

Experimental Characterization of Turbo-Coded 20 Gbps Fiber-Wireless-Fiber Optical Links

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ABSTRACT Fiber-wireless-Fiber links require alignment between the transmitter and receiver to a high degree of precision (typically $\sim 0.01^\circ$ for a link of a few meters), and channel coding can be used for mitigating the link margin reduction caused by the limited precision of the beam-steering and tracking system. This paper reports results from an experimental study of the misalignment tolerance attained by channel coding. Explicitly, the received power penalties imposed by misalignment are characterized, and then forward error correction techniques are adopted for mitigating the performance degradation inflicted, which is quantified experimentally. Our results characterize trade-offs between coding rate, decoding complexity and the degree of misalignment. Overall, an improvement of the tolerance to misalignment up to $\sim 50\%$ was attained for coded links compared with the uncoded counterpart.

INDEX TERMS Optical wireless communications, fiber-wireless-fiber, forward error correction, link misalignment, beam-steering, tracking, dynamic range.

I. INTRODUCTION

A. MOTIVATION

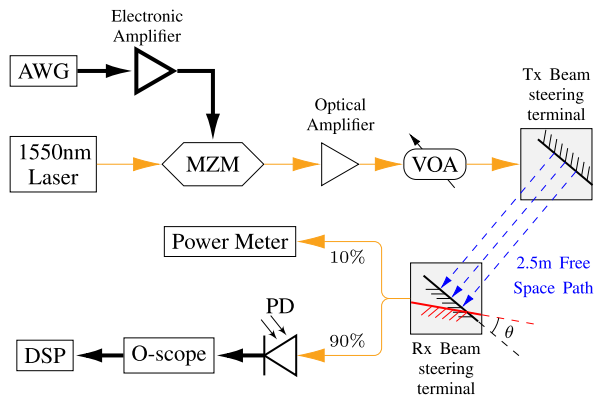
Since the precious low-attenuation radio frequency (RF) spectral resources are becoming congested, optical wireless communications (OWC) is growing in popularity, especially in the form of fiber-wireless-fiber (FWF) links [1]–[5] for applications demanding multi-Gbit/s connectivity. In our previous research [6]–[8], we have conceived and implemented a pair of FWF terminals for bidirectional indoor communications. The FWF terminals feature fast steering mirrors (FSMs), infrared beacons and complementary metal-oxide-semiconductor (CMOS) cameras to perform beam-steering and tracking. A fully assembled FWF transmitter terminal is shown in Fig. 1b. Compared to other beam-steering and tracking systems reported in [3], [9]–[11], this design reduces the overall cost by using a pair of cost-effective,

small-form-factor cameras and adopts a two-step localization algorithm, which provides higher accuracy and improved field-of-view (FoV). The design has been tested for terabit/s full-duplex transmission in [6], as well as for orthogonal frequency division multiplexing (OFDM) modulation and automated tracking in [7]. Moreover, the benefits of full-duplex transmission in multiple bands have been demonstrated in [8], showing enhanced spectral agility of the system.

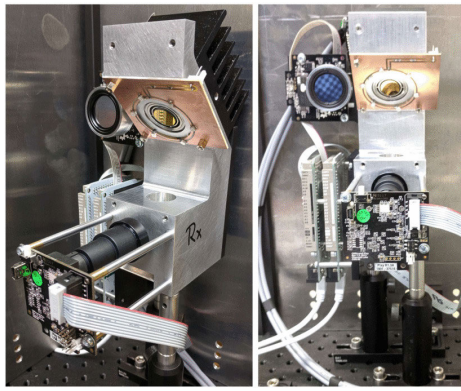
B. NOVELTY STATEMENT

Against this background, we focus our attention on the misalignment in narrow-beam OWC links arising due to limited accuracy and latency of beam-steering and tracking. We investigate the impact of using near-capacity forward error correction (FEC) techniques in enhancing the link misalignment tolerance of FWF OWC links and quantify the performance as a function of different coding rates and decoding complexities. Tab. 1 contrasts our contributions to the

The associate editor coordinating the review of this manuscript and approving it for publication was Barbara Masini¹.



