Spatially Superposed 16-QAM System with Two Offset-QPSK Signals

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We propose a spatially superposed 16-quadrature amplitude modulation (QAM) system composed of two offset-quadrature phase-shift keying (OQPSK) signals and investigate its performance over typical nonlinear channels. The system incorporates two OQPSK modulators. Their output signals are fed to high power amplifiers (HPAs), where each OQPSK signal is separately power-amplified in a highly efficient nonlinear region of an HPA. The amplified signals are then combined in a vector-sum manner with two beams formed by spatial power-combining technology to spatially produce a 16-QAM signal. The amplitude change of OQPSK is smaller than the change of 16-QAM, and this enables the system to be operated on power amplifiers with high efficiency as compared to conventional 16-QAM or 16-amplitude and phase-shift keying (APSK) systems. Moreover, we explain here that even after the nonlinear amplification of OQPSK-modulated radio frequency (RF) signals, the frequency side-lobe levels are similar to ones of conventional 16-QAM or 16-APSK signals. Thus, we can achieve more efficient RF power amplification of 16-QAM signals without expanding the spectral occupancy. Finally, the power consumption is qualitatively discussed based on specific HPA characteristics, and its performance is compared to conventional 16-QAM and 16-APSK, with a remarkable gain shown in both power and spectral efficiency. We show that a reduction in power consumption of 50% is achievable compared to a conventional system. We found through this study that the proposed system is feasible and will enable broadband transmission with efficient use of power and bandwidth.

Nomenclature

\( a_i \) = amplitude for OQPSK-\( i \) signal

\( A_{m,k} \) = amplitude weight of the \( k^{th} \) element on the \( m^{th} \) circle of array antenna

\( B \) = required bandwidth

\( F(\varphi, \theta) \) = antenna array factor in the direction of \((\varphi, \theta)\)

\( f_c \) = center frequency

\( \kappa \) = wave number

\( K_m \) = number of elements on the \( m^{th} \) circle of array antenna

\( M \) = number of circles in combined circular array

\( OBO \) = output-back-off

\( PAPR \) = peak-to-average power ratio

\( P_{dc} \) = HPA average power consumption

\( P_{ave}(t) \) = average input power of HPA

\( \phi_{i,j} \) = phase for OQPSK-\( i \) signal (\( j=0, 1, 2, 3 \))

\( \varphi_{m,k} \) = azimuth location of the \( k^{th} \) element on the \( m^{th} \) circle of combined array antenna

\( \psi_1, \psi_2 \) = phase compensation after OQPSK-1 & -2 modulation

\( R_m \) = \( m^{th} \) element radius of circular array

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\[ \lambda = \text{wavelength} \]
\[ S_1, S_2 = \text{complex signals from OQPSK modulators, OQPSK-1& -2} \]
\[ v_{in}(t) = \text{HPA instantaneous input voltage} \]

I. Introduction

A broadband multimedia wireless communications system is a promising network access system because it can provide a broadband system over a wide area more easily and rapidly than other wired systems. Using M-ary signals would be effective for broadband transmission in a frequency-band-limited system. However, an M-ary modulation scheme is generally much more vulnerable to nonlinear distortion from power devices than the widely used quadrature phase-shift keying (QPSK) scheme \cite{1, 2}, and is hence inefficient in radio frequency (RF) power amplification.

We present a new wireless communications system featuring a novel 16-quadrature amplitude modulation (QAM) scheme that uses spatial power-combining technology instead of two amplitude-modulated carriers in quadrature.

We have already proposed a spatially superposed M-ary wireless communications system with multiple QPSK signals and an antenna system suitable for this purpose \cite{3-5}. We have shown that it enables broadband transmission with less power consumption than a conventional system under the condition of non-wave-shaping as a first approximation. We have also done a reliability study and have shown that the new system is feasible and reliable \cite{6}.

For practical use, we investigate the more precise analysis of the proposed system, taking account of wave-shaping to suppress the frequency side-lobes.

In section II, we explain the process for spatial power combining. The system incorporates two offset-QPSK (OQPSK) modulators. Their output signals are fed to power amplifiers, where each OQPSK signal is separately power amplified. The amplified signals are then combined in a vector-sum manner with two beams formed by spatial power-combining technology to spatially produce a 16-QAM signal.

