Evaluation of Switch-Over Algorithms for Hybrid FSO-WLAN Systems

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***Abstract*—Free Space Optic (FSO) communication systems have the great potential of serving as high bandwidth links. However, their popularity and widespread use is limited by the fact, that this technology is dependent upon an unobstructed line of sight more than any other wireless communication system. Especially weather conditions affecting visibility, such as fog or heavy rain, often cause unacceptable link failures. To increase reliability, a variety of hybrid FSO/RF systems has been introduced, among them a great number of switch-over systems. These systems require an accurate and timely detection of link failure and an appropriate algorithm to react.**

Generally, the received signal strength is considered as an indicator for link quality. Fluctuations in this indicator prohibit the use of simple threshold comparison techniques. In this paper, a set of switch-over algorithms is introduced and analyzed, using attenuation measurement data of fog events.

***Index Terms*—Availability, optical communication, communication systems, decision making, optical propagation meteorological factors**

I. Introduction

Free-space optics (FSO) and hybrid FSO communication systems are a well investigated field of research. FSO provides high data rates, licence free communication and an invulverability to electromagnetic interference and wiretapping. However, unlike other media FSO is strongly affected by atmospheric variations. Availability and reliability are highly reduced during weather conditions like fog, haze, and strong rainfall [1]–[4].

FSO hybrid systems have been discussed in literature extensively. Especially hybrids with radio frequency (RF) links are of vital importance to increase performance in terms of reliability by coping with weather conditions harmful for FSO. A multitude of systems was evaluated, with different frequencies and data rates [5]–[9]. Especially higher frequencies allow comparable bandwidths, but suffer from similar weather conditions and therefore cannot be used to increase availability efficiently. Lower frequencies, on the other hand, provide capabilities for highly reliable links but lack of high data rates due to limited bandwidths. Furthermore, licensing is another issue for designing the RF link, often limiting the designer to a small set of frequency bands. Several types of hybrid systems were implemented or proposed in the literature: simultaneous redundant transmission over both links [18], dynamic load balancing [6] and switch-over systems [5], [7], [8]. Since simultaneous redundant transmission requires either comparable data rates in order to fully exploit the bandwidths of each link, only higher carrier frequencies can be used for that purpose. Also, dynamic load balancing requires similar data rates on the primary and secondary links in order to keep efficiency high due to overhead. Switch-over systems on the other hand do not have this requirement when the FSO link is available. The data rates of the secondary link only affect the overall system during fog or haze events. Thus, also low data rate, low-frequency links can be considered in this scenario.

Switch-over systems require a proper detection of fog events in order to change the active link in a timely manner. This, in turn, requires an accurate measurement of the signal levels of both links and a decision rule for selecting the active link. While the first requirement is usually fulfilled by the equipment itself, the latter one parallels to adaptive coding [10]–[12], adaptive modulation [13] and statistical process control [14]. Methods developed there are now evaluated for FSO/WLAN systems, where short term variations in the optical signal strength prohibit the use of simple threshold comparison techniques.

The remainder of this paper is organized as follows: Section II defines the setup of the intended switch-over system, whereas Section III introduces decision methods derived from literature. Finally, Section IV presents simulation results evaluating the introduced algorithms.

II. Application Setup

The concept of a switch-over system can be illustrated as follows: The primary link is built up of a high-bandwidth, high data rate FSO link. Simple modulation schemes and narrow beams lead to robust performance of this link over a wide range of signal-to-noise ratios (SNR). However, as soon as the line-of-sight is obstructed link failure occurs. Therefore, FSO is strongly susceptible to certain weather conditions such as fog and strong rainfall. The idea of a switch-over system is to provide a secondary low-bandwidth link which is invulnerable to weather conditions harmful for FSO. This link most likely is going to be a wireless radio link with a carrier or center frequency in the lower GHz, since higher radio frequencies suffer from similar weather conditions as FSO does. Therefore, in this work we will consider a commercial WLAN link with