(a) Experimental setup for transmission over the FWF terminal with angular misalignment θ .



(b) Fully assembled FWF Rx-Tx terminals [6].

FIGURE 1. The OWC System.

TABLE 1. Contrasting our contribution to the state-of-the-art.

Topic	Publication	[3]	[9]	[12]	[11]	[6]	This Work
Narrow-Beam OWC		✓	✓		✓	✓	✓
Beam Steering Tracking		✓	✓		✓	✓	✓
Link Loss Compensation							✓
Channel Coding				✓			✓
Throughput Analysis		✓		✓		✓	✓

literature and to the range of investigations covered in them. To the best of our knowledge, this is the first reported study that characterizes the benefits of FEC codes having various coding rates for transmission over a narrow-beam optical wireless channel, and quantifies the coded throughput vs. transmitter-receiver (Tx-Rx) misalignment angle trade-offs.

C. PAPER STRUCTURE

The rest of this paper is structured as follows: The experimental setup and the associated challenges are highlighted in Sec. II. The FEC-coded experimental results are reported in Sec. III, while further discussions are provided in Sec. IV. Finally, our conclusions are offered in Sec. V.

II. SYSTEM MODEL

A. FWF LINK SETUP

Fig. 1 depicts the experimental setup, where the arrows in thick-solid, thin-solid and dashed lines indicate signal

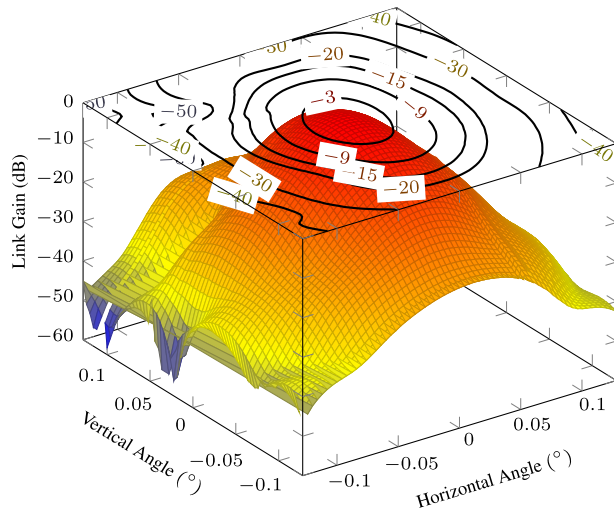
transmission through coaxial cable, through optical fiber and wirelessly over a free-space link, respectively. The original information bits were firstly modulated by On-Off Keying (OOK) and loaded into an Arbitrary Waveform Generator (AWG, Tektronix AWG70000) for generating the analog electronic signal. The electronic signal was then amplified (iXBlue DR-AN-20-MO) and entered into a Mach-Zehnder intensity Modulator (MZM) (Thorlabs, LN81S-FC) for electro-optic conversion, where the information was modulated onto a 1550 nm continuous-wave optical signal (generated by Agilent 81606A). The optical signal was then amplified by an optical amplifier (EDFA), followed by a Variable Optical Attenuator (VOA50-APC) for power control. In order to ensure eye-safe operation, the optical output power of the transmitter was set to 7 dBm (i.e. 3 dB below the eye-safety limit at 1550 nm as per the IEC60825-1 standard). The power of the received optical signal was then split into two parts (using TW1550R2A2), where 10% of it was forwarded to a power meter for measurement, while the rest was detected by a Photo-Detector (PD, New Focus 6-GHz Model 1517). The PD converted the signal back to the electrical domain, and the resultant signal was digitized by an Oscilloscope (Keysight MSOV334A) for capturing the digital waveform for off-line analysis using Digital Signal Processing (DSP).

