The Effects of Weather on the Life Time of Wireless Sensor Networks Using FSO/RF Communication

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Abstract. *The increased interest in long lasting wireless sensor networks motivates to use Free Space Optics (FSO) link along with radio frequency (RF) link for communication. Earlier results show that RF/FSO wireless sensor networks have life time twice as long as RF only wireless sensor networks. However, for terrestrial applications, the effect of weather conditions such as fog, rain or snow on optical wireless communication link is major concern, that should be taken into account in the performance analysis. In this paper, life time performance of hybrid wireless sensor networks is compared to wireless sensor networks using RF only for terrestrial applications and weather effects of fog, rain and snow. The results show that combined hybrid network with three threshold scheme can provide efficient power consumption of 6548 seconds, 2118 seconds and 360 seconds for measured fog, snow and rain events respectively resulting in approximately twice of the life time with only RF link.*

Keywords

FSO, fog, hybrid network, wireless sensor networks, simulation.

1. Introduction

Wireless sensor networks (WSN) are a technology suitable to monitor a wide range of environmental parameters such as pressure, temperature, acceleration, chemical composition etc. and used for battlefield surveillance, habitat monitoring, home automation and health-care applications [1], [2], [3]. The WSN have been realized by integrating the functions of sensing, computation and communication, into smart sensor nodes. With the advent of robust distributed sensors, WSN can be deployed in inaccessible environments and harsh weather conditions [4], [5]. However, the rising demand of WSN for physical environments monitoring has raised increased interest in long lasting wireless sensor networks. In fact, long time period operation of a sensor has to rely on its battery, which also limits the long lasting performance of the whole WSN. Therefore the problem of efficient use of the energy budget of the sensors is a major issue. The battery power is consumed by all the sensors' activities: sensing, processing, storing and communication, however the optimization of the energy spent in the communications is one of the most important problems in energy efficiency [6], in fact, the radio consumes a significant part of the energy budget of the sensors, furthermore the major energy savings are achieved by turning off the radio, which however means disconnecting the sensors from the rest of the WSN. Under this respect a promising approach is to base communications on FSO links [7]. Hybrid WSN having both RF and FSO links for communications are known to survive up to twice as long as WSN with only RF links in indoor environments [8]. When used in outdoor WSN, the FSO/RF hybrid links are however subject to different weather conditions. Among different weather conditions, rain, fog, and snow are known as the most important attenuating factors of optical communications. This motivates to include the most important effects of fog, snow and rain on optical communications applied to long lasting, terrestrial WSN applications, which is the subject of investigation of this paper. In particular, considering a pair of sensors connected by both an RF and an FSO link, this paper gives two main contributions: (i) it provides a scheme based on three thresholds for switching among FSO and RF links for the communications (one to activate the RF link, one to switch from RF to FSO, and one to switch from FSO to RF), and (ii) it evaluates the performance in terms of energy efficiency of the proposed switching scheme, by considering FSO links availability measurements obtained during long measurement campaign in Graz.

The remainder of this paper has been organized as follows: Section 2 describes the organization of wireless sensor network for power consumption analysis. Section 3, 4 and 5 present the fog, rain and snow effects on wireless optical communication and RF links respectively. In Section 6, results and analysis is presented for snow and fog events power consumption of FSO/RF for wireless sensor networks. Concluding remarks finalize this paper in Section 7.

2. Wireless Sensor Network Organization and Power Consumption

We consider a hybrid WSN where the sensors are equipped with both RF and optical interfaces. In particular, to the purpose of our analysis on the effect of fog, rain and snow, we consider a pair of nodes with the potential to communicate on both RF and FSO links. Regarding the alignment and acceptable attenuation, the FSO links are assumed to have reasonable transmission and receiver diameters. However, for the sake of simplicity, we also assume that each sensor can communicate through line of sight FSO link with only one other sensor. In our analysis and experiments we assume that the FSO links use the transmission wavelength of 850 nm. The motivations behind selecting this transmission length are the readily commercial availability of Vertical Cavity Surface Emitting Laser (VCSEL) and the high response of silicon photodiodes at this wavelength [9]. Furthermore we have already available measurements on the attenuation at this wavelength that can be used to analyze the power consumption for rain and snow events. The FSO link consists of VSCEL driver, VCSEL Laser diode, PIN photodiode and corresponding Transimpedance and limiting amplifiers.

On the other hand we assume that the RF links are omni-directional and they are based on transceivers compliant with the standard IEEE 802.15.4. Thus all the nodes are assumed to have RF communication capability with 2.4 GHz carrier frequency and data rate of 250 kbps. Finally, we assume to have a receiver sensitivity of -90 dBm and even less as provided by some commercially available WSN [34].

