FQPSK Doubles Spectral Efficiency of Telemetry: Advances and Initial Air to Ground Flight Tests

Dr. Kamilo FEHER*
Digcom, Inc., 44685 Country Club Drive, El Macero, CA 95618 and
ECE Department; University of California, Davis; Davis, CA 95616

ABSTRACT

FQPSK is the abbreviation for Feher Quadrature Phase Shift Keying (FQPSK) patented systems [1]. Digcom, Inc. licensed FQPSK products demonstrated significant spectral saving and RF power efficient robust BER performance advantages. These bit rate agile modems and Non Linearly Amplified (NLA) transceivers, DSP and hardware implementations, and in some instances "software-radios" (20kb/s to more than100Mb/s) and RF frequency agile (from 150MHz to more than 40GHz) developments and systems have recently been demonstrated and deployed. The spectral efficiency, i.e., data throughput capability of the 1st generation of FQPSK, as demonstrated in initial Advanced Range Telemetry (ARTM) flight tests, approximately doubles while 2nd generation "FQPSK-2" systems have the potential to quadruple the spectral efficiency of operational PCM/FM telemetry systems and be backward compatible with the 1st generation of FQPSK technologies. It is also demonstrated that the spectral efficiency advantage of FQPSK over that of NLA power efficient GMSK, OQPSK and QPSK modulated transceivers is in the 50% to 300% range and that the potential spectral efficiency advantage of FQPSK-2 over GMSK [1] is in the 200% to 500% range.

Based on extensive multi-year studies of alternative solutions for spectral and RF power efficient, robust BER performance systems, several commercial US and international organizations, AIAA, CCSDS, NASA, ESA, CCSDS and various programs of the US Department of Defense (DoD) concluded that FQPSK offers the most spectrally efficient high performance-high speed proven technology solutions and recommended FQPSK standardization for several data links. Initial DoD-ARTM Program Office Air-to-Ground L-band and S-band jet airborne telemetry Test and Evaluation (T&E) data, obtained during the summer of 1998 are briefly highlighted. These include simultaneosly tested FQPSK and PCM/FM. In these tests the following ARTM objectives have been demonstrated: (a) FQPSK approximately doubles the spectral efficiency of

---

* *Significant parts of the material in this publication are based on publications, inventions and patents of K. Feher et al. And rights remain with K. Feher – Digcom [1].*

currently operational PCM/FM; (b) The Data Link Performance of these two systems is comparable. The American Institute of Aeronautics and Astronautics (AIAA) draft modulation standard recommended to the DoD, NASA and CCSDS, was approved by the AIAA [23]. The AIAA standard recommends "that FQPSK modulation be immediately adopted as the interim *increment–1* standard."

KEY WORDS

FQPSK - Feher Quadrature Phase Shift Keying patented systems [References 1 and 2]

GMSK - Gaussian Minimum Shift Keying - Feher's patented cross-correlated quadrature GMSK implementations [References 1 and 2] are highlighted in this publication.

NLA - Nonlinearly Amplifed Amplifier or transceiver (operates in C-class or other fully saturated mode)

1. FQPSK Offers a Proven Technology Solution for Robust Performance Increased Data Rate in Decreased Available Spectrum

The *most important - efficient high performance communications requirements* include:

- spectral efficiency (e.g.,out-of-band Integrated Adjacent Channel (ACI) spectrum @ –70dB)
- robust BER = $f(E_b/N_0)$
- Non-Linearly Amplified (NLA), i.e., fully saturated or C-class transceivers

In this paper NLA spectrally efficient Feher patented FQPSK [1] transceiver developments having significant advantages over linearly amplified modulated and over other NLA systems are highlighted. References, including [1-23], present technical information and other relevant data related to FQPSK. Performance charts demonstrate that RF power efficient FQPSK systems double (200%) the spectral efficiency over that of compatible OQPSK, GMSK systems (having a comparable simple hardware and software - DSP implementations) and that FQPSK is more than 400% 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, including entire receivers and down-converter IF stages.

In an AIAA - January, 1998 announcement 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 1Mb/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.

The FQPSK technologies meet and exceed the aforementioned AIAA-stipulated requirements and, as of the Summer of 1998, FQPSK [1] has been recommended by the AIAA for standardization by the DoD, by NASA and by the international CCSDS[22] for DoD-NASA–CCSDS applications and other "dual-use" spectrally and RF power efficient standards [15-23].

For **dual-use commercial and defense** technologies and products for U.S. and international applications, FQPSK spectral saving and bit rate & RF frequency agile digital radio transceivers demonstrate better BER performance than compatible GMSK, MSK, OQPSK and QPSK, PCM/FM.

2. Increased Data Rate Requirements in Reduced Spectral Environments

An Illustrative Example: The 17Mb/s bit rate filtered QPSK [2], fully saturated or C-class RF power efficient 0.5Watt to 100 Watt RF transmitter operated between 150 MHz and 5.7GHz or other RF bands exhibits a significant spectral restoration. 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/low power, e.g., 3V dc battery operation. For these reasons C-class fully saturated cost/power efficient smaller NLA transceivers have to be implemented. The NLA spectral efficiency improvement attained by FQPSK over filtered QPSK in the critical –40dBr to –70dBr range is **more than 300%** and over filtered OQPSK **more than 200%** [2;8;13; 14;15]. The Adjacent Channel Interference (ACI) results, –65dBr, demonstrate the approximately 2:1 FQPSK (and 4:1 of FQPSK-2) data packing advantage over GMSK (matched 4^{th} order Gaussian receive filtered GMSK [1;14;15].

