Optimized SAW Spectral Control Filters for Digital Satellite Communications System

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Abstract—A series of SAW filters with bandpass characteristics optimized for digital transmission has been developed for use in the Defense Satellite Communication System (DSCS). Features of the SAW filters, then implementations into the system, and results of system tests are described. A spectrum efficiency 30 percent greater than by competing techniques is achieved.

I. Introduction

ONE OF THE most valuable features of surface acoustic waves (SAW) technology in improving system performance is the relative independence of phase and amplitude response of transversal-type filters. Almost immediate exploitation was made of the ability of SAW filter to provide linear phase characteristics consistent with duplication of highly useful amplitude–frequency characteristics based on well-known filter theory. Subsequent advances have led to even more useful amplitude–frequency characteristics by direct computer synthesis allowing both phase and amplitude characteristics to be independently determined through optimization processes. This optimization was performed to produce spectral control filters with particular bandpass characteristics optimized for digital transmission. This process leads to characteristics which would be difficult or, at best, very expensive to duplicate in quantity in multipole *LC*, crystal, or resonator-type filters. This paper provides an example of such an application in which the objective was transmission of offset quadraphase shift key (OQPSK) modulation while achieving minimum channel spacing required for an acceptable error rate performance at a given signal-to-noise ratio.

Unlike terrestrial line-of-sight communication systems, satellite system downlink transmission is severely power limited. This has led to the use of large earth terminal antenna apertures and to error correction coding which improves power efficiency in exchange for increased bandwidth. The rapid growth of user data rate requirements, however, calls for improved spectrum utilization. Thus to satisfy user requirements with limited satellite transponder bandwidth, increased spectrum efficiency consistent with the efficient use of downlink signal power is an increasingly important objective. The SAW filter program was initiated by the Defense Communications Engineering Center with the test and production contract going to Westinghouse Defense and Electronics Systems Center managed by the U.S. Army Satellite Communications Agency [1].

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I. Synopsis of System

The system is frequency-division multiple access (FDMA) in which user stations access channels from available spectrum space on the repeater satellite. A simplified diagram of a typical satellite link is shown in Fig. 1. Although only two accesses of the satellite are shown, a large earth station would typically have many accesses. Additionally, a DSCS transponder can include up to fifty accesses with many other stations sharing the satellite. With FDMA the accesses are separated by operation at different assigned frequencies. If the frequencies can be assigned close to each other, then the maximum use can be made of the limited satellite bandwidth. Also compliance with international frequency management regulations require tight control of emission outside assigned bandwidths. The filters which have been developed, minimize the bandwidth requirements for digital PSK accesses.

Because of extremely rapid growth of demand for channel space, recognition of the need for improved spectrum control came after many elements of the system were developed and in place. A mechanization approach was selected which allowed for use of the filters on existing equipment as well as their incorporation in future equipment. For this reason, in addition to their favorable electrical properties, the predictability and reproducability of SAW filters was significant to the application where very precise bandpass characteristics were to be important. Field implementation of this system began just two years after the original concept was identified and nine months after a go-ahead decision was made.

Spectral control is necessary at both the transmitter and receiver. The transmit filter limits the occupied bandwidth of the transmitted signal. Use of OQPSK, rather than conventional QPSK (because of the nearly constant envelope characteristics of band-limited OQPSK), minimizes regrowth of the sidelobes which were removed by the

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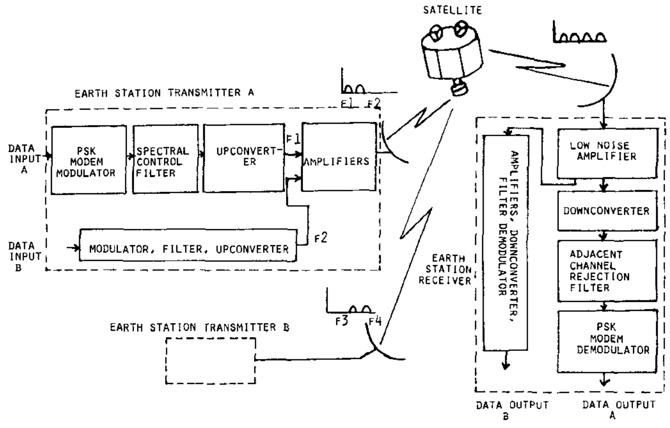

Fig. 1. Simplified satellite link.

