# On the Feasibility of Efficient Multiamplitude Communication

## J. G. Smith

### Telecommunications Division

Bandwidth constraints in Earth-satellite communication systems force consideration of uncoded M-ary modulation to obtain increased data rates. M-ary phase shift keying (MPSK) at first glance seems most promising because of the high transmitter efficiency achieved through Class C operation. Multiple phase-and-amplitude modulation candidates such as quadrature amplitude shift keying (QASK) appear less promising because the transmitter must operate at lower efficiency (in linear or multimode operation). However, initial studies indicate that QASK offers significant raw dc-power savings over MPSK, despite the reduced transmitter efficiency. For example, at S-band both solid-state and traveling wave tube (TWT) QASK transmitters can provide a 3-dB average dc-power savings over comparable 16-ary phase shift keying (PSK) for the same bit rate and error probability. The reason for this savings is that QASK requires much less average signal-to-noise ratio that 16-ary PSK for the same error rate.

## Introduction

In a bandwidth-constrained communication environment, one means of achieving an increased data rate for a fixed channel bandwidth is to increase the number M of signal levels. Four-phase phase shift keying (PSK), for example, is replacing binary PSK in many such environments because of the doubled data rate at no price in band-width, power, or bit error rate. Further increases in data rates are available with M-ary phase shift keying (MPSK) in general by increasing transmitter power. Most significantly, MPSK transmitters can operate in a saturated (Class C) mode because of the constant energy nature of the signals. Thus, the relatively high transmitter efficiency of binary PSK can be maintained independent of the number of levels M.

Another form of M-ary modulation warranting consideration is quadrature amplitude shift keying (QASK), a form of multiple phase-and-amplitude modulation. QASK is inherently more efficient in terms of average transmitted power than MPSK. Variable amplitude signals, however, must

have lower transmitter operation efficiencies than those of MPSK. This is because the transmitters must be run Class A (for linear operation), or use data-rate-switched Class C final amplifiers (multimode operation). It will be shown, however, that QASK, despite the poorer transmitter efficiency, compares favorably on a raw power basis with MPSK.

In selection of a system to meet the requirements of a communication environment with specified data rate, bandwidth, noise level, and error rate, competing systems initially must be compared on the basis of the raw dc power needed to meet the communciation requirements. If the system average power-to-noise density ratio (PNR) is defined as $PT/N_o$, where $P$ is the average required dc power, $T$ is the reciprocal of the specified bandwidth, and $N_o$ the specified noise level, then selection can be said to be made on the basis of minimum PNR.

The PNR can be written as the ratio of average signal-to-noise ratio (SNR) to average transmitter $\eta$. That is, transmitter efficiency $\eta$ is $S/P$, where $S$ is the average RF output power, and SNR is $ST/N_o$. Thus, PNR $=$ SNR$/\eta$, and competing systems can be compared on the basis of the ratio of required SNR to transmitter efficiency $\eta$. The reason for portraying the PNR as this ratio is that even though one system has a lower transmitter efficiency than another, it may still be preferred if its SNR requirement is sufficiently low.

The aim of this article is to show that there are QASK transmitter configurations with lower PNRs than competing MPSK despite the reduced transmitter efficiency. This is possible because the required SNR of the QASK system is considerably less than that of a PSK system.

It is first shown that a particular multiple phase-and-amplitude system denoted QASK4, requires only 40% of the SNR necessary for 16-ary PSK (PSK16) with the same bandwidth, data rate, and error rate, at all error rates less than $10^{-3}$. Then the transmitter efficiency of PSK16 is compared with the transmitter efficiency of two QASK4 transmitter configurations. Finally, the PNR's of the PSK16 and the QASK4 systems are compared.

The approach taken in the second and third steps is to specify four S-band PSK16 systems, with RF output powers of 1, 10, 20, and 30 W, respectively, and to compare each of these with one or more QASK4 systems of appropriately scaled average RF output power. This is to permit consideration of the transmitter efficiencies at realistic power levels and operating frequencies. Each of the four PSK16 systems are assumed appropriately sized for a communication environment of established noise level, bandwidth, and data rate. Power drains and efficiency of the S-band devices required in each transmitter configuration are based on current development technology levels.