The sensor nodes can store small amount of energy due to their small size [11]. The energy per bit for FSO communications is set to $1.48 \cdot 10^{-7}$ mJ/bit whereas energy per bit consumption for RF link is $2.03 \cdot 10^{-4}$ mJ/bit [9].

In the actual communications between a pair of nodes, the nodes use as long as possible the FSO link (that ensures the highest energy savings), however signal attenuation due to fog, rain, or snow requires switching back and forth to RF or FSO.

A simple way of such switching consists of using two thresholds on the FSO attenuation: one to switch from FSO to RF (once the signal on the FSO links approaches the limit of its sensibility), and the other to switch from RF to FSO (once the signal on the FSO regains its operation received signal strength). In order to avoid continuously switching back and forth between FSO and RF, the two thresholds are kept separate, and the second is higher than the first. However, switching off and on the RF link takes time that may result in periods of link unavailability, in particular, if the threshold on the optical signal is too low, there may be an interruption in the service because the optical link is unavailable and the RF still needs to be turned on. To take into account this fact, we introduce an additional intermediate threshold that is used to turn on the radio (to keep it ready), but to continue to use the FSO link. In this way the radio is immediately available as soon as the FSO link becomes unavailable. Therefore our switching schema uses three thresholds on the received signal strength of Free Space Optics link. At one threshold level, called *RF activation,* the RF link is activated but the transmission continues on the optical link. The criterion for selecting FSO link is that the received signal strength should be 3 dB above the receiver sensitivity to ensure bit error rate 10^{-9}[12]. The fog measurements that we conducted in Graz (Austria) show that the specific attenuation of the optical link changes at the rate of ±10 dB/km in one second [10] in the case of snow events. The corresponding change in specific attenuation for fog events is ±10 dB/km in one second [10]. At the second lower threshold level, called *RF transmission,* the transmission on the optical link is stopped and the transmission on the RF link is started. The third threshold level called *FSO Switch back* is used to deactivate the RF link and to restart the transmission on the optical wireless link.

3. The Fog Effects and Measurements

The communication medium strongly influences the signal propagation. The communication medium for terrestrial applications is atmosphere. Among atmospheric effects on FSO, fog is the most detrimental. There are several physical parameters such as liquid water content, particle size distribution, average particle size, fog temperature etc. that play important role in characterization of fog. The fog causes attenuation at transmission wavelength of optical and near infrared waves due to scattering and absorption as the size of fog particles is comparable to these wavelengths. The most accurate way to calculate attenuation in case of fog droplets is based on Mie scattering theory. However, it requires detailed information of fog parameters like particle size, refractive index, particle size distribution etc. which may not be readily available at a particular location of installation. Moreover the calculations based on Mie scattering are complex and involve difficult computation.

An alternate is to use the visibility data to predict the fog attenuation. The determination of fog attenuation in terms of visibility has been investigated in detail by Kruse [11], Kim [12] and Al Naboulsi [13], [14].

The fog effects on hybrid networks are investigated and it has been analyzed that attenuation for RF links below 10 GHz is insignificant [15].

As fog is more crucial for optical wireless communication link, its effects are focused in analysis. The data used for the analysis were taken in two different measurement campaigns at Graz (Austria). In one measurement campaign, the specific attenuation of FSO was measured in the winter months from 2004 to 2005 and 2005 to 2006 [10]. The measurements were carried out at a wavelength of 850 nm and 950 nm at a distance of 79.8 m and 650 m. The optical transmitter having two independent LED based light sources, one operating at 850 nm centre wavelength and 50 nm spectral width at a full divergence of 2.4 deg which emits 8 mW average optical power; average emitted power in this case after the lens is about 3.5 mW. The second source operated at 950 nm centre wavelength and 30 nm spectral widths at a beam divergence of 0.8 deg using four LEDs each emitting 1 mW to produce the same average power at the receiver. The data was collected and sampled at every 1 s.

The availability of FSO link reduces drastically due to such fog events. The availability of FSO link was measured in another experimental setup for four years from 2000 to 2004 [10]. The tested FSO system MultiLink155F features a multiple beam system. The distance between the two setup FSO units was 2.7 km. The PC transmitted two PINGS every minute and recorded the replies.

4. The Rain Effects on Hybrid Network

When the optical signal passes through the atmosphere, it is randomly attenuated by fog and rain. Although fog is the main attenuation factor for optical wireless links, the rain attenuation effect cannot be ignored, in particular in environments where rain is more frequent than fog.

