Switch over implementation and analysis for hybrid wireless network of optical wireless and GHz links

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***Abstract*— High bandwidth optical wireless communication links are of prime importance, having tremendous potential to serve for the future huge data transmission requirements especially for the next generation optical networks. The inherent electromagnetic nature of the transmitted optical signals and the stochastic nature of the earth atmosphere create a number of technical challenges preventing widespread acceptance of technology and its implementation. One of the major concerns for Free Space Optics (FSO) links is fog that causes very high attenuation over non-negligible amounts of time. Another technology offering negligible fog attenuation and acceptable data rates is license free ISM band, which can be used as back up link. However, a switch-over mechanism is required for optimal selection of any link depending on weather condition and link quality maintaining an acceptable data rate. Moreover, synchronization of transceivers is the basic requirement of a communication link. This paper presents an implementation of a self-synchronizing switch-over system and the behaviour of this hybrid network is simulated for measured fog events.**

***Keywords*—Availability, FSO, Hybrid network, Switch-over, Simulation**

I. INTRODUCTION

Wireless optical communication has the great potential to solve problems like first/last mile access connectivity, broadband internet access to rural areas, disaster recovery etc. Due to the high carrier frequency in the range of 300 THz, optical communication allows highest data rates. Among other advantages license free communication, easy installation, avoiding electromagnetic pollution and wiretapping safety are few to name. Some of the possible applications are delay free web browsing and data library access, electronic commerce, streaming audio and video, video on demand, video teleconferencing, real time medical imaging transfer, enterprise networking, work-sharing capabilities and high speed interplanetary internet links [1]. However, the widespread deployment of wireless optical communication system has been hampered by reliability or availability issues related to atmospheric variations. Research studies have shown that attenuation has peak values of 130 dB/km in continental fog in Graz (Austria) and 480 dB/km in maritime fog in La Turbie (France) [2]. This makes the carrier class availability 99.999% questionable.

802.11a/b/g networks operating at GHz carrier frequencies can be used as back up link for providing comparable data rates. The fog attenuation for GHz frequency is not significant and increased humidity causes less than 5 dB/km [3].

In order to achieve high availability, both types of technologies can be combined. In an experiment over 15 months during 2002 – 2003, data was sent simultaneously over two such parallel links of FSO and mmW with a frequency of 40 GHz [3]. An availability of 99.93% could be achieved for the hybrid combination in Graz [3]. Such a hybrid system can be implemented by using a switch-over algorithm so that only one technology has to be operational depending on weather conditions. In this paper an implementation of switch-over is presented and its advantages and drawbacks are analysed by simulating hybrid network behaviour for a set of recorded fog events. The main difference to other switch-over systems proposed in literature is that switching itself is done on PHY or MAC layer, relying purely on physical measurements of the according signal levels.

The remainder of this paper has been organized as follows: Sections II and III give a brief introduction of FSO link and WLAN link, respectively. The hybrid network, physically and logically, will be discussed in more detail in sections IV and V, while section VI gives an overview of the hardware implementation. Section VII is dedicated to simulations done on the basis of previous measurements, whereas section VIII presents a conclusion.

II. FREE SPACE OPTICAL (FSO) COMMUNICATION LINKS

The idea behind free space optic (FSO) communication system is to transfer information data by light between geographically separated transceivers through the intervening atmospheric channel with an acceptable bit error rate (BER < 10^{-9}), while providing high reliability through a line of sight link [5]. In general, this technology can be used as an alternative for conventional wireless radio links in the 2.5 and 5.6 GHz frequency range, and alternative to fiber 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 shortterm installations or "nomadic" use like 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 architecture. Wireless optical communication links can be used in point-to-point as well as optical multi-input multi-output (MIMO) configurations for the next generation high speed optical networks [6, 7].

As the air has good transmittance in the same "windows" as used for fiber optic links, mainly at 850 nm and at 1550 nm wavelength, 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. This technology is excellent supplement to conventional radio links and fiber optics [8].