In section III, we discuss the performance of superposed 16-QAM with two OQPSKs. We analyze the square-root roll-off filtered signal-level distribution of a OQPSK signal, a conventional 16-QAM signal, and a 16-APSK signal and then show that the amplitude change in OQPSK is less than that in 16-QAM or 16-APSK, enabling the proposed system to operate on power amplifiers in the nonlinear region with high efficiency. We also evaluate the bit-error-rate (BER) and spectrum performance using an assumed high power amplifier (HPA) nonlinear model that is based on the actual power amplifier characteristics and verify that nonlinear amplification of OQPSK signals does not regenerate the high frequency side-lobes and thus, spectral occupancy is significantly reduced, while permitting more efficient RF power amplification.

Finally in section IV, the power consumption is qualitatively discussed based on specific HPA characteristics, and its performance is compared to conventional 16-QAM and 16-APSK.

II. Process for spatial power combining

A conventional 16-QAM signal waveform is generated using two quadrature-balanced modulators \cite{1}.

A 16-QAM signal can also be produced using two OQPSK modulators, whose levels differ by 6 dB, in a uniform constellation, as depicted in Fig. 1. The OQPSK signals from the two OQPSK modulators have a nearly constant envelope and are less sensitive to AM-to-AM and AM-to-PM conversions generated in a nonlinear device that follows the modulators.

A. Configuration

Our system for producing a 16-QAM signal is illustrated in Fig. 2. The modulation was performed by using superposed technology instead of the conventional amplitude modulation. The system incorporates two conventional OQPSK modulators (OQPSK-1, and 2). Their signals are square-root roll-off filtered and fed to power amplifiers, where each OQPSK signal is separately power amplified. The change in amplitude of OQPSK is smaller than the change in 16-QAM, which is explained in Section III, enabling the system to operate on power amplifiers with high efficiency and allowing the strict requirements for modulation to be relaxed compared with conventional 16-QAM systems.
The serial input data stream \( (d_1, d_2, \ldots, d_4) \) was divided into two parallel data streams \( (d_1, d_2), (d_3, d_4) \). Then, a data transformation \( (d'_1, d'_2) \) was performed in front of OQPSK-2 for Gray coding. The output signals, \( S_1, S_2 \), from the OQPSK modulators are

\[
S_1 = a_i \exp(j\phi_{i,j})\exp(j\omega t) \\
S_2 = a_j \exp(j\phi_{2,j})\exp(j\omega t)
\]

where \( a_i, \phi_{i,j}, (i = 1, 2, j = 1, 2, 3, 4) \), \( \omega \) are the amplitude, phase, and carrier angular frequency for each OQPSK signal.

The two output signals, \( S_1 \) and \( S_2 \), were then combined in a vector-sum manner \( S = S_1 + S_2 \) with two beams formed by spatial superposition technology, which has no insertion losses and does not reduce the transmitted power.
Compared with a non-spatial power-combining process with RF circuits that have insertion losses and then reduce the transmitted power\cite{7}, spatial power-combining technology enables an efficient power-combining process.

B. Antenna array for spatial superposition

The smaller the errors in the power-combining process, the better the transmission performance. We developed an antenna system that is suitable for reducing the combining error of the two beams.

Our array system that produces the two beams simultaneously is illustrated in Fig. 3(a)\cite{5}. The elements for Beam #1 and Beam #2 are alternately located on multiple circles. Thus, the average locations of the elements for Beam #1 and #2 coincide, as shown in Fig. 3(b).

Because the $K_m$ elements are equally spaced around the circle’s radius, $R_m$, the array factor $F_i(\phi, \theta)$ of Beam #i for a circular array with $M$ circles is given as

$$F_i(\phi, \theta) = \sum_{m=1}^{M} \sum_{k=1}^{K_m} A_{m,ki} e^{i\left[\kappa_x \phi - k \phi_{m,ki} \cos(\phi - \phi_{m,ki}) \sin \theta \right]},$$

where $\phi$ denotes the azimuth angle, $\theta$ denotes the angle with respect to the array normal, and $A_{m,ki} e^{i\phi_{m,ki}}$ and $\phi_{m,ki}$ denote the complex weight and the azimuth location of the $k_{ih}$ element on the $m_{ih}$ circle, respectively, and $\kappa = \frac{2\pi}{\lambda}$ and $\lambda$ = wavelength.