As the size of water droplets of rain increases, they become large enough to cause reflection and refraction processes. These droplets cause wavelength independent scattering [16]. It was found that the resulting attenuation increases linearly with rainfall rate; furthermore the mean of the raindrops size is in the order of a few millimeters and it increases with the rainfall rate [17]. Let R be the rain rate in mm/h, the specific attenuation of wireless optical link is given by [16]

$$a_{spec} = 1.076R^{0.67}\,[\text{dB/km}]. \tag{1}$$

The most general form of raindrop size distribution function N_a is given by Weibull [18]

$$N_a = \frac{N_T}{a_o V_a}\phi(n)n\left(\frac{a}{a_0}\right)^{n-1} e^{-\varphi(n)\left(\frac{a}{a_0}\right)^n} \tag{2}$$

with $a_0 = d(z_a)^b e^{-cz_a}$ and $\phi(n) = \Gamma^n\left(1+\frac{1}{n}\right)$

where z_a is the rainfall rate with raindrops of radius a mm. Typical parameters of rainfall are $d = 0.941$, $b = 0.336$, $c = 0.471\cdot10^{-2}$ and $n = 3$ [17].

The overall constant N_T in (2) represents the total number of raindrops of all sizes per unit volume. The total scattering coefficient by rain can be derived from the following equation [17]:

$$\beta_{scat}^{rain} = \sum_a \pi a^2 N_a Q_{scat}\left(\frac{a}{\lambda}\right) \tag{3}$$

where Q_{scat} is the scattering efficiency which is also referred as the Mie attenuation coefficient.

The performance of RF communications in the GHz band is also degraded by rain attenuation which restricts the use of GHz frequencies for line of sight communication link. Although the propagation of signals is greatly effected by fog, clouds and dust particles, the rain is the major attenuating factor at frequencies above 10 GHz [19], [20]. The relationship between specific attenuation and rain rate is given by

$$\gamma_R = kR^\alpha \;\; [\text{dB/km}] \tag{4}$$

where k and α depend upon the frequency and microstructure of rain. The theoretical background of the above relationship is given in [21].

According to ITU-R model [22], constants k and α in (4) are given by

$$k = \frac{\left(k_H + k_V + (k_H - k_V)\cos^2\theta\cos 2\tau\right)}{2}, \tag{5}$$

$$\alpha = \frac{\left(k_H\alpha_H + k_V\alpha_V + (k_H\alpha_H - k_V\alpha_V)\cos^2\theta\cos 2\tau\right)}{2k} \tag{6}$$

where θ is the path elevation angle and τ is the polarization tilt angle relative to the horizontal. The values of constants k_H, k_V, α_H and α_V for linear polarization (horizontal and vertical part) are given in [22].

5. The Snow Effects on Hybrid Network

The scattering of light occurs due to fog, rain and other precipitations and the received signal strength is reduced as a result of laser beam power attenuation. Consequently either complete link failure or bit errors occurs when received signal fluctuations are large and received signal level decreases drastically [23]. The amount of light attenuation increases proportionally to the number and size of fog, rain and snow particles [24, 25]. It is well known that variation in the received signal strength increases with the amount of rainfall [23, 26, 27]. As snow flakes are generally larger than rain drops, the received signal strength fluctuation will be larger for snow and snow attenuation becomes significant [28]. The size of snow flakes as large as 20 mm have been reported [29, 30] and if the laser beam is narrow, a large snowflake can cause link failure. When a snowflake crosses the laser beam, the received signal level depends on the diameter of the snowflake, and on the distance from the transmitter and the position of the snowflake relative to the cross section of the beam [28]. The FSO attenuation due to snow has been classified into dry and wet snow attenuations [31]. If S is the snow rate in mm/h then specific attenuation in dB/km is given by [31] as:

$$a_{snow} = aS^b \quad \text{[dB/km]}. \tag{7}$$

If λ is the wavelength, the parameters a and b for dry snow are given as follows

$$a = 5.42 \cdot 10^{-5} \lambda + 5.4958776\,,\ b = 1.38\,.$$

The parameters a and b for wet snow are as follows

$$a = 1.023 \cdot 10^{-4} \lambda + 3.7855466,\ b = 0.72\,.$$

The fog, rain or snow particles also affect the GHz FSO links due to scattering. The calculation of the scattering properties of different hydrometeors involves the knowledge of their dielectric properties. Dielectric properties are usually expressed by the complex dielectric constant or the complex refractive index. Snow particles are the complicated mixtures of ice with air, water, or both. The mixing rate and the shapes of the constituents may vary considerably depending on external meteorological conditions to which snow particles are exposed. For the theoretical treatment of the electrical properties of such a mixture, it is assumed that the component materials are large enough to be able to assign their dielectric functions. Nevertheless, finding the "effective" dielectric function of such a mixture is a quite difficult problem since a large number of interactions can occur among the component materials. The solutions can only be obtained by various approximations. The radio wave attenuation due to snow is difficult to analyze as there is lot of weather dependent variation in shape, dielectric constants and size distribution of snow flakes. It is certain that the attenuation due to dry snow in the microwave region is an order of magnitude less than that due to rain of the same rate of precipitation. However, wet or watery snow gives attenuation comparable to that due to rain in the microwave and millimeter-wave regions. Attenuation often exceeds that of rain; attenuation as large as six to seven times the attenuation due to rain was reported in [32]. Measurements made at a wavelength of 0.96 mm have indicated that, at this wavelength range, the attenuation due to dry snow exceeds by 30 to 40 percent the attenuation due to rain of the same intensity [33]. This indicates that the snow attenuation may be increasingly important as wavelengths get short. The specific snow attenuation A in terms of snow rate R is given as follows [33].

