OFDM over Mm-wave OAM Channels in a Multipath Environment with Intersymbol Interference

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Abstract—This report presents an experimental investigation of using orthogonal frequency division multiplexing (OFDM) on orbital-angular momentum (OAM) channels when there is intersymbol interference (ISI) caused by multipath effects. The impulse response measurement indicates that due to the divergence of OAM beams, channels of larger OAM number are more affected by the ISI caused the reflections from surrounding objects. Channel performance of three different OAM numbers \(l = 0, +1\) and \(+3\) are studied. When a single QPSK channel is used, the more channel performance degradation in term of BER and EVM is observed for higher OAM channels. OFDM with 4 subcarriers is used on the OAM channels to help reduce the ISI and improve the channel performance to some extent.

Keywords—Orbital angular momentum; millimeter wave; Multipath; Intersymbol interference

I. INTRODUCTION

Spatial division multiplexing has the potential to increase both the total link capacity and the spectral efficiency in wireless communication [1,2]. In this regard, the use of orbital angular momentum (OAM) of electromagnetic (EM) waves for spatial division multiplexing has recently received considerable interest [3]. OAM is associated with the “twisting” of the wavefront of a propagating EM wave. The wavefront phase of an OAM beam can change from 0 to \(2\pi l\) azimuthally, where \(l\) is known as the OAM number that can be any integer with either negative, zero, or positive value. Traditional EM beams (such as Gaussian beams) are OAM beams with \(l = 0\). Each OAM beam with \(l \neq 0\) has a doughnut-shaped intensity profile, and the beam size increases with \(l\). Ideally, each OAM beam is spatially orthogonal to (i.e., distinguishable from) all the other OAM beams with different OAM numbers when they propagate along the same axis through a single pair of apertures. Thus, OAM beams have been suggested for use in spatial multiplexing because their orthogonality enables multiple beams of different OAM numbers to be multiplexed together and subsequently demultiplexed with low inherent crosstalk among them [4]. Each OAM beam can carry an independent data stream at the same carrier frequency, and therefore, the total link rate is equal to the data rate of a single channel multiplied by the total number of multiplexed OAM beams [5-9].

In the case of conventional wireless communication links using non-OAM beams, multipath effects caused by beam spreading and reflection from the surrounding objects affect the system performance [10]. Multipath issue for OAM channels, which has larger beam divergence than non-OAM beams. Previously, we have investigated the intra-channel crosstalk and inter-channel crosstalk caused by multipath effects [11]. We have shown that an OAM channel with a high OAM number \(l\) tends to suffer from stronger intra-channel crosstalk and cause strong inter-channel crosstalk to other OAM channels. However, in the previous work the delay of the direct path and reflected path is much shorter than the symbol duration of the transmitted signal, which means the coherence bandwidth of the channel is smaller than the bandwidth of the signal. Therefore, we only observed and studied the flat-fading of the OAM channels.

Besides flat fading, frequency selective fading is a common phenomenon in wireless communication system that happens when the coherence bandwidth of the channel is larger than the bandwidth of the signal, where ISI occurs. In this case, the time delay between multiple paths is comparable to the signal duration. OFDM is usually used to overcome this issue, which convert a single frequency selective fading channel into multiple flat fading channels, and use cyclic prefix to reduce the ISI [10,12]. A worthwhile goal is to investigate the frequency selective fading of OAM channels, and study how OFDM can help improve the performance of OAM channels in a multipath environment.

Contributions: We experimentally investigate the OAM channel performance when there is ISI in a multipath environment. The impulse response measurement indicates that due to the divergence of OAM beams, channels of larger OAM number are more affected by ISI, which is caused by reflections from surrounding objects. Channels of three different OAM numbers \(l = 0, +1\) and \(+3\) are investigated with and without OFDM. The paper is organized as follows: In section II, we show the concept of ISI of an OAM channel and the experimental setup to investigate this phenomenon. In section III, we characterize the OAM channels by measuring the impulse response of the channels and the
frequency selective fading of the spectrum. In section IV, we compare the channel performance between transmitting a single QPSK channel and OFDM with 4 subcarriers and discuss the result. We summarize the results and have further discussion in Section V.

II. EXPERIMENTAL SETUP TO INVESTIGATE ISI OF OAM CHANNELS

Figure 1 shows the concept of ISI in a wireless OAM link with multipath effect. Since the OAM beam diverges faster than the conventional Gaussian-like beam \((l = 0)\), it is more likely to get reflected by the surrounding objects and the receiver may see the superposition of multiple delayed signals. If the delay is on the order of the symbol duration, there would be ISI that results in frequency selective fading and degrades the performance of the channel.