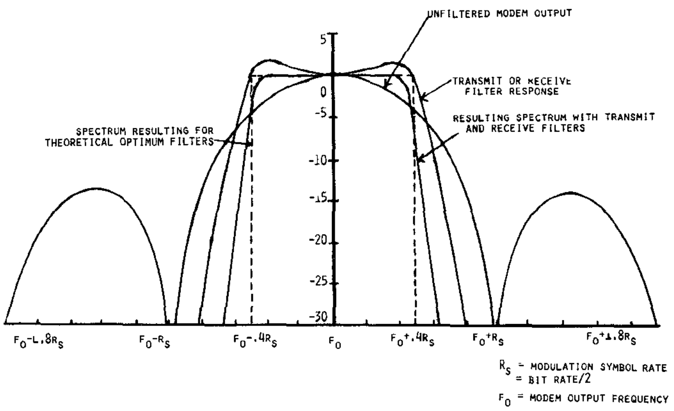

Fig. 2. Optimized shape SAW filter and unfiltered modem output.

transmit filter. Sidelobe regrowth can occur due to nonlinearity in the earth terminal high-power amplifier or, more typically, in the satellite final amplifier which is operated as close as possible, typically within 3 dB, of saturation to maximize satellite output. This operating point was established through both analysis and measurement such that all intermodulation products are significantly below the thermal-noise level. The receiver filter provides rejection of adjacent channel interference and limits the noise bandwidth. Although satellite bandwidth and power are limited, the satellite users also require that terminal size be minimized. Thus the satellite system becomes both power and bandwidth limited. The filters which have been developed and tested permit closer spacing of accesses simultaneous with maintaining bit error rate (BER) versus noise (E_b/N_0) performance near theoretical.

The filters which have been developed and tested have bandpass characteristics which have been computer synthesized for digital transmission to minimize power and bandwidth requirement [2]. The amplitude response is shown in Fig. 2. These characteristics, with the amplitude peaks, result in lower BER versus E_b/N_0 degradation due to intersymbol interference than with conventional filter types such as Butterworth. The filters also take advantage of the nearly-linear phase characteristic available with SAW filters. Linear phase is important for digital transmission. The phase nonlinearity (or group distortion) which is characteristic of conventional filters (e.g., Butterworth or Chebychev) causes intersymbol distortion which degrades BER versus E_b/N_0 performance.

Filters are used with OQPSK modems with integrate and dump detection. Identical filters are used in both the transmitter and receiver. The filter in the transmitter limits the spectral occupancy of the transmitted signal. Fig. 2 shows the filter response, the normal unfiltered QPSK modem output, and the resulting spectrum when a transmit and receiver filter used with an OQPSK modem. Also shown is the spectrum resulting from use of theoretically optimum filters (i.e., perfectly rectangular) which sets an upper bound on spectrum efficiency for a transmission approach [3]. It can be seen that the SAW filters perform significant filtering of the main lobe and substantial filtering of the secondary lobes which trail off very gradually if unfiltered. The receive filter provides rejection of adjacent channel interference.

The program for the synthesis procedure for the optimum filter begins with a conventional filter type such as a filter with the amplitude response of a five-pole Butterworth but with a linear phase characteristic [2] ([2] was produced as a part of a DCEC program). A simulated amplitude equalizer is then included in the form of a transversal filter (i.e., tapped delay lines with tap outputs summed through adjustable attenuators). The computer then uses decision-directed feedback to optimize the equivalent filter response for BER performance. The equation of the amplitude response of the resulting filter is as follows:

$$G(\omega)=0.5H(\omega)-10\log_{10}\left[1+\left(\frac{\omega\tau}{\pi}\right)^{10}\right]\text{dB}$$

where

$$H(\omega)=20\log_{10}\frac{1.115-3.78\cos(\omega\tau)+0.128\cos(2\omega\tau)-0.047(3\omega\tau)}{0.819}.$$

The second term of $G(\omega)$ is the response of a five-pole Butterworth filter. $H(\omega)$ is the transfer function of the amplitude equalizer used in the computer synthesis which provides the amplitude peaks. τ is the symbol duration (twice the reciprocal of the data rate for uncoded OQPSK). Identical filters are used at both transmitter and receiver. The response of these optimum shape filters is somewhat analogous to the baseband filters in [3] and [4]. A similar bandpass was recently reported by Henoff and Feldman [5].