$$A = 0.00349\frac{R^{1.6}}{\lambda^4} + 0.00224\frac{R}{\lambda} \quad \text{[dB/km]}. \tag{8}$$

6. Simulation and Results

We base our studies on the results of a long measurement outdoor experiment consisting in periodical packet exchange (PING) among two devices connected by FSO links that were conducted in 2003/2004 at the Technical University Graz, Austria. These measurements have been used to evaluate the availability of a FSO link. In particular the availability measurements show the effects of all weather conditions, in particular fog, snow and rain. Although the availability was measured for longer distance FSO link powered by 220 V ac, it can be used as coarse estimate of battery powered short range FSO link availability.

Fig. 1 shows the simulation results of the behavior of a pair of connected sensors that select the FSO or the RF link for their communications, depending on the availability of the FSO link resulting from the measurements. In particular a sensor selects the FSO or the RF link according to the thresholds described in Section 2. In the figure the value 1 indicates that the FSO is used, while the value 0 indicates that the RF link is used. From these simulations it results that the FSO link is used for 92.0995% of the time. The reduced availability is consequence of fog, rain and snow attenuations. During another set of measurements, the fog attenuation was measured for FSO. The behavior of the WSN has been simulated for different measured fog events. The first event took place on 22-11-2005. Although the fog event was recorded in 2005, the simulation of wireless sensor node behavior can help to analyze its behavior for any future fog event. The switching mechanism described in the previous section has been used for simulation.

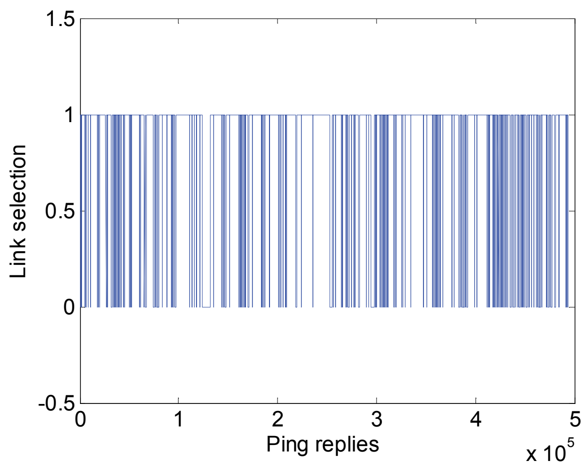

Fig. 1. One year measured availability data and behavior of wireless sensor network for selecting communication link [35].

As mentioned in [10] attenuation changes at ±6 dB per km in one second for 80 m link. Keeping in view the RF activation time and maximum change in attenuation for optical link, RF activation threshold should be selected such that RF link becomes active before the optimal attenuation reaches the receiver sensitivity.

Fig. 2 shows the simulation of wireless sensor node behavior. The received optical power of -28 dBm has been used as *RF activation threshold* and it has been represented by a switch over value of 0.5 in simulation. The receiver sensitivity is assumed to be -46 dBm. It will take at least one second from *RF activation threshold* to reach receiver sensitivity according to maximum change in attenuation of -± 6dB/km per second. The received optical power of -29 dBm has been used as *RF transmission threshold* and the corresponding value of switch over is 0 in simulation. The value of 1 for switch over corresponds to either normal operation on FSO or switch back to FSO from RF link on regaining the received optical power of -27 dBm i.e. *FSO switch back threshold*. This simulation shows that by using this switching scheme, FSO link can be used for 79.73% time of this fog event whereas RF remains in active mode and transmission mode for 2.92% and 20.26% time respectively. The RF active mode time percentage of 2.92% means 631 seconds for the given event. It means the energy saving equal to the difference of energy consumption between RF transmission mode and RF active mode for this time. It highlights the benefit of using three thresholds, otherwise with two thresholds RF will be used 631 seconds in addition to 20.26% time use with three thresholds.

