Experimental Study on Sub-Terahertz Wideband Single-Carrier Transmitter with Pre-equalizing Frequency Response

Atsushi Fukuda¹, Hiroto Yamamoto‡, Junya Matsudaira³, Sumire Aoki⁴, and Yasunori Suzuki⁵

SUMMARY This paper proposes a novel configuration for a wideband single-carrier transmitter using a sub-terahertz frequency. For wideband single-carrier transmission over a bandwidth of several gigahertz, the frequency response non-flatness derived from transmitter components in an operating band seriously deteriorates the transmission quality due to inter-symbol interference. A promising approach to address this problem is equalizing the frequency response non-flatness at the transmitter. The proposed novel configuration has a feedback route for calculating the inverse frequency response and multiplying it with a transmission signal spectrum in the frequency domain. Moreover, we verify that employing the proposed transmitter configuration simplifies the receiver configuration by lowering the calculation complexity to minimize the inter-symbol interference to meet the signal-to-interference-and-noise ratio requirements. To confirm the feasibility of the proposed configuration, the transmission quality obtained using the proposed configuration is measured and evaluated. Experimental results confirm that the proposed configuration improves the error vector magnitude value to over 5 dB for a 10 Gbaud transmission and the transmission data rate of 25 Gbps.

key words: sub-THz, single-carrier transmission, wideband transmission, pre-equalization.

1. Introduction

Recently, research and development has been conducted around the world on the 6th generation mobile communications system (6G) [1-11]. One 6G requirement is extremely high data rate communications over 100 Gbps [12]. Increasing the number of multi-input and multi-output branches, N, is one approach to achieve high data rate communications [13]. Although the data rate increases in proportion to N, so far it seems that an extremely large N is required to meet the 6G data rate requirement for bandwidths used by the mobile communications systems. On the other hand, according to Shannon’s channel capacity equation, since the data rate can be increased in proportion to the bandwidth (BW) of a transmission signal [14-15], a BW over several gigahertz is considered to meet the 6G capacity requirement [12]. Therefore, sub-terahertz (sub-THz) bands with the center frequency of below 300 GHz are candidates for 6G to assign such a huge BW [16-17].

There are several challenges in utilizing the sub-THz bands. Since the transmission signals to meet the high data rate requirement for 6G are assumed to have high index modulation schemes, the required signal-to-noise ratio (SNR) becomes high for a high-quality transmission. However, currently available sub-THz power amplifiers (PAs) have a lower output power level and power efficiency than those for lower frequency bands [18-22]. It is considered that the required PA output backoff for single-carrier transmission is lower than that for multi-carrier transmission [23]. Therefore, single-carrier transmission is considered to be a candidate transmission scheme for the sub-THz bands because the PA can operate with higher output power level and power efficiency.

A basic transmitter (Tx) is configured with a baseband (BB) part, an intermediate frequency part, and a radio frequency (RF) part. Then, each part comprises cascade connected devices with its own frequency response due to dedicated circuit design schemes and parasitic elements depending on the design frequencies. The frequency response flatness of each Tx component can be designed and achieved individually in conventional narrowband operation. However, it is more difficult to achieve flatness of the total frequency response of the Tx by flattening each of the Tx components in a huge BW over several gigahertz. That is why circuit design schemes with frequency response flatness in the sub-THz bands have not yet been well-established.

The frequency response non-flatness in the BW causes inter-symbol interference (ISI) resulting in serious degradation in the single-carrier transmission quality [24]. Generally, to avoid ISI degradation, employing an equalizer in the receiver (Rx) is a common approach. The equalizer minimizes the ISI caused by frequency selective fading generated in the propagation channel. However, equalizing the ISI caused by not only heavier frequency selective fading in a wider band but also the frequency response non-flatness in the Tx leads to an increase in the required calculation load in the Rx. Then, the increase in the calculation load for the signal with a huge BW results in high power consumption in the Rx. Especially for battery driven mobile terminals, a low power consumption equalizer is necessary for high data rate transmission in the downlink. In order to address these issues, a pre-equalization technique that equalizes the ISI caused by the Tx frequency response non-flatness in the huge BW transmission system must be developed. To the best of our knowledge, a wideband single-carrier Tx with a configuration that achieves frequency response flatness has not yet been proposed [25-31].