II. The SAW Filters

Two frequency–amplitude bandpass characteristics were evaluated in this program [6]. The first shown in Fig. 3 is equivalent to a five-pole Butterworth filter in amplitude, but is linear in phase. The SAW bandpass used to simulate the characteristics is shown to the same scale. The SAW

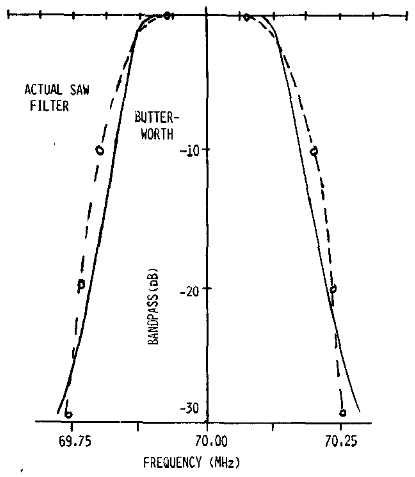

Fig. 3. Frequency–amplitude characteristics of five-pole Butterworth bandpass and SAW filter used to test error performance.

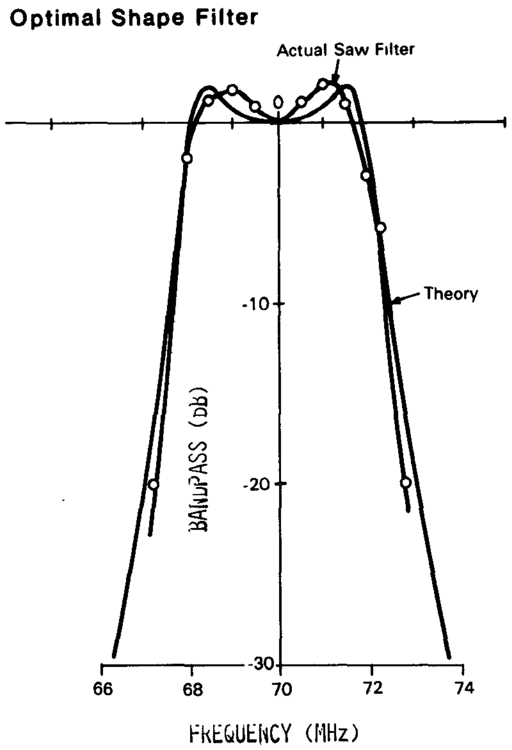

Fig. 4. Equalized filter amplitude–frequency characteristic with bandpass of SAW used to test error performance.

filter consists of one narrow-band and one broad-band transducer. The initial matched insertion loss was 16 dB but was increased to 26 dB for triple transit suppression. (Triple transit is a spurious due to acoustical reradiation of signal received at each transducer with resulting reverberation. The second time or triple travel is the most serious.) The latter was required to achieve a ripple suppression of 0.1 dB.

The second filter evaluated was based on synthesis of the equalized frequency–amplitude bandpass described above. Fig. 4 is an amplitude characteristic of this equalized bandpass along with an approximate synthesis using an impulse model [7] of this bandpass by a SAW filter. (Lack of correspondence is due to an error in data transmission to the SAW mask synthesizer. The resulting filter as tested, however, performed well enough to allow evaluation of the approach.)

III. Breadbord System Test

Initial system tests using actually fabricated SAW filters were conducted using major elements of the Defense Satellite Communications System (DSCS) including a DSCS II transponder and MD-1002 offset QPSK modems (the current generation DSCS equipment). These tests were conducted by the U.S. Army Satellite Communications Agency. Next to transmission via an actual satellite this provided as realistic a test as was possible. Tests were conducted on both the linear-phase Butterworth SAW filter and the equalized-amplitude bandpass filters. These tests when compared with simulated results for the same filters served as a basis for evaluation of the ability to duplicate simulated system characteristics with SAW filters. The linear phase Butterworth filtered system characteristics, along with unfiltered results, serve as a basis for evaluation of the SAW filter performance.