In the next section, the QASK4 and PSK16 forms of modulation are described, and the 4-dB SNR advantage of QASK4 over PSK16 is verified. In the section, "Transmitter Configurations," transmitter configurations for achieving QASK4 are considered. Then in the section, "S-Band Device
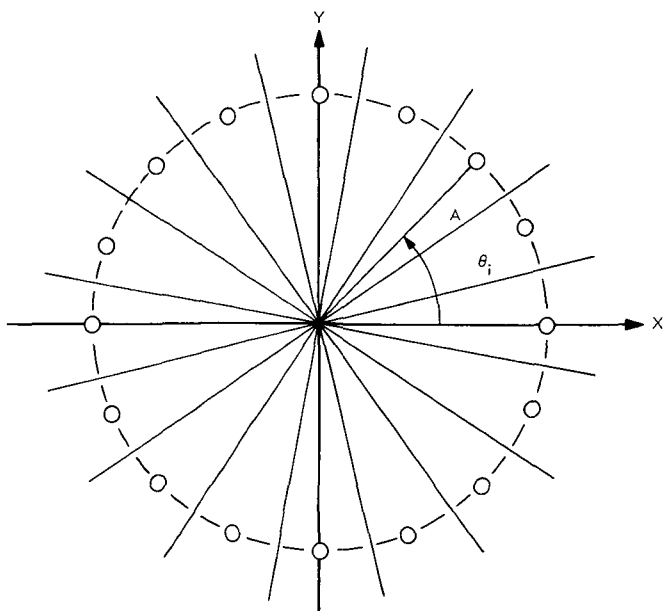
Fig. 1. PSK16 circular structure

Models," several S-band device models are specified, and finally the systems to be considered are configured and compared in the last two sections.

## Two Forms of Modulation

In the PSK16 system, during each signaling time $T$, one of 16 signals $s_i(t)$ is sent, where

$$s_i(t) = \sqrt{2} \, A \cos [\omega_o t + \Theta_i], \quad i = 1, 2, \ldots, 16$$

frequency $\omega_o$ is S band, and the phases $\Theta_i$ are uniformly distributed around a circle, as shown in Fig. 1. The average RF signal power $S$ is the square of the amplitude $A$, the bandwidth is the reciprocal of the signaling time $T$, and the data rate is $4/T$ bits/s. The signal $r(t)$ received during the signaling time $T$ is $s_i(t) + n(t)$, where $n(t)$ is a sample of Gaussian white noise of two-sided noise level $N_o$. The probability of an M-ary symbol being correctly received is equal to the probability that the received noisy signal $r(t)$ lies in the correct detection region (the decision regions are the pie-shaped regions of Fig. 1) (Ref. 1).

In the QASK4 system, during each signaling time $T$, one of the 16 signals $s_i(t)$ is sent, where

$$s_i(t) = \sqrt{2} \ [X_i \cos \omega_o t + Y_i \sin \omega_o t]$$

$$= \sqrt{2} \ A_i \cos [\omega_o t + \Theta_i]$$

and the $(X_i, Y_i)$ as shown in Fig. 2, form a 4 by 4 matrix of uniformly spaced points. The matrix is characterized by the signal separation parameter $\Delta$, where $X_i = \pm\Delta, \pm3\Delta, \ Y_i = \pm\Delta, \pm3\Delta$.

Alternately, the signal points can be characterized in terms of power levels $A_i^2$ and phases $\theta_i$ as shown in Fig. 3. Note that the three power levels have relative values of 1, 5, and 9 with average power equal to the middle value. This average RF output power S is $10\Delta^2$. As with PSK16, the probability of an M-ary symbol being correctly received is equal to the probability that the received noisy signal $r(t)$ lies in its correct decision region – in this case, the rectangular regions denoted in Fig. 2.

