64-QAM Communication System using Three-beam Spatial Power Combining Technology
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A satellite communication system is presented that features a novel three-beam spatial superposition, which improves the usage efficiency of frequency resources and energy. The system incorporates three quadrature phase-shift keying (QPSK) modulators and multiple high power amplifiers (HPAs) that operate in the nonlinear region with high efficiency. Their output signals are spatially combined using a specially tailored antenna array to produce a 64-QAM (quadrature amplitude-modulated) signal.

The validity of the spatial superposition was verified experimentally, and the performance of a 64-QAM system using this scheme was investigated and analyzed. The system had better bit error rate (BER) performance than a conventional 64-QAM system when operated in the HPA nonlinear high efficiency region. Although superposition error is inherent to the system, theoretical transmission analysis showed that a gain error of 1 dB and a phase error of 10 degrees were acceptable. An antenna array system composed of three circular arrays embedded on multiple circles is presented for reducing the error due to combining the three beams. Beam pattern analysis showed that the gain and phase errors were satisfied over a +/-10 degree angle from the normal direction of the antenna array. An antenna array study demonstrated that the acceptable errors could be attained with the proposed circular array system and that this range is wide enough to cover satellite communication service areas.

Spectral performance analysis showed that the frequency side-lobe levels were similar to those of the conventional system operated in the linear region. HPA power consumption was reduced about 50% compared with that of the conventional system. Thus, more efficient RF power amplification of 64-QAM signals can be achieved without expanding the spectral occupancy.

In short, the proposed system is feasible and will enable broadband transmission with more efficient use of energy and bandwidth.

Nomenclature

\[ a_i \quad = \quad \text{amplitude of QPSK-i signal} \]
\[ A_{m,k} \quad = \quad \text{amplitude weight of } k^{\text{th}} \text{ element on } m^{\text{th}} \text{ circle of array antenna} \]
\[ F(\theta, \phi) \quad = \quad \text{antenna array factor in direction of } (\theta, \phi) \]
\[ f(\theta, \phi) \quad = \quad \text{antenna array element pattern in direction of } (\theta, \phi) \]
\[ G(\theta, \phi) \quad = \quad \text{beam pattern in direction of } (\theta, \phi) \]
\[ f_c \quad = \quad \text{center frequency} \]
\[ \kappa \quad = \quad \text{wave number} \]
\[ K_m \quad = \quad \text{number of elements on } m^{\text{th}} \text{ circle of array antenna} \]
\[ M \quad = \quad \text{number of circles in combined circular array} \]
\[ P_a \quad = \quad \text{average power consumption of HPAs} \]
\[ P_{m,\text{av}}(t) \quad = \quad \text{average input power of HPAs} \]
\[ \phi_{m,j} \quad = \quad \text{phase of QPSK-i signal } [j=1, 2, 3] \]
\[ \varphi_{m,k} \quad = \quad \text{azimuth location of } k^{\text{th}} \text{ element on } m^{\text{th}} \text{ circle of combined array antenna} \]
\[ R_m \quad = \quad m^{\text{th}} \text{ element radius of circular array} \]
\[ \lambda \quad = \quad \text{wavelength} \]
\[ S_i, S_2, S_3 \quad = \quad \text{complex signals from QPSK modulators, mod-1, -2, and -3} \]
\[ v_m(t) \quad = \quad \text{HPA instantaneous input voltage} \]

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I. Introduction

Broadband multimedia wireless communication systems are promising for network access because they provide a broadband system over a wide area more easily and rapidly than wired communication systems. If the signal frequency band of the system is limited, M-ary transmission is effective. However, the 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 and is thus inefficient for radio frequency (RF) power amplification.

We present a wireless communication system featuring a novel 64-quadrature amplitude modulation (QAM) scheme that uses spatial power combining instead of two amplitude-modulated carriers in quadrature.

Our group previously reported spatially superposed M-ary wireless communication systems with multiple QPSK signals that use two-beam power combining \([1-5]\). We showed that two-beam power combining enables broadband transmission with power consumption less than that of a conventional system. A feasibility and reliability study showed that a two-beam power combining system is feasible and reliable \([4]\). We have now developed a 64-QAM system with three-beam power combining that has better bit error rate (BER) performance and lower power consumption.

In section II, we explain the process for spatial power combining for a system incorporating three QPSK (QPSK) modulators. Their output signals are fed to power amplifiers, where each QPSK signal is separately power amplified with high efficiency. The amplified signals are then combined in a vector-sum manner with three beams formed by spatial power combining to spatially produce a 64-QAM signal.

