Spatially Superposed Highly Efficient 64QAM Transmission System

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A highly efficient 64-quadrature amplitude modulation (64QAM) transmission system for satellite broadband communication that improves the usage efficiency of frequency resources and energy is presented. It features a two-beam spatial superposition. The system incorporates three quaternary phase-shift keying (QPSK) modulators and multiple high-power amplifiers (HPAs) that operate in their nonlinear region at a high level of efficiency. The lower amplitude change for the QPSK signals enables the HPAs in the proposed system to operate in the nonlinear high-efficiency region in which conventional systems, such as (4+12+20+28) 64-amplitude and phase shift-keying (64APSK) or 64QAM systems, cannot operate. After being power-amplified, their output signals are spatially superposed using a specially tailored antenna to produce a 64QAM signal.

We investigated the performance of the spatially superposed 64QAM (SS-64QAM) system and found that it had a better bit-error rate (BER) than the conventional 64APSK or 64QAM system when operated in the HPA nonlinear high-efficiency region. The results from a theoretical transmission analysis helped to determine the acceptable timing delay among QPSK signals and the spatial superposition errors.

Based on experiments and analysis, the SS-64QAM system is feasible and consumes about 40% less HPA power than the (4+12+20+28) 64APSK system.

Thus, the proposed system is feasible and will enable broadband transmission while more efficiently using the available amount of energy and bandwidth.

I. Introduction

Satellite communication systems have the advantage of being able to efficiently transmit digital multimedia information, and direct-to-home (DTH) digital television broadcasting is a notable example of this. Satellite systems also provide an unparalleled way to construct communication channels in scarcely populated or maritime regions. Thus, the demand for larger capacity and innovative services via satellite is increasing.

The plan is for “4K” and “8K” ultra-high-definition broadcasting on broadcast satellite (BS) channels to start sometime in 2018. In addition, digital video broadcasting links have been proposed for point-to-point transmission of television programs to directly convey audio/video material originating directly from the studios and/or from remote locations to the broadcaster’s premises without requiring local access to the fixed telecom network. Satellite-based ultra-high-definition image transmission technology is also expected to play an important role in land and marine surveying, resource investigation, and disaster monitoring.

A multi-level modulation is effective for improving the spectrum efficiency of broadband signals because the signal frequency band of satellite communications is limited. Multi-level modulations such as 32APSK and 64APSK have been investigated for broadband applications. However, a multi-level modulation scheme is generally much more vulnerable to nonlinear distortion from power devices than QPSK or 8PSK schemes and is thus inefficient for radio frequency (RF) power amplification because it is used in the inefficient linear region of HPAs. Therefore, the need for spectrum and power efficient systems has greatly increased.

The general techniques that are used to mitigate the nonlinear distortion effects have been well covered in the respective literature [3-6]. The pre-compensation techniques counteract the amplifier distortion through the constellation pre-distortion in the transmitter, while the post-compensation techniques mitigate the nonlinear distortion effects on the demodulator side using nonlinear equalization.

In addition to these technologies, spatially superposed 16QAM, and 32APSK wireless communication systems have also been reported on for use as a spectrum and power efficient modulation scheme [9-17]. They spatially superpose certain signals with less amplitude variation using multiple-beam power combining technology. The spatial power combination is expected to enable broadband transmission at a lower consumption of power than that of the conventional system.

In this paper, we present investigations to demonstrate the feasibility and effectiveness of the SS-64QAM system.

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In Section II, we explain the spatial power-combining process for a system incorporated with three QPSK modulators.

In Section III, we discuss the performance of the new system. We analyzed the effect of the timing delay among modulators and the gain and phase errors when combining two beams. The allowable errors were derived from the study.

In Section IV, we propose spatial superposition error compensation in a receiver to improve performance.

In Section V, we present a high gain antenna system that is suitable for the two-beam spatial superposition. We propose a parabola reflector antenna with a circular array of feed horns embedded on a circle that reduces the inherent error when combining two beams.

