Missile Communication Links

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Standard Missile (SM) is a family of surface-to-air missiles used on U.S. Navy destroyers and cruisers. As the U.S. Navy's Technical Direction Agent for SM, APL has been involved with the development and in-service use of numerous aspects of this missile, including all of its variants, since their conception. One of the many aspects of APL's involvement is in the area of missile communications links that were introduced into SM in the early 1970s to support its new midcourse guidance mode. APL's efforts in this area include concept development, design, analysis, testing, test equipment design, modeling and simulation, and systems engineering. This article provides an overview of the current communications links used by SM and discusses the Preplanned Product Improvement Link, a new communications link development for SM and the Evolved Seasparrow Missile that also is used by the U.S. Navy on some of their combat ships.

INTRODUCTION

All Standard Missiles (SM) except for SM-1, the oldest variant, use a communications link. SM-1 was a home-all-the-way guided missile that received its homing guidance signal from target-reflected energy provided by a high-power transmitter, called an illuminator, residing on the Terrier and Tartar ships from which it was launched. The development of SM-2, the first SM to use a communications link, began in the early 1970s, with General Dynamics/Pomona as the design agent and APL as technical advisor.[1] The principle upgrade made to SM-1 in order to realize the SM-2 variant was the addition of a midcourse guidance phase of flight. This midcourse phase of flight allows the support of more missile engagements in a given time period because the illuminator, which is required for the entire SM-1 flight, is a limited shipboard resource. Aegis destroyers have three illuminators, and cruisers have four. When midcourse guidance is used, the illuminator is required only during the brief terminal homing phase of flight. The reduced terminal homing time increases the illuminator's availability to support other missiles entering into terminal homing. A communications link between the ship and missile, which is the topic of this article, is a required component for midcourse guidance. This article provides an overview of current SM and Evolved Seasparrow Missile (ESSM) communications links and discusses a new link development for these missiles. APL was a key contributor to the current communications links and is playing a key role in the new link development.

CURRENT LINKS

SM-2 has five distinct operational phases, as shown in Fig. 1. In the first phase, called prelaunch, the ship-to-missile communications link is initialized via wire to be in either the Aegis mode or the Terrier/Tartar (2T) mode. The boost phase comes next. In the Aegis mode, the wireless RF communications link is used by the AN/SPY-1 radar to acquire and track the missile. The 2T link does not have a downlink, and missile tracking is done by the ship's radar return signal. The midcourse phase follows with the ship sending data to the missile by a wireless RF transmission referred to as an uplink, and in the Aegis mode, the missile responds to each uplink with a wireless RF transmission referred to as a downlink. In the homing phase, the missile uses its sensor to guide to the target using RF or IR energy. In the Aegis mode, the ship continues sending uplinks to the missile during the homing phase. In the 2T mode, the ship can send its missile an uplink in the homing phase, but this typically is not the case. During the endgame phase, the missile uses fuzing and a warhead to damage the target.

The Aegis mode implements a type of midcourse guidance referred to as command guidance. In the case of command midcourse guidance, acceleration commands computed by the launch ship are transmitted to the missile on the uplink. The Aegis uplink, transmitted by the AN/SPY-1 radar to SM or ESSM, is in the S-band (defined as 2–4 GHz) portion of the RF spectrum. Data bits are encoded in either one of two frequency tones. A tone transmitted at frequency f_1 represents a logical 0, and a tone transmitted at frequency f_2 represents a logical 1. This modulation is called frequency-shift keying (FSK). Also, the phase of the tones is continuous between bit transitions. Phase continuity between bit transitions results in a narrower frequency spectrum than do phase discontinuities between bit transitions. A narrow frequency spectrum is important to prevent an uplink transmission from interfering with an SM or ESSM that might be receiving uplinks on an adjacent channel. In the Aegis system, the missile always responds to an uplink with a downlink transmission. The downlink, also at S-band, uses pulse position modulation and sends back missile status information.