III. IEEE 802.11 STANDARDS AS BACK-UP

The IEEE 802.11 [9] is an international standard of physical and MAC layer specifications for wireless local area networks (WLANs) in the 2.4 GHz public spectrum bands. Its original specification supports data rates of 2 Mbps. More recent amendments (IEEE 802.11a/b/g) allow higher data rates (11 Mbps and 54 Mbps, respectively) and exploit other frequency bands (5 GHz band with 54 Mbps).

The selection of an IEEE 802.11a standard compliant backup link has been governed by different reasons: The major goal of the backup link is to maintain link availability when main link (FSO) is strongly affected by fog. Research studies have shown that frequencies below 10 GHz show negligible attenuation due to fog [10]. Therefore, a hybrid wireless network built up of FSO and a 5 GHz WLAN link provides high availability regarding weather conditions. Another advantage of this link is the fact that it is using a license-free band at a relatively low frequency, where the technological problems of amplification, temperature drift and similar have mostly been overcome. The 5 GHz band is less populated and, thus, devices in this band are less susceptible to interference. A higher transmit power allows greater distances than IEEE 802.11b/g devices do.

In addition to that, the emerging IEEE 802.11n standard allows for data rates up to 600 Mbps in a MIMO scenario. Thus, data rates comparable to the FSO link can be achieved with off-the-shelf equipment in WLAN scenarios as well. Future studies will show if this also holds for long-range directional links.

IV. SYSTEM SETUP AND LINK CHARACTERISTICS

The wireless optical communication system available at Technical University Graz is the GoC MultiLink 155/2 and supports data rates up to 155 Mbps over a distance of 2 km. The WLAN link was built with two embedded PCs using high-gain grid antennas and Ubiquiti XR5 miniPCI WLAN cards. These are getting used for further performance improvements since they provide fairly high receiver sensitivity and therefore are able to connect sites over up to 50km depending on the antennas used. The properties of the FSO and the WLAN system are given in Table 1.

The system proposed by the authors uses a hybrid link to interconnect two sites of the campus of the Technical University of Graz: The newest part of the campus bearing most developed lecture rooms and high speed internet access (“Inffeldgründe”) and a remote observatory of the campus devoted to space research (“Observatorium Lustbühel”). Figure 1 shows the proposed link together with a map of the city of Graz. The distance of 2.7 km between these two parts exceeds the manufacturer’s specification of the FSO system. Still, as it was proven in a test setup this increased link distance only reduces the error margin, while still making a undisturbed communication possible during acceptable weather conditions.

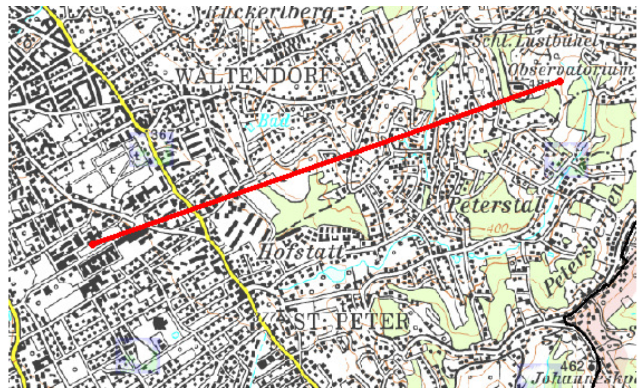

Fig. 1: Link between different campus sites (2.7 km)

TABLE 1

PROPERTIES OF FSO AND WLAN SYSTEMS USED

System	FSO	WLAN
T_X wavelength/frequency	850 nm	5.20-5.825 GHz
T_X technology	VCSEL	Semiconductor amplifier
T_X power	2 mW (+ 3 dBm)	1.26mW (1 dBm)
T_X aperture diameter	4 x 25 mm lens	30 dBi
Beam divergence	2.5 mrad	
R_X technology	Si-APD	Semiconductor amplifier
R_X acceptance angle	2 mrad	30 dBi
R_X aperture	4 x 80 mm lens	
R_X sensitivity	- 41 dBm	-94 dBm
Spec. Margin	7 dB/km	14 dB/km

V. SWITCH-OVER FOR FSO AND WLAN

The idea of switch over is quite trivial. The FSO link is the default link, as it allows for a higher bandwidth. If the optical received signal strength (ORSS) on this link falls below a certain value, the multiplexer switches to the WLAN link [4, 11]. If the received signal strength on the FSO link goes up again, the system switches back. Therefore, it is only necessary to acquire the FSO link quality, which is measured in 10 levels. At level 0 the optical link completely breaks down, whereas all higher levels show little to no bit errors at all.

