Free-Space optics and E-band radio: Complementary techniques for Gbit/sec Wireless

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Abstract—Free Space Optics (FSO) and E-band links operating in parallel are investigated. In contrast to previous work in this field equal transmission rate of the two is assumed— 1 Gbit/sec in existing systems with a likely increase in the near future. Propagation characteristics are briefly presented. It is shown that practical difficulties preclude microwave backup to FSO links. Equal transmission rate leads to the possible application of parallel MIMO techniques. Outage capacity based on that is determined regarding for both binary and quaternary modulation and both Direct Detection (DD) and heterodyne techniques in the FSO link. The unexpected conclusion is that it is more the FSO link that serves as backup to the E-band link than the converse.

I. INTRODUCTION

This paper deals with Gbit/sec wireless links. The transmission rate of equipment available at the time of this writing (early 2010) is 1 to 1.25 Gbit/sec. 10 Gbit/sec is foreseen in the not too far future, maybe with an intermediate step of about 3 Gbit/sec.

In principle, microwave i.e. radio at <30 GHz, mm-wave and Free-Space Optical (FSO) bands would equally be appropriate for Gbit/sec transmission, with radio below 10 GHz very likely yielding the best characteristics. Surprisingly, microwave performance is inadequate, as we will explain later. Among mm-waves E-band is allotted to high-speed fixed-service digital transmission with two half-bands for forward and return channels, respectively: 71-76 and 81-86 GHz. The explicitly formulated reason to allocate this band was to make possible Gbit/sec point-to-point transmission via mm-waves. In the optical frequency band practical rather than technical or regulatory factors determine the applicable wavelengths, among these available components and eye safety; these lead to 850 nm and 1550 nm.

It turns out that both FSO and mm-waves have rather adverse propagation characteristics. Interestingly enough, these characteristics are to some extent complementary. Therefore they offer themselves, self evidently, as two diversity routes of one link. The purpose of this paper is to describe the adverse propagation effects which make this diversity necessary and to discuss these heterogeneous diversity links.


The mm-wave propagation characteristics are, for example, described in the European Union sponsored COST reports [5] and [6] on terrestrial and satellite aspects respectively; [7] deals with various aspects of propagation characteristics of satellite links with a detailed discussion of mm-waves. For characteristics of hybrid FSO/microwave-mm-wave links see [1] and [8].

As far as is known by the authors, experimental studies of parallel FSO/E-band links have not yet been made or are not published. In our institution BME, in addition to the long existing mm-wave test range, an FSO link was deployed during the last days of 2009. Preliminary results of our propagation tests will hopefully be available by the date of this Workshop.

Organization of this paper is as follows. Section II briefly summarizes the main characteristics of FSO and E-band systems and channels. We stress that from practical points of view E-band radio is much preferable to the lower, microwave frequencies proposed in previous texts. Section III deals with these hybrid links as so called parallel MIMO systems and analyzes their characteristics. In section IV numerical results are presented and conclusions are drawn in Section V.

II. A SUMMARY OF THE MAIN CHARACTERISTICS OF WIRELESS GIGABIT/SEC LINKS

As it turns out our two investigated frequency bands – optics and E-band – are similar from the equipment point of view and complementary from the channel point of view.

A. FSO

1) Modulation

As usual in optical communications most FSO systems operate with OOK/DD (On-Off Keying/DD). Consequently most investigations relate to that. However, due to better power economy the application of coherent methods is not excluded. Among these, differentially encoded PSK (Phase Shift Keying) with heterodyne detection would be the
primary candidate. OOK-PPM/DD (PPM: Pulse Position Modulation) could also have some advantages.

2) **Adverse channel characteristics** [1], [4].

The most important among these are rain, fog, atmospheric turbulence and beam pointing error.

The main adverse effect is fog, being most responsible for the non-availability of FSO links. As usual in meteorology, intensity of fog is characterized by visibility. Just to state some indicative values, valid for 850 nm wavelength: light fog – visibility of about 10 km – causes low attenuation, about 1 to 4 dB/km. The attenuation of heavy fog – visibility of < 0.5 km – produces very high loss, > 40 dB/km, and up to 300 dB/km if the fog gets denser. Fog-induced attenuation depends somewhat on the wavelength; it is lower at longer wavelength but the orders of magnitude are similar.