As shown in Fig. 2, the 2T mode implements a type of midcourse guidance referred to as inertial guidance, where the missile is sent information about a point in space to fly toward; this point is known as the primary command point (PCP). Once the missile reaches the vicinity of the PCP, it begins to search for the target using the RF seeker to track the target-reflected energy from the illuminator. In this mode, additional uplinks are not transmitted in the midcourse phase unless the target maneuvers enough to cause the PCP to change significantly. The 2T link, which is used by our foreign missile sales customers (e.g., The Netherlands, Germany, South Korea, Taiwan, etc.), employs SM-2 and ESSM and provides only an uplink from the launching ship to the missile. A downlink can be added to respond to the 2T uplink. Taiwan, for example, uses an S-band downlink with the 2T uplink. The 2T uplink operates in the X-band (defined as 8–12.5 GHz) portion of the RF frequency spectrum and uses FSK of a phase-modulated subcarrier of the ship's illuminator. The 2T bit rate is more than three orders of magnitude lower than the bit rate of the Aegis link. This difference results because the 2T link modulates a subcarrier, whereas the Aegis uplink modulates the carrier directly.

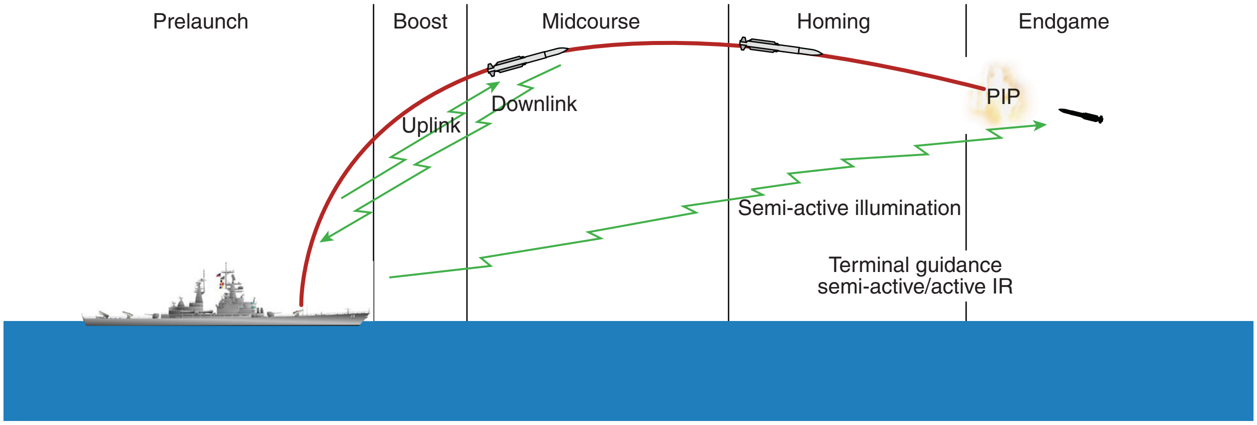

Figure 1. SM-2 flight phases. The missile communications link provides data to allow the missile to fly an efficient trajectory toward the predicted intercept point (PIP). The trajectory may be computed on the missile (inertial guidance) by using data on the uplink from the ship or at the ship (command guidance) and sent on the uplink to the missile.

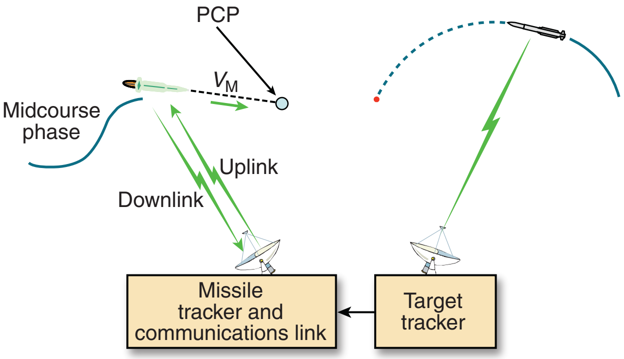

Figure 2. Illustration of inertial midcourse guidance. The ship radar tracks the target and missile and sends target-state vector and PCP coordinates to the missile as required based on target maneuvers.

