IEEE 802.11

WIRELESS ACCESS METHODS AND PHYSICAL LAYER SPECIFICATIONS

Title: 1 Mb/s and Higher Data Rate PHY/MAC : GFSK and FQPSK

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ABSTRACT

Preamble and PHY header bits for the recently standardized 1 Mb/s rate GFSK-FH system are suggested. Bits to develop " ... means for negotiating a switch to higher data rates from the data rate defined ..." are also proposed.

For higher data rate FH, DS spread spectrum, and infrared applications, we propose FQPSK and FQPSK-KF nonlinearly amplified (NLA) robust power and spectrally efficient solutions. These wireless systems operated with simplest threshold detectors in an interference environment (binary robust eye diagrams in the I and Q channels of the coherent demodulator) have an increased bit rate of 1.5 Mb/s while the 4-state systems have a bit rate capability of over 2 Mb/s (with 3 Mb/s potential), in a 1 MHz bandwidth. Here bandwidth is defined at 99% or –20 dB power spectral density (PSD), that is, the "conservative" FCC definition is used. An integrated ACI-FCC interpretation, suggested in this submission, would lead to significantly higher data rates. Product/hardware measurement results, computer analysis and study demonstrate the following key parameters:

	Standardized	Proposed Higher Speed			
	GFSK	FQPSK-1	FQPSK-KF	FQPSK 4*4	FQPSK 8*8
Max. bit rate in 1 MHz	1 Mb/s	1.1 Mb/s	1.5 Mb/s	2.048 Mb/s+	3 Mb/s +
Required E_b/N_0 for BER = 10^{-5} in Gaussian noise	19.3 dB (15.5*)	10.5 dB	15.7 dB	15 dB	19.8 dB(?)

*with more complex receiver baseband processor

The BER performance of the proposed FQPSK modems in a NLA-AWGN (Additive White Gaussian Noise) and also Rayleigh faded interference controlled environment [BER = f(C/I)] is evaluated. A performance comparison with other proposed "higher bit rate systems," is undertaken. Based on the critical BER = $f(E_b/N_0)$ and highest possible bit rate criteria, the FQPSK-KF family of NLA radio/modems outperform 4-FSK and FLOQAM systems proposed in References [15; 24]. Notice of patent applicability has been given in Document IEEE P.802.11-93/138 [5].

Low power, miniaturized cost efficient VLSI based FQPSK and FQPSK-KF modem/radios, suitable for smallest PCMCIA card implementations are presented in an accompanying paper presented by Dr. S. Kato of NTT [7]. These coherent systems have a rapid synchronization time, short preamble, and reduced number of PHY header bit requirements.

Preliminary data indicate that reduced data file transfer time/message delay and increased throughput could be attained with more robust modems having lower E_b/N_0 and C/I requirements. A detailed investigation is proposed.

1. INTRODUCTION

During the Denver, July 12-15, 1993, IEEE 802.11 meetings, a motion in regards to the IEEE standardization of the Frequency Hopped (FH)-Wireless Local Area Network (WLAN) was approved. Reference Document: [IEEE P.802.11-93/117, Denver, July 1993, pp. 7-10]. This standard requires that

> **FH-PHYs shall be capable of operating using GFSK with BT = 0.5 and a minimum deviation of 160 kHz with a data rate of 1 Mb/s.**

In this submission the **unedited draft** wording of the standard is used as the exact content of the final edited version is not known to me. It was stated that the FCC 15.247 rules apply for this 2.4 GHz to 2.48 GHz ISM band application and that the maximal RF 99% bandwidth is 1 MHz. The reader is advised to consult the official standardization documents. The following was also approved:

> **A means for negotiating a switch to higher data rates from the data rate defined above is for further study.**

This second part of the approved standard, "a means of negotiating a switch to higher data rates ..." has been followed up by the newly formed "IEEE P.802.11 WLAN Higher Data Rate FH-PHY Ad-Hoc Interest Group" with co-chairs W. Moyers and N. Silberman. More than 30 Ad Hoc members have expressed a substantial interest in the investigation and possible standardization of higher (higher than 1 Mb/s) rate FH-PHY systems.

In this report, Nonlinearly Amplified (NLA) techniques which could attain a considerably higher data rate than the standardized basic rate of 1 Mb/s are described. NLA techniques have been recommended due to their increased RF power/battery efficiency ratio. Proposed simple and robust coherent binary filtered offset QPSK (or FQPSK) systems attain about 1.5 Mb/s while with 4-level (in I and Q) more than 2 Mb/s could be transmitted. With more elaborate 8*8 states up to 3 Mb/s could be transmitted in 1 MHz. Preamble and PHY header bits for the standardized GFSK and for "switch to higher data rates" are suggested.

This presentation and paper is a continuation of our IEEE 802.11, July 13, 1993, Denver, CO paper, Ref. [6].

2. NOMENCLATURE AND ABBREVIATIONS

Frequently used terms in this report and also in other submissions to the IEEE 802.11 Physical Layer (PHY) Committee are listed below.

FQPSK	Feher's patented filter/processor for QPSK (term "FQPSK"), offset QAM and other applications Ref. [1-5]. The term "FQPSK" represents a general term for a large class of processed filtered QPSK, offset QPSK, offset QAM (OQAM) and other systems. Illustrative examples presented in this report.
FQPSK-1	One of the basic Intersymbol-Interference Free (IJF) based patented "filter" processors [1]. Other modified systems are claimed in [1-6].
FQPSK-KF	Kato-Feher based invention a cross correlation between the I and Q quadrature data streams. Applies to FQPSK and others. S. Kato of NTT Japan and K. Feher, UC Davis [2; 13; 17]
FQPSK-4*4	Four signaling states in the demodulated I and Q signals. The transmitter is a nonlinearly amplified (NLA) offset 16 QAM or 16-OQAM having 4*4 independent NLA signal states.
GFSK	Gaussian Frequency Shift Keying (this modem has a variable modulation index and is suitable for noncoherent demodulation)
GMSK	Gaussian Minimum Shift Keying (MSK) has a modulation index of m = 0.5. For exact values of m = 0.5 coherent as well as noncoherent demodulation can be used
NLA	nonlinearly amplified

3. FQPSK AND FQPSK-KF NONLINEARLY AMPLIFIED (NLA) RADIO

A description of FQPSK-NLA modems and radio systems has been presented to the IEEE 802.11 committee during the Denver, CO, July 13, 1993 meeting [6]. A detailed description has been presented in more than 30 IEEE and other journal and conference papers, patents [1-5], and a book [13]. For details, please see the reference list in [6].

In Fig. 1 and Fig. 2, a generic block diagram of FQPSK modulation and parts of radio systems which could be **suitable for**

FH	Frequency Hopped Spread Spectrum
DS	Direct Sequence including CDMA
IR	Infrared-PHY

WLAN applications are illustrated. The **FQPSK family of NLA modems/radios** has many other possible applications not described in these basic conceptual block diagrams and/or report of FH-PHY.

FQPSK-KF: Correlated Signal Processor - A Review of Basic Concepts

The **Kato** and **Feher** (KF) modem radio or "FQPSK-KF" technique [2; 13; 17; 7] relates to a signal processor invention which is particularly useful for bandwidth efficient and power efficient nonlinearly amplified (NLA) wireless and other radio system applications. In order to reduce the envelope fluctuations of an IJF (Intersymbol and Jitter Free) processor or filter, or of a similar related processor, [see reference patents 1-5], a simple "crosscorrelator" is introduced. Illustrative circuits and concepts of the basic first set of filters, called "IJF" have been described in numerous patents and papers including [1-7; 10-13; 17; 25]. The resultant output of the IJF encoder is illustrated in Fig. 4a. A typical crosscorrelated output signal at the I-input drive of a quadrature mixer is illustrated in Fig. 4c [2; 7; 17].

One of the simplest "filtered" QPSK is the "FQPSK-1" set of signals. This set obtained by deleting the crosscorrelator. A large class of modulated crosscorrelated signals can be generated by numerous independent combinations of the processed baseband wave form or IJF and the coefficients/algorithms of the correlator. The basic FQPSK invention [Patent Ref. "Filter" 1; 3; 4] describes the generation of a very large class of useful baseband signals. Combined with the crosscorrelator or "X" functions, and followed by a simple DSP (or other technique) low-pass filtering or processing, a large class of two-level, as well as multilevel signals can be generated. These are all suitable for nonlinear amplification. The crosscorrelator patent could also be used for processing non "IJF" signals and non "FQPSK" signals.

Block Diagrams/Circuits/Results

In Fig. 3, an **FQPSK-KF** transmitter/receiver is illustrated. The FQPSK-KF (Kato/Feher correlated FQPSK) has a very simple Baseband Processor (BBP) in an offset QPSK or equivalent filtered offset QAM or for short **FOQAM** [13] configuration. The "F" filter provides one of the many possible simple processed baseband bandlimited waves, as explained in Patents [1-5] and also in Ref. [6; 7; 13; 17]. Following a basic crosscorrelation or "X", simple digital (or analog) LPF (low pass filters) are inserted for final spectral shaping. For example, these LPF's could be chosen from a large class of 4th or 8th order filters having Butterworth, Chebycheff, Bessel or approximately Double Jump or variable shape responses. The receiver is a conventional offset mode QPSK receiver, such as described by NTT's Dr. Kato during this September 1993 Atlanta 802.11 meeting [6; 17].

One of the many possible Intersymbol-Jitter Free (IJF) waveforms of the FQPSK baseband signal is illustrated in Fig. 4(a). Other types of non IJF signals can also be generated by the inventions of [1-5]. The block diagram of a crosscorrelated or FQPSK-KF modulator and one illustrative resulting "I" and "Q" baseband drive signal of the quadrature modulation (OQPSK or offset QAM, i.e., OQAM) inputs is illustrated in Fig. 4(b) and Fig. 4(c).

A very simple circuit and implementation diagram concept is shown in Fig. 5. In this circuit discrete IC components are used. The "simple digital filter" could be a 4th or 8th order filter as described previously. The schematic diagram for a possible DSP implementation is shown in the lower part of Fig. 5 [25]. Large scale or VLSI single chip implementation are low-cost, low-power and simple [7; Dr. Kato et. al., NTT].