One of the inherent characteristics of a circular array is the presence of high side-lobe levels in its beam pattern. The side-lobe levels and the gain and phase differences between the two beams depend on the number of circles, $M$, the number of elements, $K_m$, the radius, $R_m$, and the weight, $A_{m,ki}$, for the elements, and can be controlled by selecting the proper values for $M$, $K_m$, $R_m$, and $A_{m,ki}$\cite{5}.

III. Performance of superposed 16-QAM with two OQPSKs

We analyze the peak and average powers of a square-root roll-off filtered OQPSK signal and compare it with that of a conventional 16-QAM or 16-APSK signal. We also evaluate the BER and spectrum performance over a typical nonlinear channel using an assumed HPA nonlinear model that is based on the actual power amplifier characteristics.

A. Signal power distribution

The amplitude of the modulated signal fluctuates after passing through the roll-off filter. Figure 4 shows the waveforms of square-root roll-off filtered conventional 16-QAM, 16-APSK, QPSK, and OQPSK signals. The change in the 16-QAM and 16-APSK signals is larger than that of the QPSK and OQPSK signals.
Figure 5 is a comparison of their signal distributions. The OQPSK signal is concentrated in a smaller area than the other signals. The peak-to-average power (PAPR) as defined by Eq. (3) is an important factor to evaluate the signal fluctuation.

\[ PAPR = \frac{V_{in}(t)_{\text{max}}^2}{V_{in}(t)^2} \]  

Figure 5 Distribution of square-root roll-off filtered signal level of OQPSK, QPSK, 16-QAM, and 16-APSK (roll-off ratio=0.35).

We therefore analyzed the PAPR values to determine the operational point of the HPA that affects the out-of-band spectral levels as well as the HPA power consumption and obtained 6.7 dB, 5.1 dB, 4.1 dB, and 3.7 dB for square-root roll-off filtered signals of 16-QAM, 16-APSK, QPSK, and OQPSK, respectively. From the figures and the PAPR values, it is clear that the amplitude change of OQPSK is the smallest among the signals, and this makes it possible to operate the proposed system on power amplifiers with high efficiency, as compared to a conventional 16-QAM or 16-APSK system.

**B. BER performance**

We investigated the bit error rate (BER) performance of the proposed 16-QAM, conventional 16-QAM, and 16-APSK. Figure 6 plots the BER performance at the same 1.5-dB output-back-off (OBO) point of the HPA. The
proposed system shows the most superior performance among them when operated in the nonlinear high efficiency region of the HPA.

\[ \text{Proposed 16QAM} \]

\[ \text{Conventional 16QAM} \]

\[ \text{Conventional 16APSK} \]

\[ \begin{array}{c}
0 & 2 & 4 & 6 & 8 & 10 & 12 & 14 \\
1E+0 & 1E-1 & 1E-2 & 1E-3 & 1E-4 & 1E-5
\end{array} \]

\[ \text{BER} \]

\[ \text{Eb/No [dB]} \]

**Fig. 6** BER performance of proposed 16-QAM, conventional 16-QAM, and 16-APSK at 1.5dB OBO of HPA.

**C. Spectral performance**

We discuss here the spectral performance. Figure 7 shows the spectra of two spatially superposed OQPSKs and QPSKs at the 1.5-dB OBO point of the HPA. The out-of-band spurious levels of the superposed OQPSKs are well below the superposed QPSKs because of a lower PAPR.

In addition, we investigate the spectral performance of the proposed 16-QAM, a conventional 16-QAM, and 16-APSK signals at the same HPA 1.5-dB OBO point. Figure 8 shows their spectra. It is clear from the figure that the out-of-band spurious levels of the proposed 16-QAM are well below the conventional schemes when operated in the nonlinear high efficiency region of the HPA.

