New M-ary QAM Transmission Payload System

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This paper presents a new M-ary modulation satellite payload system that can provide efficient use of the frequency resource and transmitted power. The system incorporates a superposed M-QAM modulation scheme with a spatial power-combining technology. However, the new system is sensitive to the superposition error. This paper discusses a configuration for the 64-QAM payload system and also presents the effects of a specially tailored modulation/demodulation method and forward error correction (FEC) coding on the superposition error. It also presents theoretical studies of the signal transmission characteristics of the system and the investigation results in comparison with the conventional systems. The results show that the power efficiency of the new spatial superposed 64-QAM system is better than that of the conventional system. This unique configuration enables the reliable transmission at higher data rates with the efficient use of power and bandwidth.

I. Introduction

The rapid advances in information technology have led to a growing demand for high-speed access to the Internet, anytime, anywhere, at a reasonable cost to the consumer. A broadband multimedia satellite communications system is a promising network access system because it would allow us to construct a broadband access system easily and rapidly over a wide area compared with other systems, such as fiber-to-the-home (FTTH), CATV, or ADSL.

However, before satellite communications systems can be used as a broadband network, we have to resolve several big issues. One is the need for an economical system design. We will also have to boost capacity and find a way to transmit over a band-limited channel at very high data rates. Reducing the output power and the power consumption of the high power transmitters is indispensable for constructing an economical satellite system.

In this context, employing M-ary signals would be effective for broadband transmission with a frequency-band-limited system. A 16-QAM scheme has been employed in a satellite high-speed data transmission system. However, an M-ary modulation scheme is generally much more vulnerable to thermal noise and nonlinear distortion from power devices than a QPSK scheme. This means we have to increase the carrier-to-noise power ratio (CNR) and reduce the distortion to achieve a specific transmission quality. Some back-off is required in order to attain an acceptable level of distortion for a practical power amplifier. However, with back-off, the available power from a power amplifier becomes lower than the maximum and the power efficiency decreases. This is the main reason an M-ary system has not been widely used for a power-limited system and is the major barrier to actualizing an inexpensive satellite communications system. Several approaches have been proposed to overcome the issue, such as a superposed 16-QAM, a spatial power combined superposed 16-QAM, and the use of a linearized TWTA.

In this paper, the main focus is placed on a 64-QAM signal transmission system, in which nonlinearity becomes a big problem. We propose a new system that, through the use of a superposed modulation scheme and power-combining technology, can provide transmission at higher data rates with high power efficiency. Then, on the basis of this configuration, we present a theoretical study of transmission characteristics under Gaussian noise and evaluate the system’s performance in comparison with the conventional system. The effect of power-combining errors and the variation of system elements on total performance and the allowable errors are also investigated.

II. M-ary Modulation

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M-ary communication (communication using M symbols) is an effective way to increase transmission capacity, since each M-ary symbol carries as much information as \( \log_2 M \) bits. However, it requires higher transmitted EIRPs or larger receiving antenna diameters because of its intrinsic sensitivity to noise and interference. In addition, it is more sensitive to nonlinear distortion. Thus, M-ary signaling provides us with additional means to achieve the optimal trade-offs between the transmission rate, transmission bandwidth, and transmitted power.

Three types of M-ary signaling have been proposed. They are multi-amplitude signaling (MASK), multi-phase signaling (MPSK) and multi-tone signaling (MFSK). In MFSK, the transmitted power decreases with M. However, the transmission bandwidth increases linearly with M or exponentially with the rate increase factor k \((M=2^k)\). In MPSK and MASK, the bandwidth is independent of M, but the transmitted power increases as \( M^2/\log_2 M = 2^{2k}/k \); that is, the power increases exponentially with the information-rate increase factor k. Hence, we should use MPSK or MASK if the bandwidth is at premium.

Quasi-constant envelope modulations, such as QPSK and 8PSK, are power efficient in a single carrier configuration, since they can operate on high power amplifiers (HPAs) driven near saturation. Quadrature amplitude modulation (QAM) signaling can be viewed as a combination of amplitude shift keying (ASK) and phase shift keying (PSK) or a combination of two independently amplitude-modulated carriers in quadrature. The general QAM signal \( s(t) \) is given by:

\[
s(t) = x(t) \cdot \cos \omega t - y(t) \cdot \sin \omega t
\]  

where \( x(t) \) and \( y(t) \) are amplitude-modulated signals.

The generation of a QAM signal is shown in Fig. 1 and a uniform 64-symbol QAM signal constellation is shown in Fig. 2.

QAM offers better spectrum efficiency for quasi-linear channels. However, conventional QAM is not power efficient since it can only operate on quasi-linear power amplifiers with large output back-off (OBO). In this paper, main focus is placed on a QAM scheme and a new type of power efficient 64-QAM system is proposed and discussed.