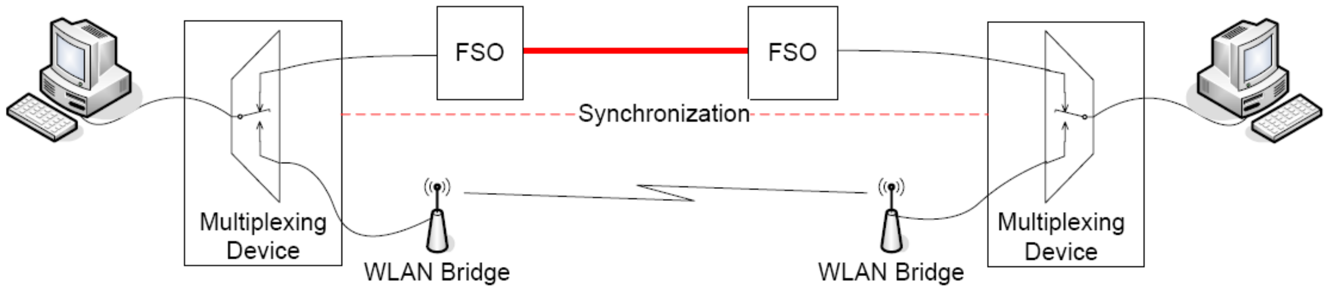

Fig. 1. Application setup of FSO-WLAN switch-over system

frequencies between 2.4 and 5 GHz as a backup link (see Fig. 1). This link is not affected by fog, but looses performance during rainfall only.

Since the FSO link is the primary link because of its high bandwidth, the FSO link status exclusively determines every switching operation: If a connection loss is indicated for FSO, a switch-over operation to the WLAN system is performed. Similarily, as soon as the FSO system restores connectivity, it is chosen as the active link again. The assumption that signal strength measurements are available to the operator may be problematic. However, throughout this paper it is assumed that link status information is available at least for the FSO link in an accurate, timely manner.

In order to provide full connectivity, synchronization between the different sites has to be established. Since a redundant transmission is prohibited by the big difference in data rates, this can be done by transmitting side information over an additional, reliable channel. Another possibility would be some a self-synchronizing setup as it was introduced in [17]. This simpler system suffers from higher link loss times (LLT) during the switching operation. A final, but unreliable method results from the theoreme of reciprocity: If the assumption holds that both sites acquire the same link quality measure, they would switch to the according link simultaneously.

The switching operation itself can be performed with a wide variety of systems operating at different layers in the OSI reference model. The choice of one of these systems is therefore governed by delay, bandwidth limitation and LLT. Yet, often it turns out that requirements of fast reaction, bandwidth efficiency and high availability are contradictory, constraining the designer to achieve only one of these objectives.

III. Switch-Over Methods

The most easy way of implementing a switch-over system is by threshold comparison (TC) applied to the optical received signal strength (ORSS). This method, however, suffers from variations in the ORSS and therefore leads to prohibitve link loss times (see Tab. I). This holds regardless if the threshold coincides with the receiver sensitivity or not. Thus, other algorithms had to be considered, including power and time hysteresis, filtering, and combinations thereof.

In any case a trade-off has to be made between availability and bandwidth efficiency. Bandwidth is low for the WLAN link, whereas this link has good availability during fog events. Therefore, bandwidth is not only dependend on the FSO availability, but also on FSO underutilization which is determined by the choice of the switch-over method. Although availability is the major goal of this work, optimization was done under the constraint that the FSO underutilization stays below 10% in order to guarantee a minimum bandwidth.

A. Power Hysteresis (PH)

Employing a power hysteresis is popular in wide fields of electronics, communications and signal processing and will be covered only briefly. Making use of PH has the purpose of getting hold of the unwanted variations of the ORSS by preventing too many switch-over operations. The hysteresis has to be designed dependent on the amplitude of variations. Moreover, in order to guarantee an increase in availability, the lower threshold has to be set to values greater than or equal to the receiver sensitivity. Setting it to higher values leads to even further increased availability figures. The higher threshold on the other hand has to be set so that fluctuatiopns in the ORSS do not cause a switch-over operation, as long as the FSO link suffers from link failures.

B. Time Hysteresis (TH)

TH is another method which operates directly on the ORSS values but still prevents performance decrease due to numerous switch-over operations. Here only one threshold is defined, again greater than or equal to the receiver sensitivity. If this threshold is crossed the measured ORSS values are evaluated for a certain wait period T. If within that period no other threshold crossing occurs, a switch-over operation is performed. Otherwise the timer for this wait period is restarted.

