Development of 1-bit Digital Radio-Frequency Transmitter

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In wireless communication, there has been a growing demand for high-speed and high-quality data transmission, particularly since the advent of smartphones. To meet these requirements, multiple-input and multiple-output (MIMO) technology and array antenna systems have been developed. Meanwhile, wireless systems are increasingly being integrated for improved communication performance. To this end, we have developed a 1-bit digital radio frequency (DRF) transmitter using a bandpass delta sigma modulator. This modulator directly transmits wireless signals without an RF circuit, and is therefore expected to reduce the size and power consumption of transmitters according to Moore's Law. Our prototype 1-bit DRF transmitter achieved a high adjacent channel leakage ratio of about 60 dB.

Keywords: digital radio frequency, bandpass, delta sigma

1. Introduction

1-1 Development background

To cope with the recent rapid increase in communication traffic, various measures are being implemented for communication systems such as distributing traffic pathways using wireless LANs or other systems and increasing transmission capacity by introducing multiple-input/multiple-output (MIMO) technology or array antenna systems. The appearance of smartphones has accelerated the increase in communication traffic, pressing radio communication systems to further increase both capacity and communication speed. Reflecting the situation surrounding radio communication, the introduction of various new technologies has been studied. A typical example of these is carrier aggregation, which intelligently combines multiple radio networks in a cooperative manner. Therefore, future radio equipment is required to be further integrated and downsized while responding flexibly to the progress of various radio systems and their performance.

In response to the above technological trend in radio communication, Sumitomo Electric Industries, Ltd. has developed a 1-bit digital radio frequency (RF) signal transmitter comprising a bandpass delta-sigma modulator (BP-DSM[1,2]). Since the BP-DSM outputs radio signals generated only by a digital circuit instead of an analog circuit, development of the new digital RF transmitter benefits directly from silicon semiconductor nanofabrication. In other words, the size and power consumption of the new digital RF transmitter is expected to decrease according to Moore's Law.

Meanwhile, the common view has been that the advantages of a radio signal generated only by a digital circuit are obtained only when the radio signal has an ideal waveform (square wave). Therefore, with a time wave that changes its form so smoothly as shown in **Fig. 1**, it is difficult to achieve high wireless performance. The digital radio equipment used in wireless base stations must meet a severe requirement for adjacent channel leakage power ratio (ACLR) in order to avoid the interference with other wireless networks. The technical problem preventing practical use of digital radio equipment is its non-square signal waveform.

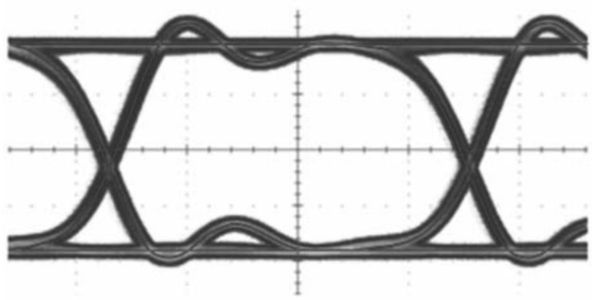

Fig. 1. Time waveform

In developing the new digital RF transmitter, we carried out quantitative analysis of the time waveform[3,4] shown in **Fig. 1** by introducing a waveform separation method[5] in order to clarify the effects of a time waveform on the ACLR performance of the transmitter. As a result, we discovered the conditions for a time waveform that ensures high ACLR performance even if the waveform contains ringing, and achieved ACLR performance close to the ideal level.

This achievement encouraged us to develop a 1-bit digital RF transmitter that could ensure high communication quality.

1-2 Features of the new 1-bit digital RF transmitter

The newly developed 1-bit digital RF transmitter performs digital signal processing without using any high frequency analog circuit and outputs radio signals directly from a digital device. Therefore, this transmitter eliminates mutual interference between circuits that has been a long-standing problem with high frequency circuits, opening prospects for further integration of the circuits in digital chips. Further, the new digital RF transmitter can be controlled by software to set the carrier frequency of the high frequency circuit to the value required for specific countries where the transmitter is used. This will enable communalization of radio transmitter components and their subsequent mass production, thereby reducing the cost of signal processors. Furthermore, the technology used for the new

RF transmitter is characterized by the capability of changing the wireless performance by changing the output data, allowing the transmitter to conform flexibly to various radio communication standards.

