Free-Space Optics Communication Systems: First Results From a Pilot Field-Trial in the Surrounding Area of Milan, Italy

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***Abstract*—A multiple FSO field-trial has been deployed in the surrounding area of Milan, Italy. After a brief description of the setup we focus our attention on the factors impacting system availability. In particular, we will investigate the effect of visibility and turbulence.**

I. Introduction

In the recent past, there has been a rapidly growing interest for terrestrial point-to-point free-space optical links, as an alternative (or a supplement) to fiber optics connections [1]. The main reason for this interest is the possibility for the quick deployment of a licence-free high-speed link when i) the market requires so (introduction of new services, etc.); ii) there is the need for a temporary connection during events, emergencies, etc.; and iii) the fiber is difficult to deploy for logistic reasons.

However, the performance of these links can be seriously impaired by adverse atmospheric conditions; in particular, one important atmospheric effect is attenuation due to scattering and absorption; in this respect, the impact of fog and rain can be quite dramatic. Another important effect is scintillation due to turbulence.

II. Experimental Setup

To investigate the impact of atmospheric effects on the systems' performance, a multiple FSO field-trial has been deployed during 2001 in the surrounding area of Milan. The importance of this kind of experiments cannot be overstressed: to predict the overall performance of an optical wireless link, in fact, it is most important to assess the relations between local meteorological measurables and attenuation at infrared wavelengths; these relations can hardly be obtained through a purely theoretical approach.

Both short (195 m) and long links (3160 m) have been installed. The long path features two parallel links, a 20 Mb/s system operating at $\lambda = 840$ nm, and a 155 Mb/s system operating at $\lambda = 1550$ nm. It is mainly used to assess the effect of attenuation on system's performance.

The short link of this experimental field-trial is used for the investigation of the effects of scintillation. The link's parameters are: $\lambda = 850$ nm; height of the transmitting station = 15 m; height of the receiving station = 10 m; TX divergence at $1/e = 2.8$ mrad; fade margin $= 50$ dB; diameter of the receiver's lens = 7.6 cm; sampling rate of the received optical power = 1 sample/s. As ancillary equipment, a Vaisala visibility meter was installed at the common end.

The links have been operational since April 2001, and a quite large amount of data has been collected. However, the data need to be carefully examined, before some clear indication can be extrapolated; in some cases, for example, system outages were due to pure mechanical reasons, i.e., deformation of the structures that support the equipment.

By the light of our experience we believe that is safer to proceed on "event basis," rather than trying and drawing questionable statistical conclusions, built over a large database of heterogeneous data.

For this reason we will focus here on two "case studies" of interesting events recorded in the period between autumn 2001 and spring 2002; our findings will be thoroughly discussed.

III. Attenuation: 20 October, 2001

During the month of October, 2001, several events were recorded, where a strong fading of the received signal was observed. These events were analyzed to investigate the accuracy of the analytic relation that relates visibility and specific attenuation, by comparing measured attenuation (on the "long" 1550 nm optical link) and estimated attenuation (from visibility measurements).

As far as the optical link is concerned, specific attenuation has been calculated as the difference between "clear air" signal level and the current signal level. The first has been evaluated as -11 dBm. The total attenuation is then divided by the link's length (i.e., 3160 m) to obtain the specific attenuation α.

Measured visibility is converted into estimated specific attenuation by applying the relation proposed as "Beer's law" [2], [3]

$$\alpha = \frac{17.138}{V}\left(\frac{\lambda}{550}\right)^{-q} \tag{1}$$

where α is the specific attenuation (dB/km), V is the visibility (km), λ is the wavelength (nm), and q is the distribution of particulate with size, what in case of low visibility (less than 6 km) is

$$q = 0.585V^{1/3}. \tag{2}$$

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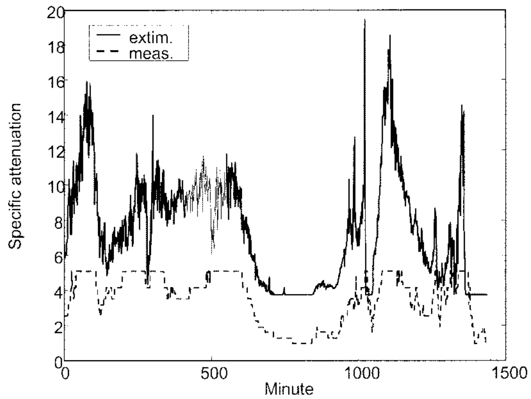

Fig. 1. Time series of measured (lower line) and estimated (upper line) specific attenuation; raw data.