In weather conditions unfavourable for FSO, transitions between optical signal strength levels occur at a quick succession. Therefore, without a hysteresis the switching rate of the multiplexing device could exceed the network's ability to adapt to a changing infrastructure. In fact, the RS232 interface of the GoC MultiLink 155/2 updates the link quality data every second. Hysteresis is ultimate solution to avoid rapid switching back and forth.

A synchronization-efficient switch-over algorithm is implemented. The block diagram in figure 2 shows the physical arrangement of the system. At one end there is a multiplexing device, while de-multiplexing on the other end is performed by any commercially available switch. As a multiplexing device, two possibilities were evaluated; A self-made PHY layer multiplexer and a Linksys WRT54GL, in which we exploited the virtual LAN (VLAN) capabilities to switch between the two links. The latter device operates on the MAC layer, but still provides transparency.

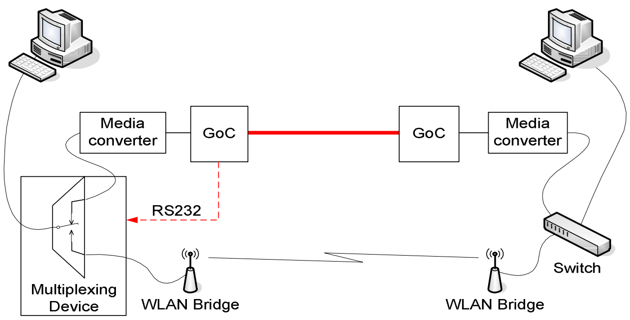

Fig. 2: Physical arrangement of the system

The transceiver on multiplexer-end always connects to the active link, i.e. either the FSO link with high bandwidth or the WLAN link with a lower bandwidth. The switch on the other end assumes both links active.

Synchronization is done via MAC spoofing. Since FSO is completely implemented on PHY layer and since the WLAN link is operated in bridging mode, both links can be considered transparent to MAC layer. Therefore, the switch only receives packets with the source MAC address from the multiplexer-end transceiver. This switch now maps source MAC addresses to ports, and stores this mapping in the MAC table, in order to determine through which port the return packet has to be passed - if a packet with the source MAC address from the multiplexer-end arrives at the switch, the port from which it came becomes the outgoing port for packets with according destination MAC addresses. If now, due to a switch-over operation, a packet with the same source address arrives at another port (e.g. the port associated with the WLAN link), the MAC table gets updated, so that the new port is the destination for outgoing packets. Thus, this system is self-synchronizing. In addition to that, link speed is determined by the switch according to the capacity of the medium connected to the outgoing port. Therefore, the bandwidth on the main link is not limited by the redundant link bandwidth.

However, there may be cases where the MAC table is not updated timely, which results in packet loss. For one example, if the multiplexer on the multiplexer-end side switches over but no packets are transmitted from the multiplexer-end. If in such a case the switch-end transmits, these packets are lost at the multiplexer or on the inactive link. This can be overcome with the ordinary TCP, which automatically transmits ACK packets and thus ensures a proper and fast MAC table update.

Furthermore, one has to admit that this kind of synchronization contains a number of problems different to the ones described above: Besides an asymmetric setting, which may not be desirable in network design, MAC spoofing, as it is often called, is prohibited by high-quality network equipment to fight harmful hacking attacks often related to MAC spoofing, Thus, current research considerations focus on developing Ethernet switches purely designed for heterogeneous hybrid networks, which allow both MAC spoofing and fast link selection.