Both the transmitter and the receiver featured a beam steering terminal for transmitting and receiving the wireless optical signal. The mirrors can be mechanically steered with a fine resolution of 0.01° , so that both near-perfect Tx-Rx alignment and arbitrary misalignment angles can be set up. A specific misalignment angle of θ is shown in Fig. 1, where the original and rotated mirrors of the beam steering receiver are shown in dark and light colors, respectively.

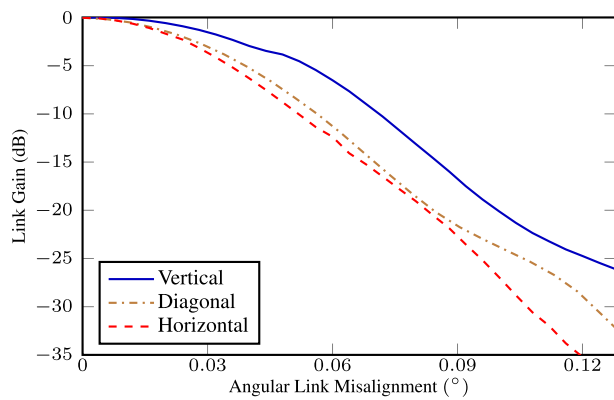
B. LINK LOSS DUE TO ANGULAR MISALIGNMENT

Initially, we investigated the additional link loss of the FWF setup imposed by the imperfect Tx-Rx mirror alignment. The FWF link was first perfectly aligned with the aid of a beacon-based localization system operating at wavelengths where low-cost CMOS cameras of Fig. 1b can be used as tracking sensors (see [6] for details of the localization system). Then, the link was gradually misaligned over a range of approximately -0.13° to 0.13° , in both the horizontal and vertical directions. This was achieved by manually steering the FSM at the receiver side, in a 2.5m link. The results are shown in Fig. 2a, where significant losses can be observed even for slight misalignment.

A contour plot of the link loss is also shown at the top of the coordinate system in Fig. 2a. Observe that the contours are slightly more dense along the horizontal axis, which indicates that the link loss is more sensitive to horizontal misalignment than to vertical. More clearly, in Fig. 2b we present the link loss vs. the misalignment angles from different directions, where the diagonal angle represents the combined effect of equal contributions from both the vertical and horizontal impairment. For example, a diagonal misalignment of $\sqrt{2}^\circ$



(a) 3-dimensional view



(b) 2-dimensional summary

FIGURE 2. Additional loss (negative-valued link gain) vs. horizontal and vertical misaligned angles at the receiver.

indicates 1° of misalignment in both the vertical and horizontal directions. It is clear that the link loss performance is more sensitive to horizontal misalignment than to its vertical counterpart. For example, with 0.06° of misalignment, the link loss would be -6.5 dB in the vertical direction, while it would be -12 dB if it happened in the horizontal direction. This difference in attenuation is caused by the ellipticity induced by the dichroic filter used for splitting the tracking beacon and communication signals within the terminals [6]. The diagonal misalignment was investigated in this work, as it represents an average effect on the link loss.

The link misalignment caused by the limited precision of the localization and beam-steering will naturally result in the degradation of the link quality due the additional link loss, which reduces the signal-to-noise ratio (SNR) at the receiver [13]–[15]. The severity of this link loss in high-capacity narrow-beam OWC depends on the divergence of the optical beam and the FoV of the receiver, which generally specify the accuracy required for beam-steering and tracking [16]. The SNR reduction directly degrades the overall Bit

Error Ratio (BER) performance. As a result, it is necessary to use FEC coding for mitigating the misalignment problem.