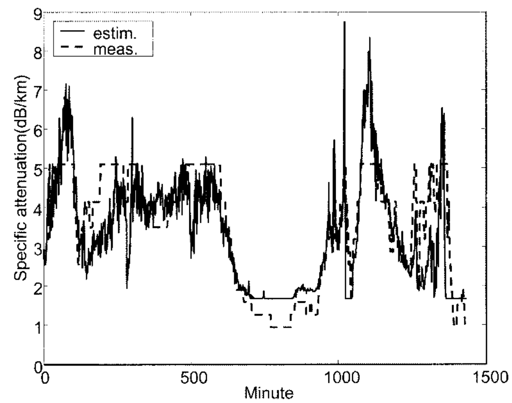

Fig. 2. Time series of measured (lower line) and estimated (upper line) specific attenuation; estimated attenuation has been corrected.

It must be noted that the available instrument is not able to measure visibilities greater than 2000 m, that correspond to a specific attenuation of 3.99 dB/km at 1550 nm.

In Fig. 1, the time series (with a resolution of 1 min) of specific attenuation (dB/km) are shown, as measured by the optical link (dashed lower line) or estimated from measured visibility (continuous upper line); the date is October 20th, 2001. These are raw data, i.e., no correction of any kind has been applied.

From Fig. 1, it can be noted that the optical link is in outage when specific attenuation is greater than 5 dB/km (i.e., the lower line saturates). As can be observed from the figure, even if the trend is reasonably predicted, there is a systematic overestimation of the measured attenuation.

This difference can be due to i) a constant offset or ii) a multiplying factor. A constant offset (ΔdB) could be due to the imperfect evaluation of the reference zero-level of the receiver; however, the valued needed to balance the two quantities is too high to be justified (i.e., 2.5 dB/km). A multiplying factor could be introduced by at least four different causes: spatial variability of visibility, a systematic underestimation of visibility by the instrument, an error in the Beer's expression (1), or problems with the receiver's calibration curve.

It is impossible to identify the cause (or the causes) responsible for this effect, without resorting to a more focused experiment. For the purposes of this discussion, let us ignore what the actual causes are, and let's concentrate on their effects.

We have evaluated the unknown correction factor (that will multiply the estimated attenuation) by applying a least-square regression algorithm to the measured versus estimated data. For the data set presented in Fig. 1, this coefficient was found to be equal to 0.45. When this correction factor is applied, a quite good agreement between observations and estimates is found, as can be observed in Fig. 2. Please note, however, that this does not imply that the Beer's law needs to be corrected; the actual cause of this overestimation must be identified; in fact, it can also be due to problems with the (commercial grade) receiver (i.e., measured attenuation is lower than the actual one).

IV. SCINTILLATIONS: 22ND MARCH, 2002

For the analysis of scintillation, we focus our attention on data collected by the short link on March, 22nd, 2002, from 00 h to 19 h; meteorological conditions were good, with sun and no clouds. Figs. 3 and 4 show air temperature (in °C) and wind velocity (m/s) as a function of local time, respectively. To separate scintillation from slow signal variations (due to slow variations in visibility), the time series of attenuation have been high-pass filtered. For this purpose, we have applied a fifth-order Butterworth filter with a cutoff frequency of 0.05 Hz; this particular value was chosen following a well known procedure [4], as the point A corresponding to the change in slope of the signal's power spectrum (see Fig. 5). However, the choice of the cutoff

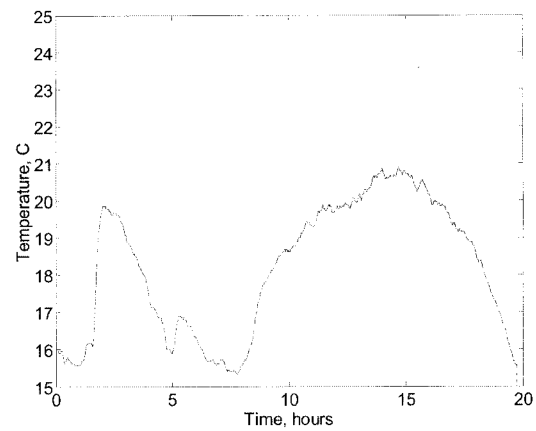

Fig. 3. Time series of temperature, in °C.

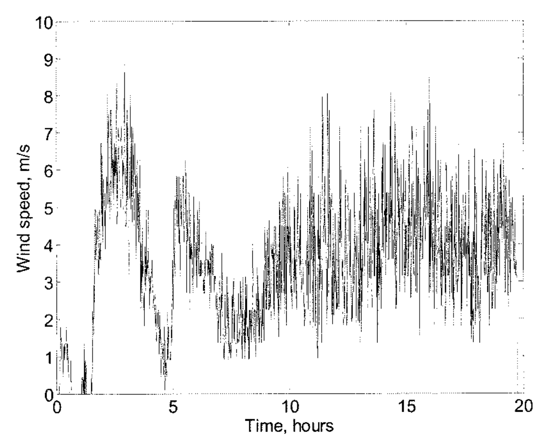

Fig. 4. Time series of wind speed, in m/s.