The HPA power consumption is analyzed in Section VI. We discuss the validity of the spatial superposition and the feasibility of the reduction of HPA power consumption on the basis of the obtained data.

Finally, the conclusion is presented in Section VII.

II. Spatially superposed modulation

A. Principle of spatially superposed modulation

The 64QAM signal constellation is shown in Fig. 1 (a) and the conventional (4+12+20+28) 64APSK signal is shown in Fig. 1 (b). The waveforms of the conventional signals were generated using two quadrature-balanced modulators and then transmitted using one beam.

The newly developed SS-64QAM system can be produced by spatially superposing three PSK signals using three or two beams as illustrated in Fig. 2. However, it is difficult to construct the three-beam 64QAM system shown in Fig.2 (a) because of the antenna limitation. In this paper, the two-beam 64QAM system is mainly studied.

![Signal constellations of 64QAM and (4+12+20+28) 64APSK](image)

![SS-64QAM with three beams](image)
**B. Signal constellation design**

The SS-64QAM system superposes three QPSK signals, QPSK1, QPSK2, and QPSK3. The ratio of their amplitude, \( r_1 \), \( r_2 \), and \( r_3 \), is 1 : 0.5 : 0.25, which is the ratio to maximize the value of the \((\text{point distance})^2/\text{average power}, d^2/(r_1^2+r_2^2+r_3^2)\).

**C. System configuration**

The configuration of the SS-64QAM system is illustrated in Fig. 3. It uses superposed modulation instead of the conventional M-ary modulation. It incorporates three QPSK modulators, QPSK1, QPSK2, and QPSK3.

Their signals are square-root roll-off filtered and fed to the power amplifiers, where each signal is separately power amplified in the nonlinear high-efficiency region. The amplified QPSK2 and QPSK3 signals are then combined into a 16QAM signal, \( S_{23} \), by a power combiner circuit.

The two output signals, \( S_1 \) and \( S_{23} \), are then combined in a vector-sum manner into \( S = S_1 + S_{23} \) with the two beams formed by using spatial superposition, so there is no insertion loss or reduction in the main transmitted power, \( S_1 \).

Spatial power combining is more efficient compared with non-spatial power combining using RF circuitry, which results in insertion loss and a reduced amount of transmission power [18].

The change in amplitude of the filtered QPSK signal is less than that in the filtered 64QAM signal, enabling the amplifiers to operate in the nonlinear region at a higher level of efficiency, and thus, the strict requirements for modulation when using conventional 64APSK or 64QAM systems are relaxed.

![Diagram](image-url)
III. Performance of proposed system

The experimental tests for spatially superposed 32APSK system have already verified that the spatial superposition system is feasible [17]. We evaluated the signal constellation, BER, and allowable superposition errors over a typical nonlinear channel by using an assumed HPA nonlinear model that was based on the actual HPA characteristics in our previous study [16]. In this study, we analyzed the effect of the timing delay of two modulations as well as the spatial superposition errors for the two-beam system.

A. Timing error in modulation and spatial superposition errors

The timing delay and superposition errors are inherent in the system. We analyzed the effect of the timing error among modulators and the gain and phase differences between two beams. Figure 4 indicates the analytical model of the two-beam system for these errors, where $\Delta t$, $\Delta G$, and $\Delta \theta$ represent the modulation timing delay, the gain, and phase differences.

Fig. 4 Analytical model of timing error in modulation and spatial superposition errors for two-beam system.

B. Allowable timing delay and superposition error

We investigated the allowable delay and the gain and phase errors of the new system using the forward error correcting (FEC) scheme, which is composed of Bose-Chaudhuri-Hocquenghem (BCH) coding and low-density parity-check (LDPC) coding (coding rate=3/5) for correcting errors. The HPA output back-off (OBO) points were selected at 0.9 dB.

Table 1 shows the BER under the timing error during modulation and the gain and phase errors in superposition. We can see from this figure that a timing delay of one-sixteenth symbols, a gain error of 0.5 dB, and a phase error of 5 degrees are acceptable.