Figs. 5 and 6 show the BER versus E_b/N_0 (signal-to-noise) degradation from theoretical ([1]) for linear-phase Butterworth and the optimum shape filters. The simulation is from the computer analysis in [1]. The simulation predictions shown in Figs. 5 and 6 indicated that the optimized shape filter is superior to the linear-phase Butterworth. The optimized shape filter has approximately 2.3-dB advantage in E_b/N_0 performance for a 10^{-5} BER at a $B\tau$ of 1.0 ($B\tau$ is the bandwidth time product where τ is the symbol period). The Butterworth response used in Fig. 5 assumes linear phase; if conventional Butterworth phase distortion were assumed, the E_b/N_0 degradation would be significantly greater.

Fig. 7 shows FDMA tests using accesses that were unfiltered, with Butterworth filters, and optimum shape filters. The spectral occupany efficiency of the optimum shape filters is important for FDMA systems where access spacing is adjusted for small intra-access effects. The figure shows that both filtered accesses can operate with approximately one half the access separation as the unfiltered accesses. It also shows that the equalized amplitude bandpass access can be operated with approximately 2.3 dB lower signal-to-noise ratio than the Butterworth amplitude access. For conventional filters, even those with linear phase, a tradeoff is necessary in changing the $B\tau$ product because tighter filtering reduces adjacent channel interference but increases filter degradation (intersymbol interference). Fig. 6 indicates that this choice is not nearly so critical with the optimum filter. Additional tests, not shown here, were made with variable $B\tau$ products which substantiate this effect.

For FDMA operation using the optimum shape filters, the required access spacing for acceptably low degradation (less than 0.5 dB due to filter degradation and adjacent channel interference) is approximately 1.25 times the symbol rate. This corresponds to 1.6 bits/s/Hz, where bits per second per hertz is in terms of the access spacing in a

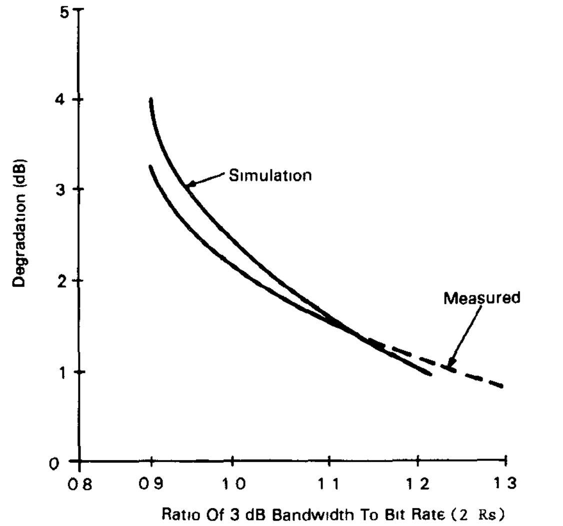

Fig. 5. Degradation of performance of QPSK for Butterworth amplitude-frequency bandpass. Baseline error rate is $P=10^{-5}$.

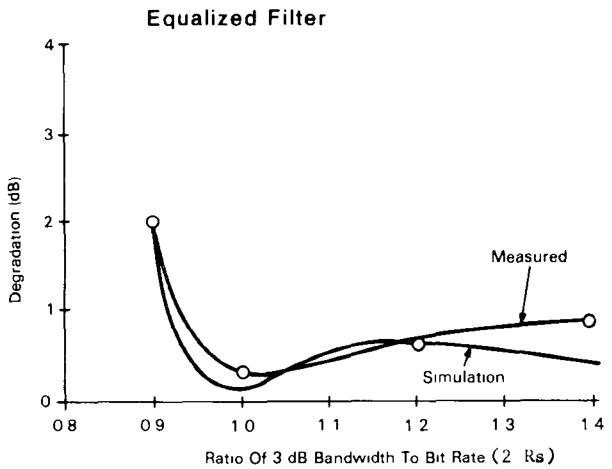

Fig. 6. Degradation of performance of QPSK for optimum shape bandpass. Baseline error state is $P=10^{-5}$.