Figure 9 shows the spectral performance of a superposed 16-QAM signal compared with conventional 16-QAM and 16-APSK signals when the same BER of $1 \times 10^{-1}$ is attained. The operating points of the conventional 16-QAM and 16-APSK are well backed-off from the 1.5-dB OBO of the HPA to 5.1 and 5.9-dB OBO, respectively, and their backing-offs cause inefficient RF amplification.

\[ \text{OQPSK+OQPSK} \]

\[ \text{QPSK+QPSK} \]

**Fig. 7** Spectra of two (each) spatially superposed OQPSKs and QPSKs at 1.5-dB OBO of HPA.
Fig. 8 Spectra of proposed 16-QAM, conventional 16-QAM, and 16-APSK at 1.5-dB OBO of HPA.

Fig. 9 Spectra of proposed 16-QAM, conventional 16-QAM, and 16-APSK when BER is 10^{-5}.

The envelope variation of the OQPSK signal is considerably less than that of the 16-QAM, and hence, even after the nonlinear amplification of OQPSK signals, the frequency side-lobe levels are similar to the conventional ones operated in a linear region. Thus, the spectral occupancy is not degraded, while more efficient RF power amplification can be achieved.

IV. HPA power consumption

The HPA power consumption of the proposed system is qualitatively evaluated based on specific HPA characteristics, and its performance is compared to conventional 16-QAM and 16-APSK.

Figure 10 plots the assumed HPA characteristics. We evaluated the HPA power consumption, $P_{dc}$, by analyzing the average in/out power of HPA, $P_{in\,\text{avg}}(t)$, which is dependent on its instantaneous input signal level, $v_{in}(t)$, as shown below.

$$P_{in\,\text{avg}}(t) = \frac{1}{T} \int_0^T v_{in}(t)^2 \, dt$$

$$P_{dc}(t) = f\{P_{in\,\text{avg}}(t)\}$$

(4)

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Table 1 summarizes the comparison of the input signal PAPR, the required HPA output back-off (OBO) and HPA power consumption, and the spectral side-lobe level (D/U ratio) at $f=fc+1.5B$ (B: required bandwidth) when the same BER ($1 \times 10^{-2}$) is obtained under the same condition of additive white Gaussian noise (AWGN).

The table indicates that the proposed system has a remarkable gain in power consumption with similar spectral side-lobes. We can reduce the power consumption by 50% compared to a conventional system.

Table 1 Comparison of HPA power consumption when the same BER ($1 \times 10^{-2}$) is obtained.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>PAPR [dB]</th>
<th>OBO [dB]</th>
<th>Power consumption</th>
<th>D/U [dB] at $f=fc+1.5B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatially superposed OQPSK+OQPSK</td>
<td>3.7</td>
<td>1.5</td>
<td>1</td>
<td>35.0</td>
</tr>
<tr>
<td>Spatially superposed QPSK+QPSK</td>
<td>4.1</td>
<td>1.5</td>
<td>1</td>
<td>25.0</td>
</tr>
<tr>
<td>Conventional 16QAM</td>
<td>6.7</td>
<td>5.1</td>
<td>1.9</td>
<td>37.0</td>
</tr>
<tr>
<td>Conventional 16APSK</td>
<td>5.1</td>
<td>5.9</td>
<td>2.2</td>
<td>39.0</td>
</tr>
</tbody>
</table>

Fig. 10 Assumed HPA characteristics.
V. Conclusion

We presented a new wireless communications system featuring a novel 16-QAM modulation scheme that uses spatial superposition of two OQPSK beams formed by a combined circular array system. We investigated its performance over typical nonlinear channels. This unique system enables an efficient power combining of modulated signals separately power-amplified with high efficiency.

The spectral performance was also discussed. The envelope variations of OQPSK signals are considerably reduced, and hence, even after the nonlinear amplification of OQPSK-modulated RF signals, the frequency side-lobe levels are similar to ones of conventional 16-QAM or 16-APSK. Thus, we can achieve more efficient RF power amplification of 16-QAM signals without expanding the spectral occupancy.

Finally, the power consumption was qualitatively discussed based on specific HPA characteristics, and its performance was compared to conventional 16-QAM and 16-APSK, with a remarkable gain shown in both power and spectral efficiency. Specifically, we can reduce the power consumption by around 50%.

We found that our system is feasible and will enable broadband transmission with efficient use of power and bandwidth.

References


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