Heavy rain causes high attenuation as well, strongly depending on rain rate (mm/hours). Very heavy rain, 90-100 mm/h, occurring in temperate climate with non-negligible probability can cause attenuation of about 20 dB/km.

Both fog- and rain-induced fading is flat both in time and in frequency.

Atmospheric turbulence causes fluctuation of optical field amplitude and phase, called scintillation. This is a rather slow fading. (“Rather slow” means constant over long strings of symbols; its time constant is in the order of seconds.) For short periods it can bring a link into outage condition. Under clear air conditions scintillation is the main channel impairment. Phase fluctuation, on the other hand, is usually negligible (both in DD and in differentially encoded PSK).

Taking into account that the laser beam carrying information is very narrow, exact pointing of the transmitter toward the receiver is of primary importance. Although usually this is kept fixed by a tracking loop, pointing errors are still harmful. Effect of pointing error and scintillation are often jointly investigated (e.g. [3-4]), as these are not simply additive.

B. **E-band radio**

1) **Modulation**

E-band systems, similarly to FSO apply simple modulation, although for a different reason. Present day technology of mm-wave circuits is not very much evolved. Transmitters of very low phase noise and receivers of very high linearity are non-existing (at least at sufficiently low prices). On the other hand this frequency band is sparsely used and antennas have rather narrow beams. Consequently equipment of higher level modulation (e.g. MQAM with M>4) are neither available nor needed. OOK, BFSK, BFSK or, at most, QPSK is applied in present-day 1 Gigabit/sec systems. (Note that a significant change in transmission rate (e.g. up to 10 Gigabit/sec) will certainly need higher level modulation, mainly due to the width of the frequency band available in E-band, i.e. 2×5 GHz.)

2) **Adverse channel characteristics**

Fog is to some extent lossy, however, its loss, in contrast to FSO is more or less negligible at least in short links. Loss depends on the liquid water content of air and on temperature. Measured and predicted loss values of a particular fog event are compared in Fig.1. Data were taken in December 2009 at BME: loss was measured on a 3.5 km link and liquid water content with our sensor. As seen, prediction and measurement values are close to identical.

In contrast to FSO heavy rain is primary cause of outage for mm waves. In E-band attenuation can be as high as 30-35 dB/km (rain rate: 90 mm/h) and it depends only slightly on frequency. Some E-band measurement results are described in [10].

Atmospheric turbulence-caused scintillation has some effect on mm-wave links being, however, negligible if the hop length is less than 20 km [9].

![Fig. 1 Predicted and measured fog-induced loss at E-band; prediction is based on water-content sensing](image)

C. **Parallel FSO/radio links; application aspects**

Against the adverse effect of fog in FSO a backup radio link offers itself as countermeasure. Its application is really foreseen since the early days of FSO. From this point of view there is a significant difference between the pre-E-band era and today.

Gigabit/sec radio did not exist in the pre-E band era. Therefore all of the publications in this field, including [1], [8] assume radio backup for increasing link availability during foggy periods at significantly lower rate. However, reasonable rate reduction must be less than, say 10-fold. E.g. [8] takes 10-fold and 5-fold reduction into account.

From the availability point of view a lower-than-10 GHz backup link would be preferable (proposed e.g. by [8]) as this is influenced neither by fog nor by rain. However, in reality this solution does not exist, for various reasons. The frequency band is congested; to find not-used frequencies is nearly impossible. The transmission rate of this backup link would have to be at least 100 Megabit/sec, possibly later as high as 300-1000 Megabit/sec which is at or over the limit of actual technical possibility. One of the advantages of FSO is being license free while this freedom does not exist for the proposed backup frequency. (While this is not valid for the 2.4 and 5 GHz ISM/UNII bands, congestion of these is extremely heavy.)

Mm-wave backup is much more applicable and often proposed (e.g. by [1] and others). Two frequency bands were proposed, with different characteristics, i.e. about 60 GHz and about 40 GHz. 60 GHz is license free virtually also free from intersystem interference and the bandwidth is sufficiently high even for Gbit/sec transmission. On the other hand this frequency band can only be applied to short links, typically below 1 km.
40 GHz is in principle an applicable choice. Details are given e.g. in [1].

According to the opinion of the authors the appearance of E-band Gbit/sec systems may result in a breakthrough in parallel FSO/radio application: transmission rate is about the same as already mentioned; somewhat longer hops than those of 60 GHz are possible; and, as seen, to some extent characteristics are complementary. E-band is not unlicensed but a simplified licensing procedure applies.