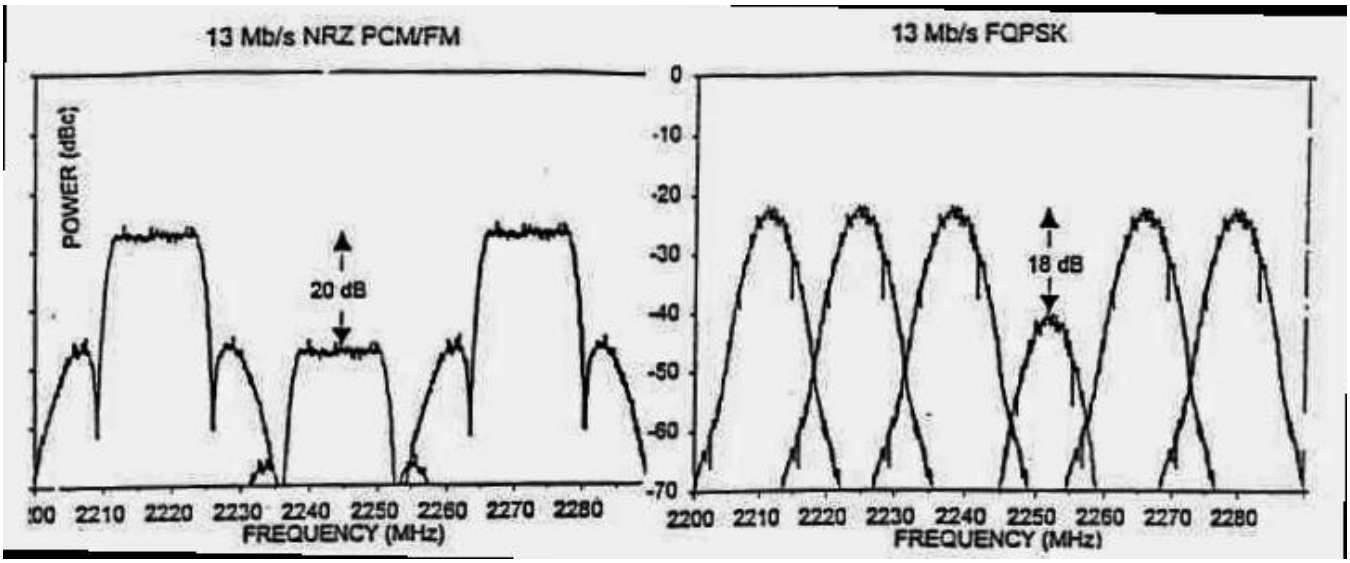

Fig. 1 Experimental hardware results indicate that FQPSK has the potential of doubling (200%) the data throughput, i.e. spectral efficiency of operational PCM/FM telemetry systems [1-23]. FQPSK 6x13 Mb/s bit rate, instead of 3x13 Mb/s with PCM/FM, would be attainable in the authorized 90 MHz S-band.

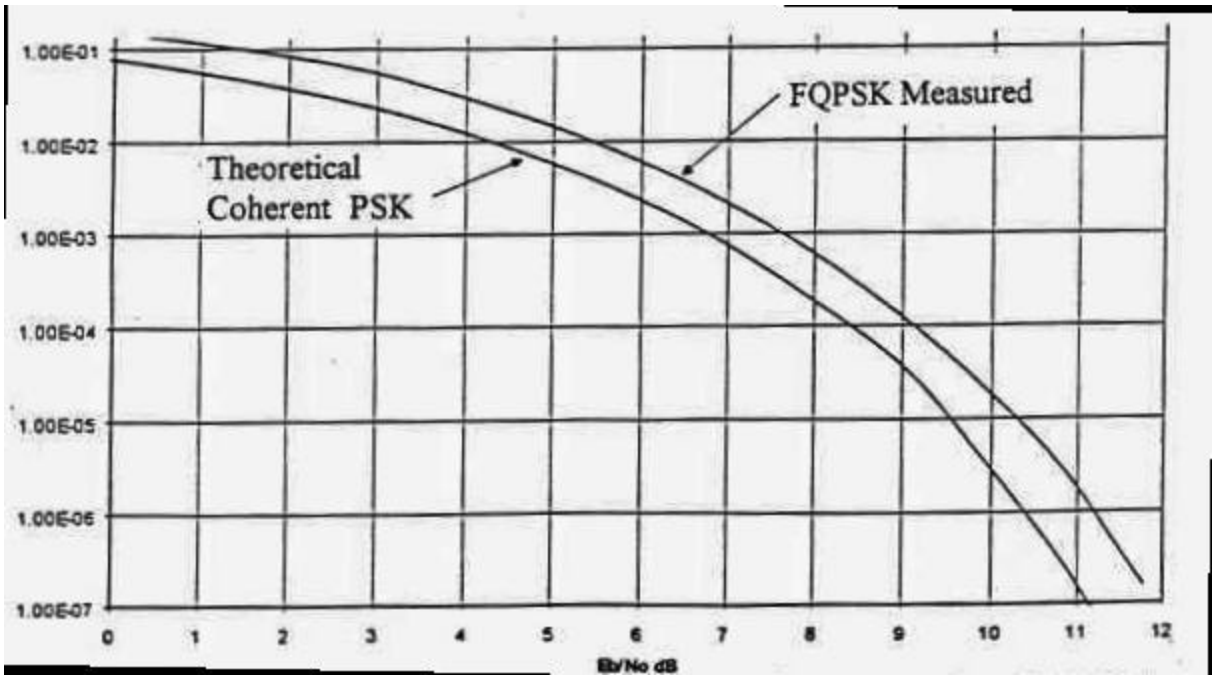

Fig. 2 BEP (Bit Error Probability)- measured performance of a 17 Mchip/second Spread Spectrum FQPSK, manufactured under Feher's patents by Lockheed Martin and by L-3 Communications Inc. demonstrate the outstanding BEP=f (Eb/No) performance of spread spectrum FQPSK. Application has been in the FCC-15 ISM bands and other commercial WLL RF systems-data links.