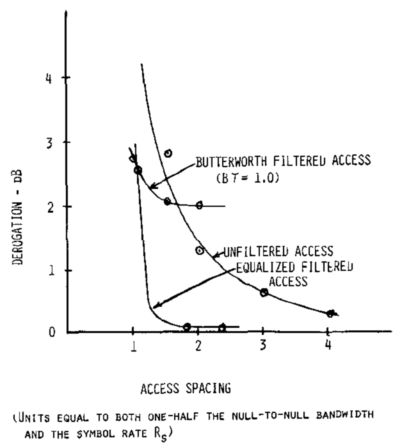

Fig. 7. Effect of access spacing on FDMA error performance of QPSK.

FDMA environment. These tests were performed with two equal-data-rate/equal-power interfering signals adjacent to the signal of interest. For the complex and realistic case of inhomogeneous signals such as is actually encountered in frequency planning, a computer program was used which ensures that adjacent channel interference and intermodulation distortion is negligible compared to thermal noise. For comparison of spectral efficiency in FDMA the INTELSAT SPADE system transmits 64 kbits/s with 45-kHz spacing for an efficiency of 1.4 bits/s/Hz. The optimum filter and OQPSK modem also gave equivalent performance to a competing new QPSK modem which employs baseband filtering (especially designed for spectral efficiency). Error correction coding allows closer spacing and tighter filtering because the error correction also partially compensates for intersymbol interference and adjacent channel interference. These filters will be used in the DSCS with OQPSK modems using rate-1/2 coding, rate-3/4 coding, or no coding. In the DSCS network, the SAW filters will increase the efficiency of utilization of the DSCS bandwidth by approximately 30 percent compared to group delay equalized cavity-type filters. This results from analysis of the optimum shape filters and elliptical response cavity-type filters with group-delay equalization. The SAW filter system additionally occupies less than 25 percent of the volume of alternative filter approaches such as the INTELSAT 70-MHz cavity-type filters with auxiliary group-delay equilizers.

Although not experimentally verified, computer analysis indicated that the optimum shape filters offer similar performance advantages for spread spectrum modems and may also be used for spectral control for DSCS modems of this type. In this case, the filters are used on the transmit side to reduce out-of-band emissions to comply with international frequency regulations.

IV. Production System

The production system was configured to best allow interfacing with existing equipment. The filters are produced as a part of a nominally zero decibel gain module so that filters can be inserted or taken out of a system as required without affecting any other parameters. Since typical earth stations have the facility for multiple simultaneous satellite coupled channels, the capability of providing multiple filtered channels must be present.

The system with which the filters are interfaced is designed to operate for data rates from 16 kbits/s to 10 Mbits/s. To accommodate these data rates, filter modules have been designed with ten bandwidths from 200 kHz to 10 MHz. The filter bandwidth most suited for the data rate being transmitted or received at the time is plugged into the system.

The system consists of a rack mounted Spectrum Efficient Network Unit (SENU) or drawer as shown in Fig. 8 which provides positions for 15 plug-in filter modules and a common power supply. One or more of these units serves a DSCS Earth Terminal depending on the number of accesses. At the rear is a set of coaxial plugs through which transmitter and receiver equipment of earth stations are connected. Recalling that identical filters are used with each transmitter and receiver, the 15 filter positions provide space for seven two-way communication channels.

Though the primary function of SENU is to provide module power and "terminal board" capability, its func-

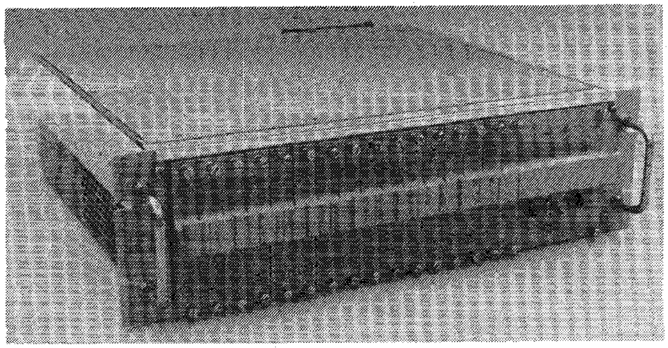

Fig. 8. Rack mounted drawer filled with fifteen filter modules and associated power supply.

