link distance, the total margin for attenuation was 20 dB and the specific margin was 7 dB/km for the FSO system. For the same link distance 2.7 km, the total attenuation margin was 7 dB and the specific margin was 2.6 dB/km for the mmW system. This was verified by separate RX power measurements under clear sky conditions.

The increase of fog attenuation in an FSO link was observed to be less than +/- 6 dB/km in one second for the continental fog at Graz [12], which means a comparatively stable attenuation, similar to rain attenuation for mmW. For high wind speed in maritime fog or low clouds, this would be different. The availability test showed that by combining two systems with low link availability of 97%, but at economic cost, the overall system availability could be improved to 99.926%, which is equivalent to a gain enlargement of transmit power up to several dB in the mmW link case [1].

The properties of both systems used for the experiment are presented in table 1.

TABLE I

PROPERTIES OF FSO AND MMW SYSTEMS USED

System	FSO	mmW
T_X wavelength/ frequency	850 nm	40 GHz
T_X technology	VCSEL	Semiconductor amplifier
T_X power	2 mW (+ 3 dBm)	EIRP 16 dBW
T_X aperture diameter	4 x 25 mm convex lense	Antenna gain 25 dB
Beam divergence	2.5 mrad	10 degrees
R_X technology	Si-APD	Semiconductor LNA
R_X acceptance angle	2 mrad	10 degrees
R_X aperture	4 x 80 mm convex lense	-
R_X sensitivity	- 41 dBm	Noise figure 6 dB
Spec. Margin	7 dB/km	2.6 dB/km

V. PROPOSED SWITCH-OVER FOR FSO AND MMW

The redundant link usage of mmW along with FSO increases the availability up to 99.92%. However, the available bandwidth of mmW link was wasted redundantly during the operational time of main FSO link. Keeping in view these considerations, a bandwidth efficient switch-over has been proposed that will efficiently utilize the overall bandwidth of the hybrid system. The implementation strategy of the proposed switch-over is explained below.

In default mode, FSO system is operational and mmW link can be used for sending additional data, hence the total bandwidth of the system is increased. The signal level at the receiver should be monitored for a certain threshold. When the FSO link received signal level falls below this threshold, the system should switch-over from FSO to mmW. Under this condition of switch-over, mmW sends the data whereas FSO transmit the test data so that receiver can monitor the FSO link for its recovery. The FSO received signal strength is continuously monitored and compared until it exceeds a certain higher threshold as an indication of its recovery so that there should be a return to load sharing on two independent data streams. In this way, system remains available all the time despite the degradation in FSO link under severe fog conditions. The same strategy is employed in case of mmW link failure by monitoring test mmW received signal strength against a higher threshold to avoid rapid back and forth switching. When both links are down, it sends test data on both links in order to detect the recovery of any of these links. The threshold for switching should be adjusted so that it should initiate and complete switching process before the actual FSO or mmW link failure. The packets received should be acknowledged and when the receiver detects corrupted packets or low threshold level, it sends this information to the transmitter on both links. When the transmitter detects any link failure either by detecting threshold or retransmission request, it sends the packet next to the last acknowledged packet by the receiver on operational link and test data on the failed link. As the link between two communicating devices is the same, the threshold detection is expected simultaneously on both sides. In addition to threshold detection, retransmission request by the receiver on the basis of exceeding a certain acceptable BER is the second check for a link failure. The test data is used for monitoring the recovery of the failed link. Once both links regains their operational status, both sides perform handshaking for the link status information transfer and acknowledgement of last packet received by the active link and then both links start load sharing. Fig. 1 and Fig. 2 below present logical block diagram and physical overview of the proposed Switch-over between FSO and mmW links respectively.