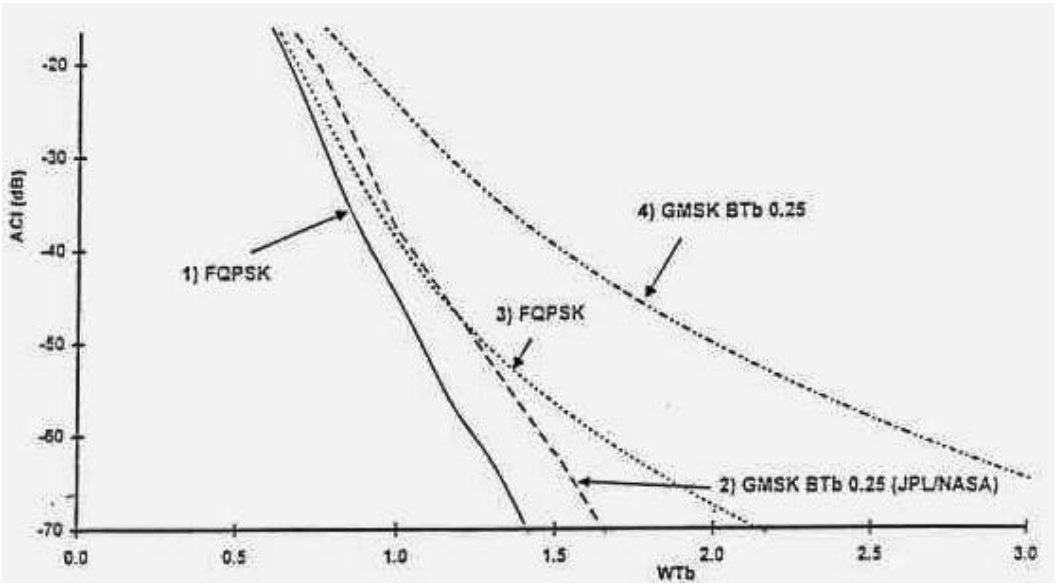

Fig. 3 Integrated ACI (Adjacent Channel Interference) computer-generated results of FQPSK (Curves 1 and 3) and GMSK Feher patented [1] NLA systems with simple receive FQPSK filters and for GMSK 4th order Gaussian filters (curve 4) and JPL/NASA optimized more advanced/complex filters (Curve 2). These computer-generated results based on [14; 15] have been practically confirmed by experimental hardware results by E. Law [3].

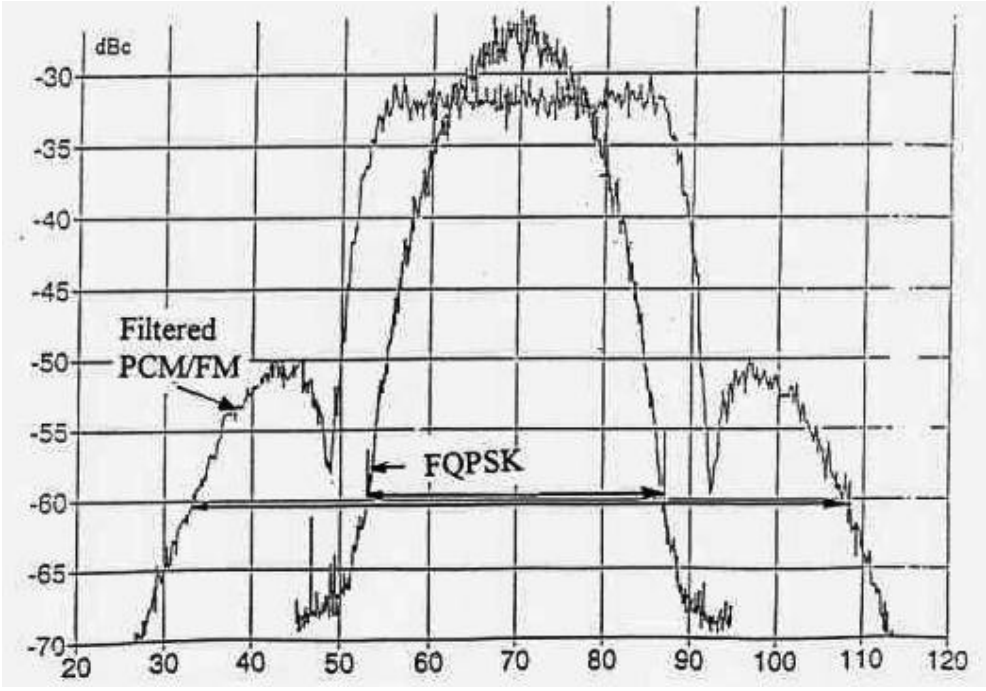

Fig. 4 Spectra of FQPSK [1; 3; 5] and PCM/FM [3; 4; 5;11] measured results at 17 Mb/s rate, NLA, in L and S Bands, downconverted to 70 MHz illustrate the potential doubling of the data transmission rate of operational systems with FQPSK.

COTS products: Coherent QPSK based systems, such as OQPSK and interoperable and compatible FQPSK have been used and manufactured in large volumes in the USA and globally at higher than 1Mb/s rates – to several 100Mb/s. GMSK has only lower speed coherent/high performance (e.g., 270.833kb/s GSM) COTS products.

FQPSK performance advantages over that of GMSK include:

BEP robustness (approx. 1-2dB) FQPSK advantage over GMSK @ BEP=10^{-2} to 10^{-4} range

FQPSK spectral efficiency advantage 25% to 100% range if Nonlinearly Amplified (NLA)

FQPSK-2 spectral efficiency advantage over GMSK 200% to 500%

Simpler Product, e.g. FQPSK has 4^{th} order Tx-Rx filters versus 100-plus taps GMSK

Smaller size - less dc power requirement - as 4 sample/symbol versus 8 sample

Considerably lower cost implementation for above 1Mb/s rate

FQPSK high speed (1Mb/s, 3Mb/s and 17Mb/s to 40Mb/s) hardware products COTS have been demonstrated - while high speed GMSK is much more complex; still in R&D

4. Recent Background INFORMATION Highlights:

- DoD's RDT&E Spectrum Requirements Working Groups (WG), based on previous CBD solicitations, considered several spectral efficient modulation proposals.
- AIAA NASA/JPL, DoD, industry and university extensive multiyear studies found that FQPSK is the most spectrally efficient robust BEP performance RF power efficient COTS modulation.
- 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 announced [1].
- AIAA-approved recommendation to DoD, NASA and CCSDS to standardize on FQPSK [23].