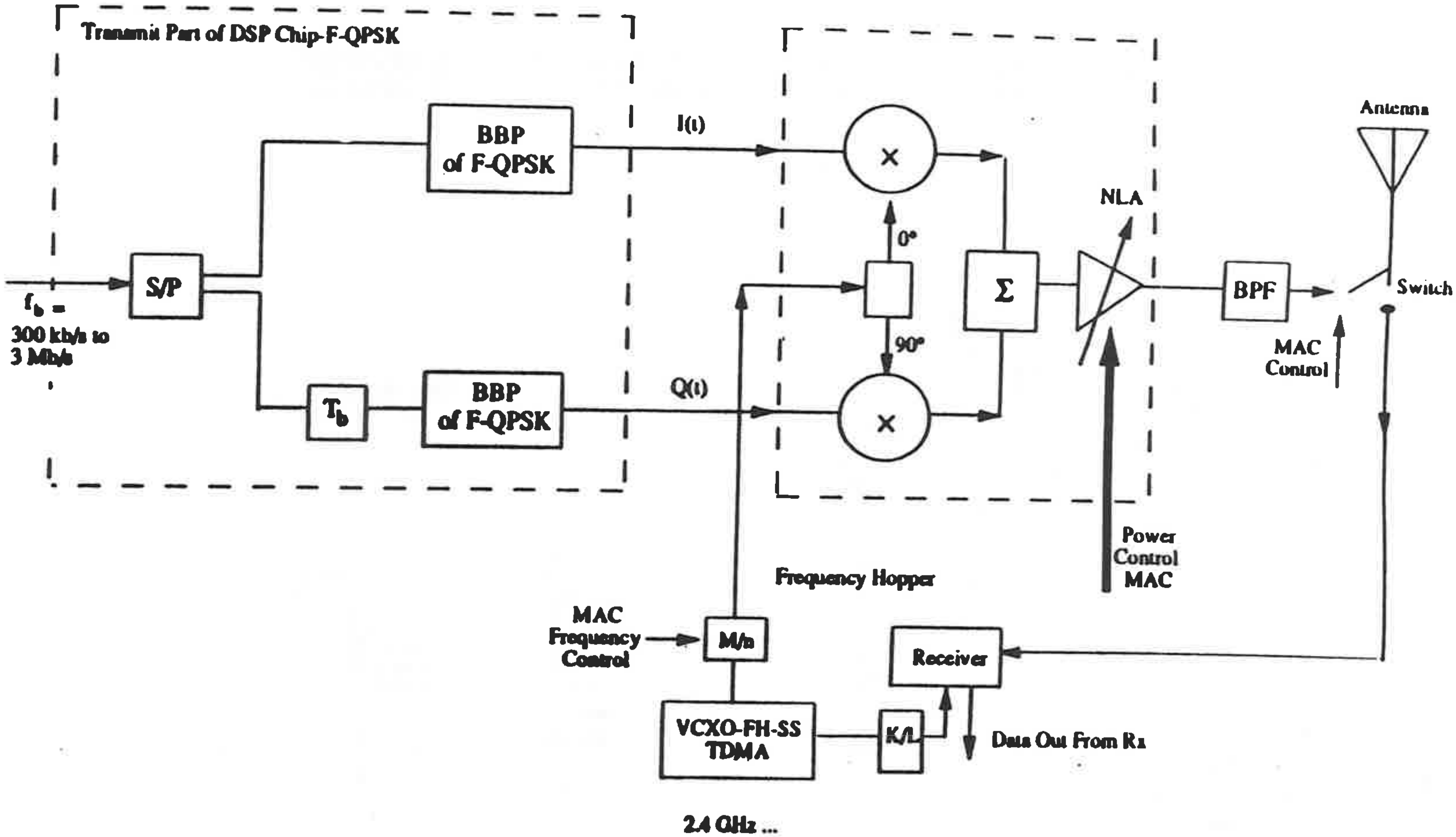


Fig. 1 Conceptual diagram of a transmitter of a FH or DS spread spectrum radio system. Bit rate "f_b" could be replaced by "chip rate f_c." A fairly general Baseband Processor (BBP) chip based on DSP implementation of a class of FQPSK Nonlinearly Amplified (NLA) systems is illustrated.

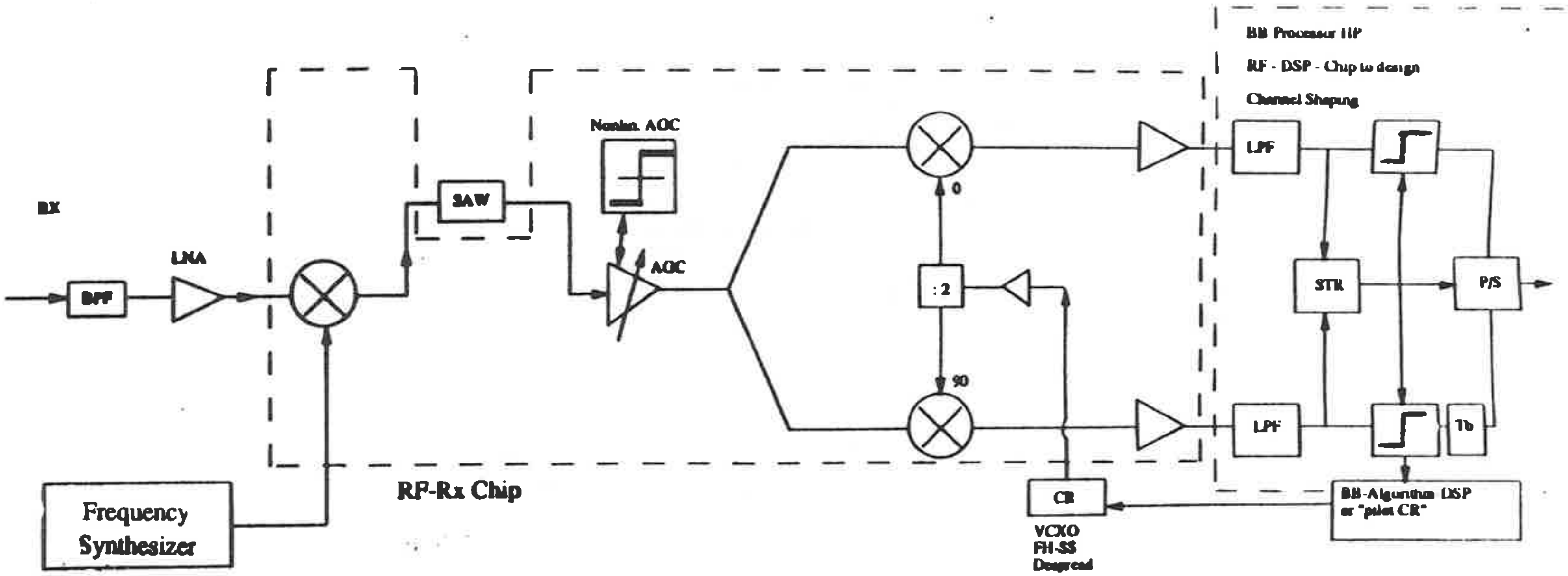


Fig. 2 Receiver with one IF stage for coherent demodulation of conventional offset QPSK (OQPSK), offset QAM (OQAM) and of FQPSK or FQPSK-KF

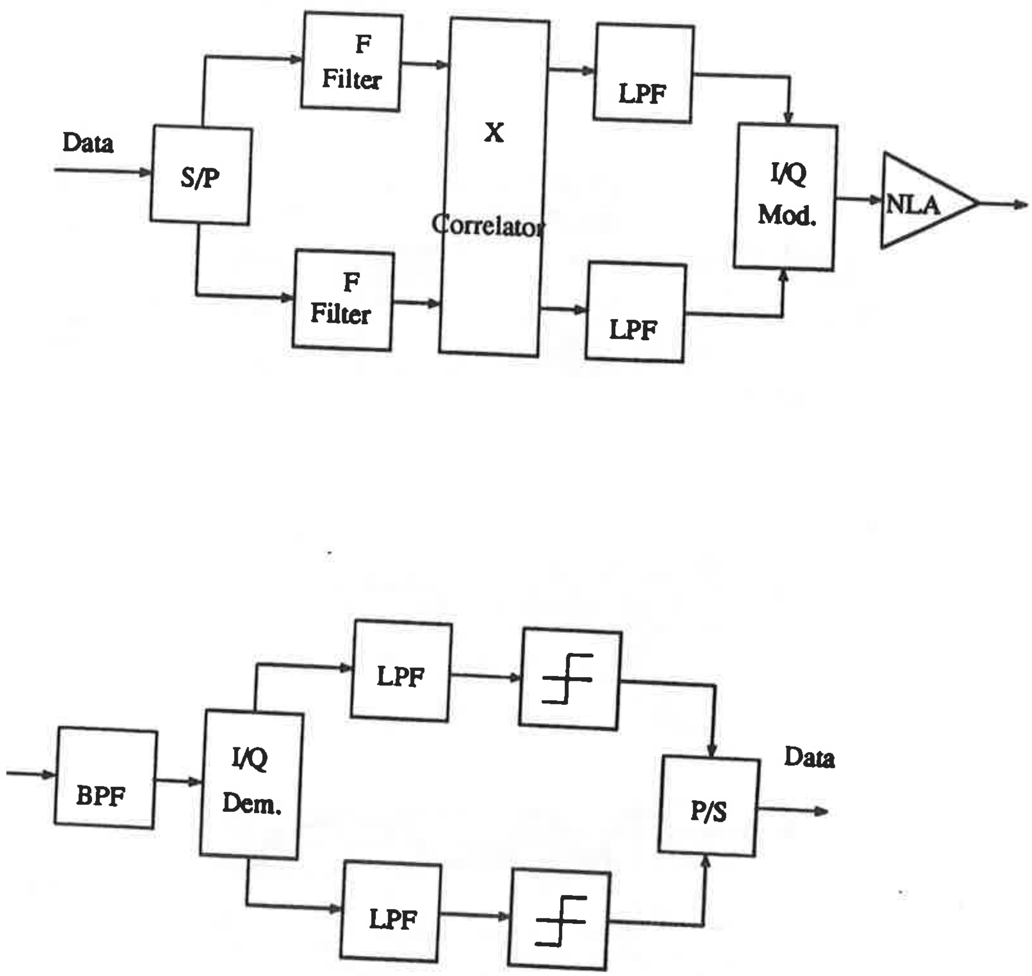


Fig. 3 Block diagram of FQPSK and FQPSK-KF modulator/demodulator (modem). The "F" filter following the Serial to Parallel converter (S/P), and the crosscorrelator "X" are described in references [1-7; 13; 17]. Following the crosscorrelator, simple Low Pass Filters (LPF), are used prior to the I and Q modulator. A nonlinearly amplified (NLA) transmitter is used.