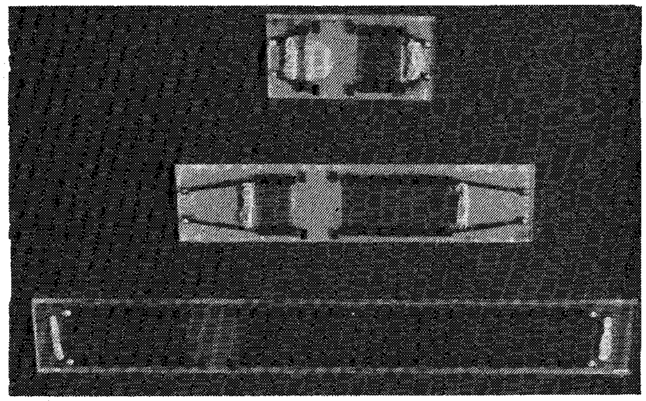

Fig. 9. Three of ten separate filters used to provide graduated bandwidth channel bandshaping and isolation. Lower filter is 9 cm long.

tion cannot be understated. Noting that it serves to connect modules which band shape transmitter and receiver, signals levels of vastly different proportion are subject to being simultaneously present in the channels connected through the SENU, a channel-to-channel isolation specification of 90 dB is required. This applies not only when both channels are connected but also when the filter module for one channel is being removed. Meeting this specification required double power supply regulation, at the power supply and at each filter module. Also required is a specially machined plug in RF connectors (regular type *N* coaxial connectors only assure 64-dB isolation). By the end of the program several hundred drawers of more than one size will have been produced.

Fig. 9 shows three of the ten separate SAW filters which are provided to cover the range of bandwidths of the system. Fig. 10 shows the side view which exposes most of the electronics of one of the eleven separate (ten filters and one bypass) modules. The two coaxial RF and power supply plugs are shown at the rear. It was these coaxial plugs and associated stop surfaces both at front and rear of the module cabinet which require very high tolerance to meet the 90-dB channel-to-channel isolation specification. The RF channel including amplifier and filter (the flatpack) is around the periphery. The regulator is in the center. By the end of the program, several thousand filter modules will have been produced.

Fabrication of the filters in quantity requires principally that adequate controls be provided so that the bypass is accurately reproduced and phase linearity is maintained. Phase linearity is maintained to within $\pm 2°$ except for the two narrowest band filters which are allowed to go to $\pm 4.5°$. This phase linearity, based on [2], is required to meet BER versus E_b/N_0 requirement. The average deviation is $\pm 1.15°$ and 2.6°, respectively, with the maximum deviations $\pm 2°$ and $\pm 4°$ and the minimum deviations, $\pm 0.06°$, and $\pm 1.6°$. Consistency of filter characteristics is important to the DSCS for interchangeability. SAW filters lend very well in this respect compared to conventional lumped constant filters because the filter characteristics are determined by photolithography. The spread of skirt selectively varies from a minimum of 0.05 for the broader filter to a maximum of 0.2 for the narrowest filter. Key fabrication considerations in maintaining this degree of consistency are metal thickness, finger width-to-space ratio,

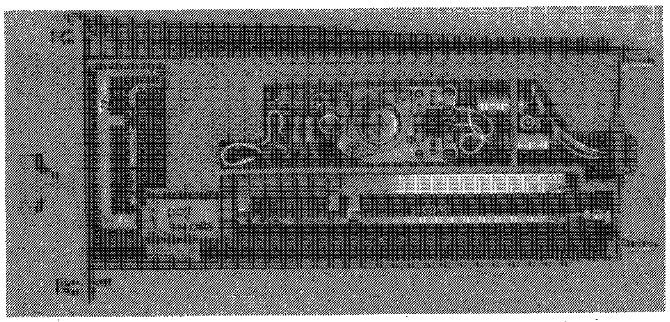

Fig. 10. Side view of plug-in filter module showing filter electronics and machined surfaces required for cross-channel isolation.