### III. Effect of Nonlinear Characteristics of Power Amplifier on M-ary Modulation

Wireless communications requires a HPA followed by an antenna for radio wave transmission. In satellite communications, we need to amplify signals to high power levels, for which high-efficiency amplifiers are desirable. Unfortunately, these amplifiers are nonlinear, and using them to amplify signals causes distortion.

AM-to-AM conversion is a phenomenon common to nonlinear devices such as traveling wave tubes (TWT) or solid-state power amplifiers (SSPA). At the device input, any signal envelope fluctuations (amplitude modulation) undergo a nonlinear transformation and thus result in amplitude distortion at the device output. Hence, HPA operation in its nonlinear region would not be the optimum choice for an amplitude-based modulation scheme such as QAM. AM-to-PM conversion is another phenomenon common to nonlinear devices. Fluctuation in the signal envelope produces phase variations that can affect the error performance for any phase-based modulation scheme such as PSK.
Conventional non-regenerative repeaters are generally operated backed-off from their highly nonlinear saturation region. This is done to avoid nonlinear distortion and appreciable intermodulation (IM) noise and thereby allow efficient utilization of the system’s entire bandwidth. However, the backing off to the linear region leads to lower output power.

Supplied power is severely limited in most satellite communications systems and most power is consumed by the HPA. Thus, the inefficiency associated with linear power amplification stages are expensive to bear. Therefore, it is important to raise the power efficiency and lower the power consumption of HPAs for economical system construction.

A. Nonlinearity of HPA
The conventional 64-QAM system configuration is shown in Fig. 1. Two independently amplitude-modulated carriers in quadrature are summed after modulation and then high power amplified. Figure 3 depicts the assumed HPA characteristics, which represent a typical 2.5-GHz band SSPA. Table 1 summarizes the gain compression, phase shift, and third IM (IM3) at the backed-off conditions, namely, OBO of 0, 3, 5, and 7 dB.

B. Channel Coding
The key to achieving error-free communication is the use of appropriate redundancy. Channel coding refers to the class of signal transformations designed to improve communications performance by enabling the transmitted signals to better withstand the effects of various channel impairments, such as noise, interference, and fading. For practical channels plagued by fading and impulses noise, coding can yield substantial gains and the coded scheme can become significantly superior to the uncoded one. In general, random-error-correcting codes are not efficient for correcting burst errors and burst-error-correcting codes are not efficient for random error correction. In most practical systems, we have errors of both kinds. Thus, in this study, a concatenated coding scheme composed of convolutional coding and Reed-Solomon (R-S) coding is used for correcting random and burst errors.

C. Transmission Analysis of Conventional System

The system model for the transmission analysis is shown in Fig. 4. It comprises an outer coder, interleaver, inner coder, modulator, demodulator, Viterbi decoder, de-interleaver, outer decoder, nonlinear element, and additive white Gaussian noise (AWGN) channel.

Figure 5 shows the effect of this forward error correction (FEC) coding {R-S (208,188) & R=1/2 convolution} on the conventional 64-QAM system in linear operation. It is seen that a coding gain of 6 dB is obtained at BER=1e-5.

The transmission performance of the conventional system was also evaluated under various nonlinear conditions. To understand the effects of nonlinearity and FEC on signal transmission, the BER performance was
investigated at the OBO of 3, 5, and 7 dB. Figure 6 shows the signal constellation at the 3dB OBO. The signal constellation on the nonlinear channel is deformed by AM-AM and AM-PM conversion, and the original constellation is no longer maintained.

Figure 7 shows the BER performance versus Eb/N0 for different operating conditions. The performance for linear operation is also shown. It is seen that the BER performance degrades due to the nonlinearity of the HPA. Even at the 3 dB OBO point, BER performance degrades by more than 2.0 dB in Eb/N0, compared with the linear operation. Then, to achieve quasi-linear performance, we need some additional means to compensate for the distortion, because FEC coding by itself can not do so. Additionally, a specially tailored linearized HPA must be employed or the HPA must be backed-off below 5 dB. The latter would cause an output power decrease and low power efficiency.

Fig. 5. Effects of FEC coding on 64 QAM in linear operation.

Fig. 6. Deformed constellation of 64-QAM signal due to nonlinear distortion at 3.0-dB output back-off.

Fig. 7. BER performance of 64-QAM signal at three output back-off points on a nonlinear channel.

IV. New Payload System with Spatially Superposed 64-QAM Technology

A conventional 64-symbol (M=64) QAM signal waveform can be generated using two quadrature-balanced modulators as shown in Fig.1. On the other hand, a 64-QAM signal can also be produced using three QPSK modulators whose levels differ by 6 dB (0, -6, and –12dB) in a uniform constellation as sketched in Fig. 8. The QPSK signals from the three QPSK modulators have a nearly constant envelope and are less sensitive to AM-AM conversion generated in a nonlinear device that follows them. Therefore, special attention has to be paid only to the phase distortion produced by each HPA.

