FQPSK Transceivers Double the Spectral Efficiency of Wireless and Telemetry Systems

An update on work to increase the capacity of digital systems

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The FQPSK family of inventions and proven technologies offers solutions for high performance RF power, spectral efficient bit rate, and RF frequency agile increased data rate transmission systems. These commercial and government 'dual use' transmitters, receiver and transceivers are suitable for deployment in decreased available spectrum.

FQPSK is the abbreviation for Feher-patented Quadrature Phase Shift Keying (FQPSK) with patents referenced in [1], [2] and [12-19]. Digcom, Inc.-licensed FQPSK developments, systems and products are manufactured and used worldwide by government organizations and corporations of all sizes. They have demonstrated unprecedented spectral savings and RF power efficient robust BER performance advantages. FQPSK bit-rate-agile modems and Non Linearly Amplified (NLA) radios, DSP and hardware implementations, and in some instances "software radios" (10 kb/s to more than 100 Mb/s) and RF frequency agile (from 150 MHz to more than 40 GHz) developments and products have recently been demonstrated and deployed. The spectral efficiency, i.e., data throughput capability in an authorized RF spectral band, of FQPSK is double that of the currently operational PCM/FM telemetry systems [3-5]. Based on extensive studies of alternative solutions for spectral and RF power efficient, robust BER performance systems, several US and international commercial organizations, along with NASA, ESA and various programs of the US Department of Defense (DoD), concluded that FQPSK offers the most spectrally efficient high performance/high speed technology solution.

FQPSK Technologies

FQPSK offers a proven technology solution for robust performance and increased data rate in decreased available spectrum.

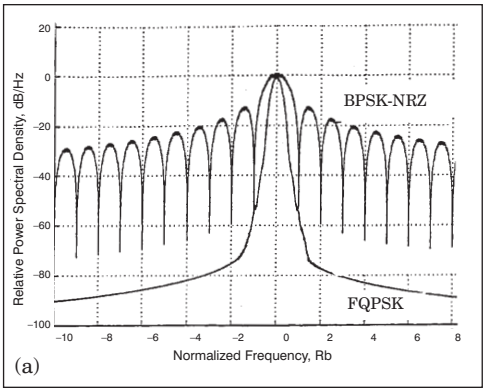
The most important, efficiency-related high performance communications system requirements include spectral efficiency, e.g., out-of-band integrated Adjacent Channel Interference (ACI) spectrum at –70 dB, and robust BER = $f(E_b/N_0)$. Non-Linearly Amplified (NLA), i.e. fully saturated or class-C transceivers, are more RF power efficient, have a lower cost, are smaller size and require less battery power than linearly amplified RF systems. In this paper, NLA spectrally efficient FQPSK [1-20] transceivers having significant advantages over modulated linearly amplified systems, and over other NLA systems are highlighted.

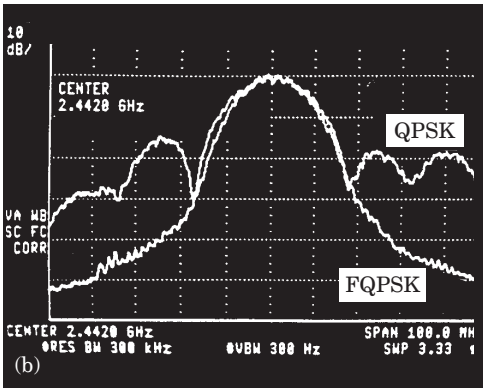
Numerous references, including [1-19], present technical information and other relevant data related to FQPSK. For example, a comprehensive and practical treatment of wireless digital communications, modulation/RF amplification, and initial-previous FQPSK-GMSK is contained in Feher's book [2]. In this publication some of the cross-correlated quadrature modulated GMSK and FQPSK [1] techniques are highlighted. Numerous performance charts and illustrative FQPSK-based applications suitable for NLA transceivers demonstrate that RF power efficient FQPSK systems double (200 percent) the spectral efficiency over that of compatible OQPSK, GMSK systems (having comparable simple DSP hardware and software implementations) and that FQPSK is more than 400 percent more spectrally efficient than filtered NRZ-BPSK, MSK or NLA conventional QPSK [2]. The spectral efficiency (data throughput capability in an authorized RF spectral band of FQPSK) is double that of the currently operational PCM/FM telemetry systems. It is also demonstrated that FQPSK operates over the PCM/FM installed base infrastructure, includ-

ing entire receivers and down-converter IF stages.