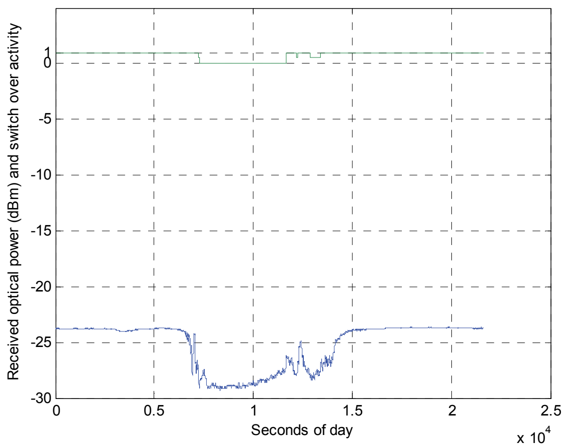

Fig. 2. Fog event of 22-11-2005 and behavior of wireless sensor network for selecting communication link.

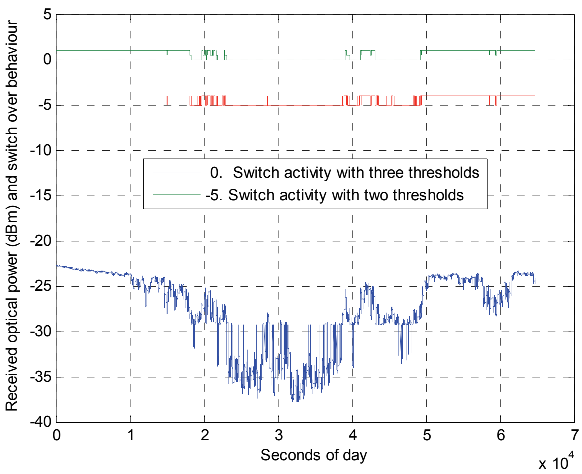

Fig. 3. Fog event of 31-01-2006 and behavior of wireless sensor network for selecting communication link.

Another event that occurred on 31-01-2006 is also analyzed. Wireless sensor behavior has been simulated both for two and three thresholds of selection. Fig. 3 shows that with three thresholds, FSO link is used for 59.55% of time whereas RF link is used in active and transmission mode for 4.02% and 40.44% of time. Here 4.02 % time of RF active mode corresponds to 2609 seconds. The behavior of wireless sensor with two thresholds has also been simulated. The usage of FSO reduces to 58.36% which is 774 seconds less usage in comparison to three threshold case.

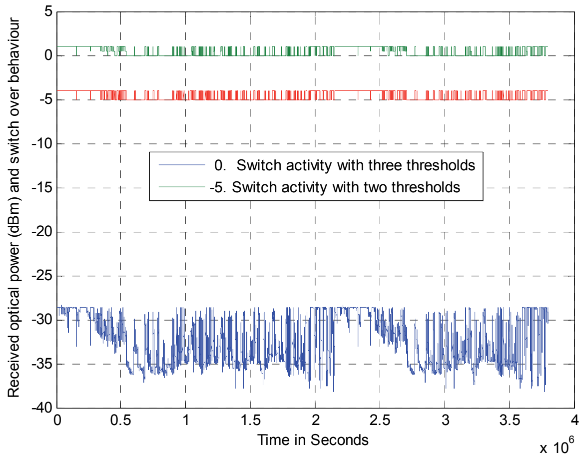

Fig. 4. All recorded fog events and behavior of wireless sensor network for selecting communication link.

Fig. 4 shows the behavior of wireless sensor network for all recorded fog events. The benefit of using three thresholds becomes more prominent. The usage of power efficient link increases from 41.42% to 41.59%. It means additional usage of RF link for 6548 seconds. This power consumption can be reduced by using the three threshold algorithm for the selection of the FSO/RF link.

The behavior of wireless sensor network has also been simulated for two measured snow events that took place on 02-02-2009 and on 28-11-2005 in Graz and results were presented in [35].

Referring to the 2009 snow event, the snow was assumed to be dry and the attenuation on the 2.5 GHz link was negligible. This is why attenuation of 2.5 GHz link is not reported here. On the other hand, wet snow attenuation for optical signal is not significant and it is not taken into account in our experiments and simulations. Fig. 5 shows the simulation on the communication link between two sensors using these measurements. In these simulations we have set the *RF activation threshold* at the received optical power of -21.5 dBm and we have considered a switch over value of 0.5. The received optical power of -22 dBm has been used as *RF transmission threshold* and the corresponding value of switch over is set to 0. The value of 1 for switch over corresponds to either normal operation on FSO or switch back to FSO from RF link on regaining the received optical power of -21.4 dBm i.e. the *FSO switch back threshold*. This simulation shows that by using this switching scheme, FSO link can be used for the 68.335% of the time of this snow event, whereas RF remains in active mode and transmission mode for 15.91% and

31.664% time, respectively. The RF active mode accounts for 15.91% of the time (i.e. 2291 seconds) in this snow event. It means that the energy savings is equal to difference between the energy consumption in RF transmission mode and in RF active mode during this period of time. This fact motivates the benefit of using three thresholds rather only two (to switch back and forth from RF and FSO directly), since with two thresholds the RF link would have been used for additional 2291 seconds.