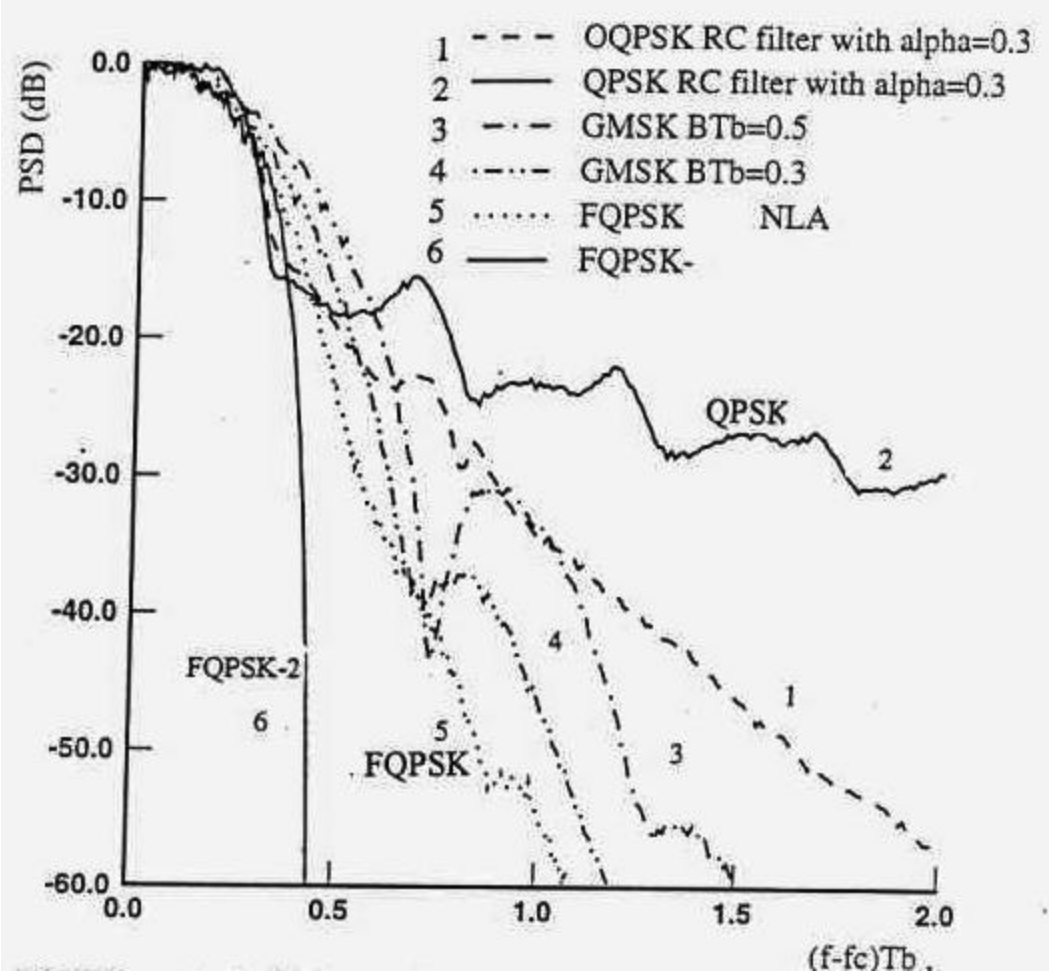

Fig. 5 FQPSK spectral efficiency advantages over other NLA transeivers

Parameter	Standard
Modulation/Demodulation	FQPSK
Multiple Access	Half Duplex: TDMA/FDMA
Message Structure	TBD
Flexible Bit Rate	In the 100 kb/s to 10 Mb/s range
Transmitter Power Control	Power control in 4 N dB
Delay Spread Mitigation	up to 4 usec delay spread
Channel Coding	Convolutional, Reed Solom
COMSEC	NSA approved device, or commercial standard. Over-air rekeying
External Interfaces	RS-232, RS-422, Universal Serial Bus, 1553, ICD-

Modulation	FQPSK	
Tx and Rx channel data rate	Maximum 30 Mb/s Minimum bit rate 16 kb/ [Bit Rate = (n/m)16 kb/s	
Tx clock accuracy	20 to 100 ppm	
Power Spectral Density (PSD) b/s/Hz relative to maximum in band at fully saturated NLA output		NLA
	-20 dB	1.0 b/s/Hz
	-40 dB	0.45 b/s/Hz
	-60 dB	0.25 b/s/Hz
Integrated Power Spectral Efficiency b/s/Hz	OIBP	NLA LIN
	99%	1.25 1.8 b/s
	99.99%	0.80 1.5 b/s
BER = f(Eb/No) requirement (uncoded) for both NLA and LIN systems specified in AWGN stationary.	Eb/No	BER
	7 dB	10^{-2}
	9 dB	10^{-3}
	11 dB*	10^{-4}

Fig. 6 Standardized/Specified FQPSK parameters of DoD's FIRST [7]

5. Exemplary Achievements of FQPSK-GMSK Licensees

Some of the achievements attained by members of the International FQPSK Consortium [1], cooperating organizations and licensees are highlighted in this Section.

Lockheed Martin (Salt Lake City, UT) designed units and (renamed L-3 Communications, Inc.) later manufactured products of Feher patented FQPSK-GMSK demonstrated, at 17Mb/s "clear mode" and 34Mchips/s spread spectrum mode, very close performance to theoretical optimum 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 5Watt RF power "CRI-400 series" standard radio systems. **Interstate Electronics Corporation (IEC), Anaheim, CA,** is developing a NLA bit rate agile medium/high data rate, miniaturized power/spectral efficient FQPSK system for the U.S. Department of Defense (DoD). Another major DoD contractor investigated, tested and evaluated FQPSK over more than 60Watt 1.7GHz NLA RF amplifiers and confirmed the spectral savings advantages of FQPSK.