In contrary to WLAN, the FSO link does not suffer from soft degradation but loses connectivity apruptly during a fog event. Fluctuations therefore cause not only a reduction in data rate, but a complete link loss. In order to meet the availability requirement, a time hysteresis is only employed for switching from WLAN to FSO. As soon as the FSO link loses connectivity, a switch-over operation to WLAN is performed immediately. This way, fluctuations and resulting periods of FSO link failure can be neglected because during these times the WLAN link is active.

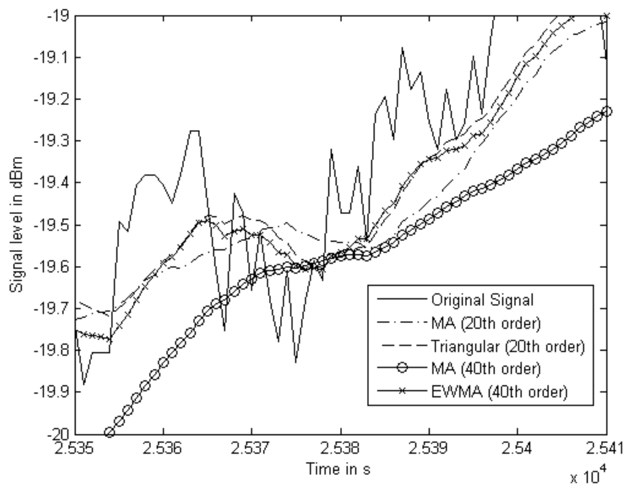

Fig. 2. Comparison of filter properties

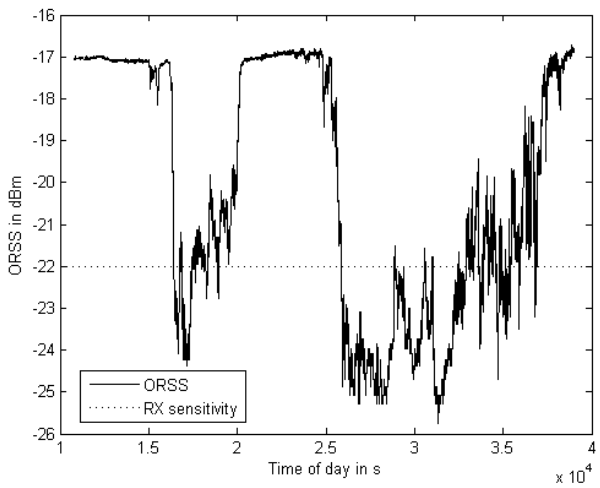

Fig. 3. Optical received signal strength from 2005-10-25

C. Filtering

Filtering is another method to reduce the amount of variations of the ORSS values. In any case, the filter has to show some kind of low-pass character so that the output still reflects long-term changes in the ORSS values due to changing weather conditions. Filter orders N and types can be chosen arbitrarily with respect to optimized availability. Moving average (MA), triangular (TR) and exponentially weighted moving average (EWMA) filtering are only a few to name.Filters have to be designed carefully in order to smooth the signal, but still allow for reacting timely on critical changes in the ORSS. As it can be seen in Fig. 2, all filters applied to the ORSS signal provide smoothing of the unwanted variations. In terms of smoothing MA performs best; on the other hand, this filter lacks of the capability to react timely on critical changes in the ORSS. Especially higher filter orders suffer from that problem. TR and EWMA filters perform similar, since both of them fulfill the fading condition. Their smoothing capabilities are small compared to MA, but in turn allow for fast reactions on link loss. A trade-off has to be found, which filter type and filter order to take. After filtering, simple threshold comparison algorithms can be performed. The thresold has to be chosen greater than or equal to the receiver sensitivity, if the overall gain of the filter is equal to 1. Otherwise, even lower thresholds would be possible choices.

D. Combined Methods

Applying two or more of the methods mentioned above was a possibility which had to be evaluated as well. It might be interesting, for example, if a combination of TH and PH yields any improvement on availability. Similarily, it might be the case that filtering beforehand improves the performance of hysteresis techniques.