In a January, 1998 announcement by AIAA, it is stated that approaches for new standards should consider only proven techniques and should meet the following performance guidelines:

1. capable of operation at bit rates of 1 Mb/s and above, while achieving
2. high RF spectral efficiency using
3. non-linearly amplified (e.g., fully saturated) RF devices without additional IF or RF filters, and
4. displaying robust bit error rate performance without coding.

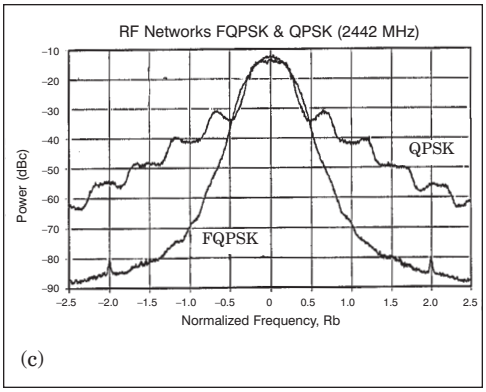


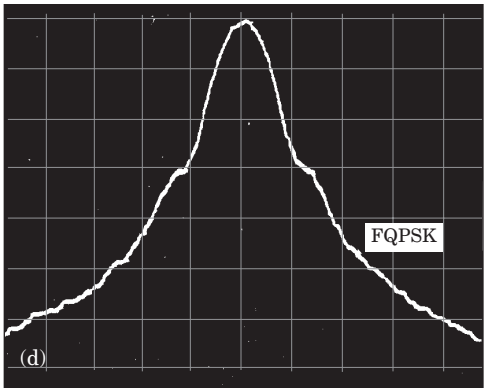


■ **Figures 1a and 1b. Spectral results of NLA (Non Linearly Amplified) FQPSK [1], and of filtered QPSK and BPSK after the output of the NLA RF amplifier. (a) From a NASA/JPL report [14], note that FQPSK (lower trace) is considerably more spectrally efficient than BPSK-NRZ and that FQPSK is the most spectrally efficient NLA alternative. (b) Hardware measurements on this Lockheed Martin (L-3 Communications, Inc.) designed FQPSK-QPSK modem over a 2.44 GHz, 1 watt commercial 34 Mb/s system demonstrate the significant spectral advantages of FQPSK over that of filtered QPSK.**

The FQPSK technologies meet and exceed these requirements and, as of the June 1998, FQPSK has been a leading candidate for several standardized and other "dual-use" spectrally and RF power efficient applications [15-20].

In short, FQPSK inventions have demonstrated unprecedented 2:1 spectral savings by doubling the spectral efficiency (2x data rate) in authorized RF bands.





■ **Figure 1c and d. Spectral results of NLA FQPSK [1], and of filtered QPSK and BPSK after the output of the NLA RF amplifier. (c) In this measurement an RF Networks, Inc. FQPSK and QPSK normalized spectra are compared. (d) A Motorola cost-efficient, large volume integrated circuit was used in this 1 Mb/s - FQPSK hardware measurement H = 500 kHz/div; V = 10dB/div. Experiments demonstrated a 400 percent RF power efficiency advantage over that of linearly amplified QPSK [2].**

