Spatially Superposed Highly Efficient 32APSK Transmission System

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A highly efficient 32 amplitude phase-shift keying (APSK) modulation satellite broadband communication system is presented here that improves the usage efficiency of the frequency resources and energy. It features a two-beam spatial superposition. The system incorporates an 8 phase-shift keying (8PSK) modulator, a quaternary phase-shift keying (QPSK) modulator, and multiple high power amplifiers (HPAs) that operate in their nonlinear region at a high level of efficiency. The lower amplitude change for the 8PSK and 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+16 APSK or 32 quadrature amplitude modulation (QAM) systems, cannot operate. After being power-amplified, their output signals are spatially superposed using a specially tailored antenna to produce a new 8x4 = 32APSK signal.

We investigated the performance of the new 32APSK system and found that it had a better bit error rate (BER) than the conventional 32APSK system when operated in the HPA nonlinear high efficiency region. The results from a theoretical transmission analysis helped to determine the acceptable timing delay between two modulators and the spatial superposition errors. In addition, a high gain antenna system suitable for combining the two beams is presented that satisfies the acceptable superposition errors.

We also performed some experiments and proved that the spatial superposed 32APSK system is feasible and that it consumes 50% less HPA power than the 4+12+16 APSK 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 broadcast digital multimedia information over very large areas, and direct-to-home (DTH) digital television broadcasting is a notable example of this. Satellite systems also provide an unparalleled way to complement the communication infrastructure 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. The multi-level modulations such as 32APSK and 64APSK have been investigated for broadband applications. However, the multi-level modulation scheme is generally much more vulnerable to nonlinear distortion from power devices than the QPSK or 8PSK schemes and is thus inefficient for radio frequency (RF) power amplification because it is used in the inefficient linear region of HPA. 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 16 (4x4) QAM, 32 (8x4) APSK, and 64 (4x4x4) QAM wireless communication systems have also been reported on for use as a spectrum and power efficient modulation scheme [9-16]. They spatially superpose some 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.

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In our previous study [16], we presented some analysis results on the 8x4 APSK system that is spatially superposed with an 8PSK beam and a QPSK beam. In this paper, we will present some additional analysis and test results to demonstrate the feasibility and effectiveness of the superposed 32APSK system.

In Section II, we explain the spatial power combining process for a system incorporated with an 8PSK modulator and a QPSK modulator.

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

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

The experimental test results are presented in Section V and 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 based on the obtained data.

Finally, satellite application scenarios using the proposed system are presented in Section VII.

II. Spatially superposed modulation

A. Principle of spatially superposed modulation

The 8x4 APSK signal constellation is shown in Fig. 1 (a) and is different from the ones from the conventional 4+12+16 APSK and 32QAM signals shown in Figs. 1 (b) and (c). The waveforms of the conventional signals were generated using two quadrature-balanced modulators [17] and then transmitted using one beam.

The newly developed constellation can be produced by spatially superposing an 8PSK beam and a QPSK beam as depicted in Fig. 2.
B. System configuration

The configuration of the 32APSK system is illustrated in Fig. 3. It uses superposed modulation instead of the conventional M-ary modulation. It incorporates an 8PSK modulator and a QPSK modulator.

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 two output signals are then combined in a vector-sum manner into $S = S_1 + S_2$ with the two beams formed by using spatial superposition, so there is no insertion loss or reduction in the transmitted power. 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 8PSK/QPSK signals is less than that in filtered 32APSK signals, 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 32APSK or 32QAM systems are relaxed.

![Diagram of 32APSK system configuration](image)

Fig. 3 Configuration of 8x4=32 APSK system using superposed modulation.

C. Signal constellation design

The 8x4 APSK superposes an 8PSK signal and a QPSK signal, as shown in Fig. 4. We designed the radius of the 8PSK constellation, $r_1$, the angle position, $\alpha$, and the radius of the QPSK constellation, $r_2$, to maximize the value of the (point distance)$^2$/average power, $d^2 / (r_1^2 + r_2^2)$.

As a result, we selected $r_2/r_1$ to be 0.442 and $\alpha$ to be 12.76 [deg]. The selected constellation for 8PSK is a modified one that differs from that of the conventional uniform 8PSK.

![Diagram of signal constellations](image)

Fig. 4 Signal constellations of modified 8PSK and QPSK that constitute new 32APSK.
III. Performance of proposed system

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.

