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QAM UWB-Impulse Radio Using Optical Pulses Position Modulation for Optical Fiber-Wireless Links

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***Abstract*—We report on investigations conducted into the improvement in quality achieved using a 5 Gb/s Quadrature Amplitude Modulation (QAM) Ultra Wide Band-Impulse Radio (UWB-IR) on fiber, which was realized using optical pulse-position modulation and its corresponding demodulation method using two-step down-conversion. The experimental results obtained indicate that a Q factor > 3 is realized over a radio transmission distance of 1.5 m following 10 km optical fiber transmission. Further, investigations via simulations into whether any enhancements can be achieved from QAM UWB-IR Multiple-Input/Single-Output using plural antennas show that communication quality is improved.**

Keywords—Impulse Radio; MISO; QAM; UWB

I. INTRODUCTION

Recently, with the spread of mobile information terminals such as smartphones, wireless data traffic has significantly increased. Therefore, substantial improvements in wireless communication speed are essential. However, before this can be achieved, the problem of limited available frequency band has to be overcome. One solution to this problem has been to reduce the cell size of a single Access Point (AP), resulting in the need for several APs in order to provide coverage over any substantial area. On the other hand, high-speed communication networks based on optical fibers are widely used in fiber to the home (FTTH) networks. Consequently, research focused on combining optical fiber and wireless links has attracted increased attention. In this combined link, depicted in Fig. 1, by transmitting data from the base station to each AP via optical fiber communication, the cell size in the radio communication between users and each AP is reduced while maintaining the communication speed.

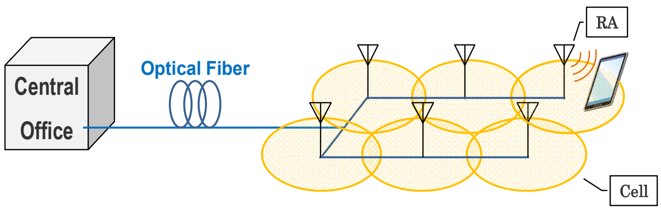

Fig. 1. Combined fiber–wireless link system.

In our research, our focus is on Ultra Wide Band (UWB) Impulse Radio (IR), which is capable of low power consumption and also facilitates broadband [1]. A UWB-IR converts short pulses into radio pulse signals called wavelets by band-limiting at several gigahertz with a band pass filter (BPF) [2]. Because no carrier wave is required, the transceiver cost and power consumption can be reduced, as the configuration can be quite simple. We previously proposed a combined fiber and wireless link system using UWB-IR [3, 4]. With the aim of achieving increased speed, we also previously proposed UWB-IR phase modulation on fiber using optical pulse-position modulation and its corresponding demodulation method via two-step down-conversion [5]. Quadrature Amplitude Modulation (QAM) UWB-IR increases the speed of communication and simplifies the modulator arrangement. More specifically, we regard the odd and even bits of the On-Off Keying (OOK) IR signal as I/Q components of the QAM signal. On the other hand, the wireless transmission distance is limited to a few meters because of the low UWB power level—equivalent isotropically radiated power (EIRP) in the UWB band is limited to less than -41.3 dBm/MHz [6]. Consequently, we considered the use of Multiple-Input/Single-Output (MISO) with plural antennas [7] for QAM UWB-IR links to improve signal quality with low UWB power.

In this paper, we examine the improvement in quality achieved using a 5 Gb/s QAM UWB-IR with a 3 GHz bandwidth. In addition, we investigate whether any enhancements can be achieved from QAM UWB-IR MISO using plural antennas and show via simulations that communication quality is improved.

II. UWB-IR SIGNALS GENERATION

To use UWB communication, it is necessary to construct a spectral mask in accordance with the laws of each country. In Japan, UWB-bands are from 3.4 to 4.8 GHz (UWB low-band) and from 7.25 to 10.25 GHz (UWB high-band). In the UWB band, EIRP is limited to being equal to or less than -41.3 dBm/MHz [6]. In our study, we focused on UWB high-band (7.25–10.25 GHz).

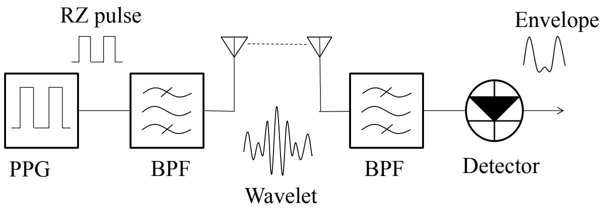

Fig. 2. The UWB-IR experimental system.