IV. Simulations and Results

All the simulations performed are based on a measurements campaign at the Technical University of Graz [18]. Over five month from October 2005 to February 2006 a set of 14 fog events was recorded with an FSO link over a distance of 79.8 m. Measurement data were available on a per-second basis. The data used for this set of information was recorded during a fog event on October 25th, 2005, between 03:00 and 11:00 (see Fig. 3). During this event, FSO availability was reduced to 67.43%. The authors chose this particular event instead of a long term period, since longer periods lack of a significant number of threshold crossings relative to the observation interval. Considering these fog events separately helps to distinguish the advantages and disadvantages of different switch-over methods. Furthermore, extending simulation results to longer periods increases availability figures. Applying pure TC to the overall measurement recordings, average availability is increased to 99.76% compared to 98.62% for the single fog event. Taking into account that the measurements were taken during a season bearing highest unavailability values, the application of more sophisticated algorithms could easily lead to carrier class availability of 99.999% on an all-year average.

For the simulations, an arbitrary receiver sensitivity of -22 dBm was assumed. This choice can be justified by the multitude of FSO equipment available, incorporating a variety of different transmitters, receivers, and link distances. The choice of -22 dBm was governed by the fact that this value was crossed by the ORSS a certain number of times. More problematic, however, is the assumption that the ORSS is measured without quantization. In fact, the system used in [17] provides a set of discrete ORSS values. If, and how, this quantization influences the performance of the introduced methods is within the scope of future work.

According to the application setup described in section II, switching from one link to the other requires a certain amount of time, during which the connection is totally lost. This link loss time (LLT), was set to 3 s according to [17], where both hardware multiplexers and VLAN switches were evaluated in a self-synchronizing setup. The WLAN link was assumed to