C. FORWARD ERROR CORRECTION CODING

We employed near-capacity turbo codes (TC) [17], [18] with various coding rates for FEC. Specifically, the turbo encoder relies on a pair of concatenated systematic convolutional code encoders having the octally represented generator polynomial of $[13, 15]_{\text{oct}}$ [17, Sec. 2.2]. Different coding rates are achieved by appropriately puncturing the encoded message according to the algorithm specified in ETSI TS 136 212 [19]. At the receiver, the soft information bits are fed into the TC decoder, where the *a posteriori* probability decoding algorithm [17, Sec. 4.3.3] having a maximum of $I = 8$ information exchange iterations is used.

A drawback of employing FEC codes is the requirement for sending redundant bits, which reduces the useful information throughput – a half-rate FEC code also halves the throughput, for example. This leads to a trade-off between the error correction capability and the throughput reduction imposed by FEC. In exchange for the overhead caused by redundant information bits, the FEC coding counteracts two effects in this work to provide error-free transmission: the increased loss due to misalignment, and the Inter-Symbol Interference (ISI) that occurs at rates higher than the 6 GHz bandwidth, that is supported by the receiver without penalty.

III. EXPERIMENTAL RESULTS

A. MISALIGNMENT ANGLE TOLERANCE

An experiment to quantify the BER performance of the link vs. misalignment angle at different transmission rates was undertaken. In Fig. 3, we show the BER vs. misalignment angles for different coding rates and transmission rates. It is clear that both the uncoded and FEC-coded BER performances degrade when the transmission rate increases, which is mainly due to the increased ISI of our bandwidth-limited link. However, with the help of FEC, the BER performance has been significantly improved. As expected, the $\frac{7}{8}$ -rate code has lower misalignment tolerance, while the $\frac{3}{4}$ -rate code is more robust. However, having higher coding rates leads to higher useful information rate. For example, a $\frac{7}{8}$ -rate TC applied to 20 Gbps transmission will have an effective information data rate of 17.5 Gbps, while the $\frac{3}{4}$ -rate code only has a 15 Gbps effective rate. These issues will be discussed in more detail in Sec. IV.

B. RECEIVED POWER TOLERANCE

The benefit of FEC coding can also be numerically quantified by the coding gain, defined as the difference of the minimum received power required for achieving a BER of 10^{-3} between the coded and the uncoded schemes.¹ In Fig. 4a

¹Explicitly, employing a stronger FEC code would reduce the BER further under a given receiver power. Thus, the system is capable of achieving a target BER (in our case 10^{-3}) with a receiver power lower than those without FEC or employing weaker FEC codes, which in turn yields a higher coding gain.