![Figure 1. Intersymbol interference (ISI) which is caused by the reflection of surrounding objects for an OAM channel.](image)

Figure 2 shows the photo of the experimental setup that we used to investigate the ISI of an OAM channel. It starts with a horn antenna with an aperture size of 2.5 cm. A spiral surface plate (SPP) is placed in front of the horn antenna to convert the Gaussian-like beam \((l = 0)\) to an OAM beam. The spiral surface induces different phase shifts in different parts of the input Gaussian beam. When the height difference of the SPP \(\Delta h = h_0(n - 1)\), where \(n\) is the refractive index of the plate material, \(\lambda\) is the wavelength of the mm-wave, and \(l\) is the OAM charge number, the transmitted beam is converted to an OAM beam with charge number \(l\) \([14]\). After a distance of 40 cm, another SPP that has an inverse spiral surface is used to convert the OAM beam back to a beam with \(l = 0\). Then a lens with a focal length of 30 cm immediately follows the SPP to focus the beam to a receiver horn lensed antenna. The horn lensed antenna has an aperture diameter of 15 cm. These SPPs and lenses are made of HDPE, which has a refractive index of 1.52 at 28 GHz \([6]\). Thus, to generate the \(l = +1\) and \(l = +3\) OAM beams, the designed height differences of the SPP are \(\Delta h_1 = 2.07\) cm and \(\Delta h_3 = 6.21\) cm, respectively. The diameter of the SPPs is 30 cm. For OAM beams of large \(l\), the ground, ring and tripod that support the SPP and other surrounding objects could be the source of reflections leading to multipath effects. In order to observe ISI effect in the lab condition, we purposely use a small antenna at the Tx in order to have a largely diverged beam, setup a short propagation distance and use lens of short focal length at the receiver to create longer delay between different paths (can be seen from the geometry in Fig. 1).

![Figure 2. Experimental setup to investigate ISI for an OAM link.](image)

Figure 3 shows the transmitter and receiver that are used to generate and detect up to 2-Gbaud QPSK signal or OFDM signal with four sub-channels. Each sub-channel carries up to a QPSK signal of 0.5 Gbaud so the total throughput is equivalent to a single channel of 2-Gbaud QPSK signal. An IQ mixer takes the 28-GHz clock signal as the LO and two independent IF signal (PRBS) waveforms from the arbitrary waveform generator to generate the RF signal at a carrier frequency of 28 GHz. The length of the PRBS signal is 2\(^{15}\)-1. The output signal is amplified and then sent to the Tx antenna. On the receiver end, the signal is received by a horn-lensed antenna. Then, an 80-Gsample/s real-time oscilloscope with an analog bandwidth of 32 GHz is used to capture the waveform of the mm-wave waveform. Finally, the recorded signal is processed offline to recover the QPSK/OFDM signal and calculate EVM and BER.

![Figure 3. Transmitter and receiver of up to 2-Gbaud QPSK signal or OFDM signal with 4 sub-carriers used in the experiment. Transmitter: AWG: arbitrary waveform generator. Receiver: detection the RF waveform using an 80-GSample/s real-time oscilloscope followed by offline processing.](image)
III. CHANNEL CHARACTERIZATION OF OAM CHANNELS

In order to characterize the ISI, we measure the impulse response of the OAM channels of \( l = 0 \), \( l = +1 \) and \( l = +3 \). We send a repeated short-pulse train at Rx through the channel, and observe the waveform by using the real-time oscilloscope. Fig. 4 shows the measured waveform from the oscilloscope at the receiver for different OAM channels (the time delay is converted to free-space length delay in x-axis). We see that for a Gaussian beam of \( l = 0 \), there is only one main pulse. For \( l = +1 \), multiple after-pulses follow the main pulse due to the multipath effects. For \( l = +3 \), there is a second pulse having relatively high amplitude, and the delay between the main pulse and the delay for the second pulse is about 15 cm (0.5 ns). Our measurement indicates that for an OAM channel of larger \( l \) value, the multipath effect is more significant due to the increasing divergence of the beam.

![Figure 4. Impulse response of OAM channels of \( l = 0 \), \( l = +1 \) and \( l = +3 \). The measurement indicates that due to the larger beam size, an OAM channel of a higher \( |l| \) is more affected by multipath effects.](image)

Since the multipath delay shown in Fig. 4 is about 0.5 ns, it is expected that when the baud rate is on the order of 1-Gbaud and beyond, significant ISI would occur. Next we measure how ISI affect the QPSK signal at different baud rate. The EVM and BER increases dramatically when the baud-rate increases. This is because ISI becomes more severe when the symbol duration becomes shorter as baud rate goes higher. Figure 5 (b) shows the spectrum of channels when a 2-Gbaud QPSK signal is used. Some dips of spectrum are circled which indicates the frequency selective fading.