We propose a wideband single-carrier Tx configuration that
implements a functionality for minimizing the ISI caused by the non-flat frequency response resulting from the transmission devices. Based on eye-diagram experimental results, the proposed configuration with a feedback route that multiplies the inverse frequency response to the transmission signal in the frequency domain minimizes the ISI [32]. In this paper, a novel wideband single-carrier transmission system that comprises the proposed Tx with pre-equalization and the conventional Rx with equalization for the propagation channel is proposed. The proposed configuration can compensate for the total frequency response non-flatness of the Tx based on the frequency characteristics of sub-THz components with desired wideband design difficulties using digital assisted techniques. This is the first experimental study to verify that a pre-equalization technique is applicable to minimize the ISI caused by the non-flat frequency response of the systems for wideband single-carrier transmission.

In Section 2, details regarding the proposed Tx configuration are given and the principles on pre-equalization are described. In addition, the transmission quality degradation caused by amplitude deviation is evaluated through experiments using wideband single-carrier transmissions. In Section 3, the effects of pre-equalization on the wideband transmission quality are verified experimentally using actual sub-THz transmission systems transmitting signals with the maximum BW of 14 GHz. According to the evaluation results regarding the improvement in the signal quality, they show that the novel Tx configuration with pre-equalization is applicable to communication systems transmitting ultra-wideband single-carrier transmission while requiring low complexity.

2. Proposed Tx Configuration

A sub-THz transmission system is required to operate in a huge BW over several gigahertz in order to achieve the high data rates expected for the 6G era. Txs and Rxs, however, have their own frequency responses in the operation band due to implemented devices such as filters, amplifiers, frequency converters, and so on. The proposed pre-equalization Tx is equipped with a function that compensates for the spectrum non-flatness of the single-carrier transmission signal with a huge BW caused by the total frequency response of the Tx. Signal flows to produce the original transmission signal in the Tx are shown in Figs. 1.

![Fig. 1 Signal flows to produce transmission signals, (a) Conventional Tx without pre-equalization and (b) Proposed Tx with pre-equalization.](image)

Figure 1(a) shows the signal flow of a conventional Tx without pre-equalization. The transfer function of the Tx, $H_{\text{tx}}(f)$, is applied to an original transmission signal spectrum, $X(f)$, in the frequency domain. Then, the output signal from the Tx becomes $H_{\text{tx}}(f)X(f)$. For a conventional narrowband transmission, since $H_{\text{tx}}(f)$ is considered constant in the operation band, no pre-equalization is required.

For single-carrier transmission schemes, the frequency response non-flatness generates ISI and leads to more serious degradation in the signal quality for a digitally modulated signal. Specially for signal transmission with a huge BW, $H_{\text{tx}}(f)$ is considered to fluctuate in the operation band which deteriorates the signal quality. Therefore, pre-equalization is applied to the original signal. Figure 1(b) shows the proposed Tx with pre-equalization. The pre-equalization scheme generates a modified signal, $H_{\text{tx}}^{-1}(f)X(f)$. Here, $H_{\text{tx}}^{-1}(f)$ is the inverse transfer function of $H_{\text{tx}}(f)$. Since the modified signal incurs the effect of $H_{\text{tx}}(f)$ in the Tx, the transmission signal output from the Tx becomes $X(f)$, which is the original transmission signal.

Signal flows to transmit the original transmission signal between the Tx and the Rx are shown in Figs. 2. Generally, an equalizer in the Rx has been used to compensate for the ISI generated by the frequency response in the propagation channel such as frequency selective fading. Moreover, it is possible to equalize the frequency characteristics of the implemented devices in the Rx. Figure 2(a) shows the signal flow of a conventional transmission system without pre-equalization. Here, the total transfer function of the propagation channel, $H_\text{ch}(f)$, and the Rx, $H_\text{rx}(f)$ is indicated as $H(f)$. The $H_{\text{tx}}(f)$ and $H(f)$ are applied to $X(f)$ in the frequency domain. Therefore, the equalizer in the Rx applies the inverse function of $H_\text{tx}(f)$ and $H(f)$, $H^{-1}(f)H_\text{tx}^{-1}(f)$, to the input signal and produces $X(f)$ as the received signal, $Y(f)$.