The missile communications link components consist of antennas, a receiver or transceiver, and an encoder/decoder commonly called a modulator-demodulator (modem). The receiver/transceiver and modem reside in separate sections, designated as plates. The Plate 3A Aegis command link transceiver contains an S-band uplink receiver and downlink transmitter. The uplink receiver takes the RF signal captured by the antenna, down-converts the signal to an intermediate frequency, demodulates it, and passes it to the encoder/decoder (Plate 4C) for decoding. The downlink transmitter amplifies and transmits an S-band signal that has been pulse position-modulated by the encoder. Figure 3 illustrates the SM-2 S-band Aegis link components. For the 2T link, the link receiver unit, designated as Plate 1, contains an X-band uplink receiver that also is used to receive the rear reference signal from the illuminator for terminal homing. The 2T waveform also is decoded in Plate 4C. Plate 2, the digital signal processor (DSP)/control computer plate, makes use of the link data to guide the missile in midcourse and search for the target.

P^{3}I COMMUNICATIONS LINK DEVELOPMENT

APL has contributed to several new SM communications link developments over the last 8 years. This article discusses the Preplanned Product Improvement (P^{3}I) link project.

New X-band multifunction radars (MFRs) recently have entered operational capability or currently are in development. For example, active phased array radar, the MFR used by the Trilateral Frigate Cooperation Program composed of the navies of The Netherlands, Germany, and Canada, is operational on seven Trilateral Frigate Cooperation ships. Active phased array radar uses the 2T link to communicate with SM and ESSM, and scheduling those links along with all of its other functions is a challenge. The AN/SPY-3 is the U.S. Navy's MFR that currently is under development for the DDG-1000 next-generation destroyer. Figure 4 shows the functions that AN/SPY-3 is required to perform.

The 2T link would pose too severe a burden on the time−energy budget of the AN/SPY-3. This was a moti-