In section III, we discuss the performance of our superposed 64-QAM system with three QPSK modulators. Analysis of the square-root roll-off filtered signal-level distribution of a QPSK signal and of a conventional 64-QAM signal showed that the amplitude change in the former is less than that in the latter, enabling the power amplifiers in the proposed system to operate in the nonlinear region with higher efficiency. Evaluation of the BER and spectrum performance using an assumed high power amplifier (HPA) nonlinear model based on actual power amplifier characteristics demonstrated that nonlinear amplification of QPSK signals does not regenerate the high frequency side-lobes, so spectral occupancy is substantially reduced, permitting more efficient RF power amplification. We also investigate the effect of gain and phase errors inherent to the system and show the allowable errors.

In section IV, we describe an antenna system suitable for power combining. We propose using a novel antenna array system composed of three circular arrays embedded on multiple circles that reduces the inherent error when combining three beams. The system was designed so that the radiator size and the layout of the elemental radiators would be suitable for practical installation. Analysis of the beam pattern and of the gain and phase differences among the three beams showed that a gain error of 1 dB and a phase error of 10 degrees are feasible over \(\pm 10\) degrees from the normal direction of the antenna.

Finally, in section V, HPA power consumption is summarized.

II. Process for spatial power combining

A conventional 64-QAM signal waveform is generated using two quadrature-balanced modulators \([6]\). A 64-QAM signal can also be produced using three QPSK modulators for which the power levels differ by 6 dB in case of a uniform constellation. The spatial combining of their output signals is depicted in Fig. 1. As mentioned above, previous experiments demonstrated the feasibility of spatial superposition with two beams \([5]\). The filtered signals from three QPSK modulators have a mild envelope, so they are less sensitive to the AM-to-AM and AM-to-PM (phase modulation) conversions generated in an HPA that follows the modulators and filters.

A. System configuration

Our proposed system for producing a 64-QAM signal is illustrated in Fig. 2. It uses superposed modulation instead of conventional amplitude modulation. The system incorporates three conventional offset-QPSK (OQPSK) modulators (mod-1, -2, and 3). Their signals are square-root roll-off filtered and fed to power amplifiers, where each signal is separately power amplified. The change in the amplitude of the filtered OQPSK signals is less than that in filtered 64-QAM signals, as explained in Section III, enabling the amplifiers to operate in the nonlinear region with higher efficiency and the strict requirements for modulation with conventional 64-QAM systems to be relaxed.
Fig. 1 Spatial superposition of HPA output signals.

Fig. 2 Configuration of proposed 64-QAM system using superposed modulation.

The serial input data stream \((d_1, d_2, \ldots, d_n)\) is divided into three parallel data streams, \((d_1, d_2, \ldots, d_n)\). Data transformation is then performed in front of the modulators for Gray coding. The signals output by the modulators are

\[
S_1 = a_1 \exp(j \phi_{1,k}) \exp(j \omega t) \\
S_2 = a_2 \exp(j \phi_{2,k}) \exp(j \omega t) \\
S_3 = a_3 \exp(j \phi_{3,k}) \exp(j \omega t)
\]

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

The three output signals are then combined in a vector-sum manner into \(S = S_1 + S_2 + S_3\) with three beams formed by spatial superposition, so there is no insertion loss or reduction in transmitted power. Compared with non-spatial power combining using RF circuitry, which results in insertion loss and reduced transmission power \(^{17}\), spatial power combining is more efficient.
III. Performance of proposed system

We analyzed the peak and average powers of a square-root roll-off filtered OQPSK signal and compared them with those of a conventional 64-QAM signal. We also evaluated the signal constellation, BER, allowable superposition errors and spectrum performances over a typical nonlinear channel by using an assumed HPA nonlinear model based on the actual power amplifier characteristics.

A. Signal power distribution

The amplitude of the modulated signal fluctuated after passing through the roll-off filter. As shown in Fig. 3, the change in the conventional 64-QAM signal waveform was larger than those in the QPSK and OQPSK signal waveforms.

![Waveform comparison](image)

*Fig. 3 Square-root roll-off filtered waveforms of conventional 64-QAM, QPSK, and OQPSK signals (roll-off ratio = 0.35).*

The peak-to-average power ratio (PAPR) was used to qualitatively evaluate the signal fluctuation.

\[
PAPR = \frac{v_{\text{in}}^2(t)}{\overline{v_{\text{in}}^2(t)}}
\]

Table 1 shows PAPR values in baseband and RF band. PAPR values of 6.4, 3.8, and 3.5 dB were respectively obtained for the square-root roll-off filtered 64-QAM, QPSK, and OQPSK signals. The lower amplitude change for the OQPSK signal enables the power amplifiers in the proposed system to operate in the nonlinear high efficiency region, which those in a conventional 64-QAM system cannot do.