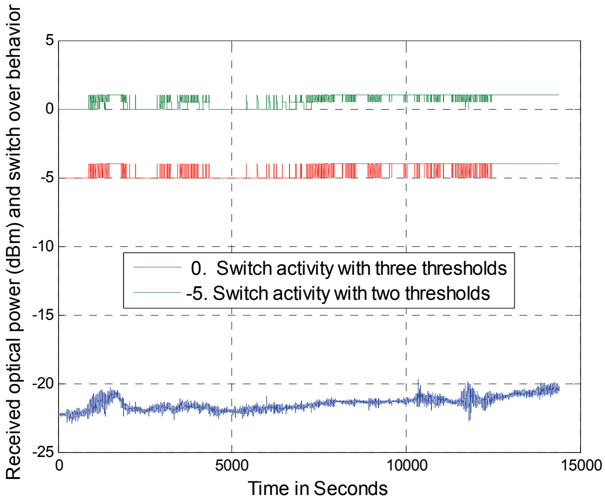

Fig. 5. Snow event of 02-02-2009 and behavior of wireless sensor network for selecting communication link [35].

The simulation results obtained from the measurements during the 2005 snow event are shown in Fig. 6. In order to show the effective switch over behavior, in this simulation the *RF activation threshold* has been set to the received optical power of -24 dBm and it has been represented by a switch over value of 0.5 in the simulation. The received optical power of -25 dBm has been used as *RF transmission threshold* and the corresponding value of switch over is 0 in simulation. The value of 1 for switch over corresponds to either normal operation on FSO or switch back to FSO from RF link on regaining the received optical power of -23.9 dBm i.e. *FSO switch back threshold*.

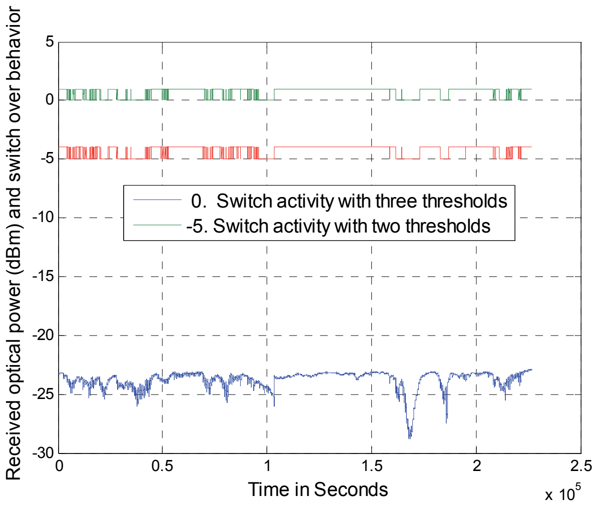

Fig. 6. Snow event of 28-11-2005 and behavior of wireless sensor network for selecting communication link [35].

This simulation shows that by using this switching scheme, FSO link can be used for 73.52% time of this snow event whereas RF remains in active mode and transmission mode for 0.9337 % and 26.47% time respectively. The RF active mode time accounts for a percentage of 0.993% of the duration of the snow event, that means 2118 seconds. In this event the energy savings are equal to the difference between the energy consumption of RF transmission mode and of RF active mode during this time. Also in this case using three thresholds rather than two avoids the use of the RF link for 2118 extra seconds, in addition to 26.47% time where the RF link is used in any case.

The behavior of wireless sensor network has also been simulated for a measured rain event in May 2002 in Graz and results were presented in [35]. Fig. 7 shows the simulation results for this rain event. The receiver sensitivity is assumed to be -20 dBm and the *RF activation threshold* is set to the specific attenuation of 16 dB/km, and it is represented by a switch over value of 40.5 in the simulation. The *RF transmission threshold* is set to the specific attenuation of 17 dB/km with a switch over value of 40. The value of 41 for switch over corresponds to either normal operation on FSO or to switch back to FSO from RF link on regaining the specific attenuation of 15 dB/km i.e. the *FSO switch back threshold*. This simulation shows that by using this switching scheme, FSO link can be used for 94.28% time of this rain event whereas RF remains in active mode and transmission mode for 2.8571 % and 5.7143% time respectively. The RF active mode time accounts for a percentage of 2.8571%, which corresponds to one minute of the rain event. This means that the energy savings are equal to the difference between the energy consumption of RF transmission mode and of RF active mode during this period of time. Also in this case we highlight the benefit of using three thresholds, otherwise with two thresholds the RF would have been used one extra minute, in addition to the 5.7143% time where the RF is used in any case.