III. PARALLEL FSO/E-BAND LINKS; TECHNICAL ASPECTS

A. General

If an FSO link is operated in parallel to a radio link, in our case parallel to an E-band link, this system can be regarded as a special case of a MIMO (Multiple Input Multiple Output) system, forming actually a $2 \times 2$ MIMO. Its dissimilarity from a conventional MIMO system is that both receive antennae “see” the opposite transmit antenna only and don’t see the neighboring one. This so-called parallel MIMO system was introduced (by Horváth and one of these authors) and investigated, relative to a quite different problem, in [11]. It is characterized by a diagonal channel matrix

$$H = \begin{pmatrix} h_1 & 0 \\ 0 & h_2 \end{pmatrix}$$

(1)

where $h_i, i=1,2$ is the transfer coefficient related to fading.

We’ll apply this model and relevant methods for the present case.

As seen in (1) the number of diversity routes is only 2. This is in contrast to more conventional MIMOs, in which a $2 \times 2$ system would produce up to 4 diversity routes. However, if we regard the two (rather special) diversity routes as one entity the concepts of Space Time (ST) trellis coding can be applied. The ST encoder-decoder serve as the innermost entity the concepts of Space Time (ST) trellis coding can be applied concatenated with the presumably also existing channel encoder – e.g. LDPC; the role of ST coding is to yield additional coding gain (and that with code rate 1). The block schematic is shown in Fig. 2. Note that coding aspects will not be dealt with here; for some details on ST codec, applied concatenated with the presumably also existing channel encoder – e.g. LDPC; the role of ST coding is to yield additional coding gain (and that with code rate 1). The block schematic is shown in Fig. 2. Note that coding aspects will not be dealt with here; for some details on ST codes optimized for a parallel MIMO channel see also [11].

![Fig. 2 Block schematic of a parallel FSO/E-band system with ST coding](image)

In the present discussion we are interested in channel capacity. As this channel is non-ergodic (channel is virtually constant during thousands or millions of symbols) it is the outage capacity that is of interest. Channel capacity can be determined from the standard MIMO capacity formula (with some modifications), written below for the deterministic case:

$$C = \log_2 \det \left( I_n + \frac{\rho}{n} H H^H \right)$$

(2)

with $\rho$ the unfaded signal-to-noise ratio (SNR)
$n$ the number of transmit antennae
$m$ the number of receive antennae
$I_n$ the unity matrix of order $n$ and superscript $H$ meaning the Hermitian transpose.

Some modifications are needed for application of this formula. First note that $\rho$ is the electrical SNR. In optical DD this is proportional to the optical power squared; in optical heterodyne detection SNR is proportional to the optical power while noise power is that of the local oscillator shot noise. Second, in the electrical case for sake of fairness it is reasonable to apply $\rho/n$. In the present case the same approach would have not too much sense: electrical and optical powers are independent. Thus in our numerical evaluations rather than being “fair” we’ll take reasonable SNR-s both for the FSO and for the E-band link. SNR of the E-band link will be designated as $\rho_1$ and that of the FSO link as $\rho_2$.

To specify the optical SNR in DD, the received optical power is approximately given as [2]

$$P_{\text{opt}} = \frac{\phi D}{\vartheta}$$

(3)

with $P_{\text{opt}}$, the transmitted optical power
$\phi$ the receiver lens diameter
$D$ the hop length and
$\vartheta$ the angle of divergence of the propagating beam.

Then the electrical SNR is

$$\rho_2^2 = \frac{(i_{\text{signal}}^2)}{(i_{\text{noise}}^2)} = \left[ R_g P_{\text{opt}} \right]$$

(4)

with $i_{\text{noise}}$ the (mainly thermal) noise current of the electrical amplifier (specified by the manufacturer) and $R_g$ is the photodetector’s responsibility.

Thus applying (2) (3) and (4), we get for DD

$$C = \log_2 \left[ \left( 1 + \rho_1 |h_1| \right) \times \left( 1 + \rho_2^2 |h_2| \right) \right]$$

(5)

In the case of heterodyne detection electrical SNR is proportional to the received optical power (not to its square). Its magnitude is

$$\rho_2 = \frac{\eta q f_c}{h f B}$$

(6)

where $\eta_q$ is the detector quantum efficiency
$h$ is Planck’s constant
$f_c$ is the carrier frequency and
$B$ is the bandwidth.