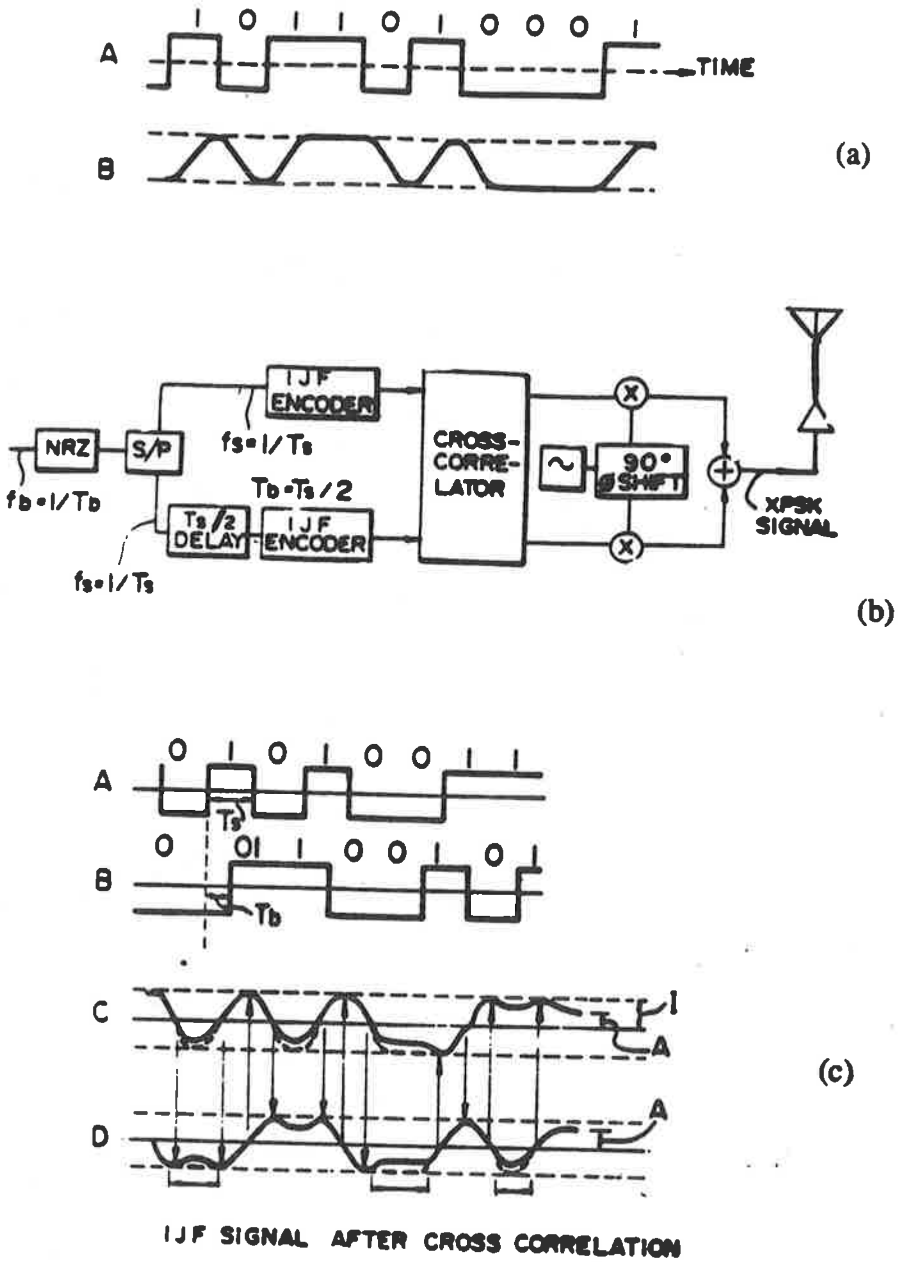


Fig. 4 Generation of FQPSK and of **FQPSK-KF**. modulated and NLA radio signals. (a) A basic FQPSK baseband processed signal or "FQPSK-1", also known as "IJF" or Intersymbol and Jitter Free Signal. (b) Filtered "F" crosscorrelator concept based on Kato-Feher (KF) invention, abbreviated FQPSK-KF. (c) Baseband I and Q crosscorrelated signals.

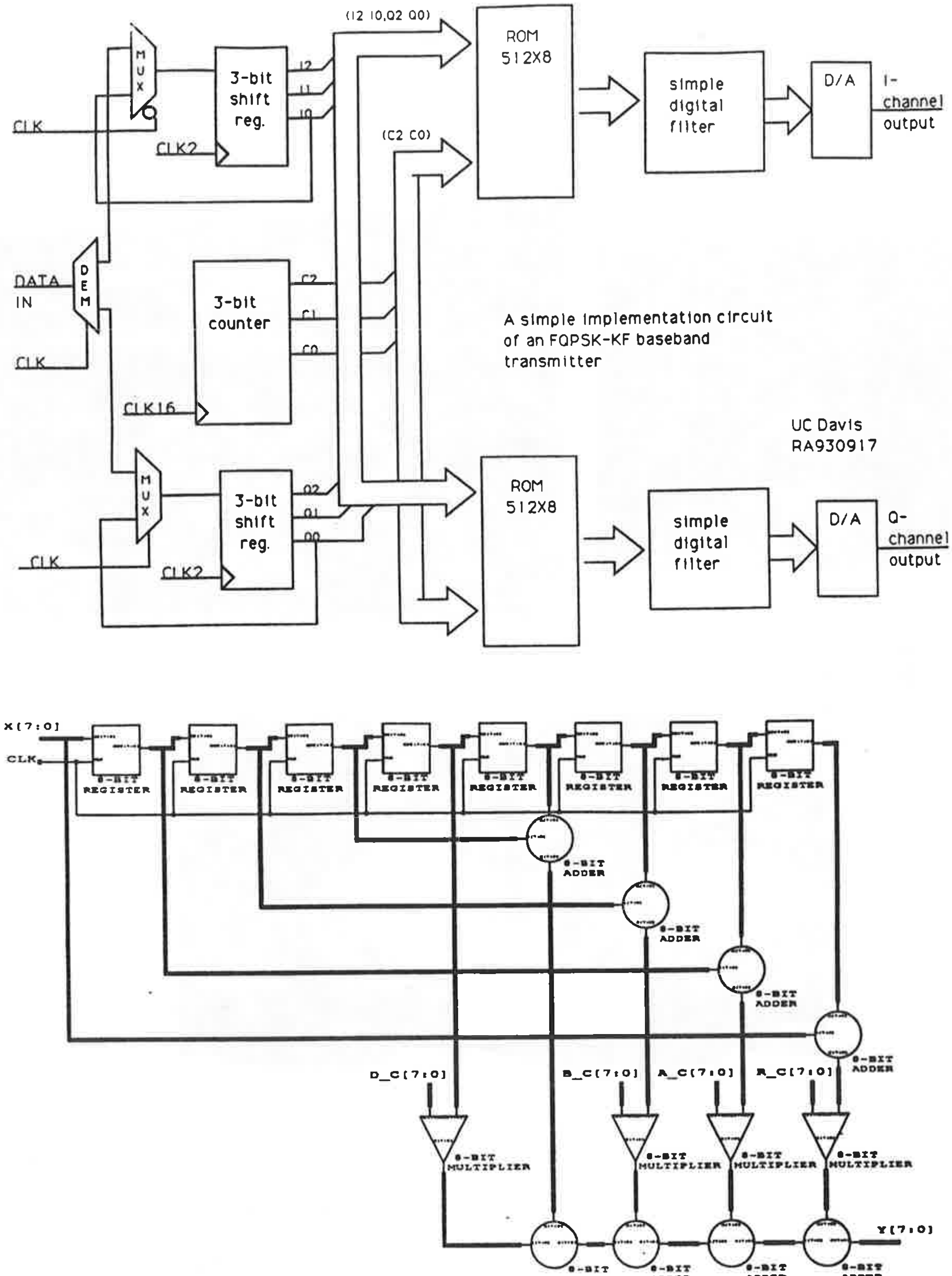


Fig. 5 An illustrative circuit diagram of (a) F-filter, crosscorrelator and serial/parallel/offset logic [18], (b) simple digital Low Pass Filter (LPF) implementation [25] based on discrete IC components. In the NTT paper related to FQPSK [7], Dr. Kato, et. al., present several VLSI implementations.