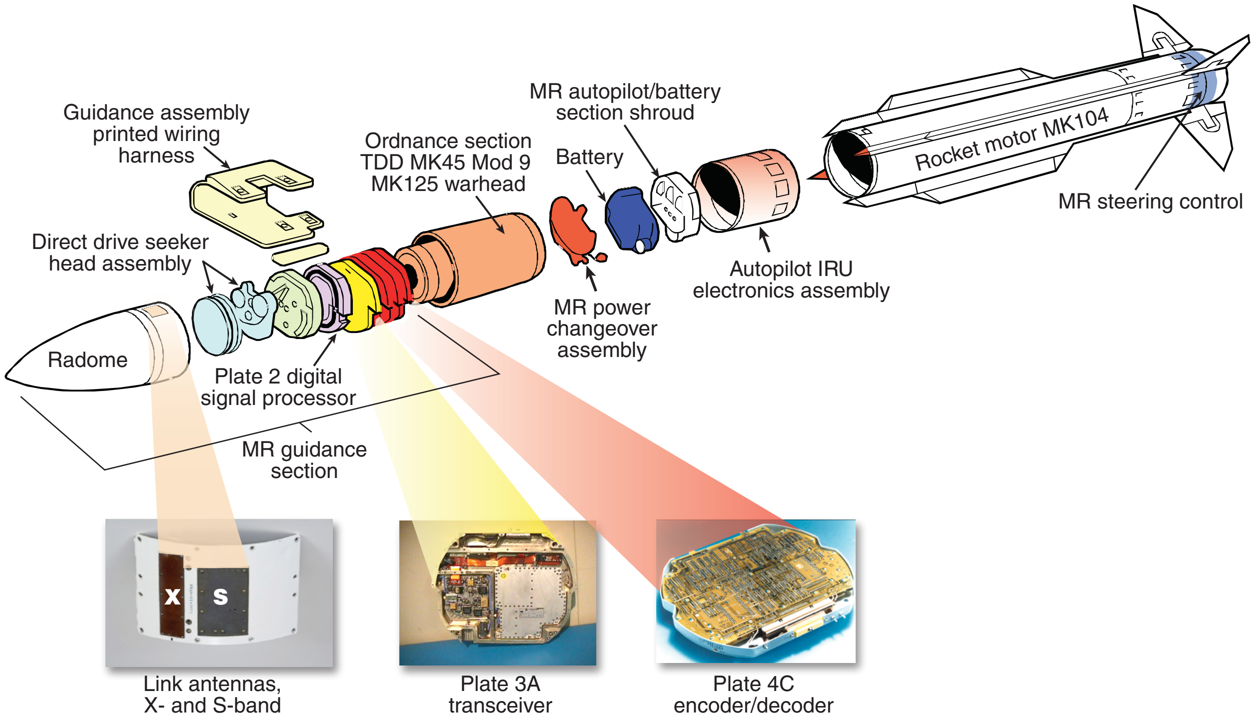

Figure 3. SM-2 S-band Aegis link components. (Upper) The medium-range configuration of the SM-2 missile. (Lower) Aegis S-band link components consisting of the antenna, transceiver, and encoder/decoder. IRU, inertial reference unit; MR, medium range; TDD, target-detecting device.

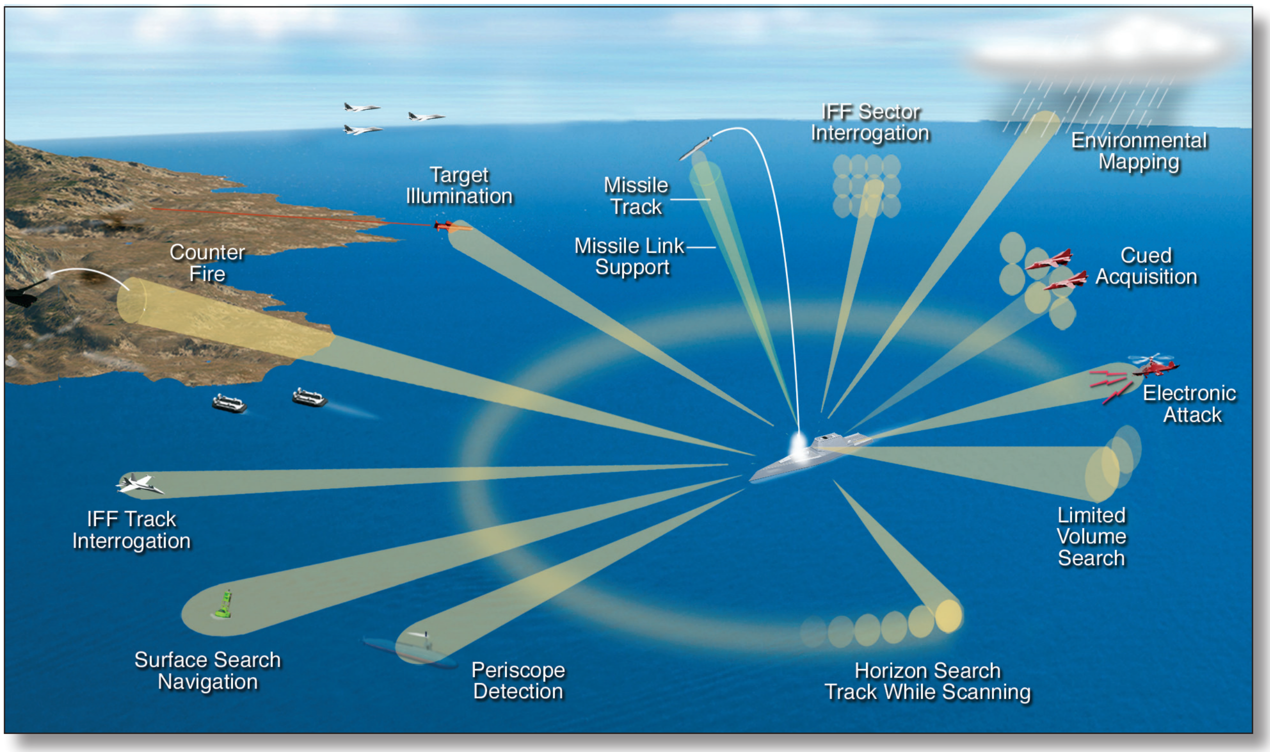

Figure 4. Functions that must fit within the AN/SPY-3 X-band radar time–energy budget. Missile link support using the existing 2T missile communications link would consume a considerable portion of that budget.