UWB-IR signals can be generated, without a microwave carrier, from short RZ pulses by passing through a BPF corresponding to a UWB spectral mask. Fig. 2 shows the experimental system used for IR generation. After passing the short RZ pulse generated from a signal generator through the BPF, the RZ pulse is converted into a wavelet-like impulse signal (wavelet). The carrier with the wavelet can be considered the central frequency (fc) of the BPF. In this method, the radio transmitter is able to configure only the BPF and the antenna. Consequently, the arrangement can be miniaturized and consumes very little power.

III. QAM UWB-IR

By using optical pulse-position modulation (PPM) with the RZ pulse signal, the IR signal that is converted from the RZ pulse signal can be treated as a phase-modulated signal. This principle can be more easily explained using the example of a sine wave signal consisting of a single frequency. Shifting the phase of such a sine wave signal is synonymous with shifting the sine wave signal in time. This principle holds with the general signal, by shifting the time position of the UWB-IR signal corresponding to the phase difference, the phase of the UWB-IR signal is changed between each bit, making it possible to perform phase modulation. Given a time delay τ as the position modulation before the RZ pulse is converted into UWB-IR, the phase of the UWB-IR signal lags $2\pi f_c \tau$. In addition, as stated above, the carrier frequency of the wavelet can be regarded as the center frequency (fc) of the BPF. When the relationship

$$f_c = \frac{n_2 R}{2} \qquad (n_2 = 1, 3, 5 \cdots) \tag{1}$$

is satisfied between the bit rate, 2R, of the RZ pulse signal and the center frequency (fc) of BPF, the time delay, τ, for which the phase difference is $\pi/2$, is given by

$$\tau = \frac{1}{f_c} \cdot \frac{n_1}{4} \qquad (n_1 = 1, 3, 5 \cdots). \tag{2}$$

In addition, when n1 = n2,

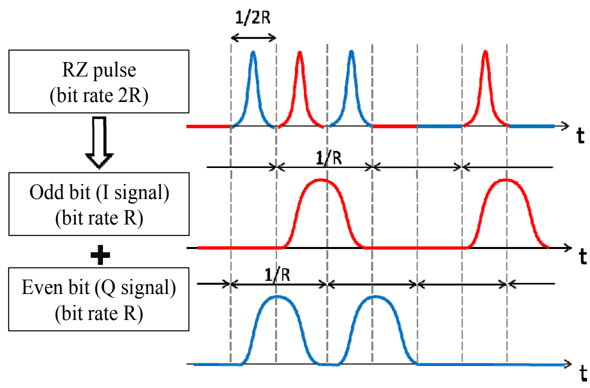

Fig. 3. Conceptual IQ components separation.

$$\tau = \frac{1}{2R} \tag{3}$$

In other words, the pulse interval of the signal (signal bit rate 2R) is $1/2R$ and is consistent with the delay time in (3). Thus, by using fc as the mixing frequency in down-conversion, the even and odd bits can be respectively separated as I signals and Q signals (Fig. 3). In this case, because the pulse time interval of each signal is twice the size it was before separation, reduction of inter-symbol interference can be achieved via separation of the IQ components.

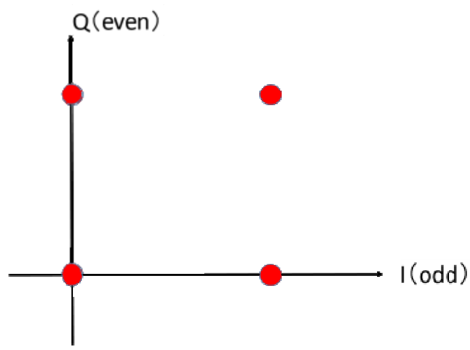

Fig. 4. QAM UWB-IR signal constellation.

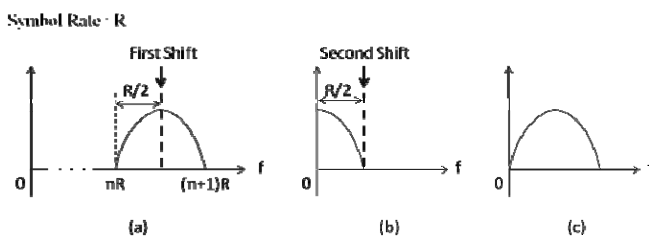

Fig..5. Two-step down-conversion pattern diagram:

As described above, the amplitude of both the I and Q signals when the RZ pulse signal is separated into I/Q components are zero or positive values (in this paper, a positive value is one). Thus, symbol constellation is not arranged in all quadrants, as is the case with QPSK. Instead, it is arranged in the first quadrant (including the I and Q axes and the origin), as illustrated in Fig. 4.