We have for this case

$$C = \log_2 \left[ \left( 1 + \rho_1 |h_1| \right) \times \left( 1 + \rho_2^2 |h_2| \right) \right]$$

(7)

The next section investigates behavior in the case of heavy rain, of fog and of turbulence. Antenna pointing error effects are not discussed.

B. Functioning in the case of heavy rain

Note that rain is usually the determining phenomenon of link outage as both propagation media – optics and mm-wave – are sensitive to it, however, to a different scale.

According to [1] and [12] the attenuation of rain, both in mm-waves and in FSO can be expressed as

$$A = \gamma D = k D R^{\alpha} \text{dB}$$

(8)

with $A$ the rain-induced attenuation in dB,
$\gamma$ the loss/km
$D$ the effective hop-length in km. In distances of interest here it is just slightly shorter than the true distance.
and $\alpha$ frequency- and polarization-dependent parameters. For 80 GHz the following apply:

$$k_{\text{sec}} = k_{\text{sec}} = 0.955; \alpha_{\text{sec}} = 0.88; \alpha_{\text{sec}} = 0.772.$$  

In the optical bands of interest

$$k = 1.076; \alpha = 0.67.$$  

As an example of rain effect see Table 1 for Budapest.

### Table 1 Rain effects in FSO and E-band; Budapest

<table>
<thead>
<tr>
<th>Probability</th>
<th>$10^{-4}$</th>
<th>$10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$, mm/h</td>
<td>35.9</td>
<td>96.2</td>
</tr>
<tr>
<td>$\gamma_1$, dB/km</td>
<td>15.15</td>
<td>32.4</td>
</tr>
<tr>
<td>$\gamma_2$, dB/km</td>
<td>11.75</td>
<td>22.94</td>
</tr>
</tbody>
</table>

$|\gamma|^2$ values are given as

$$|\gamma| = 10^{g(D)/10}/D^2; i = 1,2$$  

(9)

### C. Functioning in the case of fog

As seen in section II fog – in spite of the fact that its effect on the FSO link is detrimental – is not very harmful for the whole parallel system. Therefore a rather rough ad-hoc fog model can be adequate. So assume that 16% of days is foggy; duration of one fog event is 6 hours in the average; and with equal probability these are of very light, light and heavy density with FSO attenuation of 4 dB/km, $\leq 20$ dB/km and $>120$ dB/km, respectively. Fog attenuation at 80 GHz for radio in the same situations is 0, 0.25 dB/km and 3 dB/km, respectively.

Simultaneous occurrence of fog and heavy rain is improbably and can be excluded. Therefore – assuming the above fog attenuation at E-band – the radio equipment must insure required link availability by itself for about 1% of time and for further 1% together with a strongly and 1% with a lightly reduced quality FSO link, respectively.

### D. Effect of turbulence on parallel link capacity

Atmospheric turbulence causes fluctuation of received optical field amplitude and phase. Depending on the strength of fluctuation instantaneous received intensity (or power) follows either lognormal or gamma-gamma distribution [2]. The former is valid for weak turbulence (to be defined later) with cumulative distribution function

$$F_\alpha(h_\alpha) = \frac{1}{2} \text{erfc} \left( \frac{\ln h_\alpha + \sigma_{s/2}^2}{\sqrt{2\sigma_{s/2}^2}} \right)$$  

(10)

Here $h_\alpha = |\gamma|^2$ in the atmospheric turbulence case

$$\sigma_{s/2}^2$$ is the so-called Rytov variance, defined as

$$\sigma_{s/2}^2 = 1.23C_n^2 \beta^2 D^{1/6}$$  

(11)

with $C_n^2$ the structure parameter of the index of refraction; its magnitude in optical frequencies is in the range of $10^{-13}...10^{-15}$

$\beta$ is the wave number measured in 1/m unit

$D$ is the hop length, now measured in m unit (in contrast to km units applied in the preceding).

The scintillation is called weak if the Rytov-variance is less than $0.3...0.5$. While the distribution of (10) is strictly valid for this case only, it gives quite good results if the receiver lens is rather large; in this case the large aperture integrates to certain extent the fluctuations on that surface.