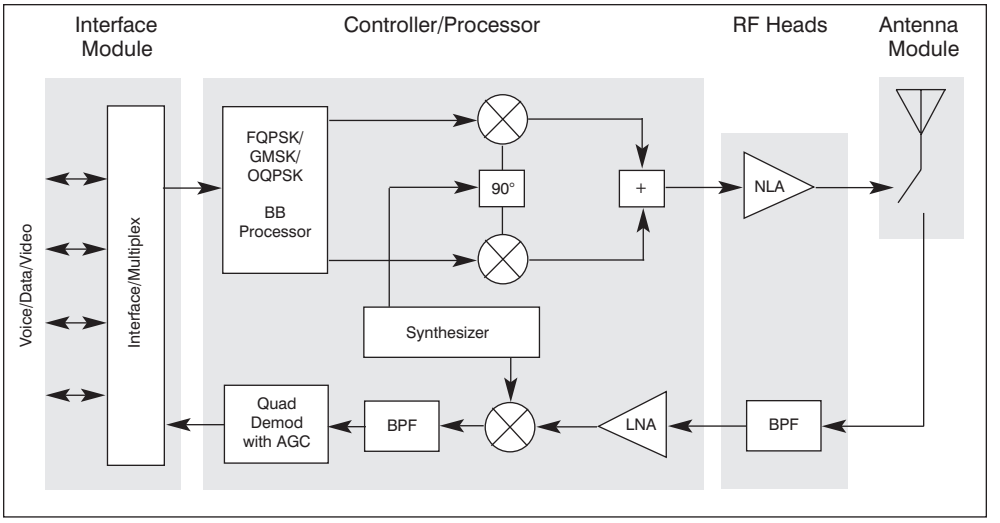
For dual-use commercial and defense technologies and products for US and international applications, FQPSK spectral saving bit rate and RF frequency agile digital radio transceivers demonstrate better BER performance than FQPSK compatible GMSK, MSK, OQPSK and QPSK, PCM/FM systems (see Figures 1-9). FQPSK doubles the spectral efficiency of alternate cost-efficient, NLA, simple filter/processor-based implementations [1-19].

A customer's challenge for increased data rates in a reduced spectral environment highlights some of the advantages of FQPSK

Challenge: The 17 Mb/s bit rate filtered QPSK [2], fully saturated or class C, RF power efficient 0.5 watt, 1 watt, 5 watt or 60 watt RF transmitters, operated at 400 MHz, 900 MHz, 1.4 GHz, 2.2 GHz, 5.7 GHz or other RF center frequencies, exhibit a significant spectral restoration. See the illustrative examples: the upper traces in Figures 1-3. Linearly operated high power RF amplifiers are too expensive or too large, have unacceptably large gain and power variations and/or are

not available for low DC voltage and low power (e.g., 3 VDC battery) operation. For these reasons, class C fully saturated cost/power efficient smaller NLA transceivers have to be implemented.

Solution: The FQPSK modulated signal, after fully saturated NLA, has negligible spectral restoration (see the lower traces in Figures 1(a) to 1(d)). The NLA spectral efficiency improvement attained by FQPSK over filtered QPSK in the critical –40 dBr to –70 dBr range is more than 300 percent, and over filtered OQPSK it is more than 200 percent [2, 8, 13, 14-20]. Integrated out-of-band ACI and robust BER are among the most important specifications for increased data rates for multiple channel high density "data packing." The ACI results of FQPSK and of quadrature modulated GMSK [1] demonstrate that at –65 dBr FQPSK has an approximately 2:1 data packing advantage over matched 4th order Gaussian receive filtered GMSK, as illustrated in Figure 4, based on References [1, 14, 15]. The "data packing" spectral efficiency and ACI advantage of FQPSK over considerably more complex GMSK receivers, as developed by NASA/JPL, is in the 25 percent range, also illustrated in Figure 4. Laboratory hardware test results which confirm some of the FQPSK-GMSK computer-generated data have been reported in [3, 12-20]. The BER performance attained over a variety of NLA transceivers, such as illustrated in Figure 2, is depicted in Figures 6 to 9.