IR signal demodulation is performed in two steps, as shown in Fig. 5. In the first stage, the mixing frequency in down-conversion is frequency fc, which is a frequency separated by 1/2 of the symbol rate from the integral multiple of the symbol rate. It is possible in orthogonal separation to demodulate the original signal. In the second stage, because down-conversion at half the frequency of the symbol rate is conducted in the first stage, it is necessary to shift the frequency spectrum to baseband.

IV. 5 Gb/s QAM UWB-IR Wireless Transmission

A. Experimental Setup

We performed a wireless transmission experiment at a bit rate of 5 Gb/s, in which we separated the UWB-IR signal into IQ signals via digital signal processing. Fig. 6 shows the experimental configuration used. Optical pulses were generated in the signal transmission and reception system using a Mode-Locked Laser Diode (MLLD) to generate periodic and

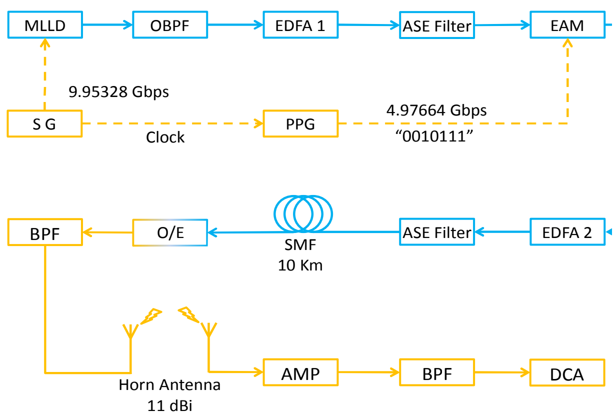

Fig. 6. Experimental configuration utilized.

regular short pulses at 9.95328 GHz. The optical short pulse train from the MLLD was inputted to the Optical Band Pass Filter (OBPF) to set an optical pulse width of 28 ps. Then, the optical pulse train was amplified using an Erbium Doped Optical Amplifier (EDFA). Amplified Spontaneous Emission (ASE) noise from the EDFA was removed using a filter. The optical pulse train was then converted to 4.97664 Gb/s RZ optical signals using an Electro-Absorption (EA) modulator. This signal was then transmitted via optical fiber. We assumed an optical fiber transmission at the access network, and used Single-Mode optical Fiber (SMF) with length 10 km. The wavelength dispersion value of the SMF used was 18 ps/nm/km, and the loss was 0.3 dBm/km.

Thus, for a transmission of 10 km, the pulse spread was 18 [ps/nm/km] × 0.08 [nm] × 10 [km] = 14.4 [ps], and a power loss of 0.3 × 10 = 3 [dB] occurred. After passing through the SMF, the optical pulse signal was amplified by EDFA 2, and

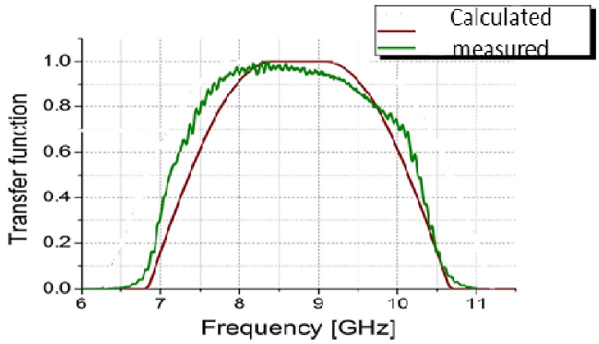

Fig. 7. Spectrum of the UWB high-band BPF

then converted into an electrical pulse signal via an Optical/Electrical (O/E) converter.