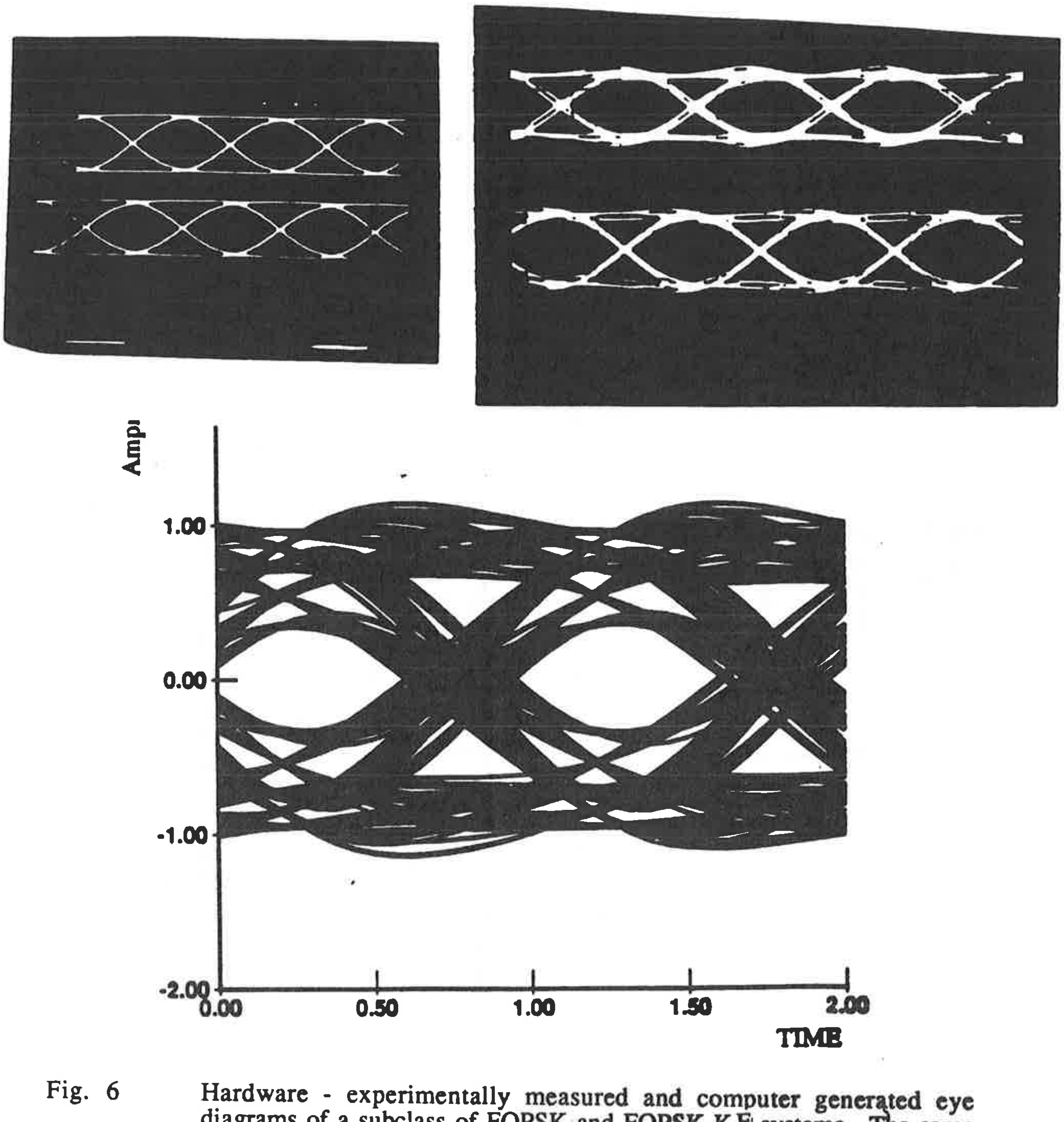


Fig. 6 Hardware - experimentally measured and computer generated eye diagrams of a subclass of FQPSK and FQPSK-KF systems. The same type of eye diagrams have been measured on operational radio/wireless products [6].

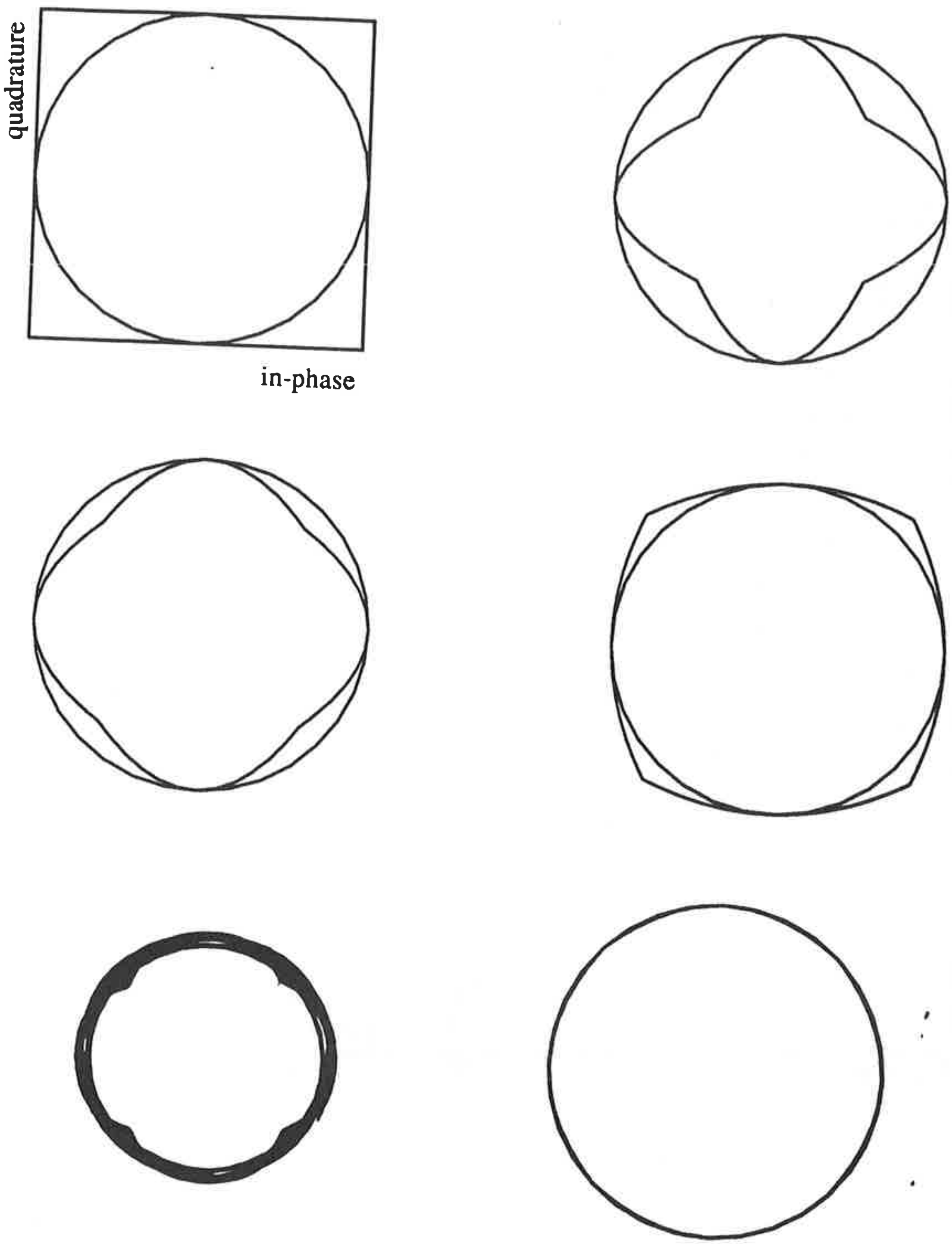
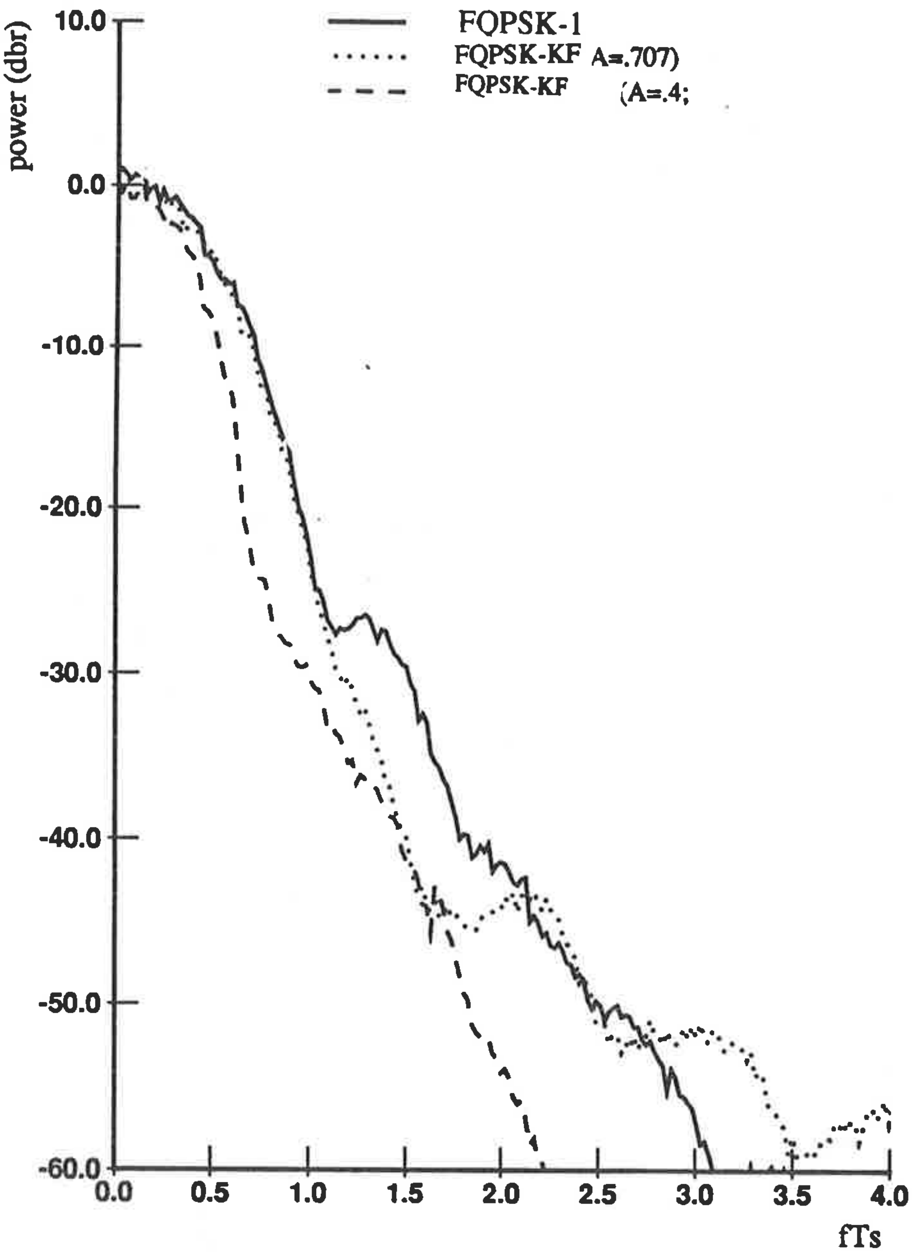
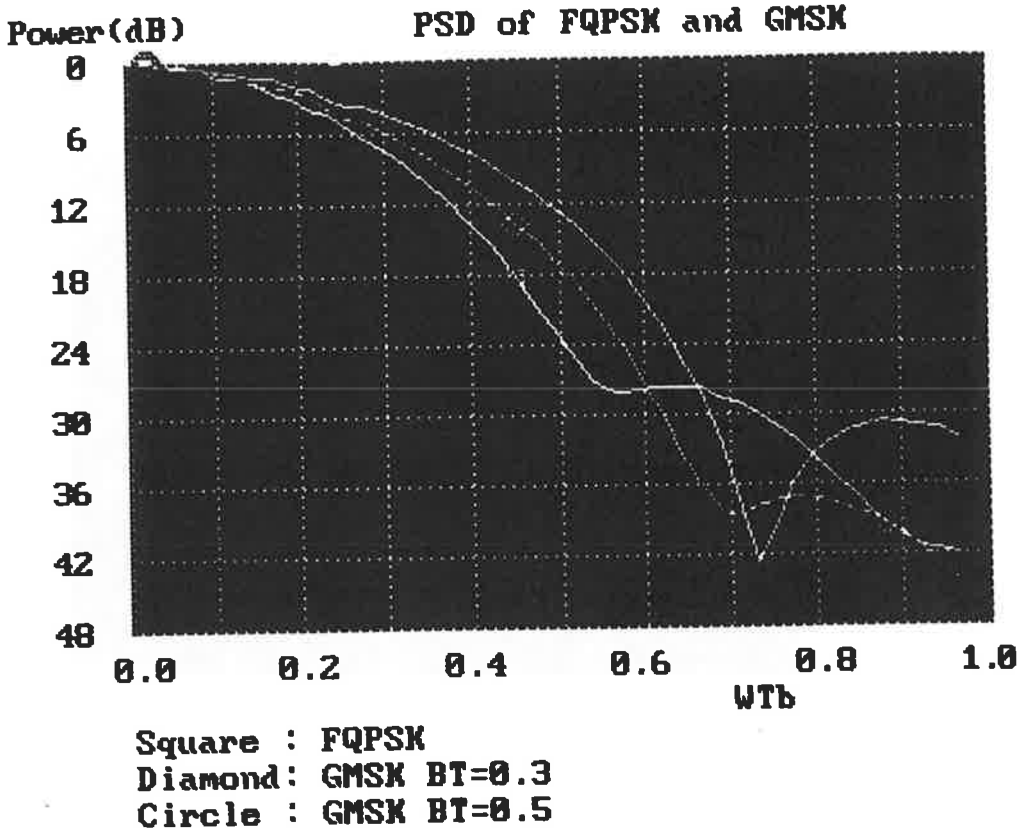