VI. Lab Tests and Results

A few tests were performed to evaluate the performance of the equipment, in terms of bandwidth and link loss time (LLT) during a switching event. In this test scenario, we substituted the FSO link with a fibre cable, so that we could measure the effects of the media converters without the influence of weather. Although the FSO system allows bandwidths of up to 155 Mbps, we have used Fast Ethernet components with a nominal bandwidth of 100 Mbps only. This is due to the reason that Fast Ethernet equipment is cheaper and more widespread, so a qualitative evaluation of different components can be done more easily. The WLAN link was built up of two Compex WP54AG Wireless Access Points in access point mode and wireless adapter mode, respectively. Bandwidth and LLT were measured with Iperf 1.7.0 [13] and WireShark 1.0.3 [14].

In the first series we tested the self-made hardware multiplexer (MUX), which simply connects one Ethernet cable to any of two other cables on the PHY layer. First, all links were built up with category 5 cables in order to evaluate the bandwidth and crosstalk of the MUX. This test showed that attenuation can be neglected for Fast Ethernet, since we achieved bandwidths of 94 Mbps. The limiting factors in this case are most likely the network interface cards of the transmitters on both ends. The bandwidth of the overall infrastructure therefore is limited by the Fast Ethernet components and the WLAN devices. Exact results of bandwidth tests can be seen in Table 2. However, another test revealed that the crosstalk cannot be neglected, which most likely will lead to a re-design of the MUX printed circuit board (PCB).

Table 2

Bandwidth and UDP Datagram Loss

	Fiber	**WLAN**	**Fiber FDX**	**WLAN FDX**
MUX				
Bandwidth TCP (Mbps)	91.9	18.8	76 + 68	8.9 + 10.2
Loss UDP 1 Mbit	0.12% Jitter: 0	0 Jitter: 0	0 Jitter: 1ms	0.23% Jitter: 0
Loss UDP 10 Mbit	0.04% Jitter:3.39ms	0.,024% Jitter: 0	0.02% Jitter:2ms	0.059% Jitter: 0
VLAN				
Bandwidth TCP (Mbps)	94.2	20.2	79.8 + 45.9	7.1 + 11.9
Loss UDP 1 Mbit	0 Jitter: 0	0 Jitter: 0	0 Jitter:0.98ms	0 Jitter: 0
Loss UDP 10 Mbit	0 Jitter: 0	0 Jitter: 0	0 Jitter: 3.3ms	0.08% Jitter: 0

Table 3

Average Link Loss Time

	MUX	**VLAN**
From WLAN to Fibre	1.62 s	1.54 s
From Fibre to WLAN	1.63 s	1.02 s

The LLT during a switching event can be related to the auto-negotiation in which the participating devices exchange information about transmission parameters, such as speed or duplex mode. The MUX physically disconnects an Ethernet cable on one port and connects another cable at another port, making such a negotiation necessary. If Fibre-Ethernet media converters or WLAN access points are used the switch does not need to perform auto-negotiation, because the connections between the devices and the switch are not influenced. Instead, only a link negotiation at the multiplexer-end has to be performed. The resulting LLT can be seen in Table 3.

Although the MUX does not influence the bandwidth, it introduces slightly more problems with UDP, resulting in a higher datagram loss, which may be due to a bad RF design of the PCB. Still, satisfying results could be achieved, which certainly will even improve after a PCB re-design.

In a second series of tests the multiplexing device was a Linksys WRT54GL wireless router with OpenWrt 7.9 [15] as an operating system. Switching between different ports was done by changing the configuration of the VLANs. This way, a switch can be logically divided into a series of switches, each one operating in a different VLAN. The actual VLAN in use was configured that way, so that it only contained the port connected to the switch-end transmitter and the port connected to the desired link, namely WLAN or Fibre, respectively. By changing the configuration i.e. removing the Fibre port and adding the WLAN port for example, the Ethernet frames were now directed over the desired link. The re-configuration was done with a single command.

Again, bandwidth and LLT were evaluated. As it can be seen in Table 2, half duplex bandwidth in VLAN implementation was increased in both WLAN and Fibre case compared to the MUX design. UDP datagram loss on the other hand could be neglected.

As it can be seen in Table 3, LLT was much lower for all scenarios tested compared to the MUX design. Yet, since the switch of the Linksys WRT54GL uses a store-and-forward algorithm, a few packets are transmitted over the in-active link after VLAN re-configuration. If now such a re-configuration is done during a total link loss, these packets stored in the internal memory of the switch cannot be properly forwarded, resulting in a slightly higher LLT. The determination of this actual time is within the scope of future work, however. Despite this fact, VLAN switching definitely outperforms MUX switching, so the final measurement scenario will most likely use this mechanism.