The RZ pulses were converted to a UWB-IR signal on passing through the BPF. Fig. 7 shows the spectrum, H(f), of the UWB high-band BPF fabricated for this experiment. Parallel coupled strip-line BPF was chosen to realize this wide frequency band and fabricated with Chebychev g-parameters. The UWB-IR signal was then entered into a highly directional antenna and wirelessly transmitted. The power of the signal input to the antenna, considering the antenna gain to meet the spectral mask, was -52.9 dBm/MHz. The transmitted signal was received using the same kind of antenna as the one used to transmit the signal and amplified using a broadband inverting amplifier at a band of 40 GHz and with a gain of 25 dB. Then, in order to remove noise outside the band, the signal was passed through a BPF with a 0.25 GHz wide-pass band at both the high and low frequency sides. This signal was then passed to a Digital Communication Analyzer (DCA), from which a time waveform of the received UWB signal was obtained.

Fig. 8 shows the digital processing system used. We performed detection processing on the time waveform of the received UWB signal with the simulation software Optisystem. A bit sequence of 256 bit at a sample rate of 256 samples/bit was used in the simulation. The detection was carried out on the envelope of the received signal using two-step down-conversion. First, the digital data obtained in the experiments were divided into two branches, which were then multiplied by a sine wave with a frequency of 8.70912 GHz to give a frequency shift in the first stage and by a sine wave with a frequency of 1.24416 GHz in the second stage. In addition, the sine wave that was shifted in phase by $\pi/2$ was multiplied by one side signal. Finally, after passing the detected signal type rectangular LPF with cutoff frequency 2.5 GHz, the Q

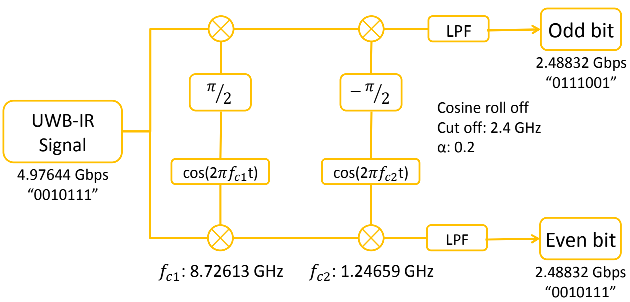

Fig. 8. Digital processing down-conversion system block diagram.

factor was calculated from the eye pattern made from the signal obtained. In addition, a signal constellation was made.

B. *Experimental Results*

The signal waveform obtained in the experiment was separated into even bit and odd bit signal data strings at 5 Gb/s by the digital signal processing system. Fig. 9 shows the eye patterns made from the detected signal. The Q factors that wirelessly transmitted it a distance of 1.5 m were respectively 4.4 and 4.3. In this way, the RZ pulse signal at a transmission rate of 5 Gb/s was converted into a UWB-IR signal, separated into even and odd bits after radio transmission, and received with a Q factor > 3.

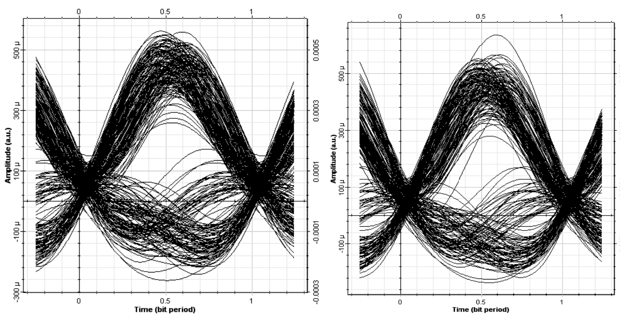

Fig. 9. Odd and even bit eye patterns: (left: even bit (Q = 4.4), right: odd bit (Q = 4.3)).

V. 5 GB/S QAM UWB-IR MISO

A. *MISO Transmission*

MISO transmission gives an improvement in the received SNR resulting from the in-phase component effect of the radio signal at the receiver. In-phase synthesis is realized by signal processing at the transmission array antennas or the receiver array antennas. Because noise immunity is improved by the array gain, the coverage and the service of the wireless network are expanded. If the overlapping transmissions are performed in the deflection transmission path when the channel response is equal, the in-phase components of the same transmission signals are automatically combined at the receiving antenna. Given x(t) as the transmitted signal, y(t) as the received signal, and z(t) as additive white Gaussian noise (AWGN), the received signal is given by

$$y(t) = x(t)/\sqrt{2} + x(t)/\sqrt{2} + z(t) = \sqrt{2}x(t) + z(t) \quad (4)$$

The SNR of the received signal is improved to two times that of SISO.