Asymptotically, for error rates $\leqslant10^{-3}$, the probability of error is largely dependent upon the minimum distance $d$ from a signal point to a decision region boundary (Ref. 2). In PSK16, $d = A \sin \pi/16$; in QASK4, $d = \Delta$. In either case, the average probability of error is about $\exp (-d^2T/N_o)$. Thus, for PSK16, $P_e \sim \exp (-SNR/25)$ while the QASK4 $P_e \sim \exp (-SNR/10)$. A comparison of the PSK16 and QASK4 systems with equal values of $T$, $N_o$, and
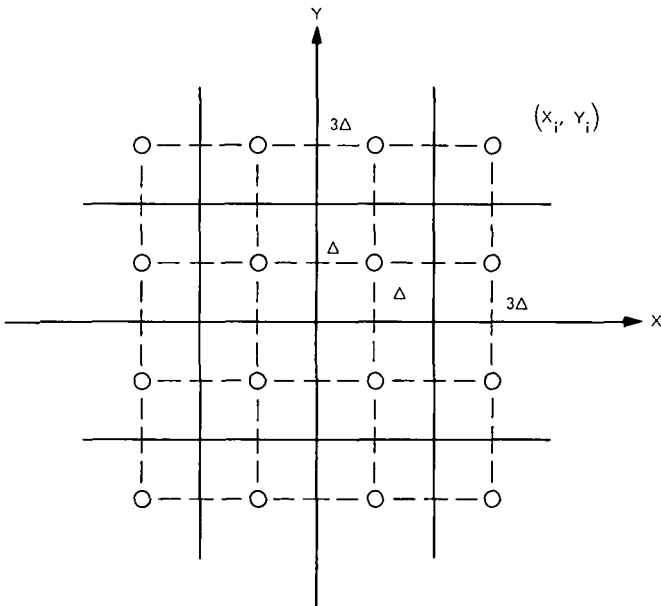
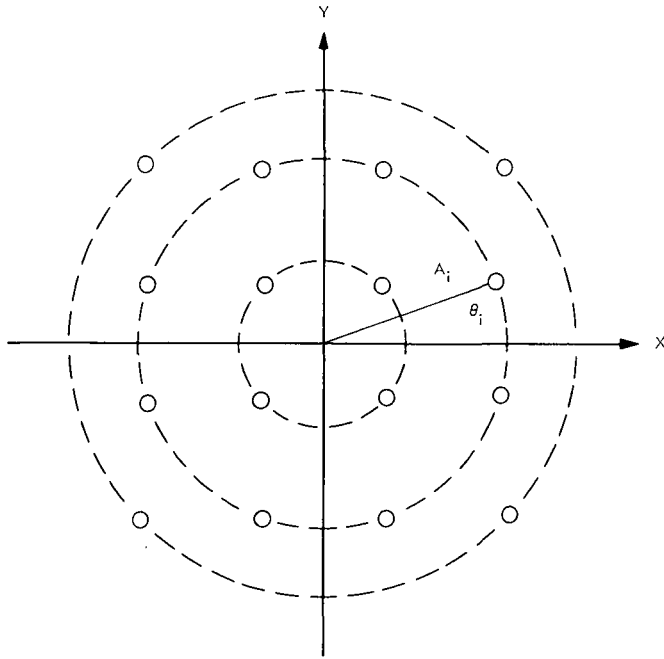

Fig. 2. QASK4 rectangular structure

Fig. 3. QASK4 circular structure

$P_e$ indeed verifies that the SNR requirements of QASK4 is 40% of that of PSK16, a 4-dB difference.

## Transmitter Configurations

The QASK4 System can be considered in terms of envelopes and phases as indicated in Fig. 3. If linear operation is to be obtained, the exciter must be phase modulated and the driver amplitude modulated simultaneously, as shown in Fig. 4. Another (multimode) configuration utilizes data-rate-switched Class C final amplifiers as shown in Fig. 5. The switching information indicates which power level is to be switched on during a particular signaling time.
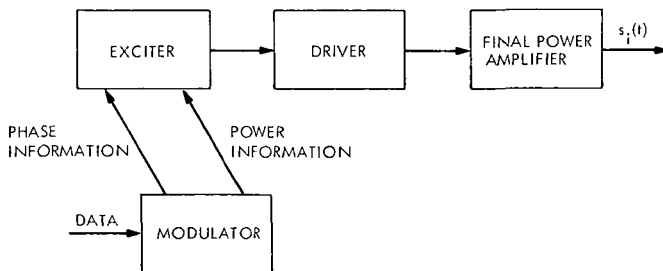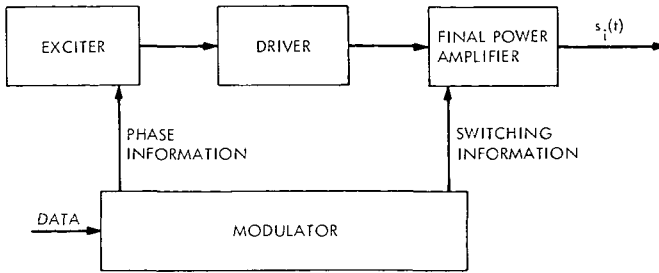


Fig. 4. QASK4 linear transmitter

Fig. 5. QASK4 multimode transmitter

The PSK16 System by comparison is fairly straightforward, requiring simple low-level phase modulation, a driver chain, and some form of saturated final stage, as indicated in Fig. 6.