Fig. 7 Constellation "I-Q" phasor/amplitude diagrams of several unfiltered and filtered FQPSK and FQPSK-KF signals. These diagrams have been measured in linearly amplified systems. In NLA (nonlinearly amplified systems), ideal constant envelopes are obtained. The "crosscorrelator" reduces the envelope fluctuation, prior to the NLA, practically to zero.



PSD of FQPSK

Fig. 8 Power Spectral Density (PSD) of a class of FQPSK signals. FQPSK-1 is the spectrum of the basic "FQPSK-1" as described in [6] and [13]. Modifications of the basic digital filtered signal, as stated in patents [1-5], lead to a large class of signal shapes and to desirable NLA spectrum and robust BER performance. For FQPSK-KF, a correlation factor of A = 0.707 and a factor of A = 0.4 with a simple LPF processed case is illustrated.



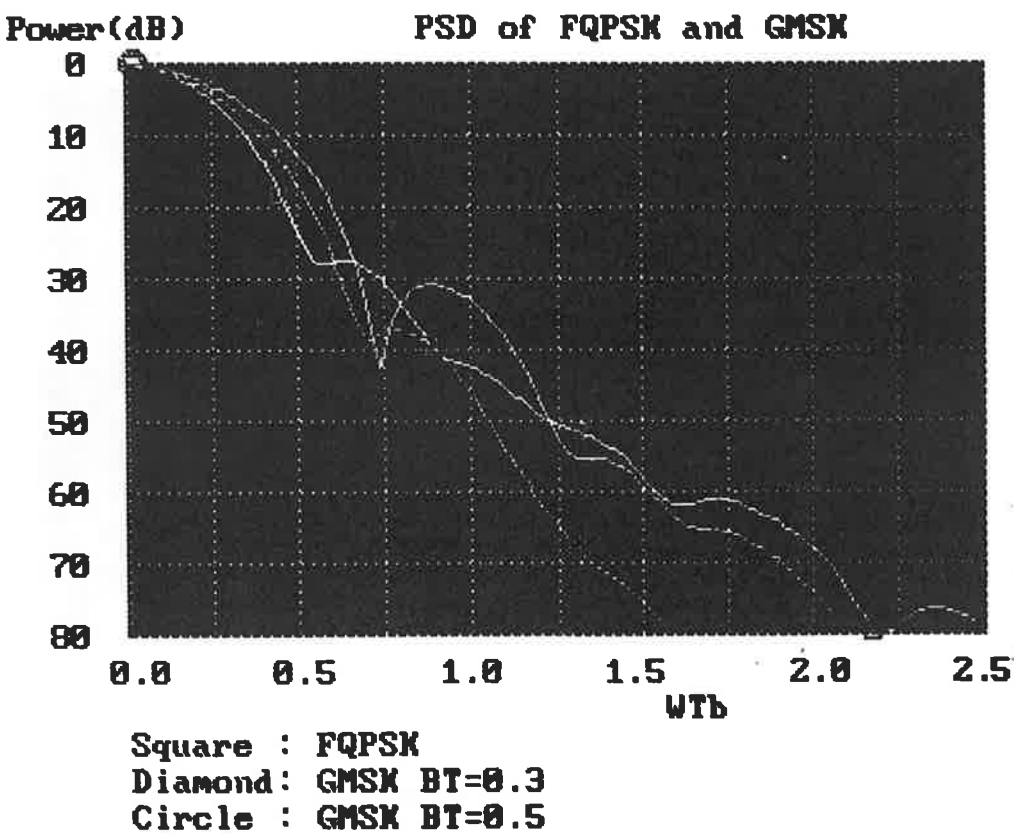
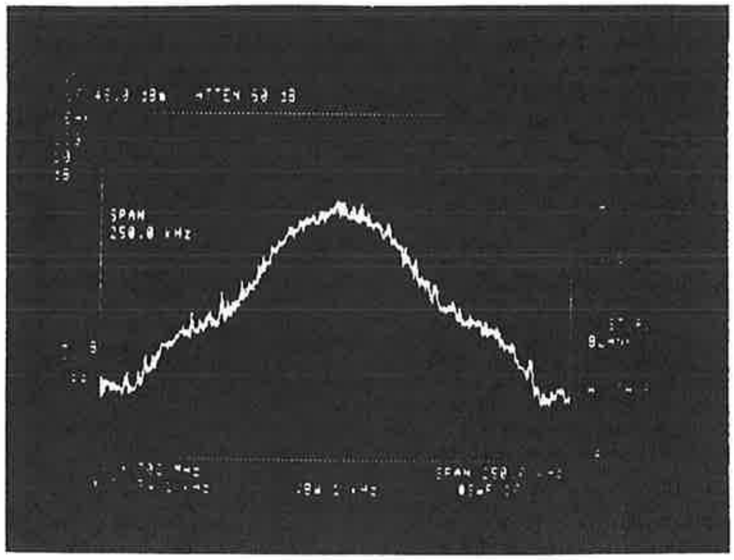


Fig. 9 The power spectral density advantage in the 20 dB (99%) range of the FQPSK as compared to GMSK is illustrated [6].



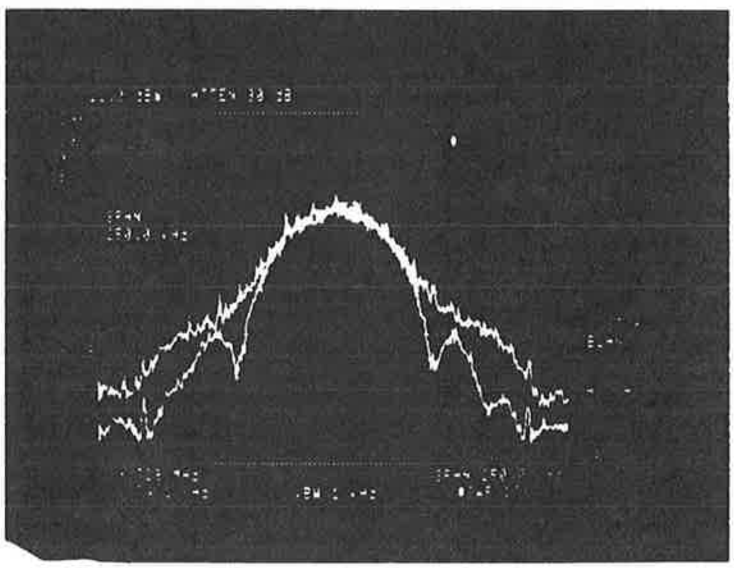


Fig. 10 Power Spectral Density (PSD) illustrative nonlinearly amplified (NLA) spectrum at f_b = 100 kb/s. Several FQPSK type of systems have been operated in the 16 kb/s to 512 kb/s range.