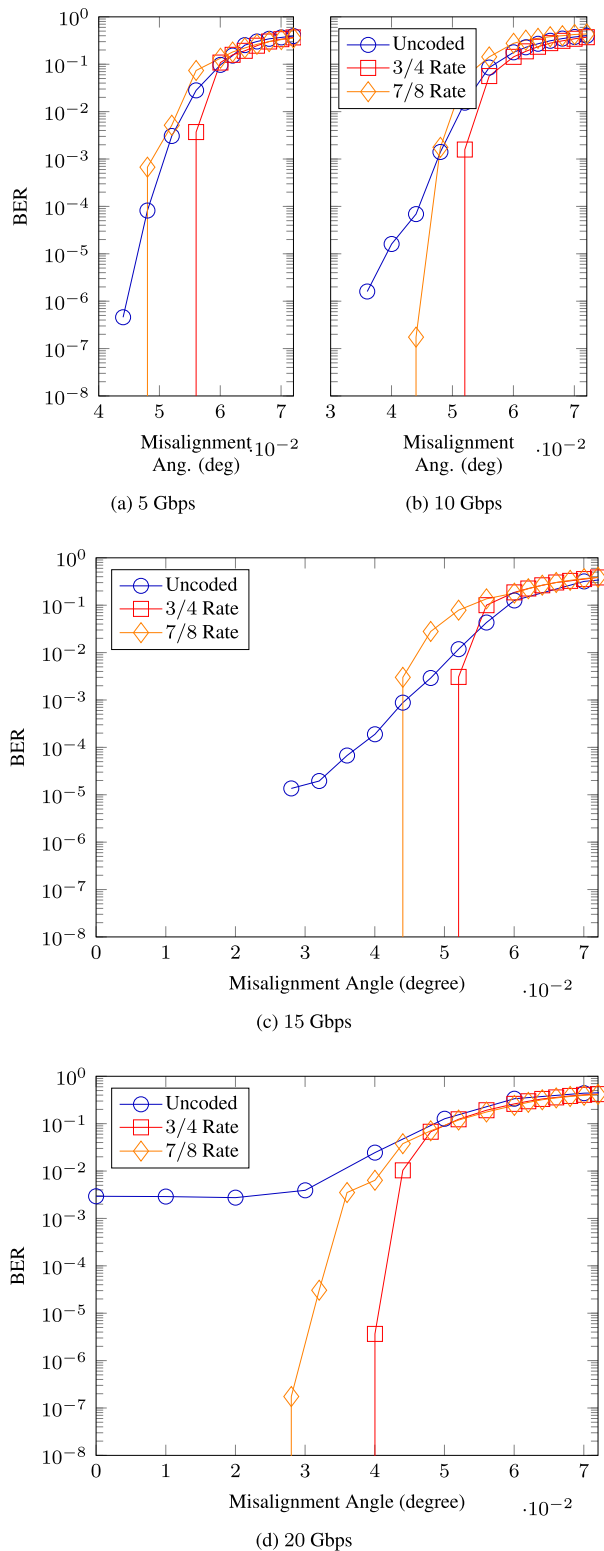


FIGURE 3. BER vs. misalignment angle for uncoded and Turbo coded transmission at different data rates.

we show the BER vs. received optical symbol power of both uncoded and $\frac{3}{4}$ -rate turbo coded OOK transmission at 5, 10, 15 and 20 Gbps, respectively. In Fig. 4b, the BER is plotted against the bitwise received power, where the power spent on

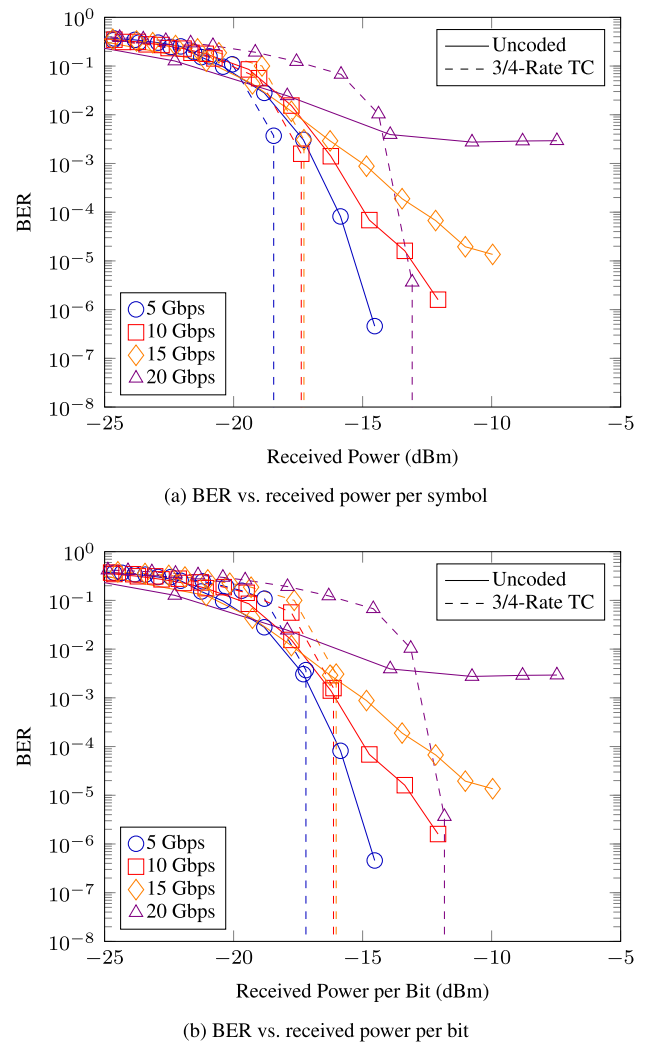


FIGURE 4. BER vs. received power performance of uncoded and Turbo coded transmission at different data rates.