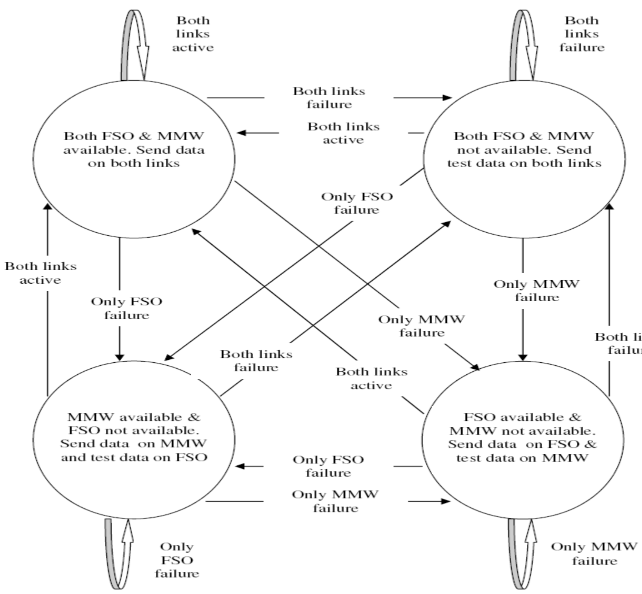

Fig. 1. Channel selection by Switch-over

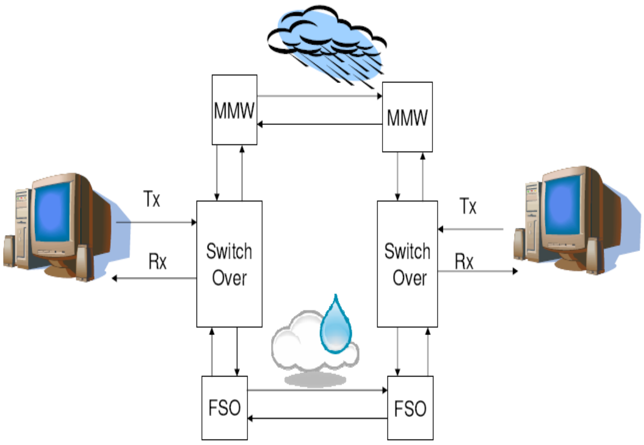

Fig. 2. Physical view of the system with Switch-over

The proposed switch-over greatly enhances the bandwidth utilization by employing the idea of load sharing during the time when both links are operational, which amounts to be more than 90% of the total measured time, This reduces the bandwidth wastage from 100% to less than 10% of the total measured time.

VI. Simulation Setup and Results Analysis

Keeping in view the availability data measured during 2001-2003 for the hybrid system consisting of FSO and mmW links, availability of the two channels is simulated with and without switch-over. This availability data consists of a ping test such that each time two ping tests were performed to measure the availability of each link. Whenever less than 2 ping acknowledgements for any link were detected, it is assumed for the simulation that switch over will detect a threshold for switching. The principle utilized for a simulation of the proposed switch-over behaviour is mentioned in Fig. 1. Results for the whole year as calculated by simulation routines for switch-over are displayed in Figs. 3, 4 and 5.

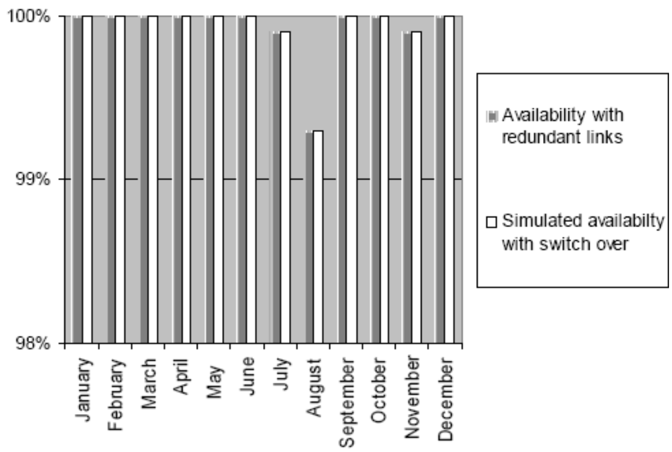

Fig. 3. Comparison of average availability by combined redundant links and simulated availability with Switch-over for all months of the year

It can be seen by the graph presented in Fig. 3 that irrespective of different weather conditions during the whole year switch-over tries to maintain the availability achieved by using redundant links. Besides maintaining the availability of the link, switch-over avoids unnecessary redundant usage of back up link. In the following graph presented in Fig. 4, mmW usage has been simulated for the exaggerated worst condition of FSO link failure and recovery on alternate instants. These results also show the significant difference between mmW usage with and without switch-over. It saves redundant transmission of mmW bandwidth which can be used to transmit useful additional data by load sharing.