However, the successful development of a hybrid network Ethernet switch could turn the tables, since in these cases the need for auto-negotiation would become obsolete and, subsequently, much lower LLTs could be achieved.

VII. SIMULATIONS AND RESULTS

The performed Matlab simulations are based on a series of accurate fog measurements recorded in 2005 [2]. A short-distance FSO link was used to measure fog attenuation and data points were recorded on a per-second basis. Receiver sensitivity was set to an arbitrary value of -22 dBm, justified by the multitude of different FSO equipment available commercially. The set of simulations presented in this paper rely on measurement data from October 25th, 2005. During this event, availability was reduced to 67.43 % for a receiver sensitive set to -22 dBm.

The choice of this particular event was governed by the fact that a) many threshold crossings occur and b) the study of a fog event allows for a more detailed evaluation of the switch-over mechanism as the study of a whole year period would. Extrapolating the simulation results to a whole year easily exceeds the carrier availability requirement of 99.999 %.

Furthermore, according to Table 3 LLT was set to 3 s in order to allow a usage of both multiplexing devices and include some time reserve for ORSS measurement. Link bandwidth was set to the values depicted in Table 2, where the case of the hardware multiplexer (MUX) was chosen. The WLAN link was assumed to be available without interruption. This assumption can be justified by the fact that the WLAN link will only be used during a fog event, which only affects the FSO link harmfully [10].

The continuously measured ORSS values in dBm were converted to discrete values in order to enable a simulation of the MultiLink 155/2 system, which provides link quality measures in ten levels. Values below the receiver sensitivity are set to 0, increasing discretely with a step size of 1 dBm. Figure 3 shows the comparison of both the continuous measurement values and the derived discrete ORSS values. Consequently, the receiver sensitivity of the discrete system has to be set to 0 in order to obtain same FSO availability as for the continuous system.

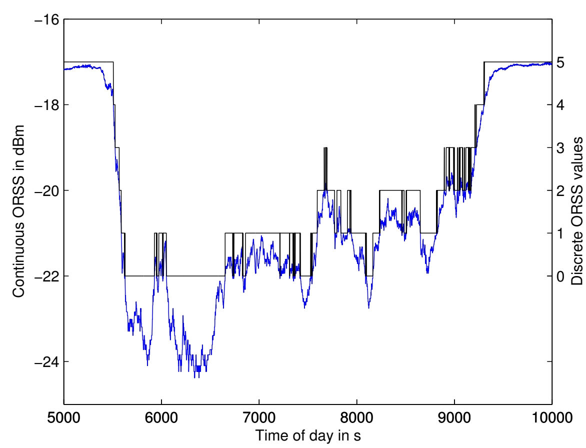

Fig. 3: Discrete and continuous ORSS values for simulation

In these simulations we were testing two different switch-over methods, both of them relying on threshold comparison. The threshold was set equal to the receiver sensitivity, although a bigger error margin may prove more appropriate. While the first set of tests performs a switching operation purely determined by the actual ORSS value, i.e. on a per-second basis, the other set implements some kind of time hysteresis. In this latter setup, over intervals of 60 s a *sliding-minimum* technique is employed: If the ORSS falls below the receiver sensitivity, the WLAN link is chosen for the remaining time within that 60 s window. At the very start of the succeeding window the ORSS values are re-evaluated and the FSO link is chosen if the signal quality allows. Figure 4 shows the equivalent ORSS values for both the threshold comparison (TC) and the 60 s sliding minimum (SM) technique.