vating factor for developing a new link that would consume only a small amount of an MFR's time–energy budget. Other considerations for a new link include the opportunity to add error-control coding and to include more data bits in the downlink. The P^{3}I link was conceived by APL and Raytheon Missile Systems in Tucson, AZ. Its primary purpose was to provide communications between an X-band MFR and missiles launched from that radar's ship while still leaving time for the MFR to perform its other functions.

As the SM Technical Direction Agent, the role of APL is to assist in the development of initial concepts, develop performance specifications, investigate solutions, assess alternatives, and evaluate design agent achievements. APL SM Technical Direction Agent responsibilities on the P^{3}I X-band link were the following:

1. Assist in the development of the link's top-level requirements.
2. Assist in the development, review, and performance confirmation of the uplink/downlink waveforms.
3. Develop independent link margin analyses, to permit review and confirmation of contractor analyses.
4. Assist in the development and review of the bit-error analysis for the selected modulation technique.
5. Suggest, review, and confirm SM trajectories and orientations to be used in link margin analyses.
6. Act as technical lead for several enhancements to be incorporated as "spiral developments."

The P^{3}I link design uses some of the principles of software-defined radio. An emerging form of radio architecture technology, software-defined radio affords the ultimate in flexibility because the radio can be reconfigured in the field by reprogramming as opposed to hardware changes. These programmable devices include a DSP, a field-programmable gate array (FPGA), a direct digital synthesizer (DDS) for waveform synthesis, and central processing units (CPUs). A block diagram of the P^{3}I link is shown in Fig. 5.

Packaging the P^{3}I link transceiver and modem in the available volume in the 13-inch-diameter SM and the 10-inch-diameter ESSM is a major technical challenge. Fortunately, because of its shorter range, ESSM does not require output power as high as that required for SM-6, the long-range SM variant. Therefore, the ESSM downlink transmitter can be smaller than the transmitter required for SM-6.

The P^{3}I link team considered various modulation types and selected a special type of minimum-shift keying (MSK) for both the uplink and downlink modulation. MSK was selected because of its compact spectrum, which minimizes interference to missiles operating on neighboring channels, and its constant envelope waveform characteristic, which is compatible with power amplifiers used in radar that are operated near saturation for high efficiency.

MSK is a binary continuous-phase FSK modulation. The binary frequencies that represent the digital infor-

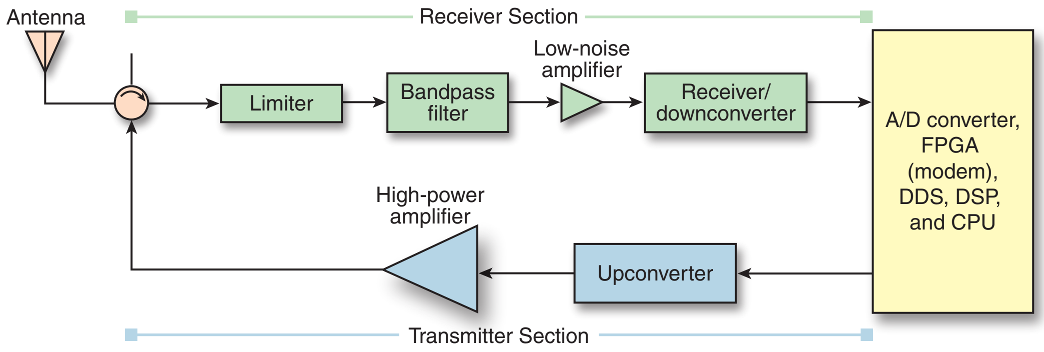

Figure 5. P^{3}I X-band data link functional block diagram. A/D, Analog to digital.