■ **Figure 2. Transceiver block diagram of the FQPSK and compatible modulation NLA-based U.S. Department of Defense (DoD) draft standardized "FIRST," as published in the IEEE MILCOM '97, co-authored by DoD, Raytheon and TASC [7], for bit rate and RF frequency agile family of transceiver solutions.**

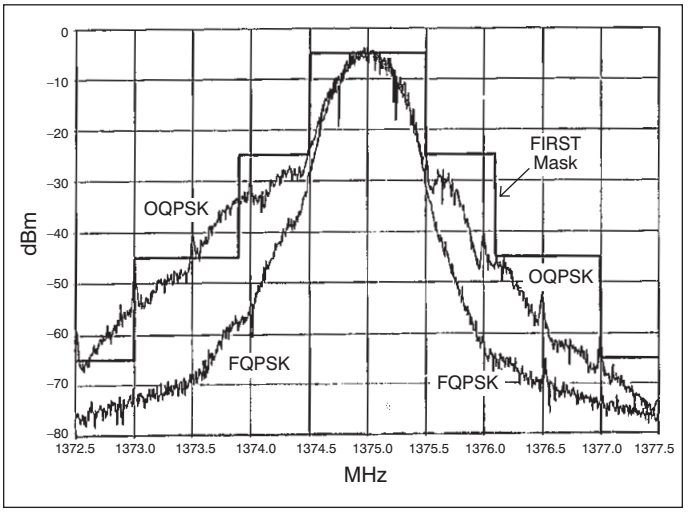
A Comparison of FQPSK and GMSK

Coherent QPSK based systems, such as OQPSK and compatible FQPSK have been used and manufactured in large volumes in the US and globally for data rates higher than 1 Mb/s. For example, the Qualcomm pioneered and licensed CDMA cellular standard has millions of OQPSK-based subscribers. NASA has OQPSK systems (to several 100 Mb/s), and several manufacturers have high-speed OQPSK products. Flexible FQPSK designs are compatible and inter-operable with OQPSK, DQPSK, QPSK, GMSK and MSK.

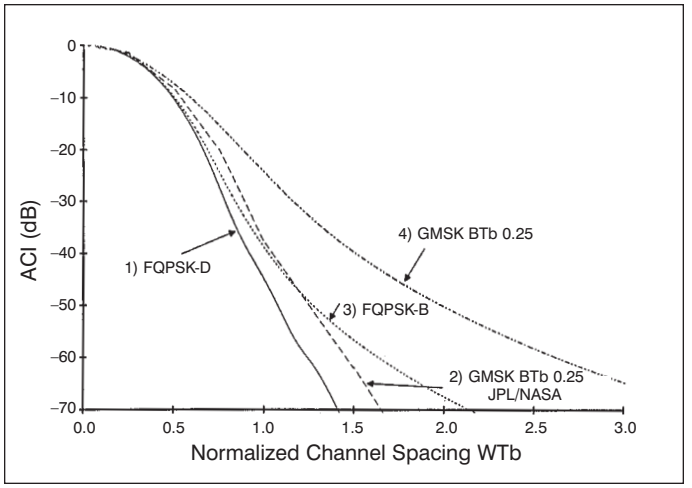
GMSK has only low speed coherent/high performance (270.833 kb/s-GSM) COTS products.