Figure 2 shows a conventional radio transmission scheme, while **Fig. 3** shows the transmission scheme that has been devised for the new RF transmitter. Whereas the conventional transmission scheme needs various analog circuits, the new scheme simplifies the circuit since this scheme is devised to generate a 1-bit high-speed digital data train and pass this signal through a filter to single out an intended radio signal. The radio signal sent from the antenna is identical with those used for conventional communication (in terms of communication quality, the amount of communication information, and carrier frequency), allowing the use of conventional receivers without replacing with specially designed ones.

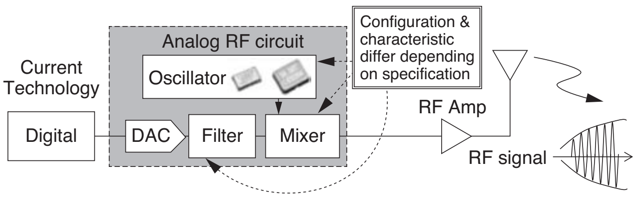

Fig. 2. Conventional radio transmitter

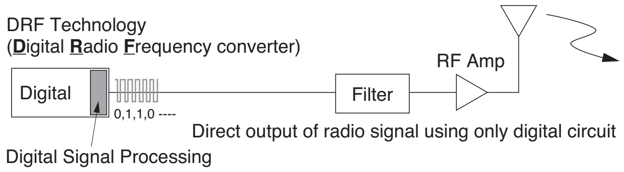

Fig. 3. 1-bit digital RF transmitter

1-3 Application of the newly developed 1-bit digital RF transmitter

The newly developed 1-bit digital RF transmitter has simple but unique features. One feature is that this transmitter can generate radio signals as digital data as shown in **Fig. 3**. Although the operating principle of the new transmitter is detailed in Section 2, this transmitter can digitize a signal independently of its output frequency.

For example, the new RF transmitter can be simplified to a radio unit that stores previously processed data in memory and retrieves them as needed. Also, the new transmitter can be used as a lightweight, compact, low-power-consumption wireless unit by additionally installing a filter suitable for outputting a desired radio signal. Since the latest memory has a large storage capacity and can read out data at a high speed of nearly 5 Gb/s, the new RF transmitter can transmit data in all frequency bands including wireless LAN frequencies by arranging the data in a 1-bit train form. The use of the latest field programmable gate array (FPGA) allows this transmitter to output data at 28 Gb/s, thereby directly reading out millimeter-wave radio signals after processing them on a real-time basis.

Furthermore, digital signals can easily be transmitted over a long distance using an optical cable, which means that the new RF transmitter can carry signals without them decaying so intensively compared with conventional coaxial cables. Therefore, the new transmitter is expected to cultivate new markets where conventional radio systems have never been used.

Another feature of the new RF transmitter is that its time waveform is square. Because of this feature, it is possible to use the new transmitter to realize a high efficiency amplifier comprising a switching amplifier.

Figure 4 shows an example of a combination of the newly developed 1-bit digital RF transmitter with an optical link. In a conventional system of this type, the baseband in-phase (I) and quadrature-phase (Q) signals are transmitted through an optical fiber and then converted to radio signals by a device installed at the destination. In contrast, the new RF transmitter converts radio signals to digital data and then transmits the data through an optical fiber. Accordingly, only a bandpass filter is necessary for the device to be installed at the destination. This reduces the size of the device and saves necessary device installation space. In addition, use of the new RF transmitter enables collective location and flexible migration of major data-processing equipment and devices at the base station having generally higher security level than the destination.