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

Digcom, Inc., El Macero, California demonstrated 1Mb/s rate FQPSK over 1.4GHz 400Watt, and 17Mb/s over 2.2GHz and 2.4GHz and 8GHz transceivers to DoD, NASA and commercial organizations and 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.

Digcom, Inc. has active FQPSK-GMSK Feher patented and related technology-technical co-operative development agreements with the **US Navy Pt. Mugu and China Lake**-CRADA), with **JPL/NASA, Pasadena** and an SBIR with the **US Air Force, Edwards AFB**, CA. **AYDIN Telemetry** demonstrated to DoD, NASA and to commercial customers in the USA and in Europe FQPSK high power NLA transmitters-receivers, including high speed bit rate agile demodulators and bit synchronizers. **RF Networks, Inc.**, **Phoenix, AZ** developed and has already delivered GSM standardized rate 270kb/s, 1Mb/s, 3Mb/s and other FQPSK-GMSK RF frequency agile (in increments of 5kHz RF) products to commercial and to government (DoD) and NASA customers. The first aeronautical telemetry ARTM flight tests used RF Network, Inc. modems. 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.

Microdyne Communications Technologies Inc., Ocala, Florida, telemetry RF to IF receivers have been used in numerous laboratory and in ARTM air to ground jet flight tests. During the May 98 DoD-FIRST meeting, one of the presentations by Mr. Tony Cirineo of the US Navy at Pt. Mugu, CA contained a description of preliminary Tests and Evaluations of Microdyne's demodulators used for FQPSK signal demodulation. These tests, (performed under a CRADA between DIGCOM and NAWCWPNS) demonstrated robust FQPSK performance-BEP with Microdyne demodulators.

6. FQPSK Used in AIAA-NASA-DoD Specifications

Following the CBD announced critical community review of FQPSK and GMSK and of other proposed alternative technologies, FQPSK, the most spectral efficient solution and robust BER performance high bit rate hardware and software proven technology with COTS (Commercially Off-The-Shelf) available products has been specified for the AIAA-NASA-DoD standardization project [20-23].

7. ARTM Air-to-Ground Flight Tests of FQPSK at Edwards AFB, CA

The Advanced Range Telemetry (ARTM) tri-service Program Office, an Office of Undersecretary of Defense CTEIP funded program (of the US Air Force, US Army and US Navy) developed an extensive Test and Evaluation (T&E) facility for new generations of telemetry systems. During the Summer of 1998, initial aeronautical simultaneous jet aircraft air to ground flight tests of FQPSK and PCM/FM have been undertaken at the US Air Force , Edwards AFB [11;17;21]. The predominant objective of these flight tests has been to compare the performance of FQPSK and PCM/FM modulation methods and transceivers using the aeronautical telemetry environment with PCM/FM as the baseline. Bit Error Probability (BEP) performance and total link availability assessment has been undertaken by the ARTM team.

AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS (AIAA)
SPACE OPERATIONS SUPPORT TECHNICAL COMMITTEE

1.0 Transmitter - AIAA Specifications Draft 1.0

Parameter	Specification
Modulator and RF Transmitter	
Bit rate	1Mb/s to 40Mb/s range selectable bit rates
Tx clock frequency accur.	≤50ppm
Transmit clock jitter	4% peak - of clock period 1 % rms - of clock period
Modulation	FQPSK
Baseband transmit processor: In-phase(I) and Quadrature (Q) Signal requirements	Processor coefficients, cross-correlated and filtered signal shapes, specific algorithms of patents, and post patent improved I and Q signal elements are specified and recommended in FQPSK technology transfer to licensees, See Ref.[1].

Item No:	Parameter	Specification	
1.58	Integrated power spectral efficiency [b/s/Hz] requirements *One or more of the Items 1.58 to 1.60 (in addition to IRIG masks) could be useful for ACI, increased data packing INFO-efficiencies*	**FQPSK**	**NLA trans [b/s/Hz]**
		99% power (-20dB out/band)	1.25b/s/Hz
		99.9% power (-30dB out/band)	1.0b/s/Hz
		99.99% power (-40dB out/band)	0.75b/s/Hz
1.59	Power Spectral Density (PSD) [b/s/Hz] minimal efficiency requirements relative to maximal in-band PSD		**NLA transceiver**
		-20dB	1.03 b/s/Hz
		-30dB	0.9 b/s/Hz
		-40dB	0.6 b/s/Hz
		-50dB	0.5 b/s/Hz
		-60dB	0.4 b/s/Hz
1.59b	Power Spectral Density (PSD) [b/s/Hz] minimal efficiency requirements relative to maximal in-band PSD		**LIN transceivers**
		-20dB	1.70 b/s/Hz
		-30dB	1.40 b/s/Hz
		-40dB	1.20 b/s/Hz
		-50dB	1.10 b/s/Hz
		-60dB	1.00 b/s/Hz

		E_b/N_0[dB]	BEP
2.19	IF modem or RF Loop of FQPSK - in NLA and in LIN transceiver AWGN Bit Error Probability Performance (BEP) BEP = $f(E_b/N_0)$ requirement (raw - uncoded) NLA and LIN systems specified in AWGN stationary environment	0.0dB ?*	$2*10^{-1}$
		1.0dB ?*	$7*10^{-2}$
		5.5dB ?*	10^{-2}
		9.0dB	10^{-3}
		11dB	10^{-4}
		12dB	10^{-5}
		13.5dB ?*	10^{-6}

Eb/No for BER=10^{-7}

Sequential code Rate	Eb/No
1/2 @ 64 kbps	4.6
1/2 @ 2 Mbps	5.4
3/4 @ 64 kbps	5.4
3/4 @ 2 Mbps	4.6

Viterbi Rate	Eb/No
1/2	5.7
3/4	7.0
7/8	8.0

Fig. 7 Standardized/Specified FQPSK parameters of the AIAA recommendation for US Department of Defense (DoD), NASA and the International CCSDS [20; 23]