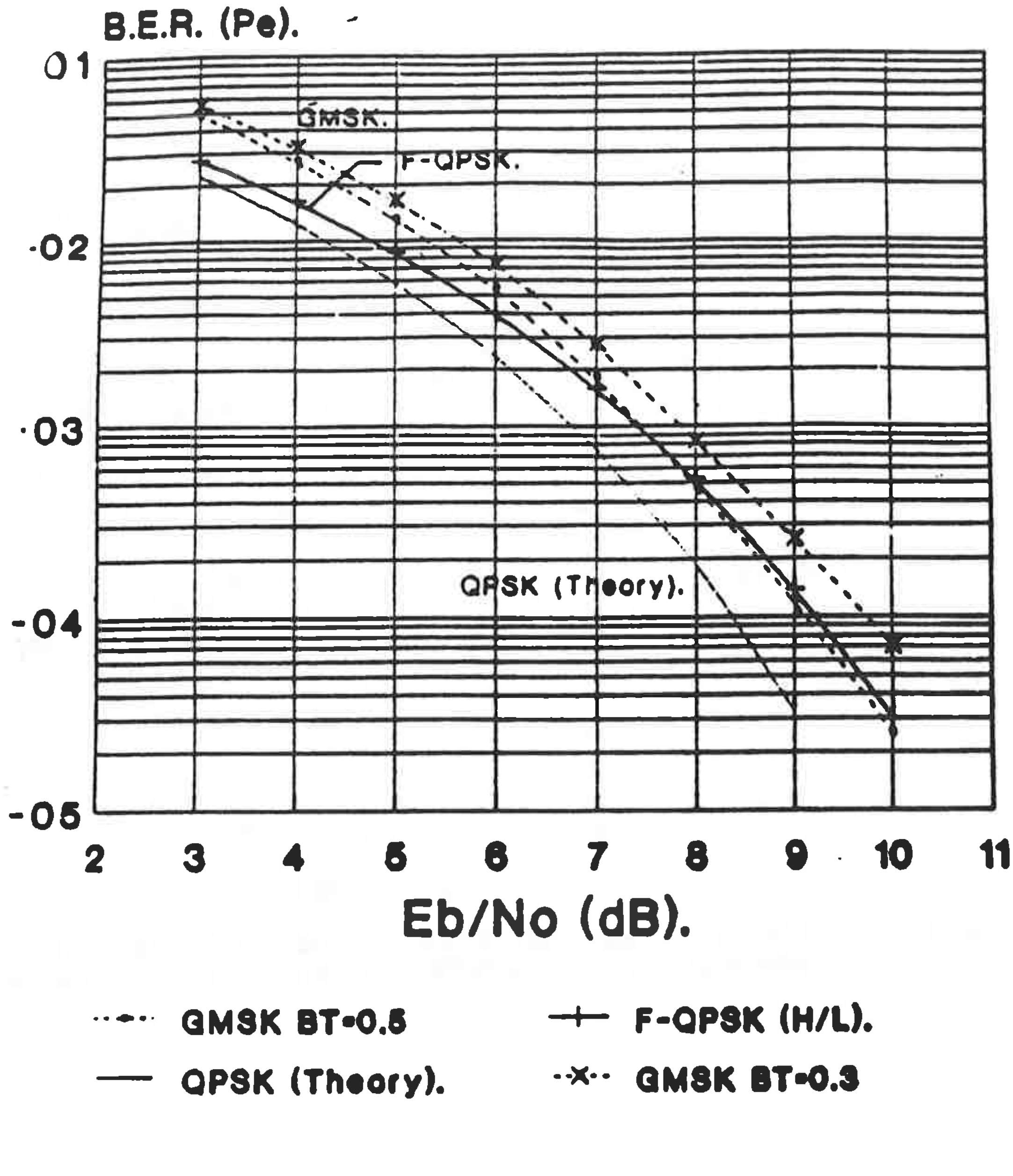


Fig. 11 BER = f(E_b/N_o) performance of nonlinearly amplified "FQPSK-1" and of coherent GMSK systems in a "stationary" AWGN (Additive White Gaussian Noise) environment.

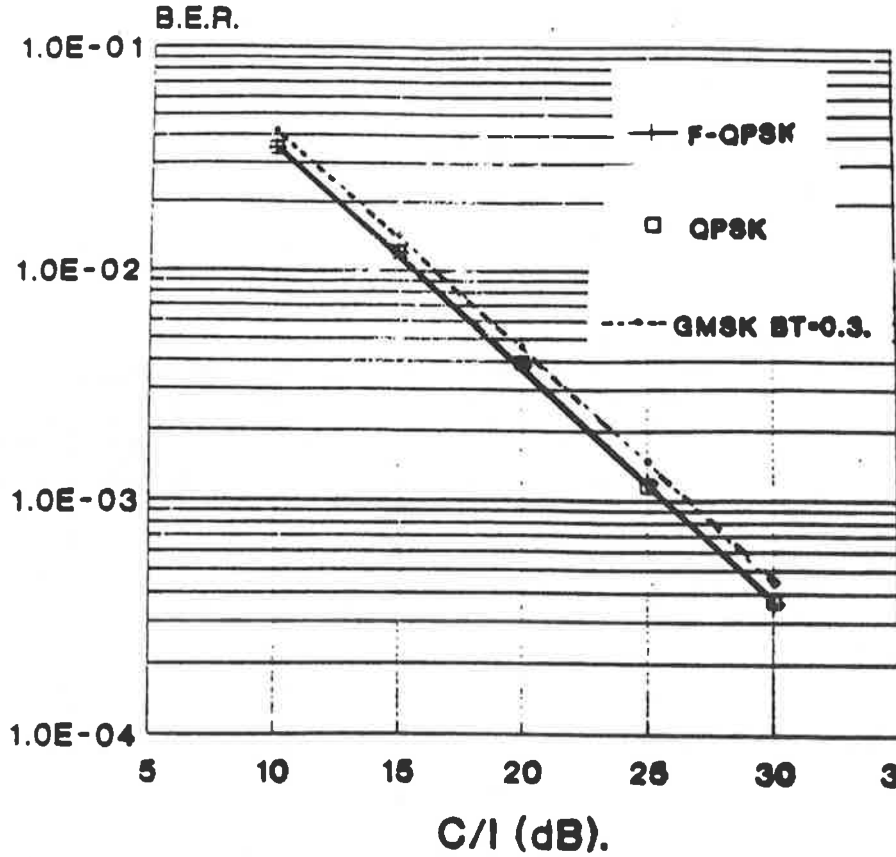


Fig. 12 BER = f(C/I)-Rayleigh: Rayleigh faded interference (C/I) controlled performance of coherent FQPSK-1 and of coherent GMSK systems.

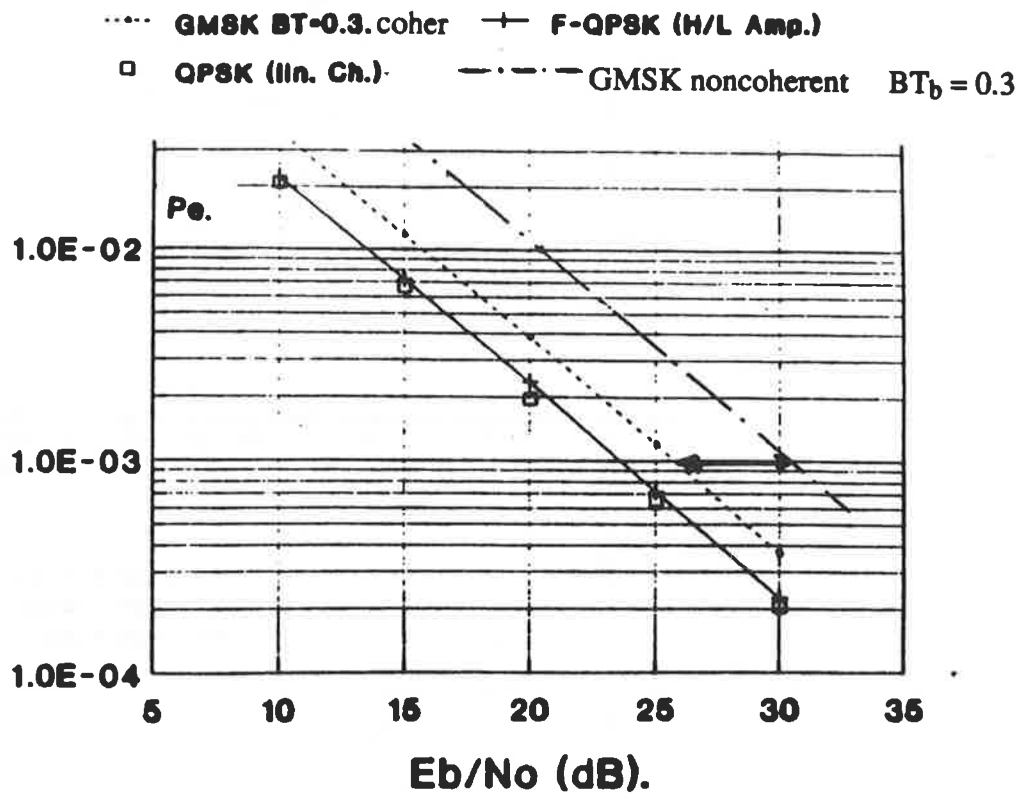
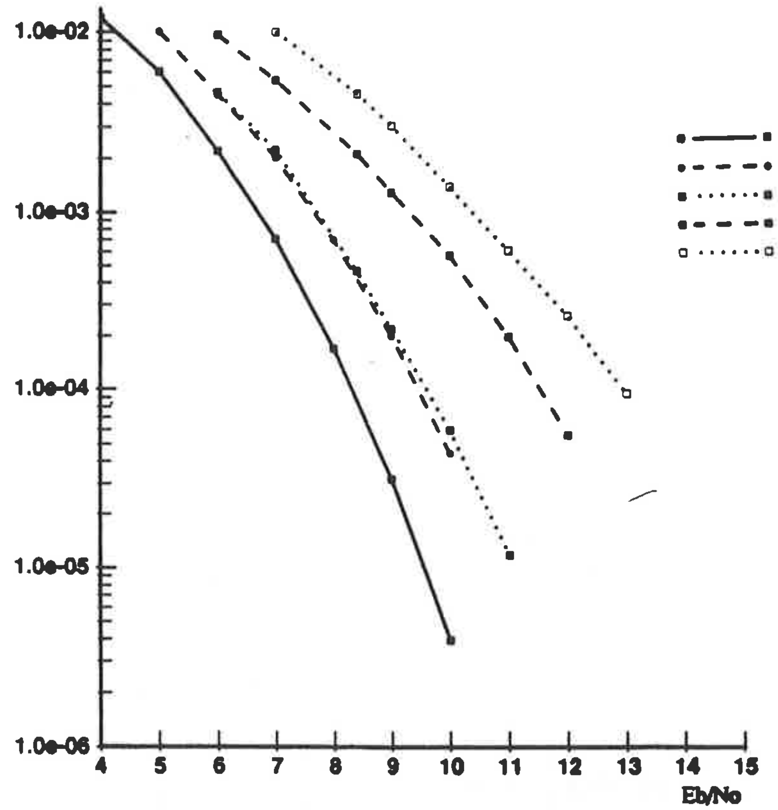


Fig. 13 Rayleigh faded performance of hardlimited (H/L) or conventional C-class nonlinearly amplified (NLA) FQPSK-1 and of GMSK (BT_b = 0.3) coherent and noncoherent systems. Note the **5.5 dB advantage** of the FQPSK systems when compared to GMSK noncoherent systems. In theoretical studies it was demonstrated that GMSK systems, in general, are more robust than reduced deviation index GFSK systems.