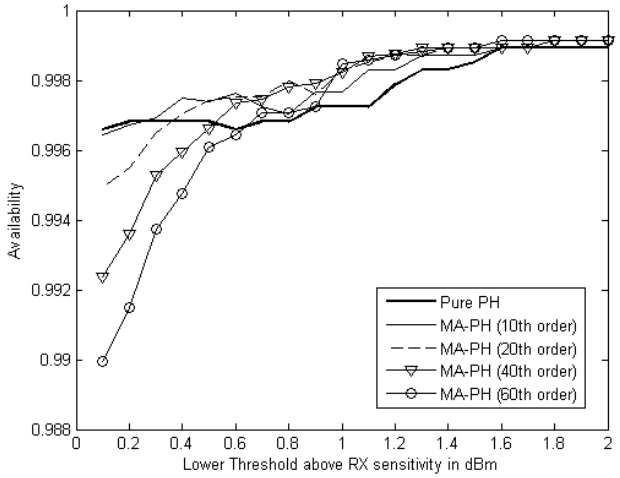

Fig. 4. Availability for PH and filtered PH

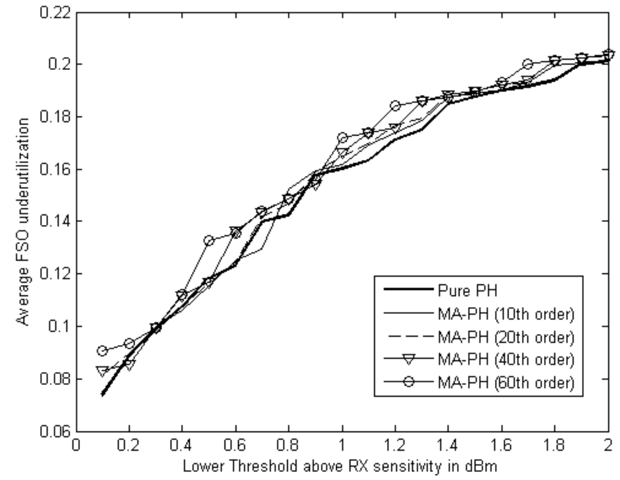

Fig. 5. FSO underutilization for PH and filtered PH

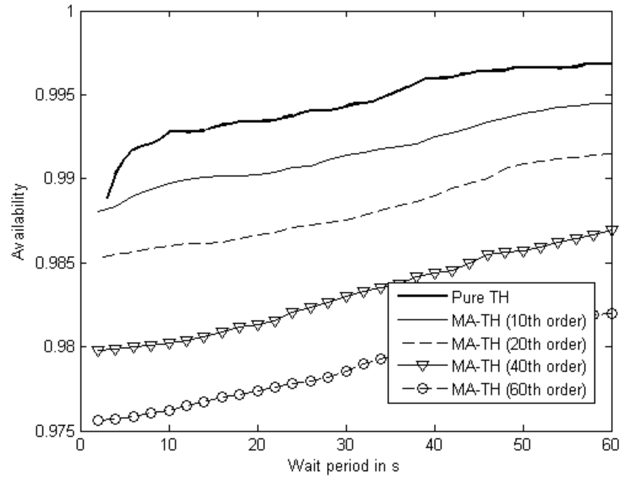

Fig. 6. Availability for TH and filtered TH

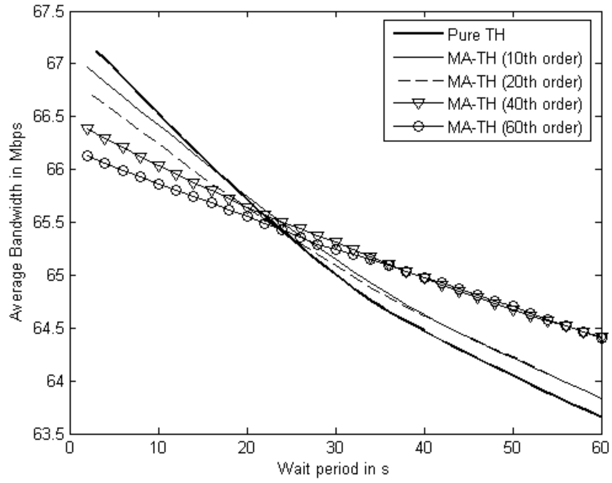

Fig. 7. Average bandwidth for TH and filtered TH

be available all the time, an assumption which can be justified by the fact that WLAN will only be used during fog events and that these events have little influence on the wavelengths used by WLAN. For bandwidth simulations FSO bandwidth was set to 91.9 Mbps and WLAN bandwidth to 18.8 Mbps [17].

Pure threshold comparison (TC) yields an increase in availability to 98.62% while achieving best bandwidth performance. Since the focus of this work is on availability, the following methods were optimized with that regard.

A. Power Hysteresis

Looking at Fig.4 one can easily see that PH is a powerful tool for increasing availability. Especially, if the lower threshold (LT) is reasonably larger than the receiver sensitivity, availabilities of 99.9% could be achieved. Even more so, if the signal was smoothed by MA filtering beforehand. Unfortunately, Fig. 5 reveals that for these thresholds FSO underutilization is prohibitively large, which in turn leads to a decrease of average bandwidth. The introduced constraint therefore limits the LT to values below -21.7 dBm. For these thresholds, on the other hand, MA filtering seems to reduce the overall availability. Moreover, higher filter orders even lead to worse availability values. This is due to the fact that both MA and PH are designed to mitigate the variations in the ORSS - combining these methods only increases the time to react on changes of the link quality. As a result availability is decreased. Other filter types, like TR or EWMA perform better than MA, because these filters allow for faster reaction because of their forgetting factor. Still, pure PH cannot be outperformed by filtering beforehand.

B. Time Hysteresis

Fig. 6 reveals that applying a temporal hysteresis cannot outperform PH in terms of availability. The threshold is set to the receiver sensitivity, since increasing the threshold to higher ORSS values only increases FSO underutilization (see Tab. I). Filtering beforehand is not a good choice, for the same reason as mentioned above. TH and MA both cope with varying ORSS, a combination of these methods fails to react on decreasing link quality in a timely manner. Again, with