mation being transmitted have a separation of $f = m/2T$, where T is the bit width and m is the modulation index. For MSK, the modulation index is 0.5. The MSK frequency separation is the minimum frequency separation that is necessary to ensure that the signal frequencies are orthogonal over a signaling interval of length T; hence the name *minimum*-shift keying. MSK provides a compact power spectrum compared to quadrature phase-shift keying (QPSK) and offset QPSK (OQPSK), two other digital modulations. The power spectral density versus frequency from the carrier normalized by the bit rate, f_b, for MSK, QPSK, and OQPSK is shown in Fig. 6.

The MSK power spectrum can be reduced further by pulse shaping with a Gaussian low-pass filter. This modulation is called Gaussian minimum-shift keying (GMSK). The bandwidth-time product BT, where B is the −3 dB bandwidth of the Gaussian filter and T is the bit width, is the parameter that defines the spectral shaping for this modulation. The power spectral density of MSK and GMSK for $BT = 0.5$ and 0.3, respectively, is shown in Fig. 7. Ref. 2 provides the fundamental properties of GMSK.

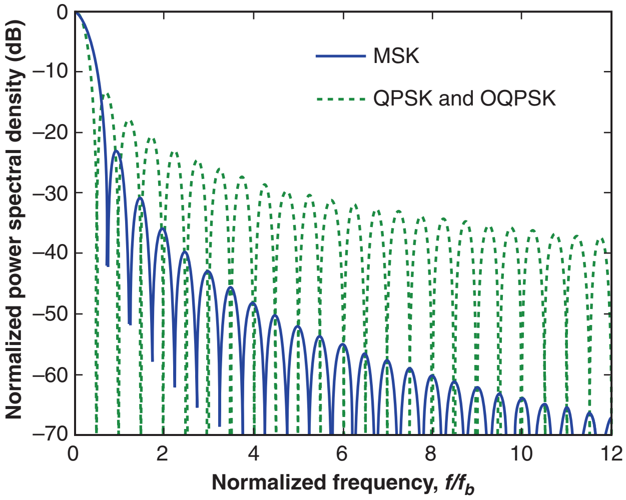

Figure 6. Normalized power spectral density for MSK, QPSK, and OQPSK. The variable f is frequency offset from the carrier, and f_b is the bit rate.

The Gaussian pulse can be described by equation 2 from Ref. 3 as follows:

$$g(t) = \left(Q[2\pi B(t - T/2)/(\ln 2)^{1/2}] - Q[2\pi B(t + T/2)/(\ln 2)^{1/2}]\right)/2,$$

where B is the filter −3 dB bandwidth, T is the bit width, and $Q(t)$ is

$$Q(t) = \int_t^\infty \frac{1}{\sqrt{2\pi}} e^{-x^2/2}\, dt.$$

Figure 8 shows GMSK pulse shapes for two values of bandwidth-time products. For $BT = 0.1$, the pulse spans multiple bit intervals and gives rise to a type of interference known as intersymbol interference (ISI), making demodulation more difficult. For $BT = 1$, nearly all the pulse is contained in one bit interval, resulting in insignificant ISI.

GMSK has been adopted as the modulation for the Global System for Mobile Communications used for European and several other international applications. The Global System for Mobile Communications is the most popular standard for mobile phones worldwide.