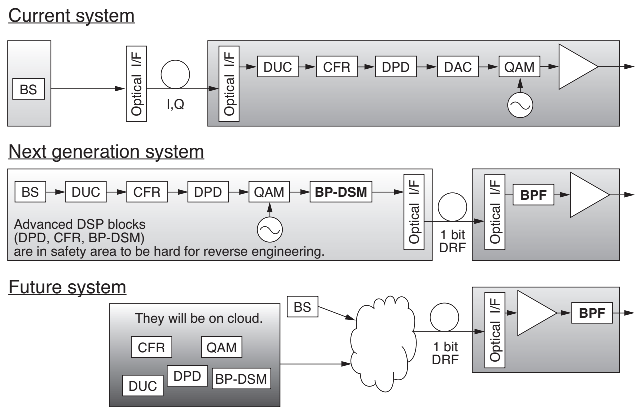

Fig. 4. Use of 1-bit digital RF transmitter with optical link

2. Overview of Technologies Used for the Development of 1-bit Digital RF Transmitter

2-1 Transmitter configuration

Figure 5 shows a block diagram of digital signal processing with the new RF transmitter. The transmitter uses baseband I and Q signals as input signals to generate a 1-bit pulse train from the pulse generator. This pulse train is then passed through a bandpass filter (BPF) to single out the desired radio signal. The baseband I and Q signals to be used as input signals are subjected to primary modulation by the quadrature- modulator. Since the new RF transmitter can be controlled by software to achieve modulation of any desired order, it can be connected to any type of wireless system. The quadrature-modulated signals are then subjected to secondary modulation by the BP-DSM for conversion to a 1-bit digital data train. The data train is then output from the pulse generator as a square-wave signal. Being an on-off signal, this signal can be processed by general digital semiconductor devices.

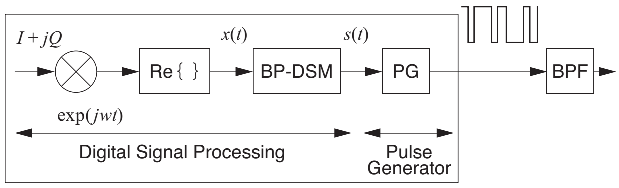

Fig. 5. Block diagram of 1-bit digital RF transmitter

Next, a detailed description of the BP-DSM used for the new RF transmitter is given below. **Figure 6** shows a block diagram of the BP-DSM. The input-output relation of the block diagram is expressed by **Equation (1)**. The second term of this equation represents the quantization error caused by digitization of the input waveform, with the input signal and output signal denoted by X and Y, respectively. **Figure 7** shows the conditions in which 1-bit digital data are generated using a modulation wave as the input signal.

Let's pay attention to **Equation (1)** and the quantization noise originating point. Then it is understood from **Fig. 6 (b)** that the quantization error Q, which is caused during digitization of the input waveform, is fed back to the input point via H. The second term in **Equation (1)** reflects the above feedback relationship, and the equation can be interpreted as follows:

The input signal X is directly transmitted as output signal Y. At the same time, the quantization error Q, which is caused during quantization (digitization), reflects the effect of the feedback and is expressed as the second term

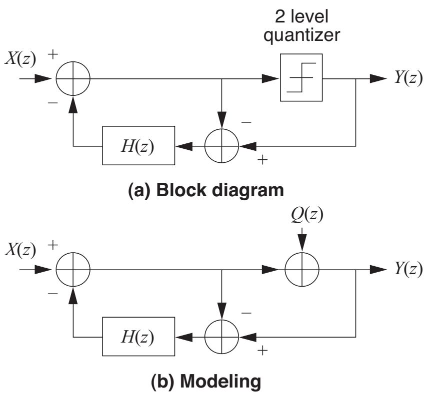

Fig. 6. Block diagram and modeling of BP-DSM

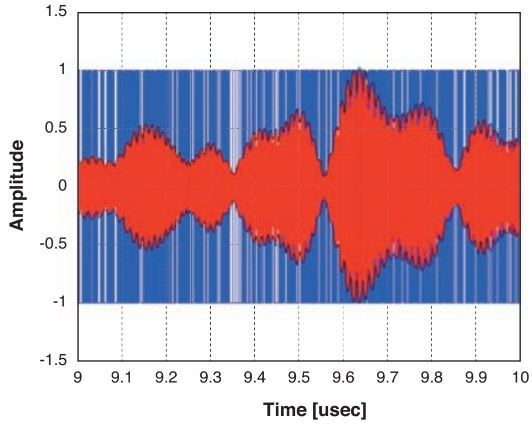

Fig. 7. Input-output waveforms of BP-DSM

in **Equation (1)**. Here, the second term includes a noise transfer function (NTF) as a coefficient of the quantization noise. This NTF can form a band-stop filter that restricts quantization noise at a desired carrier frequency. Thus a signal having a high SNR can be generated without disturbing the input signal.