<table>
<thead>
<tr>
<th>Phase error (deg)</th>
<th>0</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay (symbols)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gain_error (dB)</td>
<td>0</td>
<td>1/16</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>-0.5</td>
</tr>
<tr>
<td>1.0</td>
<td>0</td>
<td>-0.5</td>
<td>-0.5</td>
</tr>
</tbody>
</table>
IV. Compensation for spatial superposition errors

We propose a compensation function for spatial superposition errors in a receiver to improve performance.

A. Principle
The transmitter sends known reference signals to receivers periodically for a short time. The receivers detect and estimate the spatial superposition errors from the received signals. Figure 5 shows the error compensation system in the receiver.

The transmitter sends two different reference signals, $S_{t1}$ and $S_{t2}$ as shown in (1). $S_1$ is a signal for beam 1 and $S_{23}$ is a signal for beam 2.

$$ S_{t1} = S_1 + S_{23}, \quad S_{t2} = S_1 - S_{23} $$

The received signals, $S_{r1}$ and $S_{r2}$, can be expressed in (2), taking account of the phase rotation of beams 1 and 2, $\theta_1$ and $\theta_2$, and the gain error, $G_{2}/G_{1}$.

$$ S_{r1} = G_1 \cdot (S_1 \cdot \exp(j\theta_1) + (G_{2}/G_{1}) \cdot S_{23} \cdot \exp(j\theta_2)) $$
$$ S_{r2} = G_1 \cdot (S_1 \cdot \exp(j\theta_1) - (G_{2}/G_{1}) \cdot S_{23} \cdot \exp(j\theta_2)) $$

From the knowledge of the reference signals, $\theta_1$, $\theta_2$, and $G_{2}/G_{1}$ can be estimated from (1) and (2). After the phase removal of $\theta_1$, the demodulation is carried out on the basis of the modified signal constellation, $S_{r_{m}}$, shown in (3).

$$ S_{r_{m}} = S_{r} \cdot \exp(-j\theta_1) = G_1 \cdot (S_1 + (G_{2}/G_{1}) \cdot S_{23} \cdot \exp[j(\theta_2 - \theta_1)]) $$

B. Effect of superposition error compensation
Figure 6 shows the bit-error performance with and without the compensation, when the timing delay of 1/16 symbols between the modulators, the gain error of 1 (dB), and the phase error of 15 (degree) are assumed.

Fig. 6 BER performance of SS-64QAM after compensation of superposition errors.
From Fig. 6, it is found that Es/N0 is improved by 2 dB using the compensation. Table 2 summarizes the effect of the compensation of superposition errors in the receiver. It is possible to expand the allowable errors of the gain error of 0.5 dB and the phase error of 5 degrees into 1.0 dB and 15 degrees, respectively.

**Table 2 Effect of compensation for superposition errors in receiver.**

<table>
<thead>
<tr>
<th>Allowable errors</th>
<th>Delay (symbol)</th>
<th>Gain (dB)</th>
<th>Phase (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compensation</td>
<td>1/16</td>
<td>1.0</td>
<td>15</td>
</tr>
<tr>
<td>No compensation</td>
<td>1/16</td>
<td>0.5</td>
<td>5</td>
</tr>
</tbody>
</table>

V. Antenna array for spatial superposition

We propose a reflector antenna with a feed array to reduce the error inherent when superposing two beams and to create a higher gain antenna system.

A. Configuration

Figure 7 shows the proposed reflector antenna configuration. The figure on the left shows the parabola reflector antenna fed by the array feed, and the one on the right shows the array feed composed of six feed horns.

The array system simultaneously produces the two beams, and the feed elements for the two beams are alternately located on a circle, as shown in Fig. 7.

The distance between adjacent feed horns, d, was designed to be \( \frac{\lambda}{5.1} \) (wave length) and the radius R is also \( \frac{\lambda}{5.1} \) so that the system would be suitable for practical installation.