![Fig. 2 Signal flows to transmit signal with equalizer in Rx, (a) Conventional Tx without pre-equalization and (b) Proposed configuration with pre-equalization.](image)
Figure 3 shows measured frequency characteristics for a small signal gain of a commercially available D-band amplifier as one example that causes the frequency response non-flatness. According to Fig. 3, the gain decreases gradually as the frequency increases. For example, when the transmission signal has a BW of 1 GHz at the center frequency of 150 GHz, the gain deviation is 0.2 dB. However, the gain deviation is 1.4 dB for the BW of 10 GHz and becomes larger than that for 1 GHz. The difference in the amplifier gain results in frequency response non-flatness in the operation band.

\[
G(f) = S(f)10^{\frac{a_1(fT)+a_2(fT)^2+\cdots}{20}} \quad (1)
\]

where \(a_n\) is the \(n\)-th order amplitude deviation in the operation BW expressed in decibels and \(T\) is the clock period. The degradation in the signal quality due to the first-order amplitude deviation is investigated experimentally. Figure 4 shows the employed experimental system configuration for the amplitude deviations. An arbitrary waveform generator (AWG) generates a single-carrier signal and then amplitude deviations are applied to the signal. After amplitude deviation occurs, error vector magnitude with root mean square (EVM_{\text{RMS}}) values are calculated from the deviated signals in the analyzer. Here, EVM_{\text{RMS}} is defined as

\[
EVM_{\text{RMS}} = \frac{1}{M} \sum_{i=1}^{M} |S_{\text{ideal}_i} - S_{\text{meas}_i}|^2 \quad (2)
\]

where \(i\) and \(N\) denote the symbol index and number of symbols, respectively. Term \(M\) denotes the number of constellation points. Terms \(S_{\text{ideal}}\) and \(S_{\text{meas}}\) denote the locations of the ideal signal points and measured signal point, respectively.

As shown in Fig. 5, the original signal spectrum, which a carrier signal is modulated using the 64QAM modulation scheme by the transmission data, has amplitude flatness in the signal BW. However, the signal spectrum after the amplitude deviates has amplitude non-flatness. The signal quality degradation due to the amplitude deviation is investigated experimentally. Table 1 gives the investigation parameters. Test single-carrier transmission signals are modulated with 64QAM for data segments and QPSK for header segments. The header segments are employed for synchronization at an analyzer. The baud rates are 2 GHz, 4 GHz, 6 GHz, 8 GHz, and 10 GHz. Because roll-off factor \(\alpha\) is fixed at 0.4, the actual signal bandwidths, BWs, are 2.8 GHz, 5.6 GHz, 8.4 GHz, 11.2 GHz, and 14.0 GHz, respectively, which are calculated using the equation below.

\[
BW = \text{Baud rate} \times (1 + \alpha) \quad (3)
\]

The first order amplitude deviation models which monotonically decrease with amplitude frequency characteristics of 0 dB/GHz, 0.2 dB/GHz, 0.4 dB/GHz, 0.6 dB/GHz, 0.8 dB/GHz, and 1.0 dB/GHz are employed for the simplest investigation. The center frequency of the test signal is 10 GHz.
Table 1: Experimental parameters for analyzing signal quality degradation due to amplitude deviation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2, 4, 6, 8, 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baud rate (Gbaud)</td>
<td>2.4</td>
</tr>
<tr>
<td>Roll-off factor</td>
<td>0.4</td>
</tr>
<tr>
<td>Bandwidth (GHz)</td>
<td>2.8, 5.6, 8.4, 11.2, 14.0</td>
</tr>
<tr>
<td>Header segments</td>
<td></td>
</tr>
<tr>
<td>Symbol length</td>
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</tr>
<tr>
<td>Modulation scheme</td>
<td>QPSK</td>
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<tr>
<td>Data segments</td>
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<td>1958</td>
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<tr>
<td>Modulation scheme</td>
<td>64QAM</td>
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<tr>
<td>Carrier frequency (GHz)</td>
<td>10</td>
</tr>
<tr>
<td>Amplitude deviation (dB/GHz)</td>
<td>0.0, 0.2, 0.4, 0.6, 0.8, 1.0</td>
</tr>
</tbody>
</table>