$$Y(z) = X(z) + NTF(z)Q(z) \quad \cdots\cdots(1)$$

$$NTF(z) = 1 - H(z) \quad \cdots\cdots(2)$$

The quantization error suppression characteristic and computational load of the NTF do not depend on the input signal frequency but on the degree of filtering. The BP-DSM we have developed here is characterized by a constant signal processing load without reference to the carrier frequency of the radio signal that is output. Therefore, this BP-DSM can output signals of different frequencies without changing the computational complexity. Such a characteristic eliminates the requisites exerted on analog devices whose frequencies must be determined depending on the purposes of use.

Figure 8 shows an example of NTF design for an inverse-Chebyshev band-stop filter. This filter is used for signal conversion to the 1-bit data train shown in **Fig. 7**. As **Fig. 8** shows, the characteristic of this digital filter achieved an ACLR performance of 60 dB.

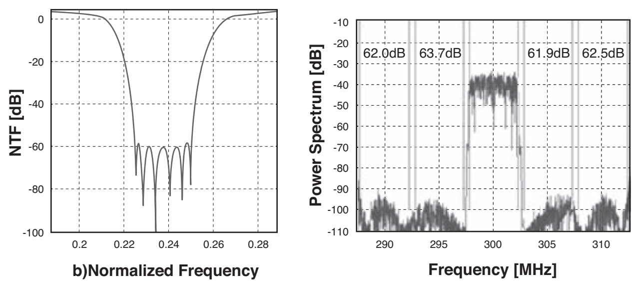

Fig. 8. Example of NTF design

2-2 Analysis of time waveform

Figure 1 shows the time waveform of a signal that was output after processing to 1-bit size using **Equation (1)**. In an ordinary wired digital communication system, data are transmitted according to the high/low level in the central part of the eye pattern.

In contrast, in the 1-bit digital RF transmission, the configuration of the entire pulse waveform is related to the analog performance, and therefore, waveforms should be managed more critically than for digital communication. Several papers published thus far report the results of approaches for refining digital waveforms to ideal square waveforms.

In the 1-bit digital RF signal transmitter development project, we analyzed the relation between the time waveform and ACLR performance. As a result, we found that ACLR performance depends largely on waveform symmetry about the time axis.

This symmetry can be understood by comparing **Fig. 1** with **Fig. 7**. Until now, every radio frequency modulator has been developed under the prerequisite of sinusoidal waves. Here, the modulated time waveforms are lower-and-upper symmetrical about the time axis, no matter how they change intensively. In contrast to the above, the time waveform shown in **Fig. 1** was basically intended for approximating a square. Therefore, no importance was placed on making the waveform lower-and-upper line-symmetrical about the time axis. Since the non-line-symmetrical component is not contained in the conventional modulation system, we consider this component to appear as a sort of distortion.

Figure 9 shows the actual measured time waveform that was output on the basis of the eye pattern shown in **Fig. 1**. Compared with **Fig. 8**, the ACLR in **Fig. 1** is substantially lower than the design target value of 60 dB. In **Fig. 9**, curve A represents the frequency spectrum recalculated by computer using the time waveform in **Fig. 1** as a base, while curve B represents the same frequency spectrum from which the asymmetrical component was removed. It is evident from these curves that the asymmetrical component is deeply related to deterioration of ACLR performance.