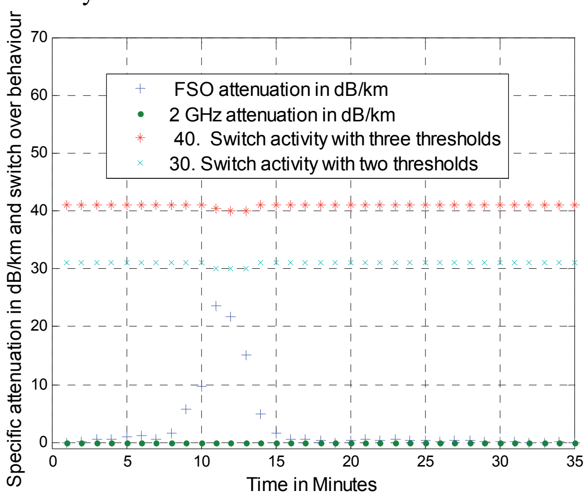

Fig. 7. Rain event of May 2002 and behavior of wireless sensor network for selecting communication link [35].

Finally we report the simulation results based on measurements of FSO availability during all the rain events that took place in 2002 in Graz. These results are shown in Fig. 8. In this simulation the receiver sensitivity, three thresholds and switch over are the same as those used to simulate the sensors behavior during the single rain event of 2002 (and that are used to produce Fig. 7). The simulation results show that by using the switching scheme with three thresholds, the FSO link can be used for 99.9735% of the time of all the rain evens duration, whereas RF remains in active mode and transmission mode for 0.0133% and 0.0265% time respectively. The RF active mode time percentage of 0.0133% means 360 second for the given event. This means that the energy savings are equal to the difference between the energy consumption of RF transmission mode and of RF active mode. Also in this case we observe the advantage of using three thresholds, since with two thresholds RF would have been used for an extra time accounting for 0.0265% of the total time.

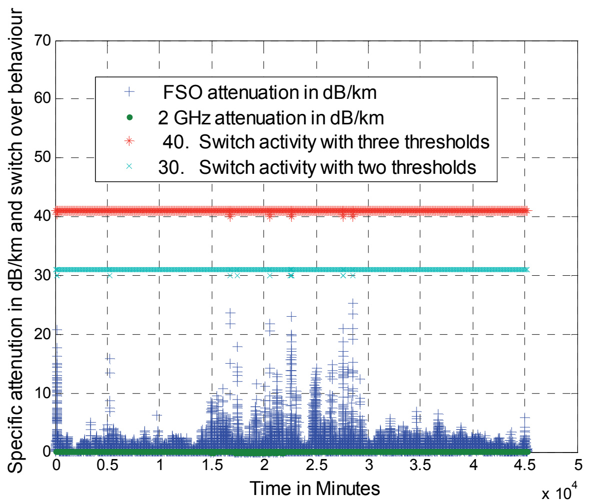

Fig. 8. Rain event of the whole year of 2002 and behavior of wireless sensor network for selecting communication link [35].

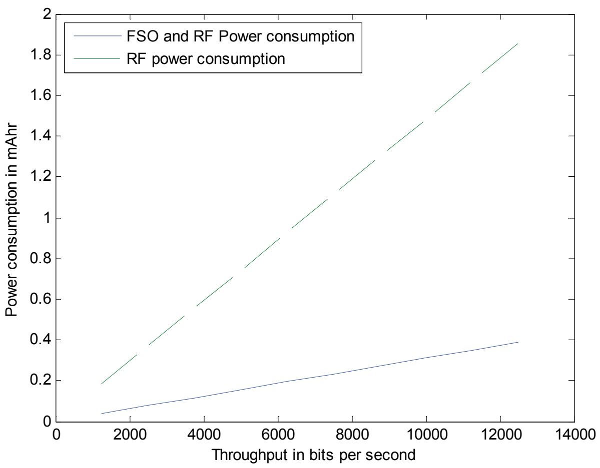

Fig. 9. Power consumption without microprocessor power consumption for wireless sensor using RF only and both RF and FSO [35].

As a result of different weather effects, the minimum measured availability of the FSO link was around 80%. The power consumption of the wireless sensors with different duty cycles is also simulated for RF only and both RF and FSO communication links setup with three thresholds. The worst availability case of FSO i.e. 80% is used to simulate wireless sensor network using both links.

To evaluate the energy consumption of the sensors and of the RF link, we have considered the specifications of Micaz. We have used Micaz specification [36] for simulation. FSO power consumption is simulated through values calculated in [9]. Figs. 9 and 10 show that power consumption improves twice even for the worst case of FSO availability.