![Figure 5. (a) EVM and BER measurement of QPSK signal at different baud rate for Gaussian channel of \( l = 0 \) and OAM channels of \( l = +1 \) and \( l = +3 \). (b) The spectrum of channels with different \( l \) when 2-Gbaud QPSK is used. Some dips of spectrum are circled which indicates the frequency selective fading.](image)

IV. OFDM OVER OAM CHANNELS

It is well known that OFDM can be used to mitigate the frequency selective fading and ISI. Here we compare the result of using a single QPSK channel, 4 OFDM sub-channels without adding cyclic prefix, and 4 OFDM sub-channels with adding 25% cyclic prefix. The advantage of using OFDM is that it can convert a frequency selective
fading channel into multiple flat fading channels when the channel number is large enough [10]. In addition, the use of a cyclic prefix can overcome intersymbol interference. Fig. 6 shows the spectrum of each OFDM sub-channel and the superposition of all four OFDM sub-channels, which is detected after the IQ mixer. The maximum data rate is 4-Gbit/s in this experiment when OFDM is used, which means each of 4 sub-channel carries a 0.5 Gbaud QPSK signal. When 25% cyclic prefix is added, the total data rate is reduced by 20% to 3.2 Gbit/s.

In the following text and figures, we will compare the result of OFDM and single QPSK channel. When we say baud-rate in the text or in the label of the figure, we mean the baud rate of a single QPSK channel, or the total OFDM data rate that is equivalent to a single QPSK channel. For example, 2-Gbaud OFDM means 4 OFDM sub-channel each carrying a 0.5 Gbaud QPSK signal. Figure 7 shows the EVM result for the Gaussian channel ($l = 0$) when a single QPSK channel, 4 OFDM channels without adding CP, and 4 OFDM channels with adding CP are used, respectively. Since the Gaussian beam ($l = 0$) does not have significant ISI in our experiment, the use of OFDM doesn’t make much difference. The BER remains zero at all baud rates for both single QPSK channel and OFDM channel.

Figure 7. EVM for Gaussian channel ($l = 0$) when a single QPSK channel, 4 OFDM channels without adding CP, and 4 OFDM channels with adding CP are used, respectively.
Next we investigate what difference OFDM makes for OAM channels of $l = +1$ and $+3$, which have significant ISI and frequency selective fading. Figure 8 (a) shows the EVM for the OAM channel ($l = +1$) when a single QPSK channel, 4 OFDM channels without adding CP, and 4 OFDM channels with adding CP are used at different baud rate, respectively. Figure 9 (a) shows the EVM for the OAM channel ($l = +3$) for the same situations.

From Figs. 8 and Figs. 9, we observe that:

1) For some OFDM sub-channels EVM and BER are significantly improved compared to the single QPSK channel. Adding CP provides more improvement. For example, Ch 1, Ch 2 and Ch 3 for OAM $l = +3$ in Fig. 9 and Ch 0 and Ch 2 for OAM $+1$ in Fig. 8. The improvement for OAM $l = +3$ is more obvious than $l = +1$ since the multipath effects are stronger for OAM $l = +3$;

2) it is noted that not all OFDM sub-channels have better performance than the single QPSK signal. For examples, Ch 1 for OAM $l = +1$ in Fig. 8 and Ch 0 for OAM $l = +3$ in Fig. 9 show that OFDM doesn’t give better performance than the single QPSK channels;

3) For the same sub-channel, OFDM has different performance at different baud rate. For example, in Fig. 9 for OAM $l = +3$, OFDM doesn’t give improvement at lower baud rate (some time even worse) but give significant improvement at higher baud rate. Above 2) and 3) can be explained by Fig. 10, which shows the spectrum for OAM $+3$ for OAM channel when the baud rate is 0.5 G, 1 G and 2 G respectively, along with the result in Fig. 9. Note that the frequency selective fading spectrum is only determined by the physical channel characteristics. Therefore when the bandwidth of the signal changes, the dips in the spectrum may locate at different OFDM sub-channel. For example in Fig. 10, we see a dip in the spectrum in the center of Ch1’s spectrum. Therefore the SNR would be very low for the channel and OFDM will not help in this case. As a result we see that in Fig. 9, there is almost no improvement.
when OFDM is used at 0.5 Gbaud and 1 Gbaud. Note that this problem could be reduced by coding across subcarriers [10]. However, due to the increasing bandwidth at 2 Gbaud, the spectrum of Ch1 moves out of the dip area and therefore the OFDM gives a significant improvement, while Ch 0 falls on the dip area, which doesn’t provide any gain for the EVM and BER.

![Fig.10. Spectrum of OFDM channels at 0.5-Gbaud, 1-Gbaud and 2-Gbaud of OAM channel of l = +3](image)

V. DISCUSSION

In our experiment, it is observed that OAM channels of higher \( l \) values are more affected by ISI and frequency selective fading due to the larger beam divergence, stronger reflected signals and longer multipath delay. The use of OFDM with adding cyclic prefix helps improve the channel performance to some extent. Due to the limitation of hardware and experiment conditions, we can only demonstrate OFDM with four sub-channels. Further study could be increasing the number of subcarriers and coding across subcarriers [10] to improve the performance.

ACKNOWLEDGMENT

This work was supported by the Intel Labs University Research Office, NxGen Partners, and NSF ECCS-1509965 and MRI-1126732.

REFERENCES