each information bit is normalized for comparison. It is worth mentioning that the variance of received power is a result of having different misalignment angles, while the optical transmitting power is always 7 dBm. Explicitly, a coding gain of 1.45 dB is attained for 5 Gbps transmission at $\text{BER} = 10^{-3}$, which equivalently compensates for an additional link loss of 1.45 dB, while even higher gains are observed at higher transmission rates. By contrast, an irreducible error-floor is exhibited at a 20 Gbps transmission rate, due to the severe ISI dominating the performance of the uncoded link. In this case, its FEC-coded counterpart is capable of reliable operation for received powers in excess of -13 dBm, demonstrating the power of FEC coding.

C. DECODING COMPLEXITY

Another important issue to consider when adopting FEC is the decoding. For turbo codes, the complexity can be quantified by the maximum number of iterations I used for information exchange between the two Recursive Systematic

Convolutional (RSC) decoders at receiver [12], [17], multiplied by the number states in each decoder and by the number of decoders, which is two. For example, an 8-state RSC requires 8 Add-Compare-Select (ACS) operations. Hence, for $I = 4$, a total of 64 ACS operations are required. In Fig. 5, we plotted the BER vs. the maximum number of iterations I used for the decoding of 15 Gbps transmissions for 3/4-rate turbo coding.

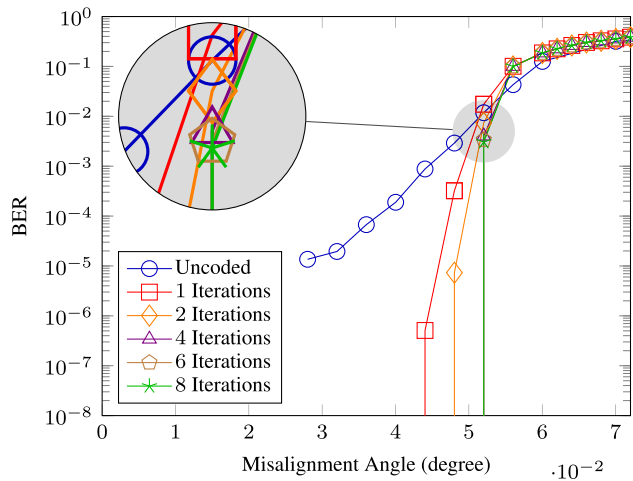


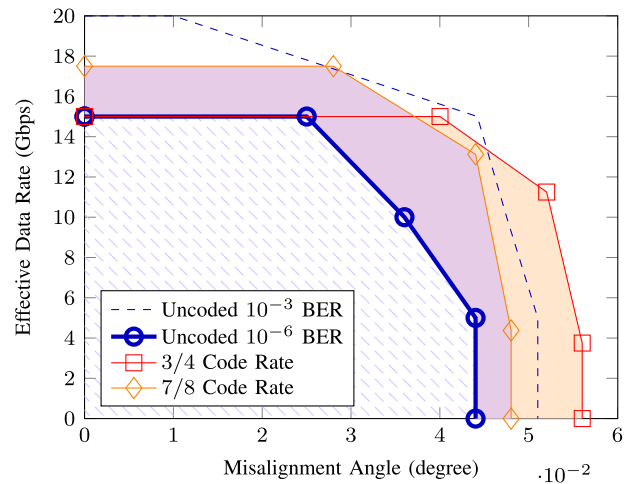
FIGURE 5. BER vs. received power performance of 15 Gbps uncoded and 3/4-rate Turbo coded transmission when applying different number of maximum decoding iterations I .