FQPSK performance advantages over that of GMSK include:

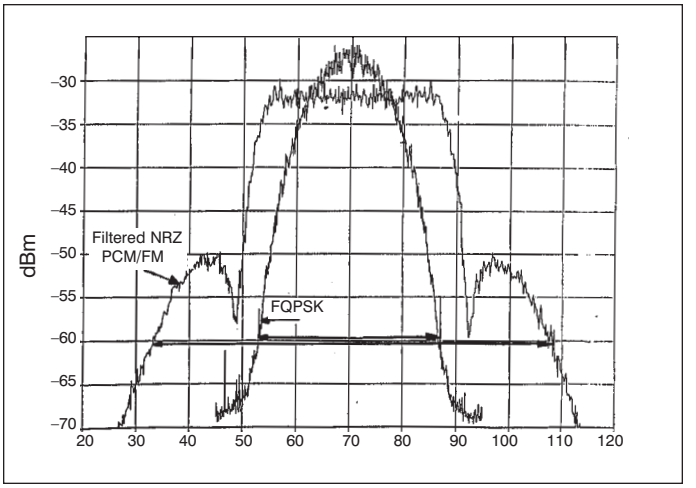
- BEP robustness (approx. 1-2dB); FQPSK advantage over GMSK at BEP=10^{-2} to 10^{-4} range.
- FQPSK spectral efficiency advantage is 25 to 100 percent range if Non-Linearly Amplified (NLA).
- FQPSK spectral efficiency advantage is 100 to 300 percent range if Linearly (LIN) amplified.
- Much simpler product implementation, e.g., FQPSK has 4th order TX-RX filters versus 80 to 640 order for-taps used/predicted for GMSK TX-RX filters.
- Smaller size and lower DC power requirement: 4 sample/symbol versus 8 sample.
- Considerably lower cost implementation above 1 Mb/s rate.
- FQPSK high speed (1 Mb/s, 3 Mb/s and 17 Mb/s to 40 Mb/s) hardware products (COTS) have been demonstrated, while high speed GMSK is much more complex and still in R&D.



■ **Figure 3. L-band (1.375 GHz) measured NLA spectra up to 100 watt optimized OQPSK and of FQPSK within DoD's "FIRST" Mask indicate that the illustrated OQPSK would not meet the Mask requirements.**



■ **Figure 4. Integrated ACI (Adjacent Channel Interference) computer-generated results of FQPSK and GMSK [1] NLA systems with simple receive FQPSK filters, and for GMSK 4th order Gaussian filters and JPL/NASA optimized more advanced/complex filters. These computer-generated results based on [14, 15] have been confirmed in experimental hardware results by E. Law [3].**



■ **Figure 5. FQPSK [1, 3, 5] and PCM/FM [3, 4, 5, 11] measured results at 17Mb/s illustrate the potential doubling of the data transmission rate of operational systems with FQPSK.**

Background information highlights

December 4, 1997 and March 24, 1998 Washington, DC AIAA meetings: AIAA, NASA, DoD's RDT&E Spectrum Requirements Working Groups (WG), based on previous CBD solicitations, numerous briefings and industry cooperation, since the Fall of 1996 (including DoD's FIRST program - and ARTM) considered several spectral efficient modulation proposals; alternative proposals were solicited until March 10, 1998.

Based on extensive NASA/JPL, DoD, industry and university multiyear studies, it was found that FQPSK is the most spectrally efficient (2x the efficiency of operational PCM/FM telemetry), robust BEP performance NLA/RF power efficient COTS modulation.

Based on briefings and received proposals, DoD, NASA/JPL and commercial R&D studies, experiments, Tests and Evaluations (T&E) and recently developed COTS (Commercial Off The Shelf) products and government programs and product developments, it has been announced in the Commerce Business Daily (CBD 01-29-98) that FQPSK and GMSK appear to yield very good bandwidth efficiency and are currently the leading candidate proposals for the future standard.

The availability of Feher-patented FQPSK and GMSK licensing and technology transfer on equal-opportunity, non-discriminatory fair market value basis for dual-use commercial and military applications has been also announced. A brief comparison of FQPSK and GMSK follows [1]:

To have a cost and spectral efficient modulation standard, one standardized modulation format has been recommended. Based on FQPSK's advantages over GMSK and other proven COTS modems (including numerous references and briefings to AIAA, NASA, DoD, DoE, NTIA and commercial forums), FQPSK has been specified for the AIAA (in cooperation with DoD and NASA) draft standard.