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 between two modulators and the gain and phase differences between two beams. Figure 5 indicates the analysis model for these errors, where $\Delta t$, $\Delta G$, and $\Delta \theta$ represent the modulation timing delay, the gain, and phase differences.

$$a(t)\exp(j\omega t)G_1\exp(j\theta_1)$$

$$b(t + \Delta t)\exp(j\omega t)G_2\exp(j\theta_2)$$

$$\Delta G = G_1/G_2$$

$$\Delta \theta = \theta_1 - \theta_2$$

Fig. 5 Analytical model of timing error in modulation and spatial superposition errors.

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 BCH coding and low-density parity-check (LDPC) coding (coding rate=2/3) for correcting errors. The HPA output back-off points were selected at 0.8 dB and 1.6 dB.

Figure 6 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.

Fig. 6 8x4= 32 APSK BER performance under timing delay and gain/phase errors in superposition.
IV. 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 newly proposed reflector antenna configuration. The figure on the left shows the parabola antenna reflector 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) so that the system would be suitable for practical installation.

![Fig. 7 Configuration of parabola 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 0.5 dB and a phase error of 5 degrees are feasible over a +/- 1.0 degree angle from the beam center. These results show that the allowable errors in the spatial superposition are feasible over a +/- 1.0 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.

![Fig. 8 Gain and phase differences between two beams.](image)
V. Experimental test of spatial superposition

We carried out an experimental test to examine the validity of the spatially superposed 32APSK performance. Figure 9 illustrates the configuration of the test system. In this test, 2+2 antenna feeds without a reflector were used instead of a 3+3 antenna system, which is shown in Fig. 7, because of the simple and easy setup. Figure 10 (a) shows the observed signal constellation, which is similar to the one shown in Fig. 1 (a). Figure 10 (b) shows the eye pattern of the 32APSK (I-channel), which has seven eyes as expected from the constellation. These data verified that the spatial superposition functions as expected from our analysis and is feasible.

VI. 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 1 summarizes the required SSPA output back off (OBO) point and the SSPA power consumption when a similar bit error rate (BER) characteristics was obtained for the new 32APSK and 4+12+16 APSK systems.

The $P_{dc}$ of the 8x4 APSK system is about 50% less than that of the 4+12+16 APSK one.

Figure 11 compares the scale of the conventional and proposed systems when the total transmitting power is 500 (W) and the same BER performance is attained in order to make the advantage of using the newly developed 32APSK system clear. It can be seen that smaller and more inexpensive HPAs are available, and moreover, their power sources and heat control system become smaller and inexpensive. These contribute toward constructing an inexpensive broadband system.
Table 1 HPA power consumption (P_{dc}) when similar BER is attained.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>No. of beams</th>
<th>SSPA Input signals</th>
<th>SSPA OBO (dB)</th>
<th>SSPA P_{dc} (relative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8x4 APSK</td>
<td>2</td>
<td>Modified-8PSK</td>
<td>1.6</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QPSK</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>4+12+16 APSK</td>
<td>1</td>
<td>32APSK</td>
<td>6.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Conventional system

Proposed system

Fig. 11 Comparison of system scale when total output power and BER performance are identical.

VII. Application scenario

We showed that the 8x4 APSK system is more power efficient than the conventional ones and that a non-spatial 32APSK system with the same signal constellation as shown in Fig. 1 (a) also performs similarly to the conventional one [15]. Thus, we are also proposing some application scenarios using the proposed system, which are shown in Fig. 12 for the broadband transmission of event link-up, disaster monitoring and maritime resources surveying. The 8x4 APSK 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.

VIII. Conclusion

The proposed 32APSK broadband transmission system features a novel modulation scheme that spatially superposes an 8PSK beam and a QPSK beam 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 32APSK system was better than that of the conventional 32APSK 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 0.5 dB and a phase error of 5 degrees were acceptable. The antenna beam pattern study showed that the acceptable level of

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superposition errors could be attained using the proposed antenna system over a +/- 1.0 degree angle from the beam center, and that this range is wide enough to cover satellite communication service areas.

The experimental tests verified that the spatial superposed 32APSK system is feasible and the power consumption of the new system consumes a 50% lower amount of power than the 4+12+16 APSK system.

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

Acknowledgment

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References