![Fig. 7 Configuration of parabola reflector antenna with combined circular array feed that simultaneously produces two beams.](image)

B. Gain and phase differences between beams

Figure 8 shows the gain and phase differences between the two beams versus the angle from the beam center, \( \theta \), when they are aimed in the normal direction, and the diameter, D, the focus point, F, and the feed position, L, of the antenna as shown in Fig. 7 were designed to be \( 80\lambda, 80\lambda \), and \( 18\lambda \), respectively.

A gain error of 1.0 dB and a phase error of 15 degrees are feasible over a +/- 1.3 degree angle from the beam center. These results show that the allowable gain and phase errors in the spatial superposition are feasible over a +/- 1.3 degree angle from the beam center. This range is wide enough to cover satellite communication service areas, and the acceptable errors are attainable using the proposed antenna system.
VI. Effect and application scenario of SS-64QAM system

A. HPA power consumption

The HPA power consumption, \( P_{dc} \), of the proposed system was analyzed using a solid state power amplifier (SSPA) and was compared with that of the conventional system.

Table 3 summarizes the required SSPA OBO point and the SSPA power consumption when similar bit-error rate (BER) characteristics were obtained for the SS-64QAM and conventional (4+12+20+28) 64APSK systems.

The \( P_{dc} \) of the SS-64QAM system is about 40% less than that of the conventional one.

Figure 9 compares the scale of the conventional and proposed systems when the total transmitting power is 500 (W) and when the same BER performance is attained in order to make the advantage of using the newly developed SS-64QAM system clear. It can be seen that smaller and more inexpensive HPAs are available, and moreover, that their power sources and heat control systems are likewise smaller and inexpensive. These contribute toward constructing an inexpensive broadband system.

Table 3 HPA power consumption (\( P_{dc} \)) when similar BER is attained.

<table>
<thead>
<tr>
<th>System</th>
<th>No. of beams</th>
<th>Modulation</th>
<th>HPA</th>
<th>OBO (dB)</th>
<th>( P_{dc} ) (relative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS-64QAM</td>
<td>2</td>
<td>QPSK-1, QPSK-2, QPSK-3</td>
<td>HPA-1, HPA-2, HPA-3</td>
<td>0.9, 0.9, 0.9</td>
<td>0.61</td>
</tr>
<tr>
<td>64APSK</td>
<td>1</td>
<td>64APSK</td>
<td>HPA</td>
<td>3.3</td>
<td>1.0</td>
</tr>
</tbody>
</table>
B. Application scenario

We showed that the SS-64QAM system is more power efficient than the conventional ones and that a non-spatial 64QAM system with the same signal constellation as shown in Fig. 1 (a) also performs similarly to the conventional one. Thus, we are also proposing various application scenarios using the proposed system for the broadband transmission of event link-up, disaster monitoring, and maritime resources surveying. The SS-64QAM modulation can be used in the uplink for a bent-pipe transponder and in both the up and down links for a regenerative transponder. In either case, we can reap the rewards from improving the usage efficiency of the frequency resources and energy.

VII. Conclusion

The proposed SS-64QAM broadband transmission system features a novel modulation scheme that spatially superposes three QPSK signals formed by a reflector antenna fed by a special circular array feed. The analysis results of its performance over typical HPA nonlinear channels showed that the HPAs in the proposed system can operate within their nonlinear high efficiency region. This unique system enables efficient power combining of the modulated signals that are separately power-amplified at a high level of efficiency.

The BER of the SS-64QAM system was better than that of the conventional (4+12+20+28) 64APSK system when the system is operated in the nonlinear high-efficiency region of its HPAs.

The theoretical transmission analysis showed that a timing delay of one-sixteenth symbols, a gain error of 1.0 dB, and a phase error of 15 degrees were acceptable with the help of error compensation in a receiver. The antenna beam pattern study showed that the acceptable level of superposition errors could be attained using the proposed antenna system over a +/- 1.3 degree angle from the beam center and that this range is wide enough to cover satellite communication service areas.

The experimental tests have verified that the spatial superposition system is feasible and consumes a 40% lower amount of power than the (4+12+20+28) 64 APSK system.

Thus, the proposed system is feasible and will enable broadband transmission while more efficiently using the available amount of energy and bandwidth.
References


