Efficient G-band Digital Communications Using Continuous Phase Modulation

J. X. Qiu, C.R. Dietlein, T.G. Ivanov, D.A. Wikner, A.S. Hedden, E.A. Viveiros, and H.A. Hung

U.S. Army Research Laboratory, Adelphi, MD, 20783, USA

Abstract — The use of continuous phase modulation (CPM) for digital communications at G-band (216 GHz) has been investigated and demonstrated. The unique combination of constant envelope and multi-level symbol-maps of CPM offer the advantages of simultaneous high power-efficiency and spectral-efficiency. A transmitter/receiver communication link consisting of an I/Q modulator followed by a multiplier is used to generate 16-level CPM waveforms at 216 GHz. Waveforms with minimal distortion at the full saturated power of the transmitter were demonstrated without output power backoff. The system architecture provides an efficient technique for generating high power digital waveform, thus extending the link distance. The technique is ideal for upper millimeter-wave and terahertz communications where output power is limited.

Index Terms — Terahertz, millimeter-wave, digital communications, continuous phase modulation, linearity.

I. INTRODUCTION

Systems operating at upper millimeter-wave and terahertz (MMW/THz) frequencies have a number of unique characteristics that can offer specific benefits for communication applications [1][2]. Their available wide bandwidth and high carrier frequency have the potential to support broadband data transmission in small operation platforms. They can also provide secure communication links due to their high directionality for a given compact physical aperture.

A number of experiments have reported MMW/THz communication links using complex digital waveforms such as quadrature amplitude modulation (QAM) [3][4]. However, the available transmitter power was low, resulting in short range. The low transmission power is due to the large peak-to-average-power-ratio (PAPR) of QAM waveforms, and additionally, the hardware limitations above 100 GHz, such as the lack of linear high power amplifiers and the low conversion efficiency of subharmonic mixers. These limitations together with high free-space path loss and atmospheric absorption have restricted the use of MMW/THz for communications.

Continuous phase modulation (CPM) is a class of constant-envelope waveforms that is jointly power and bandwidth efficient [5]. It has been used in applications with high-loss nonlinear channels such as satellite Communications [6] and cellular wireless communications (GSM). It is also being considered for 60 GHz wireless communications [7].

In this paper, the use of multi-level CPM for MMW/THz communications is presented. A system consisting of an I/Q modulator followed by a multiplier chain is used to demonstrate the generation of CPM waveforms at 216 GHz. Distortion-free waveforms at the full output power (5 dBm) of the multiplier were generated, transmitted and received without output power backoff. To the best of the authors' knowledge, this represents the highest power for multi-level digitally modulated waveform at this frequency range, which is a result of highly efficient use of the available transmit power.

II. THEORY OF CPM

A CPM waveform is described by[5]

$$s(t) = A \cos[2\pi f_c t + \phi(t, \vec{a})] \quad (1)$$

where the signal amplitude A is constant in time, and f_c is the carrier frequency. The transmitted information is contained in the phase

$$\phi(t, \vec{a}) = 2\pi h \sum_{k=-\infty}^{\infty} a_k q(t - kT) \quad (2)$$

where h is modulation index, and $\vec{a} = \{a_k\}$ is the transmitted M -ary symbol sequence. The M -ary symbols a_k take the values of $\pm 1, \pm 3, \dots, \pm(M-1)$; M is usually a power of 2. T is the symbol period. The phase function is given by

$$q(t) = \int_{-\infty}^t g(\tau) d\tau \quad (3)$$

The function $g(t)$ is the frequency shape pulse and is usually normalized such that

$$\int_{-\infty}^{\infty} g(t) dt = 1/2 \quad (4)$$

This makes the maximum phase change of the signal to be $(M-1)h\pi$ over the period of $g(t)$. By choosing different pulses $g(t)$ and varying the modulation index h and M , a variety of CPM schemes can be obtained.

If a CPM waveform as defined by (1) is passed through a frequency multiplier, the output waveform is given by

$$s(t) = A \cos[2\pi n f_c t + n\phi(t, \vec{a})] \quad (5)$$

where n is the multiplication factor. The waveform in (5) remains a CPM waveform with multiplications in both carrier frequency and modulation index.

III. EXPERIMENTAL SETUP

The block diagram of the experimental setup to demonstrate the generation and transmission of CPM at 216 GHz is shown in Fig. 1. It includes a transmitter and receiver. The key components of the transmitter consist of a Tektronix AWG5014 arbitrary waveform generator (AWG) for generating the digital baseband waveforms, a direct in-phase/quadrature (I/Q) modulator for up-converting the baseband waveforms to an intermediate frequency (IF) of 13.5 GHz, and a Virginia Diodes Inc. (VDI) multiplier chain (x16) to multiply the IF to 216 GHz. The local oscillator (LO) for the I/Q modulator is provided by an Agilent E8257D low phase-noise frequency synthesizer.

The receiver includes a VDI subharmonic mixer (SHM) driven by a LO which is up-converted from 12.08 GHz by another VDI multiplier chain (x9). The 12.08 GHz signal is provided by an Agilent E8257D low phase-noise frequency synthesizer. The 1.44 GHz IF from the SHM is captured by an Agilent E4448A 50 GHz PSA spectrum analyzer with a built-in down-converter and an 80-MHz bandwidth digitizer. The Agilent 89600 VSA software running on an external computer is used to download the captured waveforms from the PSA, and performs demodulation and analysis on the waveforms. If the IF waveform bandwidth is greater than 80 MHz, the waveform is directly captured by an Agilent DSA90404A digital oscilloscope with 4 GHz bandwidth. The VSA software is then used to acquire, demodulate and analyze the waveform.