### E. System specification

The primary specification is $K$, the number of bits per channel use supported by the parallel system. (This form of capacity description is in diversity systems more appropriate than (bit/sec)/Hz. Namely one channel is formed by the whole diversity system, whether it occupies one or more than one frequency bands.) The choice of $K$ takes into account the code rate of the outer code (see Fig. 2.) The rate of the ST code is 1.

The definition of outage probability is

$$P_{\text{out}} = \Pr \left( C < K \right)$$  

(12)

As $C$ is given as a function of SNR, (12) is equivalent to

$$P_{\text{out}} = \Pr \left( \frac{\text{SNR} < C^{-1}(\text{SNR}_{C<K})} \right)$$  

(13)

i.e. the cumulative distribution at $C^{-1}(\text{SNR}_{C<K})$.

In principle the joint distribution of each disturbing physical phenomenon could be formed. However, as the rainy, foggy, periods are not stationary this would be a formal approach without much meaning. Instead we could express the outage probability as follows

$$P_{\text{out}} = \Pr \left( \text{clear fog} \right) + \Pr \left( \text{out} \right) + \Pr \left( \text{fog} \right) + \Pr \left( \text{out} \right) + \Pr \left( \text{fog and rain} \right)$$  

(14)

The contribution of the E-band link to the first and second term of (14) is very low (as we shall see it is zero). Thus system design can be based on the third term and the possible effect of the first two terms subsequently determined.

Binary modulation is selected with optical direct detection: OOK in the FSO and BPSK in the E-band. With heterodyne FSO, we can alternatively use QPSK.

### IV. A NUMERICAL EXAMPLE

#### A. Hop length vs. specified maximal $P_{\text{out}}$

To get an idea about the performance of parallel FSO/E-band links, the effect of various phenomena will be calculated for a prototype equipment. The parameters of the FSO link are specified in Table 2. For the E-band link no detailed link parameters are given; a reasonable reference fade margin of 45 dB (for a 1 km link) is assumed.

### Table 2 FSO link parameters

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>1550 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit power</td>
<td>40 mW</td>
</tr>
<tr>
<td>Angle of divergence</td>
<td>2 mrad</td>
</tr>
<tr>
<td>Modulation level</td>
<td>Binary or quaternary</td>
</tr>
<tr>
<td>Receiver diameter</td>
<td>25 cm</td>
</tr>
<tr>
<td>Responsivity</td>
<td>1 A/W (i.e. $\eta_{e}=0.8$)</td>
</tr>
<tr>
<td>Optical detection</td>
<td>DD or heterodyne</td>
</tr>
<tr>
<td>Receiver noise current</td>
<td>200 nA</td>
</tr>
<tr>
<td>Reference hop length</td>
<td>1 km ($\rho=35$ dB in DD, 65 dB in heterodyne)</td>
</tr>
</tbody>
</table>

Maximal hop length is computed for outage probabilities of $10^{-4}$ and $10^{-5}$ for various situations: FSO only, E-band only and parallel link. This is done for DD binary and for heterodyne binary and quaternary modulation.

Table 3 contains virtual magnitudes of outage capacities vs. path length $D$— Virtual if $C>0.5$, as no higher order than binary modulator is foreseen.
Limiting $D$ for: E-band FSO Paral.

In Table 4 similar data are given for heterodyne optical detection. In this case $\rho_2$ is so much larger than $\rho_1$ that hop length is uniquely determined by the FSO link while during heaviest rain periods the E-band link is in outage.

### Table 4: Outage Capacities vs. Hop Length; Binary & Quaternary

<table>
<thead>
<tr>
<th>$D$/km</th>
<th>2</th>
<th>2.25</th>
<th>2.5</th>
<th>2.75</th>
<th>3.25</th>
<th>4.0</th>
<th>4.2</th>
<th>4.5</th>
<th>4.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{out} = 10^{-5}$; $\rho_1 = 65$ dB; $\rho_2 = 35$ dB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{out,FSO}$</td>
<td>0.94</td>
<td>0.59</td>
<td>0.35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{out,parallel}$</td>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limiting $D$ for:</td>
<td>quaternary</td>
<td>binary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