B. *Simulation*

We investigated QAM UWB-IR transmissions using MISO with one, two, and four antennas via simulations. Fig. 10 shows the simulation system used. In this simulation, the bit sequence was set to 128 bits and the sample rate to 128 samples/bit. First, an RZ pulse signal at bit rate 4.97664 Gb/s was passed through a BPF with center frequency 8.75 GHz, bandwidth 3 GHz, and roll off factor 0.7. This signal was then separated, MISO transmission performed, and AWGN added in wireless links. Then, the signal noise was removed by passing it through a BPF with the same properties as that used in the making of wavelets.

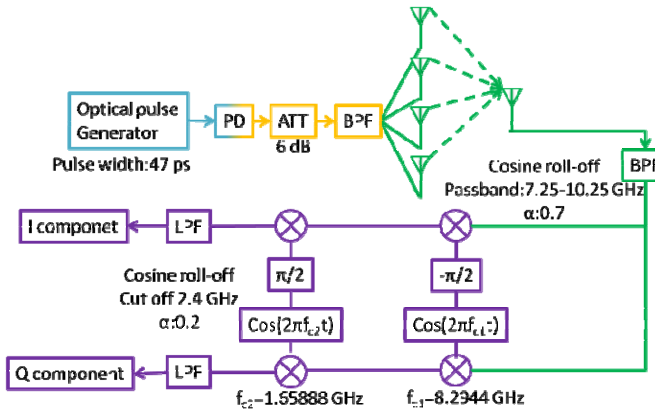

Fig. 10. QAM UWB-IR MISO simulation model.

The signal was then multiplied by a sine wave with a frequency of 8.70912 GHz to produce a frequency shift in the first stage and by a sine wave with a frequency of 1.24416 GHz in the second stage. Finally, the two-step down-converted signal was passed through an LPF (bandwidth: 2.4 GHz, roll off factor: 0.2), and the Q factor of the signals was obtained from an eye pattern made from the obtained signal. In addition, because for comparison with SISO, it was necessary to have the same total power, and the total transmission power of the antennas was set to -41.518 dBm.

Fig. 11 shows the simulation results obtained. The relationships between the Q factor of the MISO transmitted QAM UWB-IR signals and SNR were calculated as a function of antenna numbers; 1×1, 1×2, and 1×4. From the results, it is clear that the Q factor improved as the number of antennas increased. This is because the signal voltage increased with number of antennas in MISO transmission, and the SNR of the signals improved. This shows that MISO transmission of QAM UWB-IR signals can increase the transmission distance of wireless links.

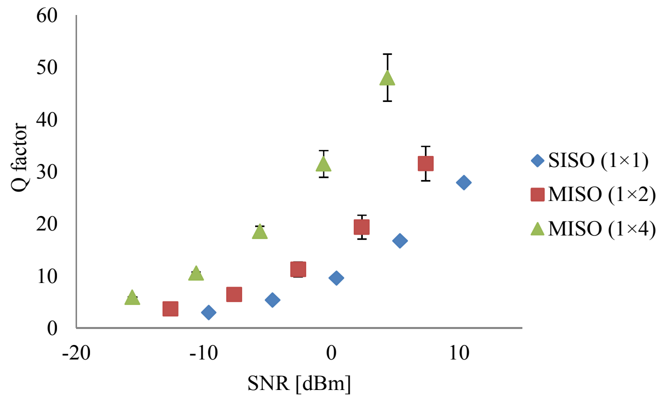

Fig. 11. Q factors versus SNR as a function of antenna number.

VI. Conclusion

We confirmed a 5 Gb/s QAM UWB-IR with a 3 GHz bandwidth experimentally. By using optical pulse-position modulation, an OOK UWB-IR signal can be viewed as a phase-modulated signal and each even and odd bit can be respectively separated as I and Q signals. To prove this theory, we performed a wireless transmission experiment and examined the feasibility of QAM UWB-IR. Consequently, we obtained a Q factor > 3 for a 5 Gb/s QAM UWB-IR signal transmitted over a radio transmission distance of 1.5 m following 10 km optical fiber transmission.

In addition, we demonstrated that the communication quality of QAM UWB-IR is improved when MISO transmission is utilized with plural antennas. Further, the results of our investigation via simulations showed that the Q factor of a 5 Gb/s QAM UWB-IR improved as the number of antennas increased. This shows that MISO transmission of QAM UWB-IR signals can increase the transmission distance of wireless links.

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