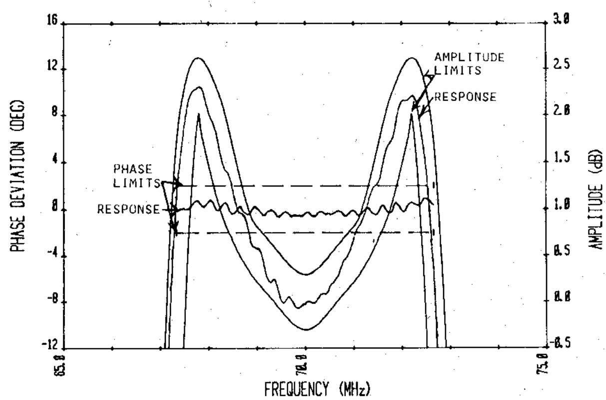

Fig. 11. Portion of example production test data sheet showing bandpass limits and test data for example filter.

crystalline orientation, and treatment to control spurious such as bulk. With reasonable attention to controls in relation to the above parameters, yield of good units relative to fabricated units has been 95 percent at the point of final test.

Testing is carried out by means of a computerized network and analyzer. The analyzer has been programmed to provide complete data necessary for government acceptance testing of the completed filter modules. Thus all the operator has to do is insert the module into a special test drawer and initiate the test. A portion of an example data sheet is given in Fig. 11 showing test results for a No. 8 filter which is optimum for 5.2 Mbit/s QPSK. The data are presented on a format which gives the data limits for that module. It then summarizes each element of data in a chart that states if the acceptance specification has been met. The complete test operation for a single filter module requires 15 min.

V. Program Status and Conclusion

The primary application for the SENU for the DSCS calls for operational utilization of approximately 2000 of the filters in approximately 100 worldwide DSCS terminals. The efficiency of utilization of the available DSCS bandwidth is approximately 30 percent greater with the SENU filters than with alternative conventional group delayed equalized filters. A tactical variation of the SENU is also in the process of being produced for the U.S. Army Satellite Communication Agency.

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Programmable Frequency-Hop Synthesizers Based on Chirp Mixing

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***Abstract*—Frequency-hopped communication equipment require synthesizers capable of providing a large number (N) of discrete frequencies over a wide band. In typical systems N lies in the range of 50 to 10 000 and the required bandwidth ranges from 10 to 500 MHz.**

One technique for implementing a synthesizer is based on mixing chirp signals generated by impulsing SAW filters. Potentially, this method allows fast frequency hop generation over wide bandwidth (<500 MHz) with large numbers of selectable hop frequencies (N<4000). Furthermore, the hardware can occupy a small volume and dissipate low power compared with conventional synthesizers.

This paper examines the techniques and establishes likely parameter and performance bounds. Deleterious mechanisms are identified and their effects on CW spectral purity and fast frequency-hopped link error rate performance is discussed. Experimental results are presented for both a high performance modem, with N equal to 480 across a 96-MHz band and a recent development comprising the basic chirp synthesizer plus phased locked loop (PLL) to provide enhanced slow frequency hop and continuous-wave (CW) spectral purity.

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I. Introduction

SPREAD SPECTRUM modulation techniques provide the capability of low error rate communications in the presence of high cochannel interference levels [1]. This is achieved by modulating the transmitted low rate data with a characteristic signal possessing a bandwidth typically in the range 10 to 500 MHz. At the receiver, data are recovered at low input signal-to-"noise" ratios (SNR's) through cross correlation with a replica of the wide-band signal employed at the transmitter. During normal link operation, the predetection correlation process results in an enhancement of SNR (processing gain) determined to first order by the ratio transmitted bandwidth-to-data rate.

In frequency-hopping (FH) systems the available bandwidth is divided into a large number of contiguous subchannels. Bandspreading is achieved by transmitting successive constant duration pulses on pseudo-randomly selected subchannel carrier frequencies. The resulting wideband signal thus consists of a sequence of mutually orthogonal frequency-shift keyed pulses pseudo-randomly (PN) hopped over the total bandwidth. The many-to-one mapping of PN code states onto carrier frequencies is determin-

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