In digital communication systems, the probability of making an error is a function of the ratio of the energy

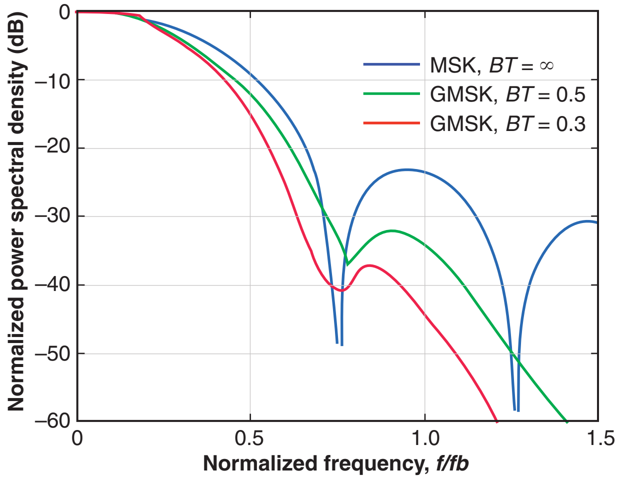

Figure 7. Normalized power spectral density for MSK and GMSK.

in the received bit, denoted as E_b, to the received noise power spectral density, N_0. MSK has an error performance that is equivalent to that for QPSK and OQPSK, as shown by the probability of error versus E_b/N_0 (Fig. 9). GMSK results in a slightly larger probability of error than MSK for a given transmitted power, but this degradation is insignificant for $BT \geq 0.8$.

Error performance can be improved with the use of error-control coding. Advances in technology make it practical to include error-control coding in the P^{3}I link. This was not the case when the Aegis link was developed in the early 1970s. With the Aegis link, when the missile detects one or more errors, it sends this information on the downlink and that uplink is resent. Error-control coding allows the trade-off of transmit power for coding gain. The P^{3}I downlink has limited effective radiated power, and error-control coding is an excellent way to improve error performance given the transmit power constraints in the missile. There are two fundamental types of error-control codes: convolutional codes and block codes. Convolutional codes can be generated by linear shift registers that perform convolution operations on the information sequence. Block codes consist of a set of fixed-length vectors called code words. When the elements of a code word consist of logical 0 and logical 1, the code is a binary code and the elements of the code are called bits. A shorthand notation for describing block codes is (n, k), where n is the number of bits in each code word and k is the number of data bits. This leaves n-k parity bits for error detection and correction. When the elements of the code consist of groups of bits, called symbols, the code is non-binary. For non-binary codes, (n, k) denote symbols. A popular non-binary code is Reed-Solomon (R-S). R-S codes can correct up to (n-k)/2 symbol errors. R-S codes were selected for the P^{3}I uplink and downlink. The Joint Tactical Information Distribution System, which may now be destined to become standard for all tactical military communications links of the U.S. Armed Forces and possibly several or all of the North Atlantic Treaty Organization countries as well, has adopted the R-S coding.

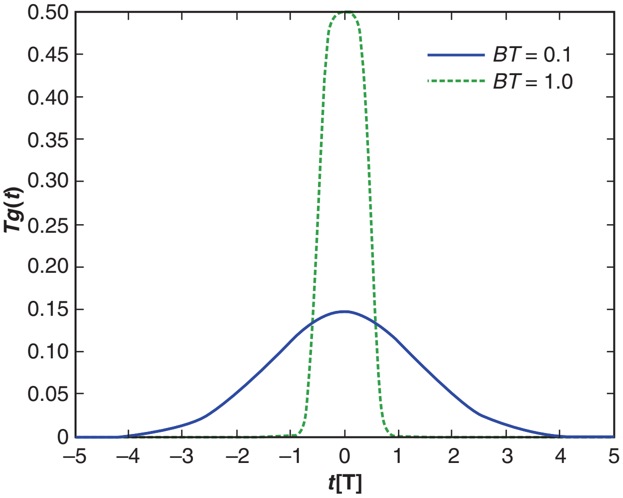

Figure 8. GMSK time-domain pulse shapes for $BT = 0.1$ and 1. For $BT = 0.1$, the pulse is spread over more than three bit intervals, giving rise to ISI. For $BT = 1$, the pulse is essentially confined to one bit interval, causing insignificant ISI.