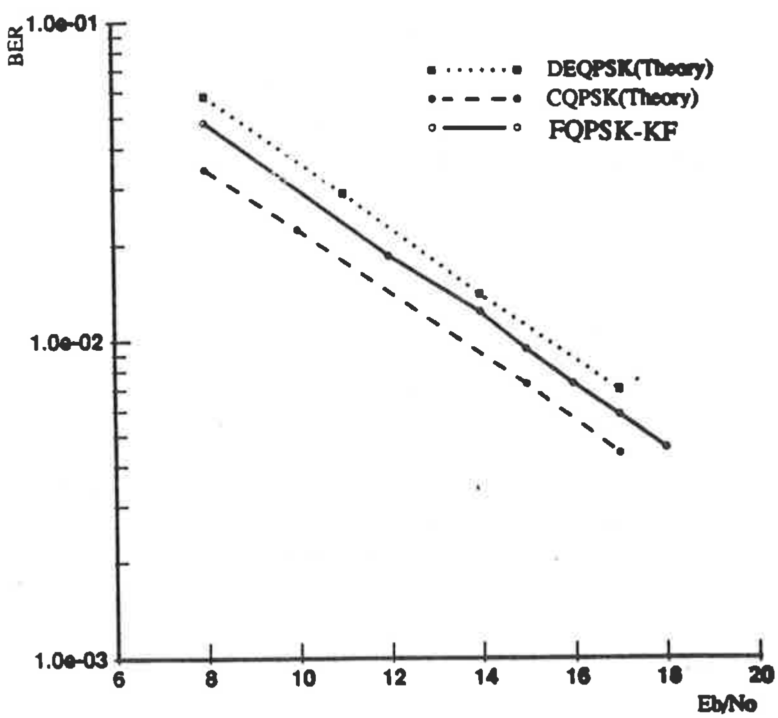
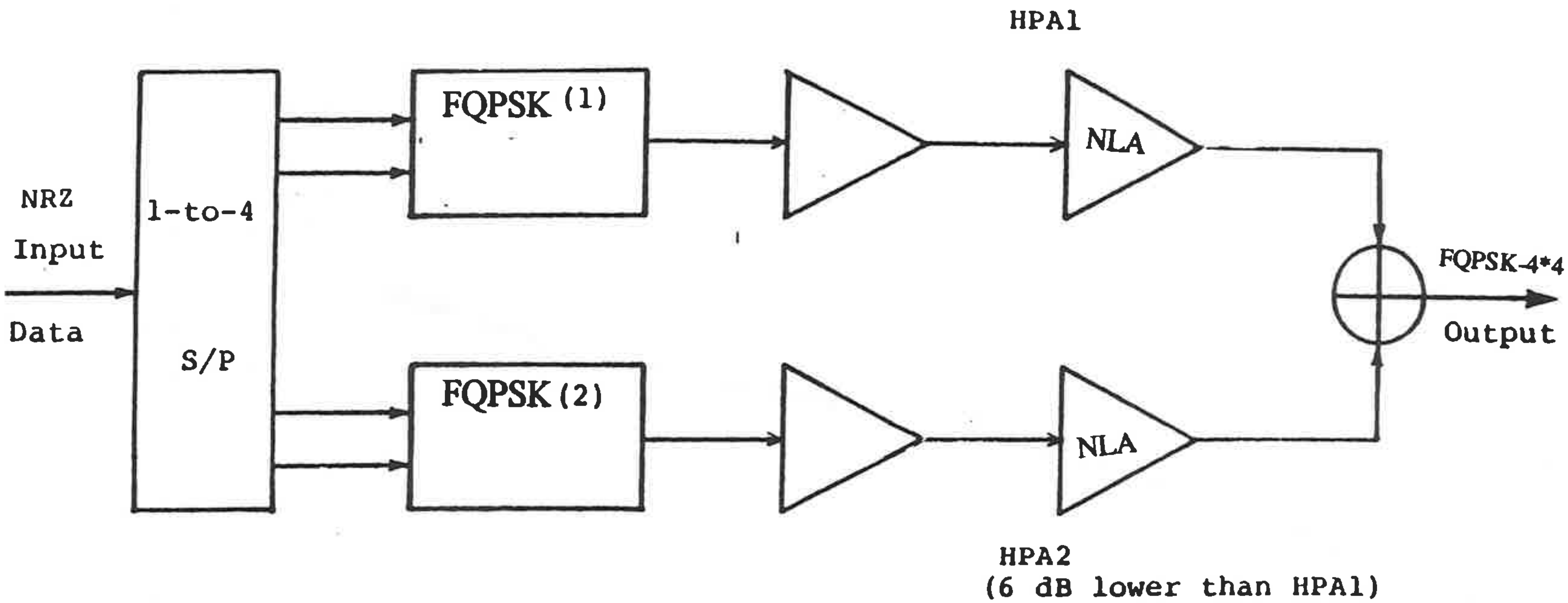


Fig. 14 BER performance of a class of nonlinearly amplified FQPSK and FQPSK-KF systems in AWGN (stationary) and in Rayleigh faded mobile environment. The theoretical linearly amplified coherent QPSK curves are also illustrated.



** HPA1 & HPA2 are operated in saturation mode.

Fig. 15 Block diagram of an "FQPSK-4*4" system with two nonlinear amplifiers (NLA). "High Power Amplifier" HPA-2 has 4 times (6 dB) lower power than HPA-1. Details have been described in [13; 1-4].

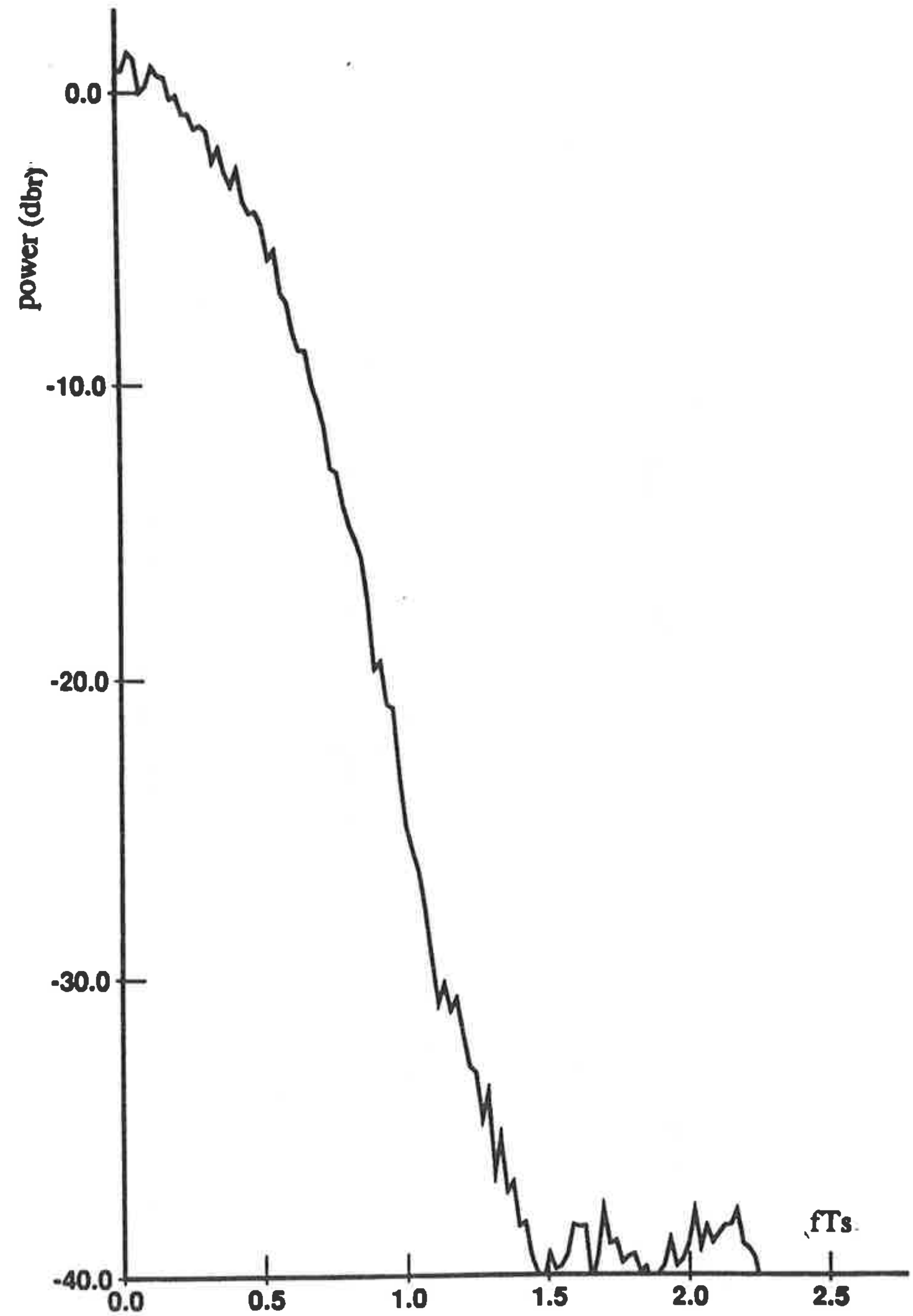
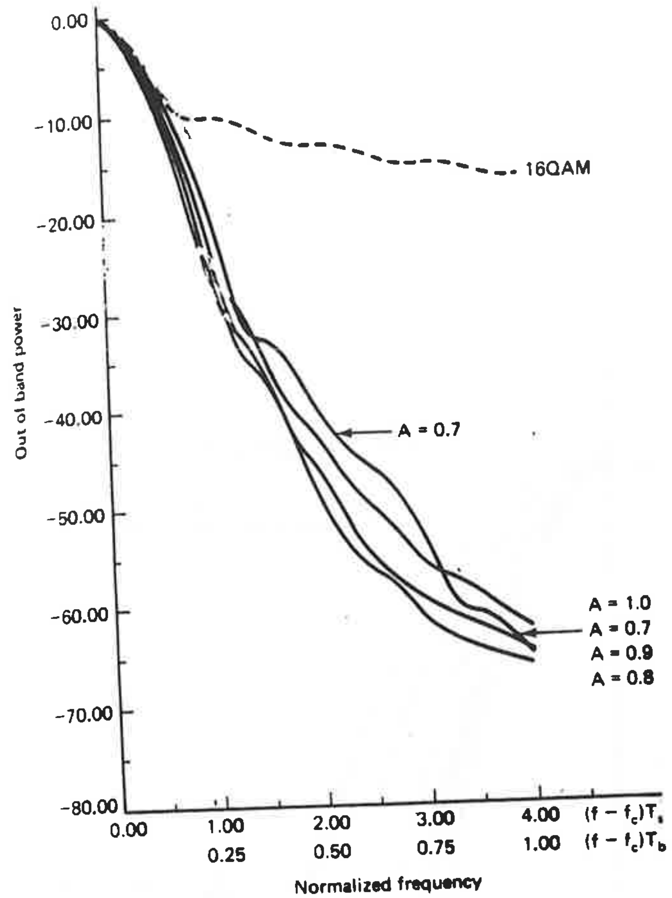