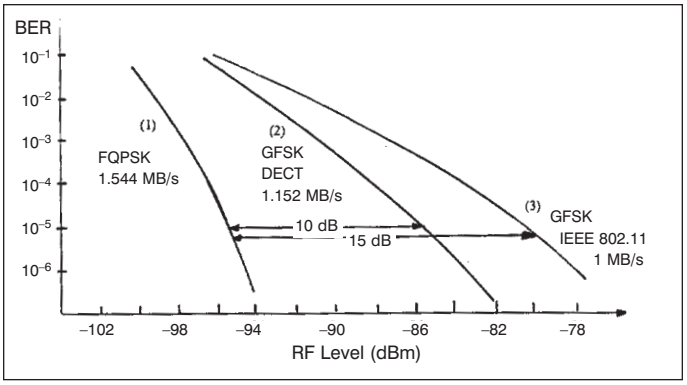
Exemplary developments of FQPSK-GMSK technology — Digcom Inc., licensees and cooperating organizations — FQPSK Consortium

Some of the unprecedented achievements attained by members of the International FQPSK Consortium [1], cooperating organizations and licensees are highlighted in Figures 1 to 9, the text of this publication and in references [1-20].

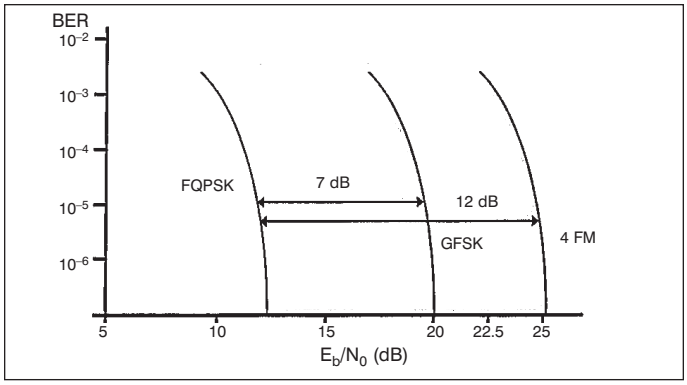
Lockheed Martin (Salt Lake City, UT) designed units (and later L-3 Communications, Inc. manufactured products) using Feher patented FQPSK-GMSK that demonstrated, at 17 Mb/s "clear mode" and 34 Mchips/s spread spectrum mode, very close to optimum theoretical performance.

L-3 Communications, Inc.-Conic (San Diego, CA) has demonstrated excellent FQPSK modulation BER performance and more than 2:1 data rate increase in several authorized RF bands through Conic's power efficient NLA 5 watt RF power "CRI-400 series" standard radio systems. Interstate Electronics Corporation (Anaheim, CA) is developing an NLA bit rate agile medium/high data rate, miniaturized power/spectral efficient FQPSK system for the U.S. Department of Defense. Another major DoD contractor investigated, tested and evaluated FQPSK over more than 60 watt 1.7 GHz NLA RF amplifiers and confirmed the spectral savings advantages of FQPSK.

EIP Microwave, Inc., Milpitas, CA, is the world's first to demonstrate excellent performance, up to 40 GHz, with their FQPSK-GMSK licensed prototype instrumen-



■ **Figure 6. Performance comparison of measured, typical BER curves of NLA constant envelope standardized DECT (GFSK, 1.152 Mb/s at 1.9 GHz in 1.75 MHz); IEEE 802.11 WLAN (GFSK, 1 Mb/s at 2.45 GHz in 1 MHz with FCC-mandated –20dBr) and superior performance Lockheed Martin-manufactured EB200KF with Celeritek IF/RF (FQPSK and GMSK 1.544 Mb/s at 2.45 GHz). For FCC Part 15 required –20dBr, the spectral efficiency of FQPSK is double that of the IEEE 802.11 and DECT-standardized and other MSK-based systems. The above FQPSK measurements have also been confirmed with RF Networks, Inc. 1 Mb/s "clear mode" and also IOTA-IOCOMM DS-SS (spread spectrum 17 Mchip/s) systems [8].**