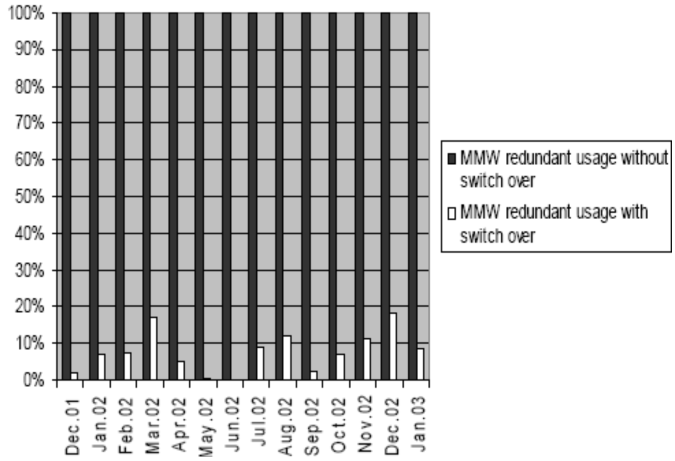

Fig. 4. Comparison of mmW usage without Switch-over and simulated mmW usage with Switch-over for all the month of the year

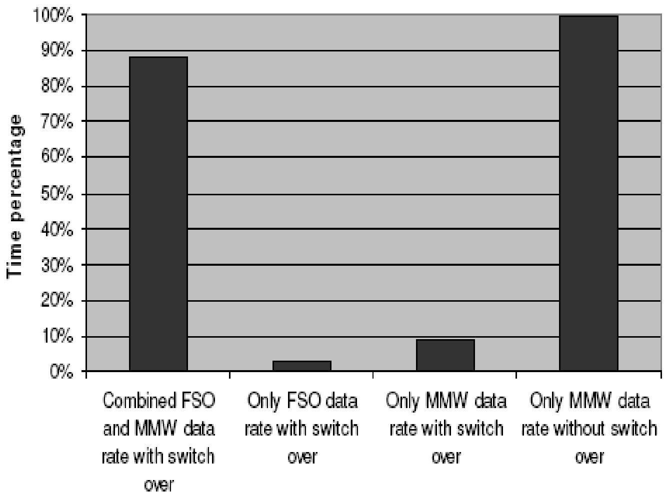

Fig. 5. Comparison of two links usage with and without switch-over

Besides maintaining the availability of the link, switch-over increases the overall throughput of the system by avoiding redundant transmission. Fig. 5 shows that switch-over uses nearly 88% of the time for sending data on both links thus increasing the bandwidth utilization. The switch-over sends data 2% of the time only on FSO and approximately 8% of the time only on the mmW link. In comparison to this approach, redundant data approach sends same data at both links for the whole time. In Figure 6, performance of switch-over is simulated for different throughput ratio of FSO and mmW link. Thus a ratio of 1 means that the throughput of FSO and mmW are equal and a ratio of 10 indicates that throughput of FSO is 10 times the throughput of mmW link.

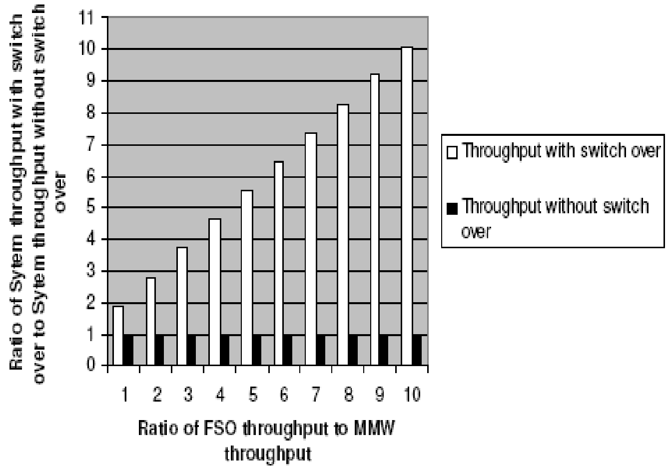

Fig. 6. Comparison of throughput with and without switch-over

Figure 6 shows that the performance of switch over increases significantly with the increases in difference of throughputs of two links. If there is a huge difference between, the throughputs of two links, switch-over exhibits many folds efficient bandwidth utilisation. Even if both systems have same throughput, throughput of the hybrid network with switch-over is 88% better than the throughput without switch-over.