Link budget analysis is another task that APL has performed on the P^{3}I link project. A link budget is the accounting of all of the gains and losses from the transmitter through free space to the receiver in a wireless communication system. Often one is interested in link margin, which is the difference between the received signal power to noise power ratio, $(S/N)_{rec}$, and the required ratio, $(S/N)_{req}$, to achieve a specified probability of message success. Link margin is usually expressed in decibels. Six-degree-of-freedom fly-out trajectories provide the missile's range from the launch point and orientation in roll, pitch, and yaw as a function of time. The missile's orientation determines the missile's antenna gain in the direction of the ship and of jamming when present. The received signal power is given by

$$S = \frac{P_t G_t \lambda^2 G_r}{(4\pi R)^2 L},$$

where S is the power received, P_t is the power transmitted, G_t is the transmitter antenna gain, λ is the transmitter wavelength, G_r is the receiver antenna gain, R is the range from transmitter to receiver, and L_r is losses (multipath, plume attenuation, and rain attenuation).

There are several types of noise, with the major contributors being thermal noise in the receiver and jammer noise produced by an adversary. Jammer noise, when present, adds to the receiver thermal noise, thereby increasing the total noise level in the receiver. The

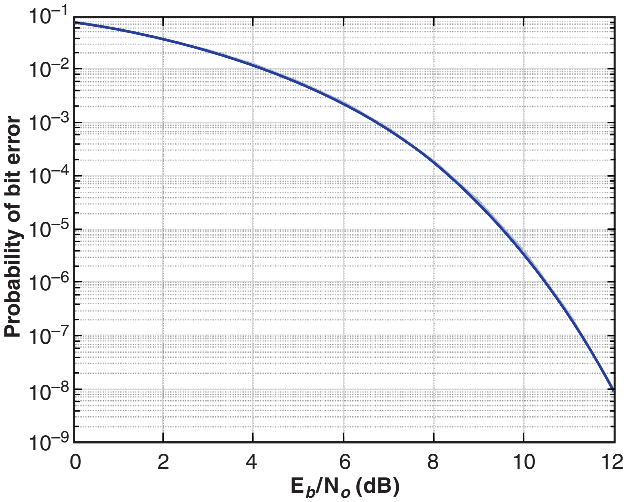

Figure 9. Probability of bit error for coherent detection of MSK, QPSK, and OQPSK in an additive white Gaussian noise channel.

receiver thermal noise is given by $N = kTBF$, where k is Boltzmann's constant (1.38×10^{-23} joules/K), T is temperature (K), B is receiver noise bandwidth, and F is receiver noise figure.

Recall that for digital communication systems, error performance depends on the received E_b/N_0, as shown in Fig. 9 for MSK modulation. The received

$$\frac{E_b}{N_0} = \frac{S}{N}\left(\frac{B}{f_b}\right),$$

where B is the receiver −3-dB noise bandwidth and f_b is the bit rate.

For the P^{3}I link, the process outlined above was iterative, with trade-offs made to arrive at the desired link margin while meeting other system requirements. For example, one needs a high transmission bit rate to minimize the time–energy loading on the system. However, high bit rates reduce E_b, which increases the bit error probability unless the transmitter power is increased or error-control coding is used. But most forms of coding increase the required bandwidth, which needs to be constrained to avoid adjacent channel interference. Therefore, trade-offs were needed to meet system requirements while simultaneously controlling design complexity and cost.

SUMMARY

APL's involvement with missile RF communications links for both U.S. Navy and foreign missile sales customers spans nearly 40 years. During this time, we have worked closely with the design agents who design and produce the systems. We have been involved in many aspects of missile communications links, including concept development, requirements, design, integration into the combat system, analysis, and testing. APL has been instrumental in ensuring that the new links include the state-of-the-art technology necessary to operate in increasingly stressful environments. The P^{3}I link with its new X-band waveform will be used on the DDG-1000, the U.S. Navy's latest destroyer, which is expected to be operational circa 2013. APL has made significant contributions to the P^{3}I link, beginning with concept development and including requirements development and performance modeling. New requirements and technology advances should keep APL involved with missile communications for the foreseeable future.

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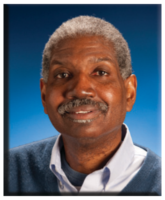

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