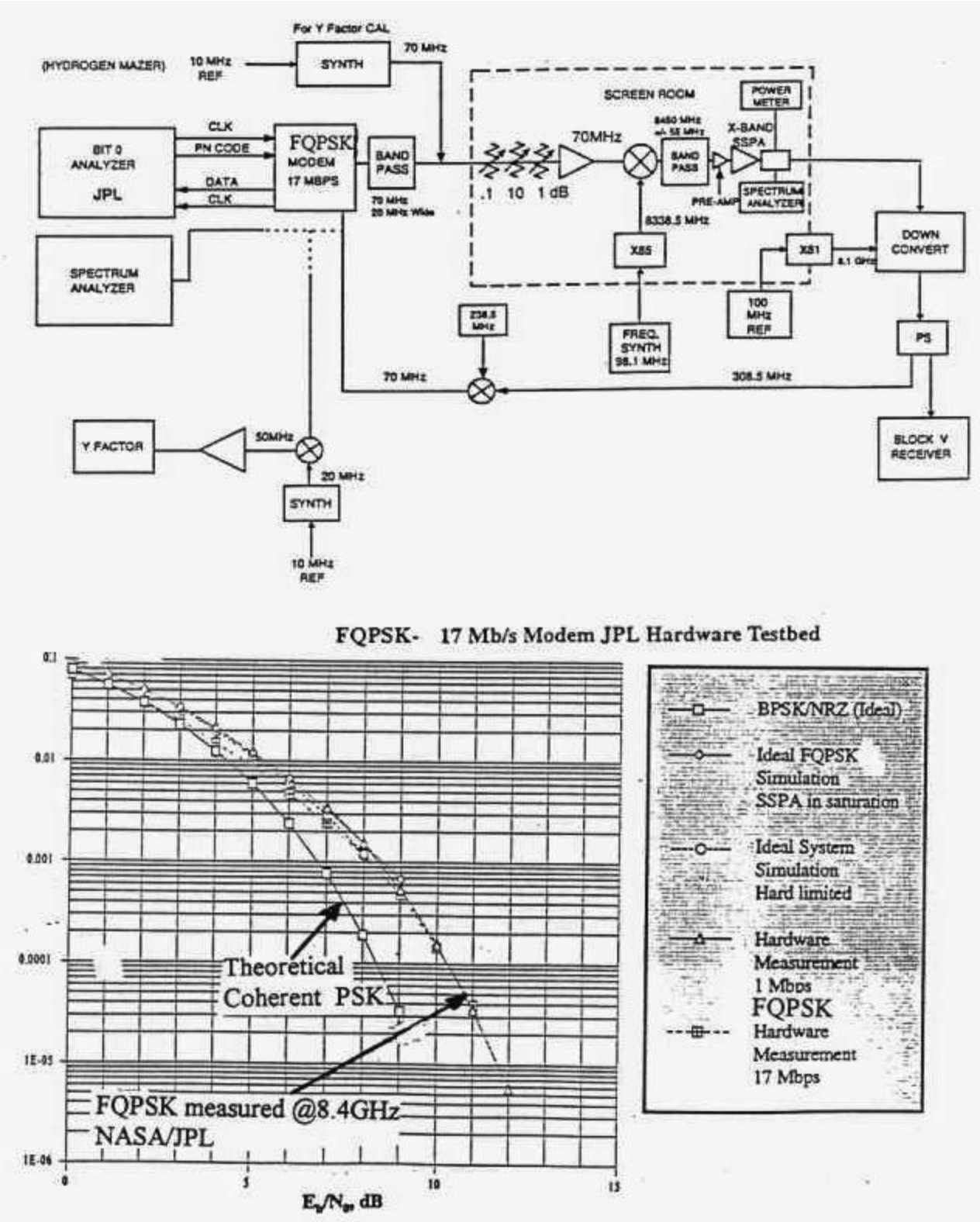

Fig. 8 NASA-JPL: FQPSK modem and 8.4 GHz NLA transceiver block diagram, used for FQPSK tests and evaluations of 17 Mb/s Lockheed Martin designed and manufactured & L-3 Communications Inc. manufactured FQPSK-GMSK Feher patented systems and of 1 Mb/s rate RF Networks, Inc. FQPSK systems and BEP results [14; 22]