In these simulations, switch-over is assumed to be fast enough to perform switching on the basis of threshold detection before the actual ping failure is received by any link. Finally, the availability reduction due to delay in switch-over is simulated and results are presented in Fig. 7. In the simulation presented in Fig. 7, a unit time is taken as the time delay between a transmission and acknowledgements of the ping. Simulation results show that if switch-over delay is very small, such that threshold detection and switch-over processes take place before the actual ping failure is detected; then switch-over maintains the availability achieved by continuous redundant link. The availability simulations with and without switch-over are based on the assumption that switch-over is fast enough to perform switching on the basis of threshold detection before the actual ping failure occurs.

In the simulations presented in Figs. 4, 5 & 6, the switch-over was assumed fast enough to perform switching before the actual ping failure occurs. However, if implementation technology introduces some delay, the performance of switch-over can be drastically reduced. In the following simulation (Fig. 7), the time taken by one ping test has been considered as a unit time. The availability reduction has been simulated for multiples of this unit time delays. It also shows that if switch-over is not fast enough to perform switching in one unit of time, available link cannot be used in this time and overall hybrid link availability is in turn reduced.

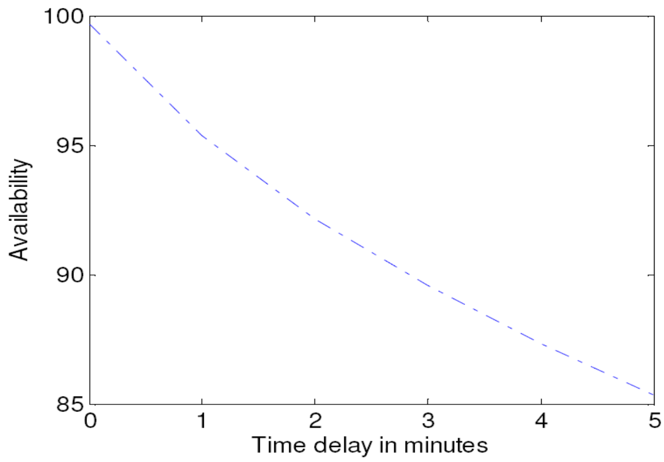

Fig. 7. Availability reduction due to delay in switch over process

The switch-over operation is also simulated for a fog event measured on 25.10.2005 at Graz. Figure 8 shows the specific attenuation measurement of 850 nm FSO link. The switch-over combined load balancing mode has been represented by a value of 40 whereas switch-over value of 0 represents only mmW usage (when FSO attenuation exceeds its specific margin of 7 dB/km). This shows that for a fog event with specific attenuation of 110 dB/km, switch over can use both links in load balancing mode for 39.14 % of total fog event time. The behavior of 40 GHz link has been simulated using [15] and [16].