## S-Band Device Models

A set of device models useful in characterizing transmitter configurations is described, based on current development technology (Ref. 3). These include exciters, Class A and Class C solid-state amplifiers, diode switches, and TWTs.

The exciter produces up to 30 mW of modulated S-band power with an input power of 1.25 W. A 33% efficient S-band Class A amplifier with 10-dB gain is typical of present technology.

At S-band below 1-W output level, 50% efficient Class C solid-state amplifiers with gains to 10 dB are not unusual. Above this power level gains of 7 dB have been obtained, also with 50% efficiency. Based on current development efforts, 10-dB gain, 50% efficient solid-state Class C amplifiers with 10-W outputs are not unreasonable projections, and are assumed here.

Recent developments in microstrip RF switches include diode switches capable of megabit switching rates of S-band power up to 50-W power levels with less than 0.25-dB insertion loss and more than 35-dB isolation. Switching power of 200 mW is required for every "on" diode. For the 2P3T
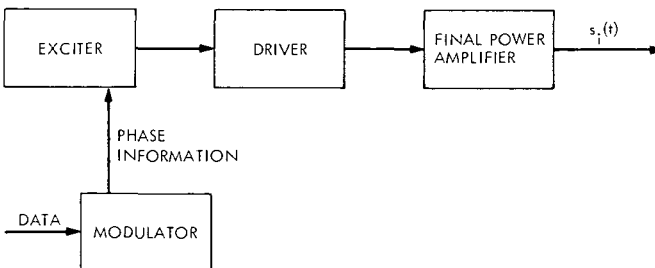


Fig. 6. PSK16 transmitter

switches considered here, this represents a constant 400-mW power drain (Ref. 4).

Traveling wave tubes designed for saturated operation at 20 or 30 W can achieve 43% and 45% efficiency, respectively. Running comparable tubes and reduced power levels, Class A, results in reduced efficiency. Recall that the QASK4 system runs at three power levels with relative values of 1, 5, and 9; that the average power is the middle value, and 4 dB below the PSK16 system compared. Thus, the QASK4 TWT competing with the 20W PSK16 TWT must run at 1.6 W, 8.0 W, and 14.4 W, while the QASK4 TWT competing with the 30 W PSK16 TWT must operate at 2.4 W, 12 W, and 21.6 W. Based on current development technology, 25%, 35%, and 45% efficiencies are assumed at each of these three relative power levels, respectively, except at 14.4 W where 40% is assumed. A 30-dB gain is assumed in each case.

## System Configurations

Consider four PSK16 systems with outputs of 1, 10, 20, and 30 W. Assume the two lower power systems use Class C solid-state final stages; the higher power systems use saturated TWTs. These four systems are the first systems shown in Figs. 7a, 7b, 7c, and 7d.

A comparison is now made of several groupings of PSK16 and QASK4 configurations. First, two 400-mW average power QASK4 transmitters are compared with the 1-W PSK16 system (Fig. 7a). One of these uses unsaturated final stage operation; the other utilizes diode-switched parallel Class C finals. Both utilize solid-state final amplifiers. Secondly, two 4-W average power QASK4 systems are compared with the 10 W PSK16 (Fig. 7b). Again, both unsaturated and diode-switched, parallel saturated solid-state finals are considered. Finally, two QASK4 systems utilizing unsaturated TWT finals are compared with the higher power PSK16s as shown in Figs. 7c and 7d. Data-rate-switched parallel TWTs are either not efficient or involve tremendous energy transients, depending on whether or not the helix and beam voltages are switched; thus, they are not compared.

## Comparisons of Systems

System power inputs, outputs, and efficiencies are shown in Table 1 along with dB power margins of competing systems.

For example, the input power to System No. 4 is 1.25 W for the exciter, 200 mW and 2 W for the Class C drivers, and 20 W for the final. Thus, 10 W of output power is achieved for 23.5 W of input, an efficiency of 42.5% for the PSK16 system. System No. 5 requires 15.9 W for 4 W out (25%) while System No. 6 consumes 11.7 W for 4 W out (34.0%).