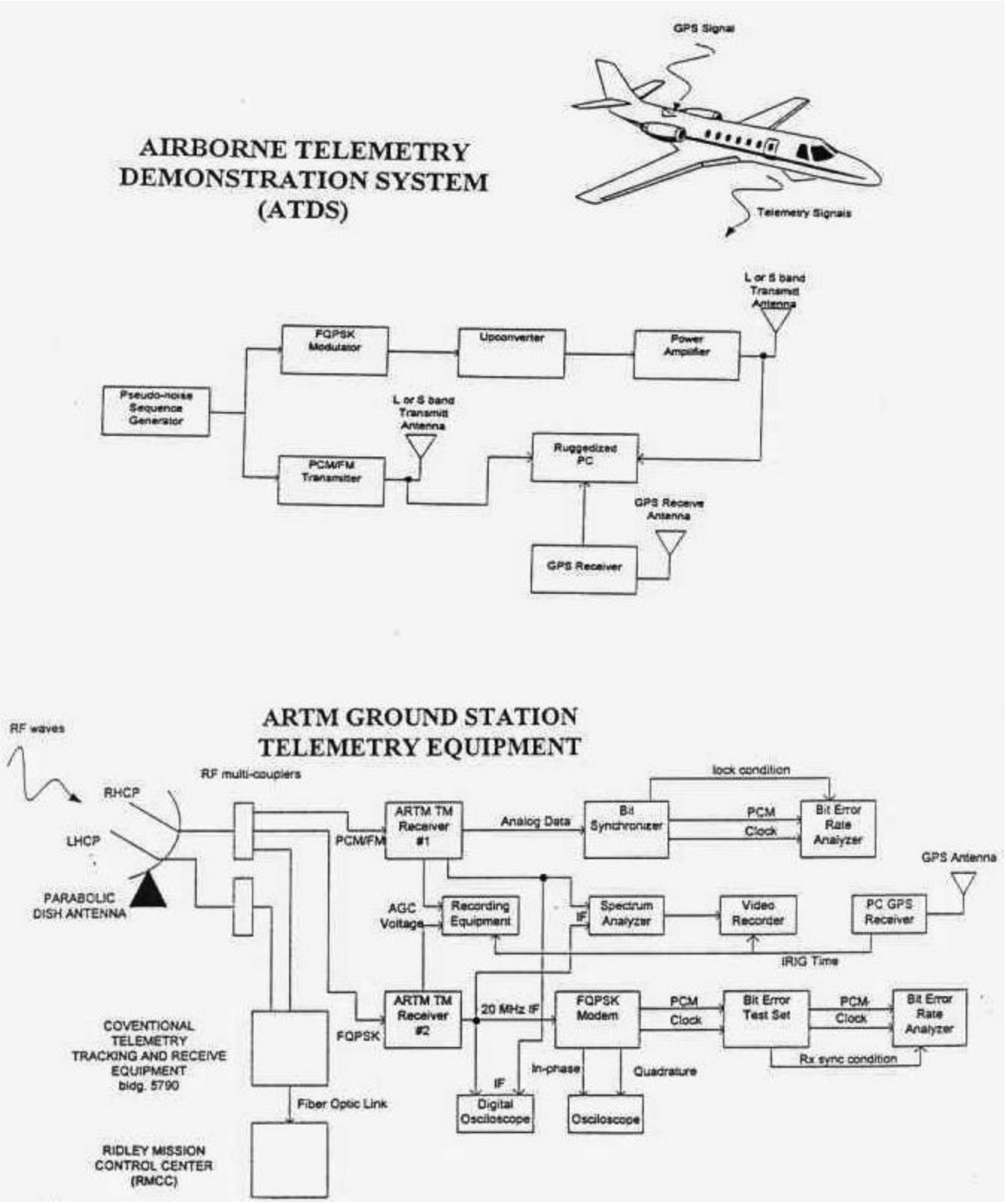

Fig. 9 ARTM Program's Airborne Telemetry Demonstration System and Ground Station Telemetry Equipment used for FQPSK and PCM/FM flight tests in the L-band and S-band, with transmit power of about 10 Watt & flight distances of about 300 km [21]

During the Advanced Range Telemetry (ARTM) scheduled Conference Session at the International Telemetering Conference, ITC-'98 in San Diego, October 98, further details and test results will be presented by members of the ARTM team. Illustrative sample BEP and datalink performance results measured in the L-Band (approx. 10 Watt RF power at 1480.5MHz & 1485.5MHz and in the S-band indicate that the data link and BEP performance of the FQPSK is very similar to that of the baseline PCM/FM system. Similar conclusions have been reached for a large class of "Flight Decks" that is, different flight trajectories. T&E flights have been performed for the initial set of FQPSK and PCM/FM comparisons for distances of up to 300km at low altitudes of only 150 meters above ground level, medium altitudes of about 4,000 meters above ground, and of 10km and higher altitudes (for "supersonic flight corridors"). In the initial set of measurements the airborne transmit antennas were omnidirectional "blade" and "button" antennas located on the belly of the jet aircraft.

The primary objective of the flight tests for TIER-1 of the ARTM Program has been to Test and Evaluate comparable datalink availability and BEP performance of the FQPSK and of the PCM/FM systems. The spectral efficiency advantage of FQPSK (of approximately 2:1 of FQPSK) has also been demonstrated to the respective Spectral Managers. It is significant to note that in Line-of-Sight (LOS) environments, even at distances of about 300km, error-free intervals of 20 minutes or longer have been recorded on both systems, i.e., for LOS environments there was no noticeable "error-floor." For example, in one of the 20 minute measurement intervals at a 1Mb/s rate, 1,200 seconds x 1Mb/s = 1.2×10^9 bits were transmitted with a 20-minute average BEP of less than $BEP=10^{-9}$. While the aircraft was maneuvering, selective fade – NLOS (Non-Line-of-Sight) induced burst errors have been observed on both systems.

ACKNOWLEDGMENTS

I wish to thank directors of the US Departrment of Defense - Office of Undersecretary of Defense – Central Test Evaluation and Investmnent Program (CTEIP) and in particular Dr. Patricia Sanders and Mr. John Gehrig for their vision and directives for bandwidth – spectral saving advanced developments and their leadership for "dual–use" commercial and military technology Tests and Evaluations (T&E). I thank ARTM's director, Mr. Charles Irving (and his predecessor, Tim Chalfant) for offering tremendous most interesting challenges. I thank the dedication, professional and friendly cooperation of the ARTM team at Edwards AFB and in particular Messrs.: R. Jefferis, V. Schiappi, K. Temple, V. Diekmann, R.Downing and special thanks to Eugene Law, US Navy, Pt. Mugu, for his guidance and teachings. E. Law introduced me to the challenging telemetry field and he has been my technical best mentor.