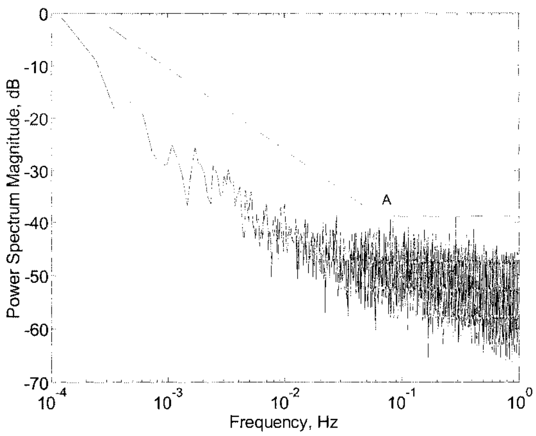

Fig. 5. Normalized power spectrum magnitude (dB) of the time series of attenuation. Point A corresponds to a change in the slope of the signal's power spectrum.

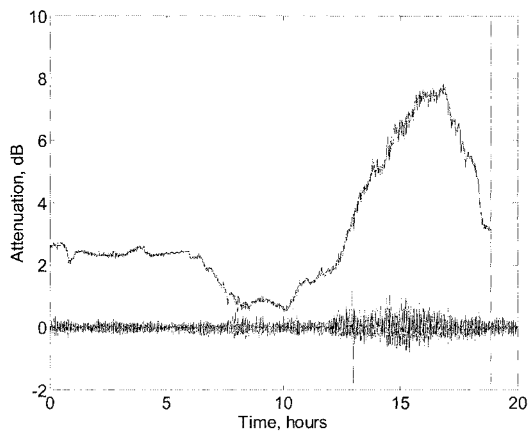

Fig. 6. Time series of average attenuation (upper line) and scintillation (lower line).

frequency has proven to be not critical, and only minor changes in the standard deviation of scintillation have been observed when the cutoff frequency is varied in the range 0.005 –0.1 Hz.

Total attenuation (dB) and scintillations (dB) are shown in Fig. 6, while standard deviation of scintillation (dB) is shown in Fig. 7; the standard deviation of the scintillations was calculated using 1 min of data (i.e., 60 samples), then filtered using an 10-min moving average.

During the night (between 2 h and 4 h) there is a strong increase in air temperature due to Phöen wind coming from the Alps. Interestingly, there is no appreciable variation in the standard deviation of scintillations; this seems to be an indication that wind without sun irradiancy does not impact scintillations even in presence of an air temperature increase.

In the afternoon (between 14 h and 19 h) the total attenuation increases after a substantially stable period, possibly because of haze; unfortunately, direct visibility measurements were not available at that time. Interestingly, the amplitude of scintillations increases with attenuation, as can be inferred by comparing

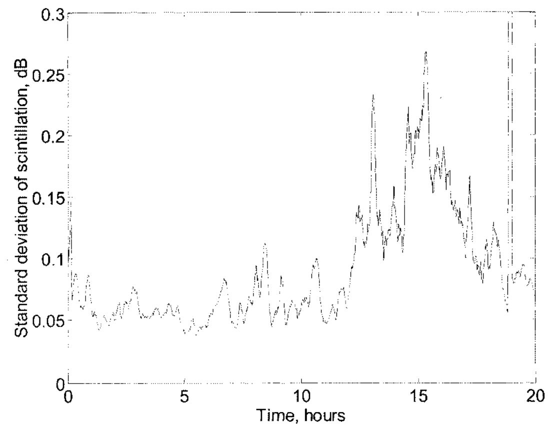

Fig. 7. Time series of standard deviation of scintillation.

Figs. 6 and 7. This common trend, that was known in the microwave "realm" [5] but was not obvious in the optical region, has been confirmed by analyses carried out on other events.

V. Conclusions

A multiple FSO field-trial has been deployed in the surrounding area of Milan. In this preliminary analysis of the first experimental results we have focused our attention on the factors impacting system availability. We have investigated first the possibility to exploit visibility measurements to estimate the optical attenuation experienced by the laser beam. Although the general trend is correctly retrieved, a quantitative evaluation of specific attenuation is made difficult by the uncertainties in the experimental setup; in particular, if a correction coefficient (that multiplies the estimated attenuation) is introduced, a good agreement is found between measurements and estimates. This can be due to a wrong calibration of the (commercial-grade) equipment built-in power meter.

Successively, we have investigated the impact of scintillation From the analysis of the data we have found that i) wind without sun irradiancy does not cause scintillations also in presence of an air temperature increase and ii) the amplitude of scintillation increases with the received field attenuation.

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