<table>
<thead>
<tr>
<th>Mod</th>
<th>PAPR (baseband) [dB]</th>
<th>PAPR (RF) [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OQPSK</td>
<td>3.5</td>
<td>6.5</td>
</tr>
<tr>
<td>QPSK</td>
<td>3.8</td>
<td>6.8</td>
</tr>
<tr>
<td>64-QAM</td>
<td>6.4</td>
<td>9.4</td>
</tr>
</tbody>
</table>

B. Nonlinear effect and BER performance

We investigated the effect of operating in the nonlinear high efficiency region on the signal constellation. Figure 4 shows the signal constellations of the proposed and conventional 64-QAM systems at semi-linear (6-dB output backoff (OBO)) and nonlinear (1.5-dB OBO) HPA driving points. The proposed system clearly performed better than the conventional one at the nonlinear driving point and was not affected by the HPA nonlinear effect, enabling its power amplifiers to operate in the nonlinear region with high efficiency.
We analyzed the BER performance of the proposed and conventional 64-QAM systems. Figure 5 plots the BER for the 1.5-dB HPA OBO point. The proposed system showed better BER performance than the conventional one when operated in the HPA nonlinear high efficiency region.

Figure 6 shows the BER performance of the proposed and conventional 64-QAM systems when the proposed system operated at the 1.5-dB OBO point, and the conventional one operated at the 5.8-dB OBO point. The proposed system operated at the nonlinear region shows the similar performance to the conventional one operated at the semi-linear point.
**C. Allowable superposition error**

Superposition error is inherent to the system. We investigated the allowable gain and phase errors employing a forward error correction coding (FEC). In this study, a concatenated coding scheme composed of convolutional coding (R=1/2) and Reed-Solomon coding (R-S (208,188)) is used for correcting errors. Figure 7 shows the BER performance for the gain errors of 1 dB and 1.5 dB, and the phase errors of 10.0 degrees and 15.0 degrees at the 1.5-dB HPA OBO point. Theoretical transmission analysis showed that a gain error of 1 dB and a phase error of 10 degrees were acceptable.
D. Spectral performance

We also investigated the spectral performance of the proposed and conventional 64-QAM systems at the 1.5-dB HPA OBO point. As shown in Fig. 8, the out-of-band spurious levels with the proposed system were well below those with the conventional one when it was operated in the HPA nonlinear high efficiency region.

Figure 9 shows their spectral performance when both attained the same BER of $1 \times 10^{-2}$. The operating point of the conventional system was well backed-off from the 1.5-dB HPA OBO point (to 5.8-dB OBO), resulting in inefficient RF amplification.

The envelope variation of the OQPSK signal is considerably less than that of the conventional 64-QAM signal, so even after the nonlinear amplification of the OQPSK signal, its frequency side-lobe levels are similar to those of a conventional system operating in the linear region. As a result, more efficient RF power amplification is achieved without expanding spectral occupancy.
IV. Antenna array for spatial superposition

As mentioned in the Introduction, we propose using an antenna array system composed of three circular arrays embedded on multiple circles to reduce the error inherent in combining three beams.

The array system produces the three beams simultaneously, as illustrated in Fig. 10(a). The elements for the three beams are alternately located on multiple circles. As a result, the average locations of the elements coincide, as shown in Fig. 10(b).

The beam pattern of an array is the product of element pattern $f_i(\theta, \phi)$ and array factor $F_i(\phi, \theta)$:

$$G_i(\theta, \phi) = f_i(\theta, \phi) \cdot F_i(\phi, \theta),$$

where $\phi$ denotes the azimuth angle, and $\theta$ denotes the angle with respect to the array normal.

If the antenna elements are all the same, the gain and phase differences among the beams depend on only the array factors.

Because the $K_m$ elements are equally spaced around the circle’s radius, $R_m$, the array factor of Beam-$i$ for a circular array with $M$ circles is given as

$$F_i(\theta, \phi) = \sum_{m=1}^{M} \sum_{k=1}^{K_m} A_{m,ki} \exp(j[\alpha_{m,ki} - \kappa R_m \cos(\phi - \phi_{m,ki}) \sin \theta]),$$

where $A_{m,ki} \exp(j\alpha_{m,ki})$ and $\phi_{m,ki}$ respectively denote the complex weight and azimuth location of the $k_{m,ki}^{th}$ element on the $m^{th}$ circle, $\kappa = 2\pi/\lambda$, and $\lambda$ is the wavelength.