### Table 4: Outage Capacities vs. Hop Length; Binary Mod. DD

<table>
<thead>
<tr>
<th>$D$/km</th>
<th>1</th>
<th>1.25</th>
<th>1.25</th>
<th>1.312</th>
<th>1.38</th>
<th>1.44</th>
<th>1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{out} = 10^{-5}$; $\rho_1 = 45$ dB; $\rho_2 = 35$ dB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{out,E-band}$</td>
<td>4.3</td>
<td>2.8</td>
<td>1.5</td>
<td>1.0</td>
<td>0.39</td>
<td>0.30</td>
<td>0.25</td>
</tr>
<tr>
<td>$C_{out,FSO}$</td>
<td>8.0</td>
<td>5.5</td>
<td>3.0</td>
<td>2.0</td>
<td>1.2</td>
<td>0.67</td>
<td>0.33</td>
</tr>
<tr>
<td>$C_{out,parallel}$</td>
<td>12.3</td>
<td>8.3</td>
<td>4.5</td>
<td>3.0</td>
<td>1.6</td>
<td>0.97</td>
<td>0.58</td>
</tr>
<tr>
<td>Limiting $D$ for:</td>
<td>E-band FSO Parallel</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

In principle outage due to fog could be determined from (14). The ad-hoc fog model of section III C shows that $P_{out} = 0$ as the E-band link, even in the worst case, is never in outage due to fog. Even in the longest hop and heaviest fog, E-band-link SNR is 17 dB, corresponding (virtually) to 6 bit/channel use.

B. Operation under heavy fog

In principle outage due to fog could be determined from (14). The ad-hoc fog model of section III C shows that $P_{out} = 0$ as the E-band link, even in the worst case, is never in outage due to fog. Even in the longest hop and heaviest fog, E-band-link SNR is 17 dB, corresponding (virtually) to 6 bit/channel use. (Note that the FSO-alone link would be in outage in the case of fog of light or of heavy density -- i.e. for about 10.5% according to our ad-hoc model described in section III C.)

### Table 4: Outage Capacities vs. Hop Length; Binary & Quaternary

<table>
<thead>
<tr>
<th>$D$/km</th>
<th>2</th>
<th>2.25</th>
<th>2.5</th>
<th>2.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{out} = 10^{-5}$; $\rho_1 = 65$ dB; $\rho_2 = 35$ dB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{out,FSO}$</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limiting $D$ for:</td>
<td>quaternary binary</td>
<td></td>
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</tr>
</tbody>
</table>

C. Effect of turbulence

According to section III.D lognormal distribution can be applied to turbulence characterization. So outage probability of the FSO link can be computed from (10). It turns out – not surprisingly – that for long paths and medium strength of turbulence the outage probability is very high. (In the case of the quaternary example with 4.2 km it can be as high as 1.2 %.) On the other hand scintillation has some effect in E-band (and in mm-waves, in general), but its magnitude does not exceed a few dB [9] and is so negligible. Thus this phenomenon is also negligible in parallel links.

V. CONCLUSIONS

While the complementary character of propagation effects on FSO and RF links was recognized in the early days of FSO, recent development in E-band changed the exploitation possibilities of this complementarity. The novelty described here is that E-band links yield the same transmission rate as FSO links, thus in up to date parallel FSO/E-band links the two technologies are of equal rank. The main consequence of that is that in such parallel systems it is not only availability that is increased due to this design but availability does not require settling for lower backup transmission rate and also quality is improved. Our main findings are:

i. Practical considerations exclude the application of a backup RF link in the microwave (in particular below-10-GHz) frequency band, as proposed by some investigations.

ii. In contrast to FSO-alone systems, rain, rather than fog, is the main cause of unavailability. Rain is the only environmental effect to which such parallel links are sensitive (determining availability, or inversely, hop-length), regardless of other effects being detrimental to FSO-alone links. Taking the last points into account it could be stated that if an E-band link is operating in parallel to an FSO link it is more the FSO serving as backup to the E-band link than the converse.

iii. By recognizing that such a parallel link can be regarded as a special, so-called parallel MIMO system, quality can be improved by applying Space-Time trellis coding, in addition to the usual channel coding ST coding with code rate 1 I can yield additional coding gain.

iv. Among optical technologies heterodyne detection has much better performance than Direct Detection at the expense of being much more complex.; perhaps an optical low-noise input amplifier could yield a much less expensive intermediate solution;

v. While FSO is fully license-free, a license is needed for E-band. However, it enjoys a much simpler licensing procedure than microwave bands.

REFERENCES