Explicitly, the uncoded transmission has a maximum 0.024° of misalignment tolerance, while a single-iteration of this turbo code almost doubles it, increasing it up to 0.048° . However, the BER improvement vs. I gradually saturates and the performance $I = 6$ and 8 iterations becomes almost indistinguishable. This indicates the upper limit of the 3/4-rate code's error correction capability. A further improvement can only be attained using a stronger code having a lower code rate, which in turn reduces the effective data rate.

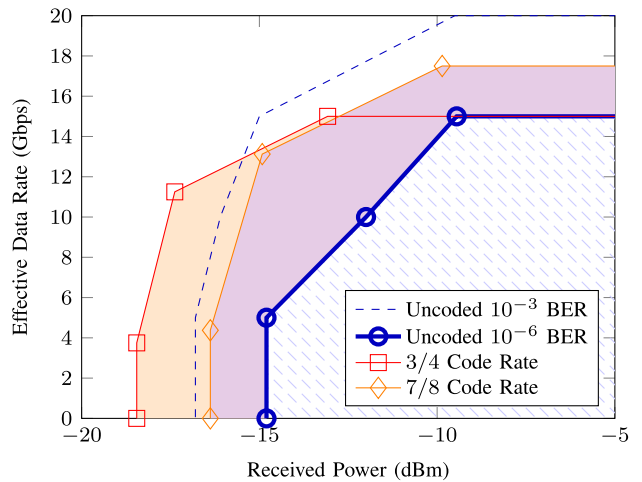
IV. DISCUSSION

In this section, we discuss the attainable misalignment angle tolerance expansion of FEC coding. Specifically, for lower transmission throughput, the maximum misalignment angle when no erroneous bit occurs is extended.

As shown in Fig. 6a, the solid line marked by circles represents the maximum data rate when uncoded transmissions can be carried out at a BER of 10^{-6} . Therefore, transmission of any misalignment angle vs. data rate combination point within the gray-shaded region bounded by the circle-marked line is possible. As mentioned in Sec. III-B, FEC techniques are capable of increasing the angular tolerance at the cost of reduced data rate. This benefit is reflected in Fig. 6a, where the regions bounded by square- and diamond-marked lines represent the expanded angular tolerance attained by using $\frac{3}{4}$ - and $\frac{7}{8}$ -rate TC, respectively.



(a) Effective Data Rate vs. Misalignment Angle



(b) Effective Data Rate vs. Received Power

FIGURE 6. Augmented (a) angular misalignment and (b) link loss tolerance and vs. effective data rate. The hatched shading is the original tolerance range, while regions bounded by square- and diamond-marked lines represent the augmented range using $\frac{3}{4}$ and $\frac{7}{8}$ code rate FEC, respectively.

Meanwhile, the same benefit can also be observed in terms of link loss compensation, as shown in Fig. 6a, where the differently shaded regions indicate the link loss compensation attained by FEC. It is also worth mentioning that while the blue uncoded bound is at a 10^{-6} BER, the coded bounds are chosen when no erroneous bit occurs during experiment, which would result in much better throughput.

Moreover, in Fig. 7a we depict the angular misalignment tolerance vs. I for the 3/4-rate turbo code at different transmission rates. The misalignment tolerance vs. I , namely the decoding complexity, can be clearly observed for all four curves. Due to its lower ISI, the 5 Gbps scheme attains an approximately 26% angular misalignment tolerance gain. This gain becomes much more significant for the high-ISI 20 Gbps scenario, where the tolerance increases from near 0 to 0.04° . Similar trends are observed for the 7/8-rate based