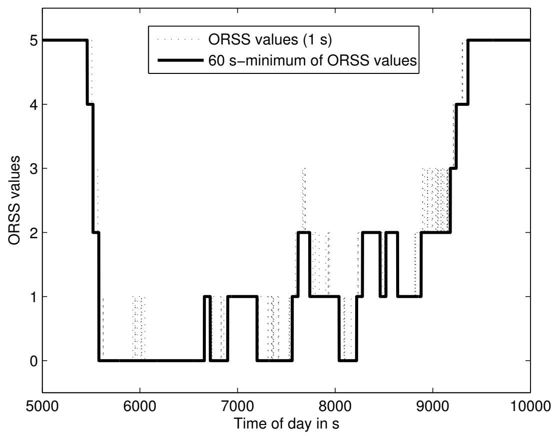

Fig. 4: Equivalent ORSS for TC (1 s) and SM (60 s)

As it can be seen in Figure 3, the continuous and the discrete ORSS values show strong variations in time. These variations are related to fluctuations, the effects of turbulences in the optical free-space link [12]. Switching on a per-second basis would therefore result in many switching operations, which in turn could reduce availability and bandwidth due to non-zero link loss times. Therefore, the choice of other switch-over algorithms has to be considered.

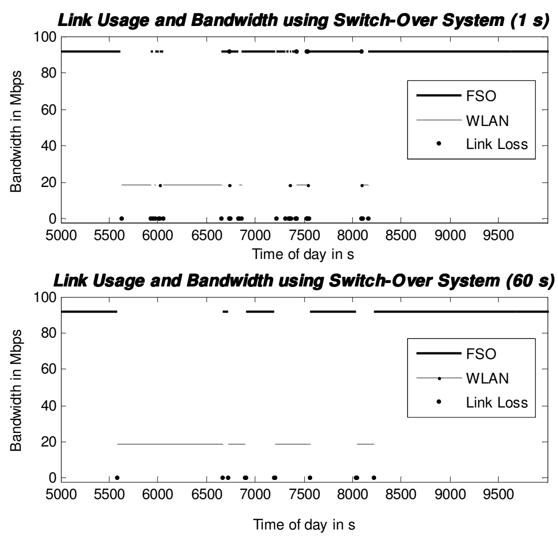

Fig. 5: Link Usage and Bandwidth for TC and SM

These switch-over algorithms have to be designed to reduce the number of switching operations while keeping availability high. As a side constraint, the average bandwidth or the FSO underutilization can be restricted. Obviously, there has to be a trade-off between availability and bandwidth, which are contradictory objectives if the difference in link bandwidth is great. Since the focus of this work is put on availability, the trade-off is met with respect to that.

Looking at figure 5 one can easily see that a 60 s sliding minimum system reduces the number of switching operations while reducing the number of link losses at the same time. This, however, is done at the cost of bandwidth, which is decreased due to FSO underutilization. Table 4 summarizes these results and clearly shows the increase in availability to 99.37 %. Furthermore, it can be seen that average bandwidth is slightly smaller than for pure threshold comparison. However, the switch-over algorithms have to be designed carefully and the optimum parameters for each have to be derived. Other methods, like moving average filtering, exponentially weighted moving average filtering, asymmetric hysteresis, or power level hysteresis are to be evaluated. This, however, is within the scope of future work.

TABLE 4

LINK AVAILABILITY AND AVERAGE BANDWIDTH

	Pure FSO	**TC**	**SM 60 s**
Availability	67.43 %	98.62 %	99.37 %
Link Loss	32.57 %	1.38 %	0.63 %
Bandwidth HDX (Mbps)	61.9	67.3	65.1
Bandwidth FDX (Mbps)	51.2 45.8	53.9 49.2	51.2 46,8
FSO Underutilization	N/A	0.69 %	3.88 %

VIII. CONCLUSIONS

The major concern for FSO is reduced availability due to weather attenuation. A back up link with potential of withstanding weather effects, especially fog, can improve the overall availability of the hybrid network. However, maintaining availability compared to the redundant transmission and providing synchronization of transmitters and receivers are the basic requirements for a hybrid network. The performance of our prototype has been evaluated by laboratory tests and analysed by simulation. The simulation shows that the proposed switch-over system increases availability as well as average bandwidth compared to a pure FSO system. However, switching should be fast enough to avoid any loss of link availability. The key to success is to reduce link loss time, a goal which can only be achieved by combining optimal switching methods, such as VLAN re-configuration, and switch-over algorithms including a proper choice of parameters.

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