At the 1-W level, savings in power (or PNR) of 1 to 1.3 dB are achieved by the QASK4 system over the PSK16. This savings is rather modest, and is limited primarily by the relatively large exciter requirements in all configurations.

No. 1

EXCITER — 20 mW — ▷C — 100 mW — ▷C — 1.0 W — PSK16

No. 2

EXCITER — 3, 15, and 27 mW — ▷A — 30, 150, and 270 mW — ▷A — 80, 400, and 720 mW — QASK4

No. 3

EXCITER — 20 mW — ▷C — 90 mW — 85 mW — 80 mW — QASK4

▷C — 425 mW — 400 mW

▷C — 760 mW — 720 mW

No. 4

EXCITER — 20 mW — ▷C — 100 mW — ▷C — 1 W — ▷C — 10.0 W — PSK16

No. 5

EXCITER — 3, 15, and 27 mW — ▷A — 30, 150, and 270 mW — ▷A — 80, 400, and 720 mW — ▷A — 0.8, 4.0, and 7.2 W — QASK4

No. 6

EXCITER — 20 mW — ▷C — 90 mW — ▷C — 900 mW — 850 mW — 0.8 W — QASK4

▷C — 4.25 W — 4.0 W

▷C — 7.60 W — 7.2 W

No. 7

EXCITER — 20 mW — ▷TWT — 20.0 W — PSK16

No. 8

EXCITER — 3, 15, and 27 mW — ▷TWT — 1.6, 8.0, and 14.4 W — QASK4

No. 9

EXCITER — 30 mW — ▷TWT — 30.0 W — PSK16

No. 10

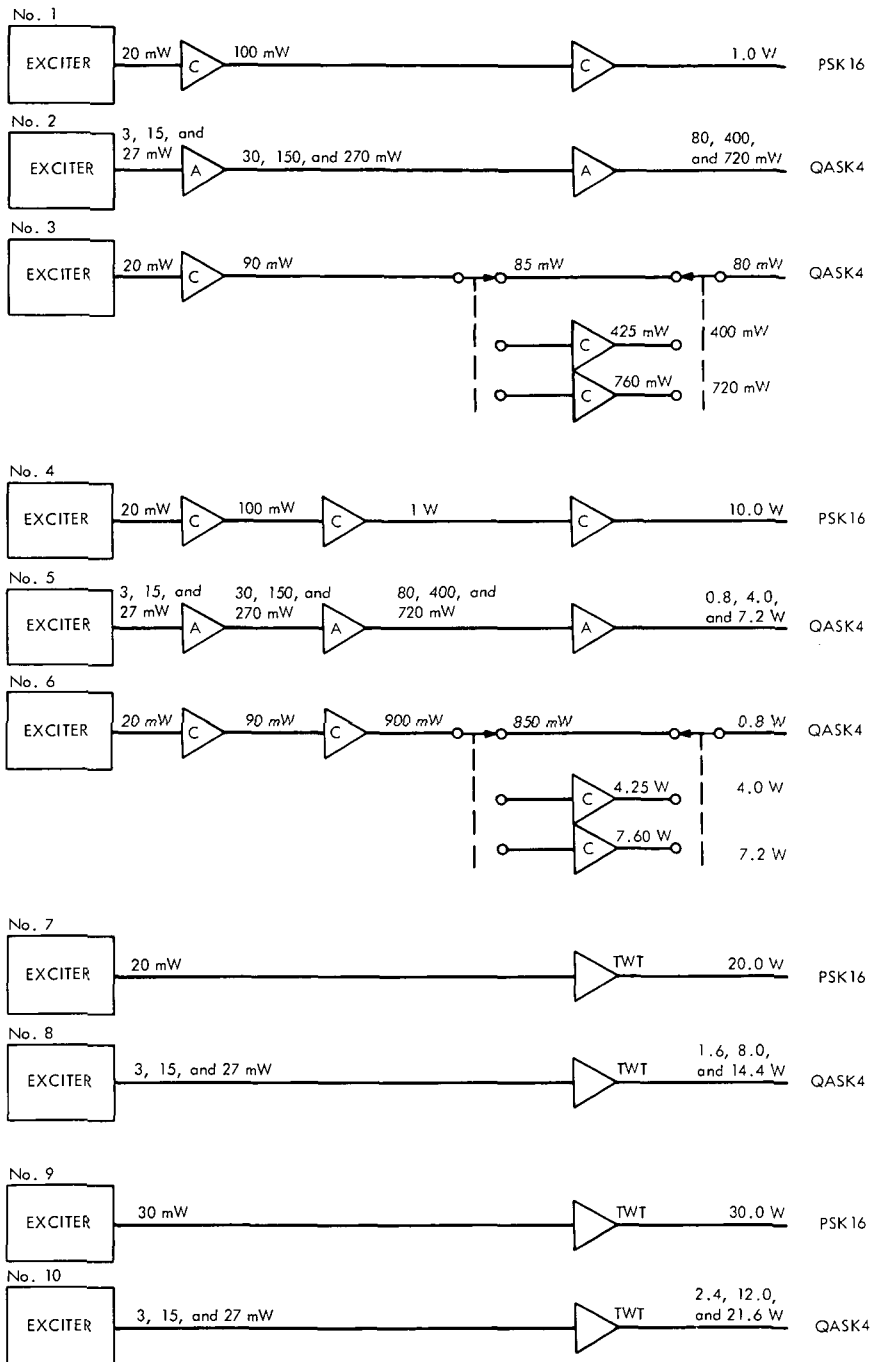EXCITER — 3, 15, and 27 mW — ▷TWT — 2.4, 12.0, and 21.6 W — QASK4