A. Configuration

The proposed new system for 64-QAM signaling is illustrated in Fig. 9. The modulation is performed by superposed technology instead of conventional amplitude modulation. The system incorporates three conventional QPSK modulators (QPSK-1, 2, and 3). Their signals are fed to power amplifiers, where each QPSK signal is power-amplified separately. The serial input data stream \( (d_1, d_2, \ldots, d_6) \) is divided into three parallel data streams
\((d_1, d_2), (d_3, d_4), (d_5, d_6)\). Then, a data transformation \((d'_3, d'_4), (d'_5, d'_6)\) is performed in front of two QPSKs (QPSK-2 and QPSK-3) for Gray coding. The output signals \(s_1, s_2, s_3\) from the QPSK modulators are

\[
\begin{align*}
    s_1 &= r_1 \cdot \exp(j\phi_1) \\
    s_2 &= r_2 \cdot \exp(j\phi_2) \\
    s_3 &= r_3 \cdot \exp(j\phi_3)
\end{align*}
\]

where \(r_i, \phi_i, (i = 1, 2, 3)\) are the amplitude and phase for each QPSK signal.

The amplified signal \(S_2\) and \(S_3\) of QPSK-2 and QPSK-3 are combined in a directional coupler as follows.

![Fig. 8. Principle of superposed 64 QAM](image)

![Fig. 9. System configuration of superposed 64 QAM with spatial power-combining technology.](image)
The two output signals $S_1$ (QPSK-1) and $S_2$ are then combined in a vector-sum manner $S = S_1 + S_2$ with a spatial power-combining technology. Microwave circuits are other candidates for the power-combining process. But they are complex and have an insertion loss that reduces the transmitted power. On the other hand, the spatial power-combining technology enables an efficient power-combining process.

Thus, the signal constellation $C$ for 64-QAM is expressed as

$$C = S_1 + S_{23}$$

(4)

If setting errors $\alpha_i, \beta_i$ exist as for gain and phase in the combining process in the transmitter, the resultant transmitting output signal $T$ is distorted and expressed as

$$T = S_1 + S_{23}[\alpha_i \cdot \exp(j\beta_i)]$$

(5)

B. Phase Compensation in Modulators

As discussed earlier, FEC code by itself can not correct the errors caused by nonlinear distortion. To improve transmission performance, a phase shifter is employed to compensate the phase deviation generated in an HPA.

In the conventional system configuration, two independent signal waveforms are amplitude-modulated and the resultant signal envelope fluctuates. Therefore, it is difficult to compensate AM-PM conversion. On the other hand, in the superposed modulation scheme, the three signal waveforms show a nearly constant envelope. Thus, as shown in Fig.9, it is easy to carry out phase adjustments separately as $\varphi_1, \varphi_2, \text{and } \varphi_3$ to cancel the phase rotation. As a result, we can maintain the original signal constellation and can expect transmission performance very close to linear operation.

In the new system, 8-level amplitude modulators are not necessary, so that the severe requirements for the modulation are relaxed compared with the conventional 64-QAM system. In addition, the power amplifier following the modulators can be operated near a saturation region because the AM-PM conversion is canceled. This unique feature contributes to improving the power efficiency of the system and also enabling economical and flexible communication equipment.

C. Spatial Power Combining for Reducing The Combining Error

In the new system, a 64-QAM signal waveform is synthesized by the three separately produced QPSK signals. The QPSK signals are spatially power-combined by phase array technology.

At the receiving side, the combining errors in amplitude and phase between two complex values $S_1$ (QPSK-1) and $S_{23}$ (QPSK-2+QPSK-3) must be kept small to achieve the same signal constellation $C = S_1 + S_{23}$ shown in (4) as the transmitting side. The combining errors arise in the superposition in the transmitter shown in (5) and in the spatial power combing process. The former can be adjusted by hardware or software. The latter is dependent on the difference in the path length and radiation pattern between the two signals, $S_1$ and $S_{23}$.

The received signal $R$ can thus be expressed as

$$R = S_1 + S_{23}[\alpha_r \cdot \exp(j\beta_r)] + \alpha_r \cdot \exp(j\beta_r) + n = S_1 + S_{23}[\alpha_r \cdot \exp(j(\beta_1 + \beta_3))] + n$$

(6)

where $\alpha_r, \beta_r$ are gain and phase errors that occur in the spatial combining process and $n$ is noise signal. To suppress the errors, $\alpha_r$ and $\beta_r$, two sets of two-dimensional phased array antenna with the same center position are preferable.
D. Modulation/Demodulation Method for Spatially Superposed 64-QAM

If setting errors exist for gain and phase in the combining process, the resultant output signal is distorted as shown in (6) and is illustrated in Fig. 10.