REFERENCES

1. K. Feher et al.: US Patents 4,567,602; 4,339,724; 4,644,565; 5,491,457; 5,784,402 and Canadian Patents: 1,211,5017; 1,130,871; 1,265,851 and post-patent improvements, including Digcom's proprietary 'know-how' and other US and international patents pending/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, make, sale, developments and other use and applications to large, medium size and small corporations and organizations in the USA and internationally by Digcom, Inc. For FQPSK Consortium, FQPSK–GMSK Feher patented licensing and technology transfer information and for FQPSK-2 (Feher Quadrature Phase Shift Keying 2nd generation) write to: **FQPSK Consortium-Digcom, Inc**., 44685 Country Club Drive; El Macero, CA 95618; USA; Tel. 530-753-0738; Fax 530-753-1788.
2. K. Feher: "*Wireless Digital Communications: Modulation and Spread Spectrum Applications."* Book published by Prentice Hall, 1995, includes computer design disk.
3. E.L. Law: "Robust, bandwidth efficient modulation methods for aeronautical telemetry applications; spectral occupancy, adjacent channel interference and bit error probability comparisons," *Proc. of European Tel. Conf.-ETC'98*, Germany, May 5-8, 1998.
4. E.L. Law, D.R. Hust: *Telemetry Applications Handbook.* Technical publication #TP000044, Pacific Missile Test Center, Pt. Mugu, CA 93042, Sept. 1987.
5. E. Law, K. Feher: "FQPSK versus PCM/FM for Aeronautical Telemetry Applications; Spectral Occupancy and Bit Error Probability Comparisons," *Proceedings of the International Telemetry Conference*, Las Vegas, NV, Oct. 27-30, 1997.
6. Y. Guo, K. Feher: "A new FQPSK modem/radio architecture for PCS and mobile satellite communications," *IEEE Journal on Selected Areas in Communications*, Feb. 1995.
7. K. Eggertsen, A. Cirineo, A. Cameron and J. Cleveland: "Approach to a Common Solution for the Family of Interoperable Range System Transceivers (FIRST)," *Proceedings of IEEE MILCOM '97 Conference*, Monterey, CA, Nov. 2-5, 1997.
8. K.F. Eggertsen, A. Cirineo, A.G. Cameron, K. Feher: "FIRST: DoD's Range Radio Data Link Standard. Synergy with Commercial Wireless Applications," *Proc. WIRELESS '97 Symposium/Exhibition*, Santa Clara, CA, Feb. 10-14, 1997.
9. C. Brown, K. Feher: "A Reconfigurable Modem for Increased Network Capacity," *IEEE Transactions on Circuits and Systems for Video Technology*, April 1996.
10. K. Feher, H. Mehdi: "Modulation/Microwave Integrated Digital Wireless Developments," *IEEE Transactions on Microwave Theory and Techniques*, July 1995.
11. T.A. Chalfant, E.H. Straehley and E.R. Switzer: "Advanced Range Telemetry (ARTM): Preparing for a new generation of Telemetry," *Proceedings of the International Telemetering Conf.*, San Diego, CA, Oct. 28-31, 1996, (Vol. XXXII, pp. 833-836).

12. K. Feher: "FQPSK Doubles Spectral Efficiency of Operational Systems," *RDT&E Spectrum Requirements Working Group - DoD, NASA and AIAA Working Group*, MITRE Corp., Reston, VA, Dec. 4, 1997.
13. K. Feher: "Alternate Modulation Methods for Telemetry Applications - Phase 2, Final Report," submitted to E. Law and distributed to the RCC Telemetry Group, IRIG No. 106, *97th Range Commanders Council, Telemetry Group Meet.*, Solomon, MD, Sept. 9, 1997.
14. W.L. Martin, T-Y. Yan, L.V. Lam: "CCSDS - SFCG: Efficient Modulation Methods Study at NASA/JPL, Phase 3: End-to-end system performance," *SFCG Meeting*, Galveston, TX,
    Sept. 16-25, 1997.
15. G. Do and K. Feher: "FQPSK-GMSK: Wireless System Tests in an ACI Environment," *Proc. of the Sixth Annual WIRELESS Symp.* Santa Clara, California, Feb. 9-13, 1998.
16. W.L. Martin, T-Y. Yan, L.V. Lam of NASA/JPL: "Efficient Modulation Methods Studies at NASA/JPL" *Proc. of European Tel. Conf.-ETC'98*, Germany, May 5-8, 1998.
17. C. Irving, US Air Force, Edwards, CA: Advanced Range Telemetry (ARTM) Program," *Proc. of European Tel. Conf.-ETC'98*, Germany, May 5-8, 1998.
18. K. Feher: "FQPSK Proposal: Distributed Briefing Notes," *'Proposed Bandwidth-Efficient Modulation Standard for Aerospace Data Communications' Workshop*, sponsored by AIAA in cooperation with NASA and the DoD, Naval Research Laboratory, Washington, DC, March 24, 1998.
19. K. Feher: "FQPSK Doubles the Spectral Efficiency of Operational Telemetry Systems," *Proc. of European Tel. Conf., ETC'98*, Garmish-Patternk., Germany, May 5-8, 1998.
20. AIAA in cooperation with NASA/JPL-DoD: "Draft Specification Radio Transceiver, Version 1.0 " Radio Transceivers AIAA, Naval Research Laboratory, Mar. 24, 1998, Washington, DC.
    Note: FQPSK is specified in this draft standard. For updates and copies, contact Dr. Tsun-Yee Yan at JPL/NASA, Tel 818-354-3016, Fax 818-393-1717, Chair, AIAA Specifications Subcommittee and Carol J.Williams NASA-AIAA, Tel 818-354-0455 Fax 818-354-9068
21. V.M. Schiappi, Project Manager ARTM: "Airborne Telemetry Demonstration System (U)-Test Plan" ARTM Program Office, US Air Force, Edwards AFB, CA, May 1998
22. J. Weese, L.V. Lam of NASA/JPL: "Selected Laboratory Measurements of FQPSK-B Modems Over 8.4GHz Nonlinearly Amplified JPL Test-bed," NASA/JPL submission–report A.I.97-14, 97-15 to CCSDS, Houston, TX, May 1998

23. AIAA (American Institute of Aeronautics and Astronautics) - Space Operations Support Technical Committee (SOS-TC): "Recommendation Concerning Use of Waveform Coded Offest Quadrature Phase Shift Keying (QPSK) modulation with baseband filtering to increase RF Spectrum Efficiency," Approved by Chair of AIAA SOS-TC on 30 June 1998. This AIAA document contains recommendation by the AIAA to the US Department of Defense, NASA and for international CCSDS standardization" that FQPSK modulation be immediately adopted as the interim increment–1 standard."