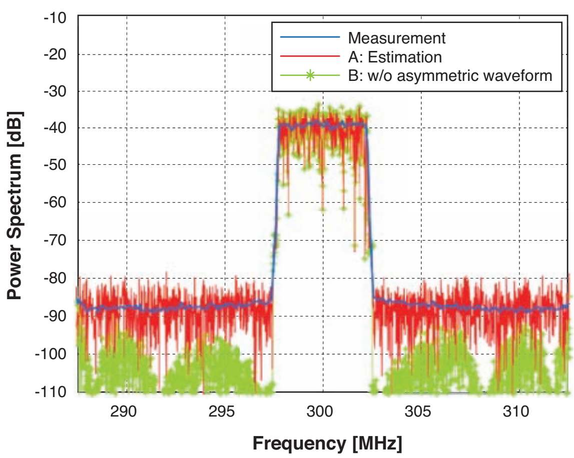

Fig. 9. Time waveform containing asymmetrical component

With an aim to clarify the general effects of an eye pattern, we also modeled it as shown in **Fig. 10**. This modeling allows various calculations using waveforms and transient times (rising and falling times) as parameters.

Regarding the exp(x) part of the time waveform, it was confirmed that the rising and falling patterns followed charge and discharge patterns, respectively. The waveform did not transition linearly but transitioned line-symmetrically about the time axis. The above waveform transition reflects the basic concept on line symmetry and non-line symmetry.

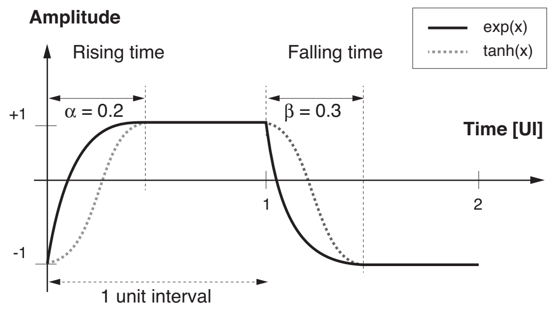

Fig. 10. Modeling of eye pattern

Table 1 shows the ACLR calculation results for different line-symmetrical and non-line symmetrical waveforms having different transition times. This table confirms that, for line-symmetrical waveforms, a high ACLR can always be obtained independently of transition time. In contrast, for non-line-symmetrical waveforms, the ACLR deteriorated remarkably but will recover its original high value if the asymmetrical component is removed. We concluded from

Table 1. Calculation results

Waveform	Setting Parameters Transition time [UI]			Result ACLR [dB]			
				Sout		Sout Removed asymmetry	
	Category	Rising time α	Falling time β	ACLR1	ACLR2	ACLR1'	ACLR2'
Ideal	Symm.	0	0	61.7	60.9		
exp (x)	Symm.	0.2	0.2	61.7	60.9		
exp (x)	Symm.	0.4	0.4	61.7	60.9		
tanh (x)	Symm.	0.2	0.2	61.7	60.9		
tanh (x)	Symm.	0.4	0.4	61.7	60.9		
exp (x)	Asymm.	0.2	0.4	44.1	44.1	61.7	60.9
exp (x)	Asymm.	0.4	0.2	43.9	44.1	61.7	60.9
tanh (x)	Asymm.	0.2	0.4	30.2	30.3	61.7	60.9
tanh (x)	Asymm.	0.4	0.2	30.2	30.3	61.7	60.9

the above results that a high ACLR can be obtained by reducing non-line-symmetrical components without reference to the transient times.

This fact shows that, as long as the time waveform necessary for a 1-bit digital RF transmission is line-symmetrical about the time axis, waveform performance does not deteriorate even if the waveform changes smoothly. In other words, eliminating the need to bring the waveform to a square will dramatically expand the range of performance improvement options. Based on the above study results, we developed a prototype of a 1-bit digital RF transmitter while placing importance on the symmetry of the time waveform.

3. Example of a Newly Developed 1-bit Digital RF Transmitter

A prototype of the circuit board for the 1-bit digital RF transmitter is shown in **Fig. 11**. This transmission circuit board outputs a 1-bit pulse train from the FPGA. Various parameters can be set through a network. In testing the circuit board, a 1-bit data string was calculated offline under the conditions shown in **Table 2** and this data string was then downloaded to the circuit board to enable the board to output the corresponding pulse train.

Using the specifications in **Table 2**, the parameters were optimized to maximize the ACLR. The signal transmission spectrum was measured as shown in **Fig. 12**.