**Fig. 7. Block diagrams and power levels of 10 systems: (a) 1-W equivalent systems; (b) 10-W equivalent systems; (c) 20-W equivalent systems; (d) 30-W equivalent systems**

Table 1. Comparisons of candidate transmitter configurations

| System No. | System description | Average output, W | Average input, W | Average PNR savings, dB | Average Efficiency, % |
|---|---|---|---|---|---|
| 1 | PSK16 | 1 | 3.5 | 0.0 | 29.0 |
| 2 | QASK4, Class A | 0.4 | 2.7 | 1.1 | 14.8 |
| 3 | QASK4, Class C | 0.4 | 2.6 | 1.3 | 15.4 |
| 4 | PSK16 | 10 | 23.5 | 0.0 | 42.5 |
| 5 | QASK4, Class A | 4 | 15.9 | 1.5 | 25.0 |
| 6 | QASK4, Class C | 4 | 11.7 | 3.0 | 34.0 |
| 7 | PSK16, W/TWT | 20 | 47.4 | 0.0 | 42.0 |
| 8 | QASK4, W/TWT | 8 | 23.4 | 3.1 | 34.0 |
| 9 | PSK16, W/TWT | 30 | 68.0 | 0.0 | 44.0 |
| 10 | QASK4, W/TWT | 12 | 34.5 | 2.9 | 35.0 |

At the 10-W level, the PNR savings (QASK4 over PSK16) is 1.5 dB if QASK4 linear operation is utilized and 3 dB if QASK4-switched Class C final stages are used.

Finally, at the 20- and 30-W levels, PNR savings (QASK4 over PSK16) of about 3 dB are achieved.

## Conclusions

In a bandwidth constrained environment, M-ary systems must compete on the basis of dc power required to maintain a specified error rate. This basis can be portrayed as the ratio of average RF output signal-to-noise and transmitter efficiency. It is easy to verify that QASK4 requires 4 dB less signal-to-noise than PSK16. The remaining issue is that of relative efficiencies. An attempt has been made to accurately assess the device and system efficiencies of PSK16 and QASK4 transmitter configurations based on current development technological levels. The results indicate that the losses in QASK4 transmitter efficiencies are more than offset by the decreased SNR requirements, in some cases by as much as 3 dB.

Many other factors, such as modulator complexity, modulator power drain, switch transients, dc/dc conversions, and receiver synchronization must be considered before asserting firmly that multiamplitude transmission does compete well with constant energy modulation systems; however, on the basis of this brief examination, multiamplitude communication does appear competitive.

# References

1. Arthurs, E., Dym, H., "On the Optimum Detection of Digital Signals in the Presence of White Gaussian Noise," *IRE Transactions on Communication Systems,* CS-10, pp. 336-372, December 1962.

2. Gilbert, E. N., "A Comparison of Signaling Alphabets," *Bell Syst. Tech. J.,* Vol. 37, pp. 504-522, May 1952.

3. Dickinson, R. M., Detweiler, H., Choi S., of Jet Propulsion Laboratory, Pasadena, California. Private communication.

4. Choi, S., "High-Power Microstrip RF Switch," *JPL Quarterly Technical Review,* Vol. 1, No. 3, October 1971.