A set of specific MATLAB programs running with the Agilent VSA software has been developed to control both the transmitter and the receiver. These programs were responsible for generating digital waveforms, transferring waveforms from the VSA software into the MATLAB environment for processing as well as system calibration.

Fig. 1. Block diagram of the 216 GHz communication link.

The output of the transmitter multiplier chain and the input of the receiver SHM are connected to two horn antennas with a gain at 216 GHz of 21.5 dB each. The two horns are separated by 0.4 m.

IV. COMM-LINK DEMONSTRATION AT 216 GHz

The AWG was programmed to generate the baseband waveforms to produce constant-envelope CPM waveform at the output of the I/Q modulator at 13.5 GHz. Waveforms with different modulation indices, levels and speeds were generated. In Fig. 2, the envelope and spectrum of a 16-level CPM waveform are shown. The symbol rate ($1/T$) of the waveform is 10 Msymbols/s which corresponds to an aggregate bit rate of 40 Mbits/s. The frequency shape pulse $g(t)$ is a Gaussian pulse with a 3-dB bandwidth (B) and symbol period (T) product of $BT=0.5$. The modulation index h is 0.025. Fig. 2(a) shows the constant-envelope characteristic of the waveform. In Fig. 3, the demodulated eye diagram of the waveform at 13.5 GHz is shown. The waveform was demodulated as frequency shift keying (FSK). The quality of the waveform is measured by FSK error defined as the RMS deviation between the measured demodulated frequencies and the reference symbol frequencies. FSK error is similar to error-vector-magnitude (EVM) but defined in demodulated

Fig. 2. Transmitter signal envelop (a), and power spectral density (b) of a 16-level CPM waveform at 13.5 GHz with Gaussian shape pulse. ($1/T=10\text{MHz}$, $BT=0.5$, $h=0.025$)

Fig. 3. Transmitter signal eye diagram for the CPM waveform at 13.5 GHz..

frequency space instead of the I/Q plane and can be used to estimate bit-error-rate. A low FSK error of 1.25 % was measured at the output of the I/Q modulator.

Fig. 4 shows the envelope and spectrum of the CPM waveform in Fig. 2 after it was multiplied in frequency to 216 GHz, transmitted over free space, down-converted to 1.44 GHz by the receiver. The envelope of waveform remains constant while its spectrum expands due to frequency multiplication. The spectral growth is also verified in the eye diagram in Fig. 5. The maximum FSK frequency deviations at 216 GHz and 13.5 GHz are approximately 41.9 MHz and 2.6 MHz, respectively. The FSK error at 216 GHz is about 1.26 %. The power at the output of the transmitter was measured with an Erickson PM4 power meter. The measured output power was approximately 5 dBm, which was also the maximum output power of the multiplier with CW input and independent of modulation index and level.

To study the link power margin, a variable attenuator was inserted between the multiplier output and the transmit antenna horn. With greater than 40 dB additional attenuation, the received eye diagram remained open and the FSK error was only increased to 1.8 %. Further increase in the path attenuation eventually closed the eye diagram. Assuming a current link margin of 40 dB, the maximum range of the current setup is about 40 m. If high-gain antennas are used, longer range can be achieved. For example, the maximum range is 10 km if both the transmitter and the receiver antennas have 60 dB gain. This calculation takes into account free space loss as well as atmospheric loss including water vapor and oxygen [8]. A long-range experiment incorporating solid-state power amplifiers at 216 GHz in the link is on-going.

V. CONCLUSION

For the first time, an efficient communication link architecture based on multi-level CPM waveforms has been demonstrated at greater than 100 GHz. The constant-envelope characteristic of CPM enables generation of high-power, high purity spectrum without output power backoff, thus offering long range MMW/THz digital communications, with maximum available transmit power, and minimal distortion in the received signal. When high power MMW/THz amplifiers are incorporated, the constant-envelope characteristic of CPM will ensure the amplifiers maintain high output power and high efficiency.

ACKNOWLEDGEMENT

The authors would like to thank Dr. K. Ikossi of DTRA for supports, Drs. B. Danly and H. Newman of NRL for useful discussions.

Fig. 4. Receiver signal envelope (a), and power spectral density (b) of the CPM waveform in Fig. 2 after it is down converted from 216 GHz.

Fig. 5. Receiver eye diagram for the CPM waveform in Fig. 4.

REFERENCES

- [1] J. Federici and L. Moeller, "Review of terahertz and subterahertz wireless communications," *J. Appl. Phys.*, vol. 19, pp. 111101 1-22, 2010.
- [2] T. Kleine-Ostmann and T. Nagatsuma, "A review on terahertz communications research," *J. of Infrared Millim. Terahertz Waves*, vol. 32, pp. 143-171, 2011.
- [3] C. Jastrow, *et al.*, "Wireless digital data transmission at 300 GHz," *Elect. Lett.*, vol. 46, pp. 661-662, April 2010.
- [4] I. Kallfass, *et al.*, "All Active MMIC-Based Wireless Communication at 220 GHz," *IEEE Trans. Terahertz Sci. Tech.*, vol. 1, no. 2, pp. 477-487, November 2011.
- [5] C.-E. Sundberg, "Continuous phase modulation: a class of jointly power and bandwidth efficient digital modulation schemes with constant amplitude," *IEEE Comm. Mag.*, vol. 24, no. 4, pp. 25-38, April 1986.
- [6] J.H. Yuen, *et al.*, "Modulation and coding for satellite and space communications," *Proc. IEEE*, vol. 78. No. 7, pp. 1250-1266, July 1990.
- [7] C-C. Chong, *et al.*, Editors, *Millimeter-Wave Wireless Communication Systems: Theory and Applications*, Hindawi Publishing, 2006.
- [8] H.B. Wallace, "AEM" software (www.mmwconcepts.com).