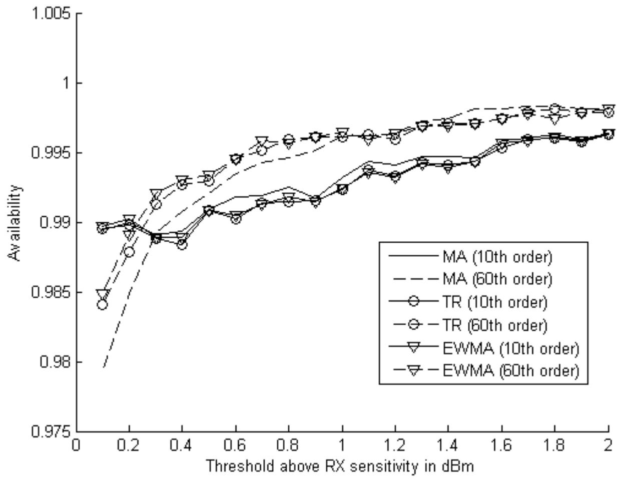

Fig. 8. Availability for different filter types and orders

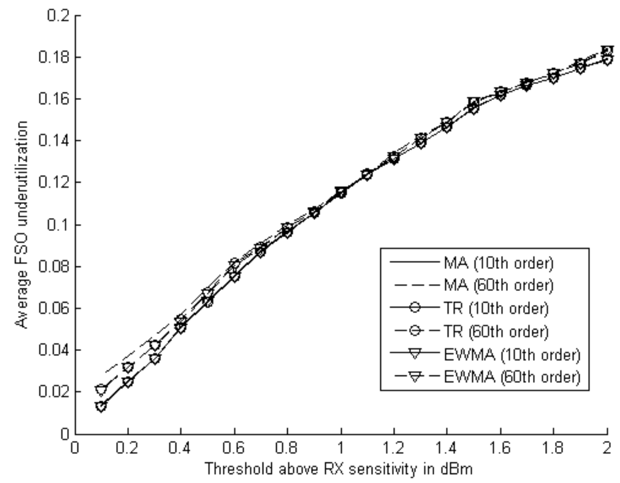

Fig. 9. FSO underutilization for different filter types and orders

increasing filter order availability values worsen. Although TR and EWMA filters perform better, pure TH still delivers best results. The advantage of TH can be seen from Fig. 7, where one can see that the average bandwidth is relatively high. This is caused by a very small FSO underutilization, which indeed stays below 6% over all possible wait periods. Pure TH, compared to filtered TH, suffers from a higher dependency between wait period and bandwidth. In fact, for longer wait periods filtered TH provides higher bandwidhts as pure TH. Yet, this does not justify filtering because of availability concerns.

C. Filtering

Fig. 8 shows that performance in terms of availability is increased by increasing the threshold. Higher orders perform better than lower ones, as long as the threshold is set to values high enough. Additionally, even more interesing is that for high orders MA performs worst, while its performance is best for lower orders. This can be explained easily by taking the fading properties of EWMA into account. High order EWMA filters perform smoothing, but also allow timely reaction on critical changes in the ORSS. Lower orders of EWMA or TR lack from these smoothing characteristics, therefore fluctuations remain harmful. Low order MA copes better with these variations than TR or EWMA of the same order (see Fig. 2). A look at Fig. 9 reveals that the increase in threshold compared to the receiver sensitivity is limited due to the FSO underutilization constraint. The threshold has to be below -21.2 dBm in order to keep underutilization below 10%. Another intersting point is illustrated in Tab. I, where one can see that for both EWMA and TR higher filter orders not only perform better in terms of availability, but also in terms of bandwidth. This astonishes even more by taking into account that also the FSO underutilization is increased for higher orders. The reason for this can be found by looking at the relatively small guard band between receiver sensitivity and threshold. By switching over to WLAN too late, link loss is not only introduced by the switching operation itself, but also by FSO unavailability. Thus, by more efficient smoothing availability and bandwidth values can be improved, even if FSO underutilization is also increased.

D. Combined Methods

Since the previous sections revealed that a combination of filtering with whatsoever type and order with either TH or PH yields no improvement, the last thing to discuss is a combination of time and power hysteresis (PT). For this, we can also try to find out if filtering is sensible here. Again, the LT was set to receiver sensitivity whereas the higher threshold was 1 dBm higher. As Fig. 10 shows, reasonable performance can be achieved by combining these two methods, as long as no filtering is involved. Unfortunately, simulation results show that the wait period is limited to less than 40 s, because for longer periods FSO underutilization is prohibitively large (Fig. 11). It is interesting, though, that with increasing filter orders not only the availability is reduced, but also the average bandwidth decreases due to higher FSO underutilization. This can again be related to the fact, that both PH and TH already cope with variations in the ORSS, and applying filtering therefore is useless. By increasing the lower threshold to values above the receiver sensitivity, availability can be improved significantly. Yet, this method is not aceptable because of its high FSO underutilization (cf. Tab. I). As the same table shows, best performance can be achieved with this method even for relatively short wait periods of 10 s.