The proposed modulation uses a non-uniform 64-QAM constellation illustrated in Fig.11, in which $r_1$ is bigger than that of the uniform one. It is effective to increase the minimum distance separating any two constellation points when $S_{23}$ is rotated against $S_1$.

On the other hand, the proposed demodulation scheme includes a function that can estimate the combining error $\alpha', \beta'$ by averaging the received signals for a known symbol $S_0 = S_{1,0} + S_{23,0}$ transmitted for a short time at the beginning of demodulation. The demodulator decides the received symbols based on the modified signal constellation $C'$ calculated by the estimated values as expressed as

$$C' = S_1 + S_{23} \cdot [\alpha' \cdot \exp(j\beta')]$$

(7)

A modified signal constellation $C'$ is illustrated in Fig. 12.

E. Effect of Gain and Phase Errors in Superposition on Transmission Performance

To investigate the effect of the errors, the transmission performance was analyzed for various gain and phase errors. Figure 13 shows the BER performance with a uniform constellation and no estimation function in the demodulator under various gain and phase errors. As a matter of course, BER degrades according to the deviation from the ideal condition.

The BER performance with a non-uniform constellation and an estimation function in the demodulator was also investigated to study the effect of the new modulation/demodulation on vector-sum setting errors. The results are shown in Fig.14. The previously mentioned concatenated coding scheme composed of R-S coding and convolutional coding was used in obtaining the data in Figs.13 and 14. It is seen from Figs. 13 and 14 that the new system with the non-uniform modulation and the demodulation with combining error estimation is effective in improving BER performance.
Fig. 13. Effects of gain error and phase error in the power-combining process on 64-QAM signal BER performance with a uniform constellation and no estimation function in a demodulator.

Fig. 14. Effects of gain error and phase error in the power-combining process on 64-QAM signal BER performance with a non-uniform constellation and an estimation function in a demodulator.

V. Evaluation and Discussion

The proposed system requires three HPAs. However, it is possible to operate them with high efficiency near the saturation region. In the conventional system configuration, the BER performance becomes improves as the back-off is increased. However, the power consumption increases. At the –5-dB OBO point, the HPA power efficiency is about one-third
of that at the saturation point. From Fig. 7, the performance change versus output back-off is obtained. As back-off increases, the required Eb/N0 for achieving the specific BER decrease.

Table 2 compares the power consumption between the proposed system and the conventional one. The new system using the superposed 64 QAM with spatial power-combining technology can operate on HPAs driven in the saturation region. As a result, the total power efficiency is remarkably improved compared with the conventional system in which HPAs are driven in the back-off linear region.

From Fig.14 and Table 2, it can be seen that 1.0 dB of gain error and 20 degrees of phase error are allowable in the new system. Therefore, the proposed 64 QAM with three-QPSK superposition with a spatial power-combining technology is feasible for a practical system.

Table 2. Comparison of power consumption for several system configurations (BER=1e-5)

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Condition</th>
<th>Eb/N0 [dB]</th>
<th>HPA efficiency(%)</th>
<th>Consumption Power (relative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional 64QAM</td>
<td>3dB OBO</td>
<td>15.1</td>
<td>20</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>5dB OBO</td>
<td>13.8</td>
<td>14</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>7dB OBO</td>
<td>13.5</td>
<td>8</td>
<td>1.73</td>
</tr>
<tr>
<td>Spatially Superposed 64QAM</td>
<td>Phase err: 30deg Gain err: 1dB</td>
<td>17.6</td>
<td>40</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>Phase err: 20deg Gain err: 1dB</td>
<td>14.2</td>
<td>40</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>Phase err: 15deg Gain err: 1dB</td>
<td>13.4</td>
<td>40</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Phase err: 10deg Gain err: 1dB</td>
<td>13.0</td>
<td>40</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>Phase err: 0deg Gain err: 1dB</td>
<td>13.0</td>
<td>40</td>
<td>0.31</td>
</tr>
</tbody>
</table>

VI. Conclusion

This paper presented a new satellite communications system featuring an M-ary QAM modulation scheme and a spatial-power combining technology instead of two amplitude-modulated carriers in quadrature. The system incorporates three conventional QPSK modulators and combines their output signals in a vector-sum manner to produce a 64-QAM signal. Thus, it can operate on high power amplifiers driven near saturation and relax the severe requirements for the modulation compared with the conventional 64-QAM system. This paper also presented a specially tailored modulator/demodulator and theoretically discussed the signal transmission characteristics of the system and the investigation results in comparison with the conventional system. Moreover, on the basis of a specific system example, allowable gain and phase errors in power-combining process were derived. The results of this study show that the proposed system can improve power efficiency remarkably.

References