Figure 6 plots the measured $EVM_{RMS}$ values at each amplitude deviation. These results confirm that $EVM_{RMS}$ deteriorates as the amplitude deviation increases, and the wider the signal BW becomes, the more severe the degradation. For the amplitude deviation of 0.8 and 1 dB/GHz for 10 Gbaud and that of 1 dB/GHz for 8 Gbaud, it is impossible to transmit any signal in the data segments due to synchronization failure caused by severe bit error of the signals in the header segments. Therefore, the spectrum non-flatness caused by the frequency response of the devices in the Tx must be compensated for single-carrier transmissions with a huge BW. The frequency response comprises the amplitude and phase characteristics. Needless to say, not only the amplitude frequency characteristics but also the phase frequency characteristics must be considered for equalization. The effect of considering both amplitude and phase characteristics in calculating the inverse frequency response are verified in [32]. Both the amplitude and phase characteristics should be corrected to obtain sufficient improvement.

![Graph](image1)

**Fig. 6** Measured $EVM_{RMS}$ corresponding to amplitude deviation against signal baud rates.

3. Single-carrier transmission experiments

3.1 Single-carrier transmission with pre-equalization

To confirm the feasibility of the proposed configuration, an experimental single-carrier transmission system including a Tx with the pre-equalizer and Rx without any equalizers is constructed as shown in Figs. 7. Table 2 gives the experimental parameters. The AWG generates a modified transmission signal for pre-equalization using the output signal of the Tx with frequency response non-flatness, $H_{in}(f)$. Figure 8 shows a block diagram of the AWG in the proposed Tx. In the AWG, $H_{in^{-1}}(f)$ is calculated from the feedback signal including a feature of $H_{in}(f)$ using a zero-forcing algorithm. Because the pre-equalization is processed in the frequency domain, the functions of the fast Fourier transform (FFT) and inverse FFT (IFFT) are included in the AWG. In this trial, time variance of the frequency response is not considered. Here, to evaluate the effects of pre-equalization for the Tx frequency response non-flatness, the frequency response of the Rx is calibrated before experiments.

The center frequency of the modified signal is 10 GHz with BWs corresponding to baud rates of 2 GHz, 4 GHz, 6 GHz, 8 GHz, and 10 GHz. Then the frequency of the modified signal is converted to 141.5 GHz by an up-converter with a local oscillator in Fig. 7. The subsequent filter constrains unwanted emissions such as harmonics. After amplification by a PA, the original transmission signal is transmitted from an antenna because of pre-equalization using the feedback signal from the filtered output of the PA. The transmission signals have the roll-off factor, $a$, of 0.4, and the modulation schemes are 64QAM.

![Diagram](image2)

**Fig. 7** Block diagram of experimental single-carrier transmission system.

Table 2: Experimental parameters.

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<tr>
<td>Header segments</td>
<td></td>
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<td>Symbol length</td>
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<tr>
<td>Modulation scheme</td>
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</tr>
<tr>
<td>Carrier frequency (GHz)</td>
<td>141.5</td>
</tr>
</tbody>
</table>

![Diagram](image3)

**Fig. 8** Functional blocks in AWG for proposed transmitter.
Figure 9 shows a picture of the experiment system. There is a distance of 3 m between the Tx and Rx. Standard gain horn antennas are employed on both sides of the Tx and Rx. As shown in Fig. 9, the trial is conducted in a line-of-sight environment in an electromagnetically shielded room.

Figure 10 shows an example of the transmission signal spectra from the Tx antenna with or without Tx pre-equalization. The spectrum after pre-equalization becomes approximately 3 dB flatter than that without pre-equalization. We confirm that the flatness of the spectrum is improved after pre-equalization in the Tx.

Figure 11 shows measured $EVM_{RMS}$ values for single-carrier (64QAM) transmission with or without pre-equalization in the Tx. According to Fig. 11, the $EVM_{RMS}$ values for the transmission with pre-equalization exceed those without pre-equalization by more than 5 dB. Specially, the pre-equalization yields greater improvement at the baud rate of 8 Gbaud and 10 Gbaud due to a flatter spectrum as shown in Fig. 10.

\[
T = \text{Baud rate} \times \log_2 M \times (1 - \text{BER}) \quad (4)
\]

In this experiment, no error correction code is used. According to Fig. 10, the throughput is improved by pre-equalization and 10-Gbaud transmission improves the throughput by approximately 25 Gbps.