V. CONCLUSION

In this paper, methods for link selection based on physical signal strength measurements are introduced. Pure threshold comparison is prohibited by the non-zero amount of variations in the measurements due to fluctuations. The proposed algorithms are optimized with respect to maximum availability under the side constraint of limited FSO underutilization. This way, a minimum bandwidth efficiency could be guaranteed.

Tab. I clearly points out that different methods have different influence on availability and bandwidth. Filtering, as it turned

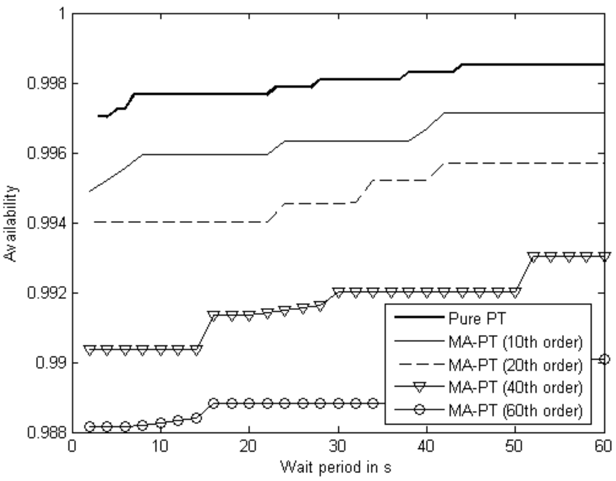

Fig. 10. Availability for PT and filtered PT

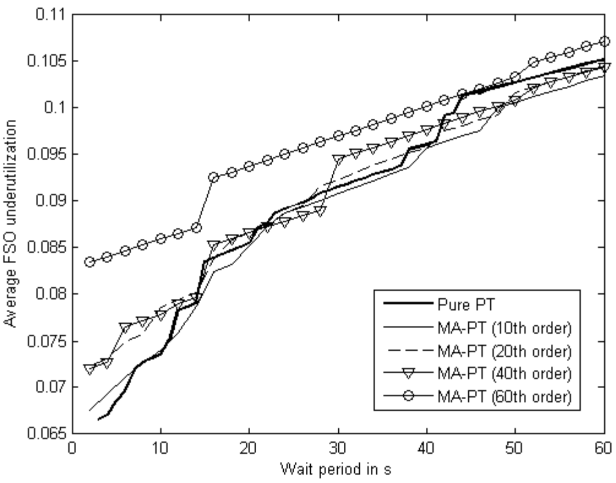

Fig. 11. FSO underutilization for PT and filtered PT

Method	LT dBm	UT dBm	T s	N -	Avail. %	BW Mbps	Under. %
TC	-22	-22	-	-	98.62	67.30	≈ 0
PH	-21.7	-20.7	-	-	99.69	60.65	9.93
TH	-22	-22	10	-	99.28	66.53	1.58
	-22	-22	60	-	99.68	63.63	5.82
	-21	-21	10	-	99.36	58.34	12.87
MA	-21.2	-21.2	-	10	99.25	60.60	9.66
MA	-21.2	-21.2	-	60	99.46	60.57	9.98
TR	-21.2	-21.2	-	10	99.15	60.56	9.65
TR	-21.2	-21.2	-	60	99.59	60.69	9.84
EWMA	-21.2	-21.2	-	10	99.18	60.59	9.64
EWMA	-21.2	-21.2	-	60	99.56	60.68	9.82
PT	-22	-21	10	-	99.77	62.58	7.35
	-22	-21	40	-	99.83	60.97	9.61
	-21	-20	10	-	99.83	55.66	16.87

TABLE I
COMPARISON OF DIFFERENT SWITCH-OVER METHODS

out, yields only little improvement compared to threshold comparison, whereas it even delivers worse results in combination with either time or power hysteresis. As it was shown, time hysteresis (TH) and combined time-power hysteresis (PT) perform best, with emphasis on the latter one. PT even bears the possibility for carrier class availability of 99.999%.

Future work could focus on the effects of amplitude and/or time discretization of signal strength measurements. Quantitatively, the proposed algorithms will achieve different performance.

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