■ **Figure 7. Measured BER = f(E_b/N_0) curves of several class C RF IC/NLA modulated systems at f_b = 1 Mb/s and 2 Mb/s rate. FQPSK, GFSK with 160 kHz deviation and digital 4FM shown. Illustrative experimental data was submitted to WLAN and PCS standardization committees such as IEEE 802.11 and TIA/JTC. The experimental data show that at the specified BER = 10^{-5}, FQPSK is 7 dB and 12 dB more robust than GFSK and 4FM, respectively. Such dramatic performance improvement in an interference controlled environment, e.g., FCC Part 15, can increase the throughput rate about 100 to 1000 times. Relatively small 160 kHz deviation is specified in order to meet the FCC Part 15 and IEEE 802.11 spectral efficiency and out-of-band attenuation requirements [2].**

tation products. Digcom, Inc. demonstrated 1 Mb/s rate FQPSK over 1.4 GHz 400Watt, and 17 Mb/s over 2.2 GHz and 2.4 GHz transceivers to DoD, NASA and commercial organizations. Digcom also provided in-depth technology transfer training courses, consulting services and licensed FQPSK-GMSK to several commercial organizations active in cable and wireless systems and to defense contractors.

AYDIN Telemetry demonstrated to DoD, NASA and to commercial customers FQPSK high power NLA transmitters-receivers, including demodulators and bit synchronizers. RF Networks, Inc., Phoenix, AZ developed and has already delivered GSM standardized rate 270 kb/s, 1 Mb/s, 3 Mb/s and other FQPSK-GMSK RF frequency agile (in increments of 5 kHz RF) products to commercial and to DoD and NASA customers. The FQPSK commercial cable, wireless and telemetry high performance-cost efficient products, manufactured by Lockheed Martin and more recently by L-3 Communications, Inc. and by RF Networks, have been used by numerous US and international commercial organizations and also demonstrated to and tested by the US Navy, US Air Force, US Army and NASA/JPL. Five years of extensive research by NASA/JPL [14-20] and ESA on efficient modulation methods for telemetry and space communications concluded that for US and global CCSDS systems FQPSK is the most spectrally efficient robust BER technology. In DoD's "FIRST" draft standard and for several telemetry applications, FQPSK is the most spectrally efficient solution. For the HIPERLAN European/Global TDMA-FDMA standard, WLL and WCDMA FQPSK could significantly increase the data rate and data throughput.

FQPSK used in AIAA-NASA-DoD specifications

Following the presentations of various proposals, in-depth technical discussions and the CBD-announced critical community review of FQPSK and GMSK and of other proposed alternative technologies (during the AIAA-NASA-DoD Workshop, held on March 24, 1998 at the US Naval Research Laboratory, Washington, DC), the NASA/JPL Session Chair and Specification Moderator distributed the AIAA (March 14, 1998) "Draft Specification Radio Transceiver — Version 1.0" document to the 100+ government and industry attendees [20]. Note that FQPSK, the most spectral efficient solution and robust BER performance high bit rate hardware and software proven technology with COTS (Commercial Off-The-Shelf) available products has been specified for the aforementioned AIAA-NASA-DoD standardization project.