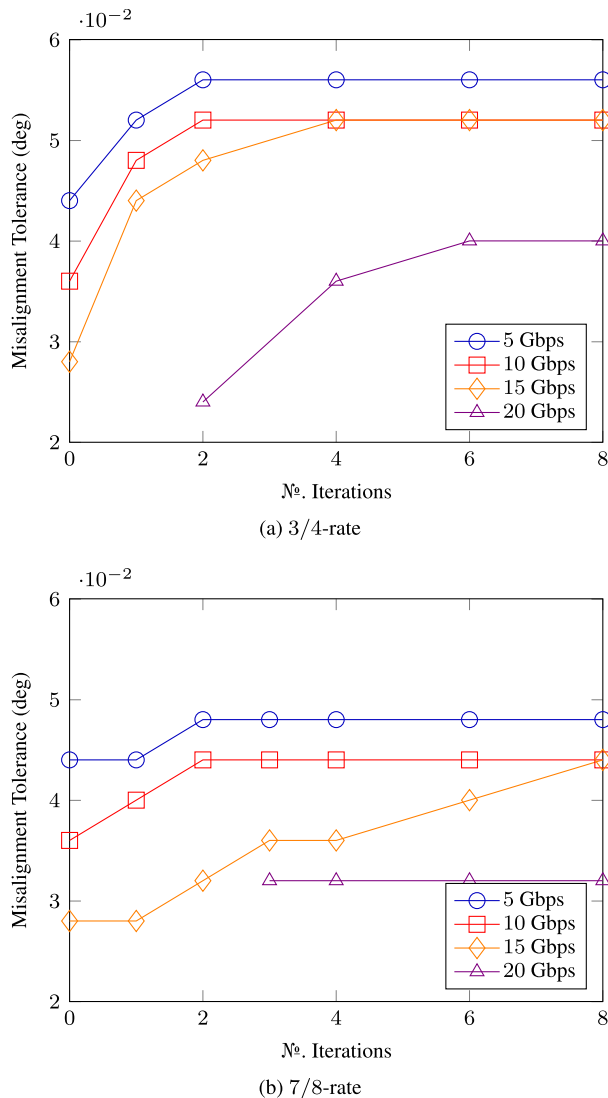


FIGURE 7. Angular misalignment tolerance vs. decoding complexity for turbo code with different transmission speeds.

results in Fig. 7b, although the overall misalignment tolerance gain is a more modest 14%, when compared to the 3/4-rate transmission.

V. CONCLUSION

Narrow-beam optical wireless links are susceptible to misalignment and require high-accuracy tracking and beam-steering. In order to relax the accuracy requirement, in this paper we have shown that encoding the links strikes a trade-off between misalignment tolerance and data rate, with increased link robustness as a result. The BER and angular misalignment tolerance of FEC coded FWF OWC links have been evaluated experimentally. The angular misalignment tolerance and link loss tolerance gains attained by FEC codes of different code rates and complexity have also been quantified. More sophisticated modulation techniques, such as optical OFDM [20], and its enhanced machine-learning aided

relatives, may offer further improvements, which is an area for future investigation.

ACKNOWLEDGMENT

(Xiaoyu Zhang and Ravinder Singh are co-first authors.)

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Programme, running from 2019 to 2024. His research interest includes optical wireless communications, with a particular focus on system demonstration, with a number of world-firsts in this area. Recent demonstrations, together with industrial and academic partners, include quantum key distribution free-space links between handheld devices, between UAVs and ground stations, and Terabit/s wireless links within buildings. He has experience in IEEE standards, contributing to early work in the IEEE802.15.7 standard on visible light communications.



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19 Wiley-IEEE Press books, and has helped the fast-track career of 123 Ph.D. students. Over 40 of them are professors at various stages of their careers in academia and many of them are leading scientists in the wireless industry. He is a fellow of the Royal Academy of Engineering (FREng), IET, and EURASIP. He is a Foreign Member of the Hungarian Academy of Sciences and a former Editor-in-Chief of the IEEE Press. (<http://www-mobile.ecs.soton.ac.uk/> and https://en.wikipedia.org/wiki/Lajos_Hanzo).

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