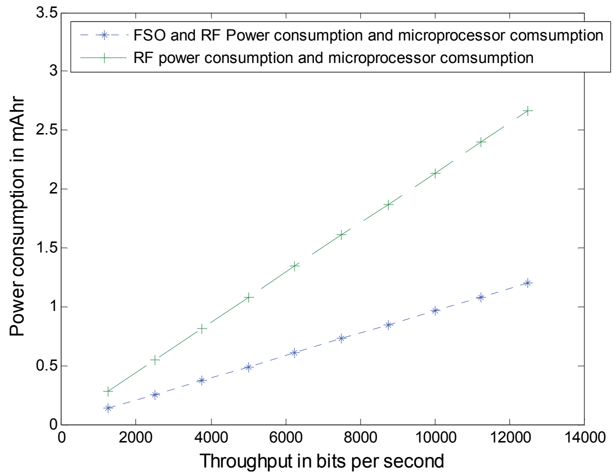

Fig. 10. Power consumption including microprocessor consumption for wireless sensor using RF only and both RF and FSO.

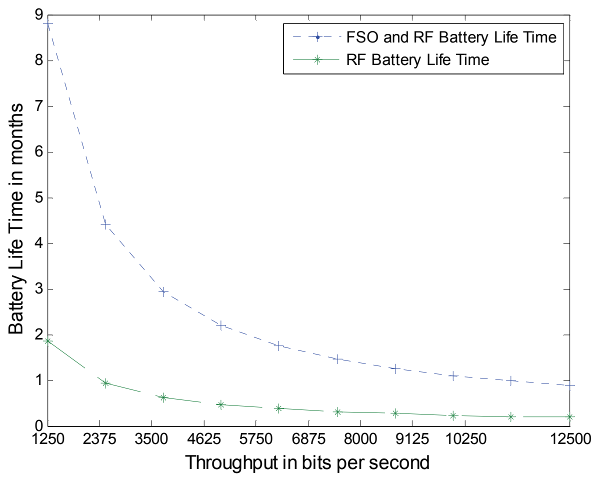

Fig. 11. 250 mAh battery life time for wireless sensor without microprocessor power consumption using RF only and both RF and FSO [35].

Figs. 11 and 12 show the lifetime of the sensors with RF and FSO link assuming a battery capacity of 250 mAh. In particular the figure shows the battery life time obtained when using only RF and when using both RF and FSO, from which it is clear that the combination of FSO and RF can provide an improvement of about two times. Furthermore this improvement proportionally increases with throughput.

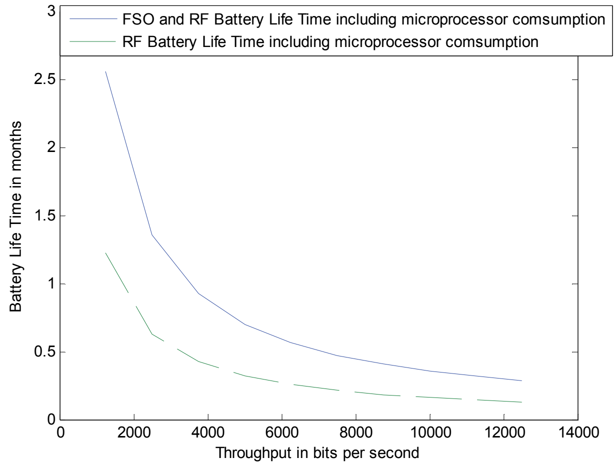

Fig. 12. 250 mAh battery life time including microprocessor power consumption for wireless sensor using RF only and both RF and FSO.

Tab. 1 shows the performance of three threshold schemes under different weather conditions. As explained in this section, the three threshold scheme provide energy saving for 6548 seconds for all the fog events, 360 seconds for all rain events and 2118 seconds for snow events.

Events	FSO Usage	RF active mode usage	RF transmission mode usage	Time of energy saving [s]
Fog event 1	79.73%	2.92%	20.26%	631
Fog event 2	59.55%	4.02%	40.44%	2609
Rain	99.9735%	0.0133%	0.0265%	360
Snow	73.52%	0.9337 %	26.47%	2118

Tab. 1. Performance of three threshold scheme for different weather conditions.

7. Conclusions

The power consumption of hybrid network has been analyzed for terrestrial environment of fog, rain and snow. The reduced link availability of FSO due to weather effects urges to include the attenuation effects of rain and snow in the analysis. Keeping in view the receiver sensitivity and changes in signal attenuation, the optimal usage of power efficient FSO links can be achieved by using proper selection of the thresholds. The simulation results for recorded fog, snow and rain events show that the power consumption saving on RF transmissions can be rather significant by using a switching schema with three thresholds. Furthermore the network lifetime in harsh outdoor terrestrial environments is doubled with respect of the case of RF links only. The effect of low energy consumption per bit by FSO links becomes prominent with the increase of throughput.

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