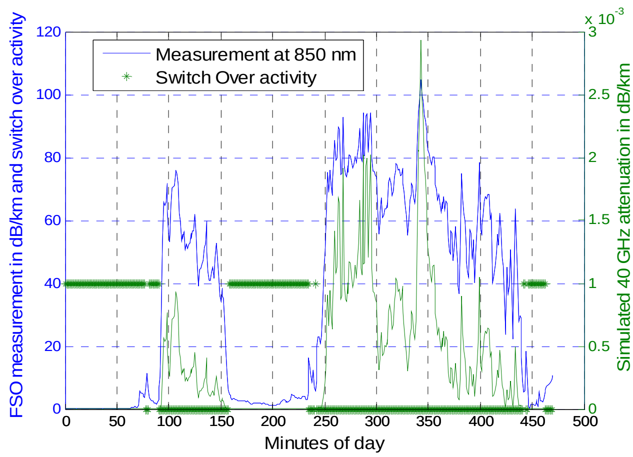

Fig. 8. Fog event and switch over behavior

Figure 9 below, shows the switch over performance for a rain event at Prague. At Prague, FSO link at 850 nm has been operated on a path length of about 850 m. Transmitted power is +16 dBm, divergence angle is 9 mrad and optical receiver aperture is 515 cm. Rain rate was measured using two tipping bucket rain gauges with different collecting areas. In Fig. 9, switch over value 4 represents load balancing for 38.09 % of rain event time, whereas switch over value 3 represents only FSO link usage for 33.33% time. The switch over value 2 represents only mmW link which amounts to be 0% of rain event. This is due to the fact that the rain is highly detrimental for mmW and there is no such time in this rain event when 40 GHz link availability is better than FSO. The switch over value 1 represents none of the link is available for 28.57 % of rain event time. This suggests that lower frequency back up links should be used in the regions with high rain rate. The behavior of 40 GHz link has been simulated using measured rain rate and [17].

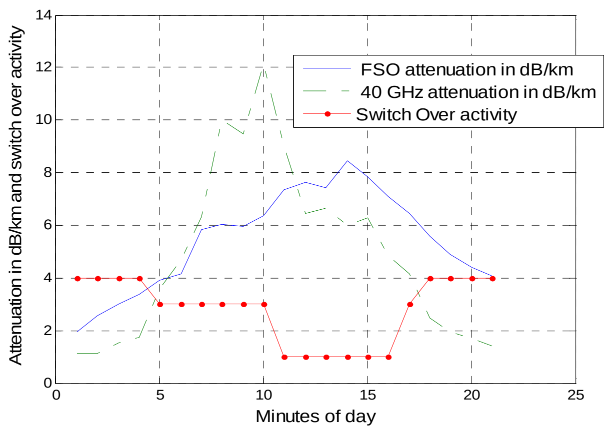

Fig. 9. Rain event and switch over behavior

Figure 10 shows the snow event recorded at Graz on 02.02.2009. Switch Over value of 10 represents the load sharing modes that constitutes 7.94% of the measured time whereas switch over value 5 represents the mmW usage only. The simulation of 40 GHz attenuation has been performed with the assumption of dry snow fall using [18].

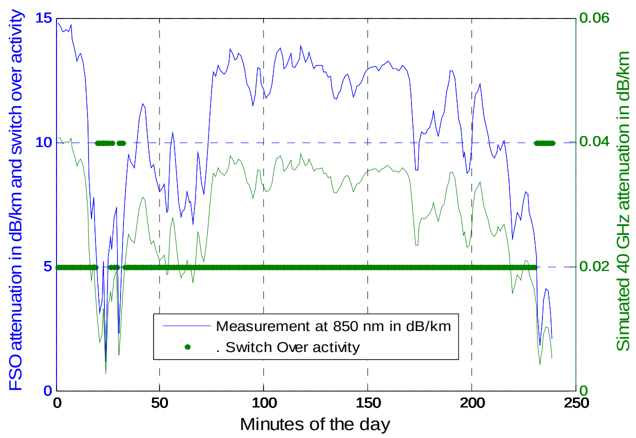

Fig. 10. Snow event and switch over behavior

VII. Concluding Remarks

The benefits of FSO motivate us to use it as last mile access. However, the deterioration of weather attenuation can be coped with backup link of comparable data rate. But use of back up link as continuously transmitting redundant link is not a good solution. The alternate solution is to use a back up link as load sharing link when main link is available and back up link if main link goes down. The fast switch-over helps increase the bandwidth utilization while maintaining high availability. By performing load sharing, it avoids wastage of redundant transmission of mmW channel bandwidth when FSO link is available. The simulation of switch over for fog, rain and snow events also shows that load balancing technique can improve the performance considerably. The simulation results also show that average redundant usage of back up link for maintaining the high availability is reduced to less than 10 % provided that switching is fast enough to avoid any link availability reductions. Consequently if both links provide same throughput, the throughput of hybrid network with switch-over is 88 % more than the throughput without switch-over. If the throughput of FSO is 10 times the throughput of mmW link, switch-over makes the throughput more than 10 times the throughput of hybrid network without switch-over. The key to the success of such a switch-over is like the implementation that must avoid any reduction in link availabilities.

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