The gain and phase differences among the three 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, so the differences can be controlled by selecting appropriate values for $M$, $K_m$, $R_m$, and $A_{m,ki}$.

![Diagram of circular array system and average locations of beam elements antenna coincide](image)

Fig. 10 Configuration of combined circular array system that produces three beams simultaneously.

The distance between adjacent radiators was designed to be $0.75\lambda$ so that the system would be suitable for practical installation.

Figure 11 shows the gain and phase patterns of array factor $F_i(\phi, \theta)$ for each beam. The gain and phase differences among the three beams are shown in Fig. 12. These results show that a gain error of 1 dB and a phase error of 10 degrees are feasible over a +/-15 degree angle and a +/-11 degree angle respectively from the normal direction of the antenna. This range is wide enough to cover satellite communication service areas and that the acceptable errors could be attained with the proposed circular array system.
Fig. 11 Gain and phase patterns of array factor for each beam (upper row: gain; lower row: phase).

Fig. 12 Gain and phase differences among beams.

V. HPA power consumption

The HPA power consumption of the proposed system was qualitatively evaluated on the basis of specific HPA characteristics and compared with that of the conventional system.

Figure 13 plots the assumed HPA characteristics. We evaluated the HPA power consumption, $P_{dc}$, by analyzing the average HPA input power, $P_{\text{av}}(t)$, which depends on the HPAs’ instantaneous input signal level, $v_{in}(t)$:

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\[ P_{in\,aver} (t) = \frac{1}{T} \int_0^T v_{in} (t)^2 \, dt \]
\[ P_{dc} (t) = f \{ P_{in\,aver} (t) \} \] (5)

Fig. 13 Assumed HPA characteristics.

Table 2 summarizes the input signal PAPR, the required HPA OBO point, and the HPA power consumption when the same BER \((1 \times 10^{-2})\) was obtained with both systems under the same AWGN conditions, as explained for Figs. 6 and 9.

The proposed system had a remarkably lower power consumption with similar spectral side-lobes, indicating that power consumption can be reduced by about 50% compared with that of a conventional system.

### Table 2 HPA power consumption \((P_{dc})\) when both systems obtained BER of \(1 \times 10^{-2}\).

<table>
<thead>
<tr>
<th>Mod type</th>
<th>PAPR [dB]</th>
<th>HPA OBO [dB]</th>
<th>Pdc (relative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed 64-QAM</td>
<td>3.5</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Conventional 64-QAM</td>
<td>6.2</td>
<td>5.8</td>
<td>2</td>
</tr>
</tbody>
</table>

VI. Conclusion

Our proposed wireless communication system features a novel 64-QAM modulation scheme that spatially superposes three offset quadrature phase-shift keying (OQPSK) beams formed by a combined circular array system. Experiments had already demonstrated the validity of the spatial superposition. Analysis of its performance over typical nonlinear channels showed that the power amplifiers in the proposed system can operate in the nonlinear high efficiency region. This unique system enables efficient power combining of modulated signals separately power-amplified with high efficiency.

Investigation of the bit error rate (BER) performance of the proposed 64-QAM system showed that it is better than that of a conventional 64-QAM system when the system is operated in the nonlinear high efficiency region of its high power amplifiers (HPAs),
Spectral performance analysis showed that the envelope variations of the OQPSK signals were considerably less than those of the conventional 64-QAM signals, so even after the nonlinear amplification of the OQPSK-modulated RF signals, the frequency side-lobe levels were similar to those of the conventional signals operated in the linear region. As a result, the proposed system achieves more efficient RF power amplification of 64-QAM signals without expanding the spectral occupancy.

Although superposition error is inherent to the system, theoretical transmission analysis showed that a gain error of 1 dB and a phase error of 10 degrees were acceptable. An antenna array study demonstrated that the acceptable errors could be attained with the proposed circular array system and that this range is wide enough to cover satellite communication service areas.

Qualitative evaluation of power consumption on the basis of specific HPA characteristics showed that the proposed system has remarkably lower power consumption and higher spectral efficiency than the conventional 64-QAM system. In particular, the power consumption is about 50% less.

Not only is our system feasible, its use will enable broadband transmission with efficient use of energy and bandwidth.

References