Figure 12 shows the measured throughput values for single-carrier (64QAM) transmission with or without Tx pre-equalization.

3.2 Combining single-carrier transmission with pre-equalization and Rx with equalizer

In the previous section, the effects of pre-equalizing the frequency response non-flatness of the Tx are verified and confirmed. However, the pre-equalization does not equalize the frequency responses of the propagation channel and the Rx. In this section, the effect of pre-equalization in the Tx is verified when a conventional equalizer is also employed in the Rx. The Rx with the equalizer is constructed as shown in Fig. 14. Here, the total frequency response non-flatness of the propagation channel and the Rx is compensated for by the equalizer using the least mean square algorithm.
Figure 14 Block diagram of Rx configuration with equalizer.

Figure 15 shows measured $EVM_{RMS}$ values for single-carrier (64QAM) transmission with the equalizer in the Rx. The equalizer comprises a tapped delay line (TDL) and outputs a weighted sum of the values in the delay line. In this measurement, the TDL length for the equalizer in the Rx is 11 taps. According to Fig. 15, for 2 Gbaud and 4 Gbaud transmission signals, pre-equalization provides little $EVM_{RMS}$ improvement resulting from ISI equalization in the Rx. However, the proposed configuration yields improved $EVM_{RMS}$ values for transmission signals above 6 Gbaud. This is why the equalizer in the Rx with the 11 TDL is unable to equalize sufficiently the total frequency response non-flatness of the Tx, propagation channel, and Rx.

Figure 16 shows the measured $EVM_{RMS}$ values for single-carrier (64QAM) transmission using the equalizer with a 21 TDL in the Rx. If a sufficient number of taps can be provided in the equalizer in the Rx, the $EVM_{RMS}$ values improve at high baud rates such as 8 GHz and 10 GHz.

Figure 17 shows the measured $EVM_{RMS}$ values for single-carrier (64QAM) transmission with the baud rate of 10 GHz using the equalizer with the TDL in the Rx. The $EVM_{RMS}$ values are plotted at each tap. In Fig. 17, 0 tap indicates the case where no equalization is performed. When the delay line length of the equalizer in the Rx is shorter than 21 taps, the pre-equalization scheme that compensates for the frequency response of the Tx is effective in improving the $EVM_{RMS}$ values.

In other words, even if the length of the TDL is short, $EVM_{RMS}$ degradation can be suppressed by pre-equalization in the Tx as shown in Fig. 17. The more taps that are equipped in the equalizer, the higher the computational complexity level becomes. If the degradation due to frequency response non-flatness of the Tx is compensated for in the Tx, the equalizer in the Rx is designed to compensate for only the frequency response of the propagation channel and Rx. The required calculation load for the equalizer is proportional to the cube of the filter length. For example, according to Fig. 17, the $EVM_{RMS}$ value of $-20$ dB can be achieved at least 9 taps and 21 taps with and without pre-equalization, respectively. Therefore, since the proposed pre-equalization can make the calculation load approximately one-tenth, it is expected to reduce the power consumption corresponding to the reduction in the calculation load. Moreover, although the frequency response non-flatness depends on the Tx configuration, the pre-equalization in the Tx enables to design the Rx regardless of the Tx configuration for the transmission using the huge BW.

4. Conclusion

In this paper, a novel Tx configuration for an ultra-wideband transmission using a sub-THz frequency was proposed. The Tx employs a pre-equalization technique that compensates for the frequency response caused by implemented components in the operation band. To verify the feasibility of the proposed configuration, a single-carrier transmission system is configured and tested. Compared to a conventional Tx without pre-equalization, it is verified that the proposed Tx improves the error vector magnitude for single-carrier transmission with an ultra-wideband over 10 GHz regardless of whether or not there is an equalizer in the Rx. The proposed configuration can meet the demand of future ultra-wideband transmission systems for 6G.
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References