Legal Note

Material in this publication is based on publications and patents of Feher et al. and rights remain with the author and his organization, Digcom, Inc. ■

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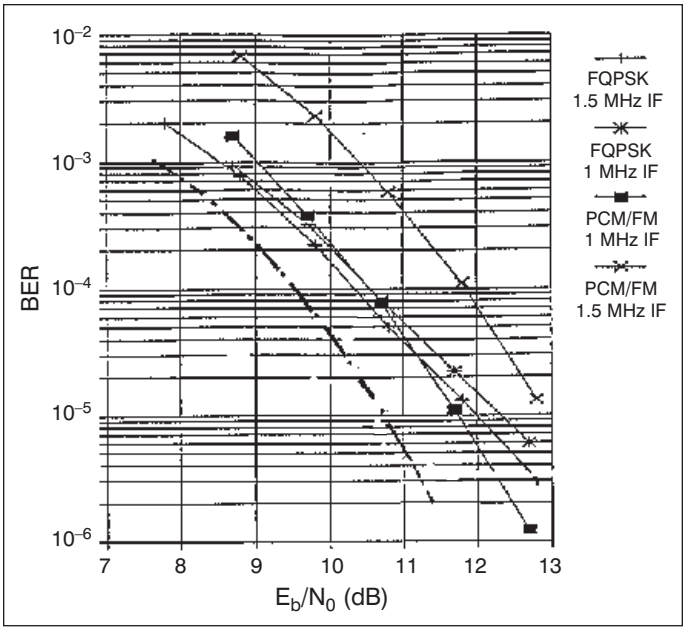
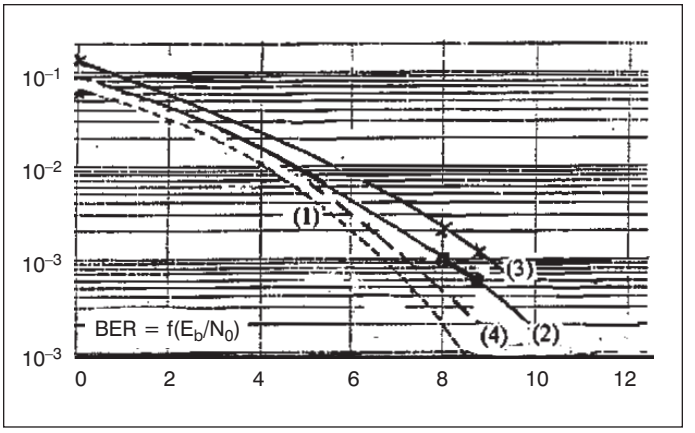


■ **Figure 8. Measured performance of an RF Networks, Inc. manufactured FQPSK [1] and of operational PCM/FM in terms of BER = f(E_b/N_0) at the U.S. Navy [3, 5] over a NLA-1.4 GHz transceiver. The BER performance of this measured 1 Mb/s rate FQPSK commercially available transceiver could be further optimized as indicated by the dashed-dotted line.**



■ **Figure 9. Measured BER = f(E_b/N_0) performance of illustrative FQPSK products operated in a clear mode (no FEC coding) at a bit rate of 17 Mb/s. In this set of measurements cross-correlated FQPSK modems have been used. The RF transmitter is operated in NLA full saturation at 5 watts. The measured curves (2) and (3) were demonstrated at the U.S. Navy Telemetry Laboratory, Pt. Mugu, CA to NASA-JPL-CCSDS representatives during 1997 [12, 13, 14]. FQPSK modems under license of Feher et al. patents, designed and manufactured by Lockheed Martin and follow-up manufacturing by L-3 Communications, Inc., have been used [1]. These 70 MHz IF modems, built for commercial markets, have been further enhanced and optimized. The BER performance is:**

Curve (1) is the ideal theoretical BPSK or QPSK curve for linearly amplified systems.

Curve (2) represents NLA measured FQPSK results with the differential encoder disabled.

Curve (3) represents NLA measured FQPSK results with the differential encoder enabled.

Curve (4) represents "optimized-practical" NLA 17 Mb/s rate FQPSK developments-in-progress.

1,130,871; 1,265,851 and post-patent improvements. Other U.S. and international patents are pending or in applications-in-process. These have been licensed on an equal-opportunity, non discriminatory fair market value basis for "dual-use" commercial and military FQPSK-GMSK use, developments and other use and applications to large, medium-size and small corporations and organizations in the USA and internationally by Digcom, Inc.

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