Figure 12 confirms that the prototype circuit board achieved an ACLR performance almost close to the design level. This performance clears the criteria specified by the Third-Generation Partnership Project (3GPP) and the Radio Act, confirming that the newly developed 1-bit digital RF transmitter can be used in wireless base stations. It has been also confirmed that the new transmitter can comprise a memory.

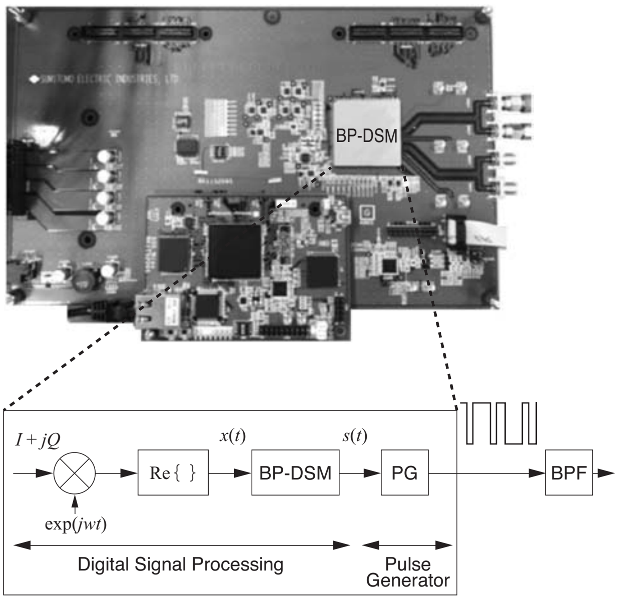

Fig. 11. Prototype of circuit board for 1-bit digital RF transmitter

Table 2. Specifications of prototype circuit board

Parameters	Value
Test signal	OFDM
Carrier frequency	1.48 GHz
Bandwidth	7 MHz
Modulation	BP-DSM CRFB*1 6 orders
Bit rate	3.9 GB/s
Oversampling rate	100
Output voltage	0.5 Vp-p
Size	160 × 260 mm

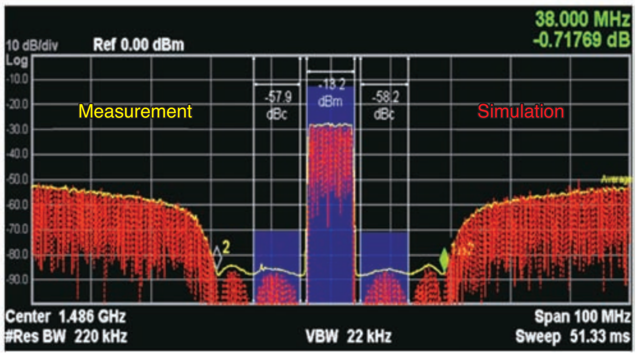

Fig. 12. Power spectrum

4. Conclusion

We have developed a 1-bit digital RF transmitter that can achieve an ACLR performance of 58 dB. This transmitter is expected to help revolutionize various analog systems. We will continue our research so that the new RF transmitter can be used widely in the market.

References

(1) R. Schreier and M. Snelgrove, "Bandpass delta-sigma modulation," Electron. Lett., Nov. 1989, vol. 25

(2) Woo-Young Kim, J. Rode, A. Scuderi, Hyuk-Su Son, Chul Soon Park and Peter. M. Asbeck, "An efficient voltage-mode class-D power amplifier for digital transmitters with delta-sigma modulation," Proceedings of the 41st European Microwave Conference, Oct. 2011

(3) Tao Shui, Richard Schreier and Forrest Hudson, "Mismatch shaping for a current-mode multibit delta-sigma DAC ," Solid-State Circuits, vol. 34, No. 3, March 1999

(4) Jeffrey O. Coleman, "The spectral products created by nonlinear intersymbol interference in NRZ data," Asilomar Conference on Signals, Systems, and Computers, Nov. 2005

(5) Takashi Maehata, Suguru Kameda and Noriharu Suematsu, "High ACLR 1-bit direct radio frequency converter using symmetric waveform," Proceedings of the 42st European Microwave Conference, Oct. 2012

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