Fig. 16 Power spectral density of nonlinearly amplified (NLA) FQPSK-KF 4*4 signal having a practical spectral efficiency of 2 b/s/Hz.



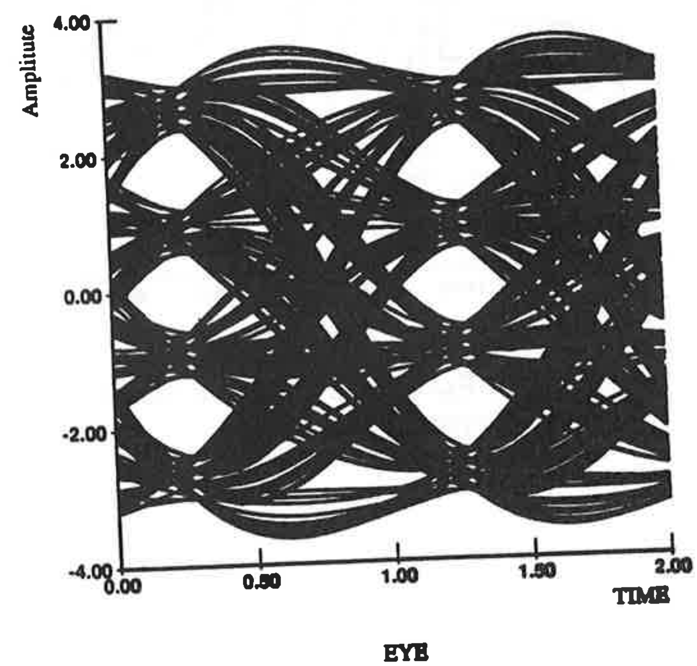


Fig. 17 Integrated out-of-band power and eye diagram of a subset of FQPSK-4*4 radio NLA applications.

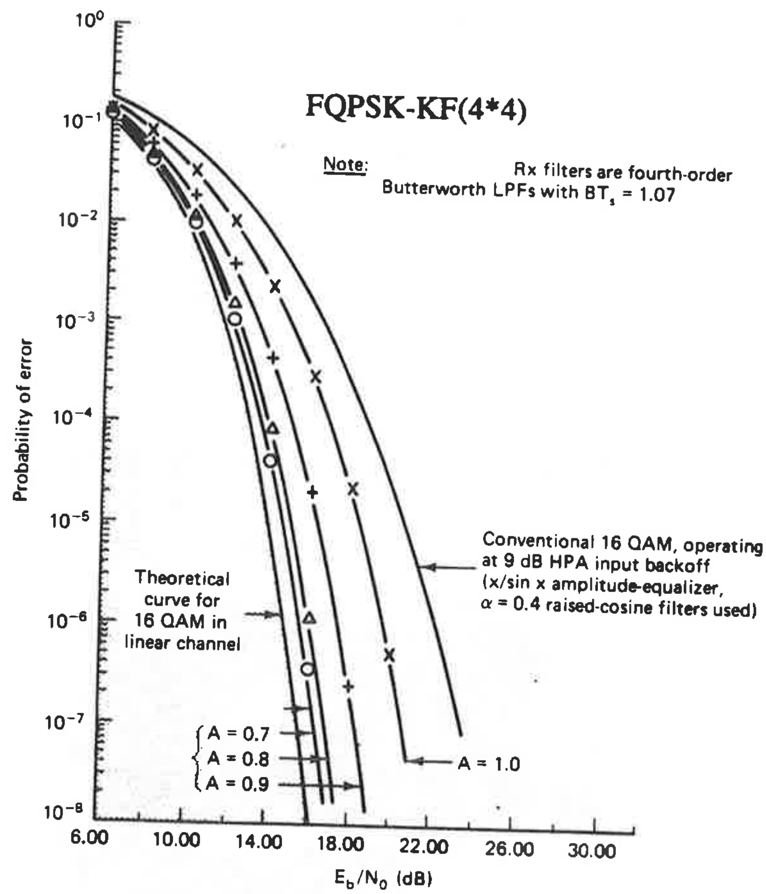


Fig. 18 BER = $f(E_b/N_0)$ curves for a subset of "FQPSK 4*4" nonlinearly amplified systems.

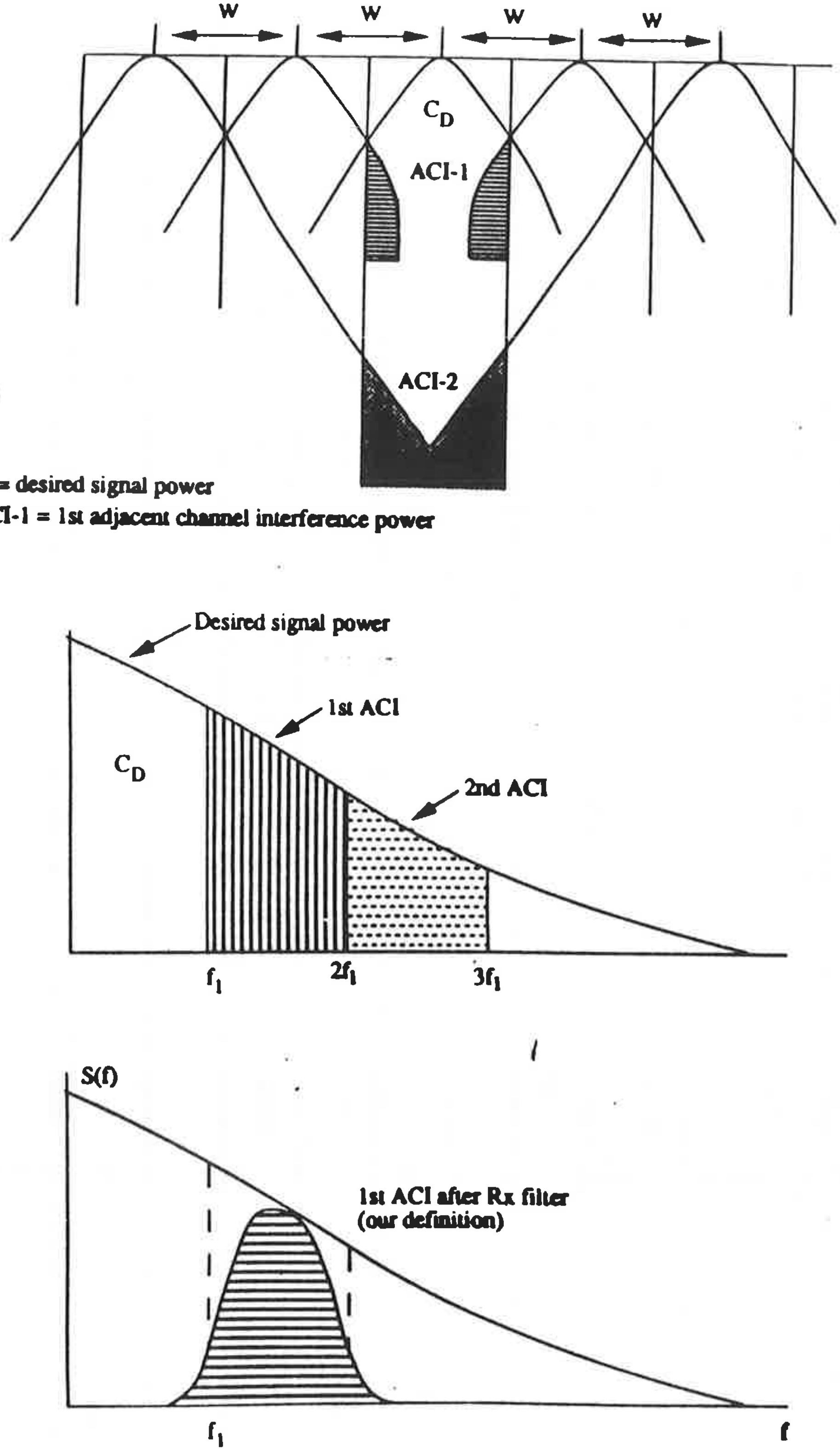


Fig. 19 **Integrated ACI definition in 1st ACI with "brick wall" and with practical bandpass or equivalent lowpass filters. We use the definition with practical filters**

1	Modulation	(a) 4-FSK	(b) 4-FSK	(c) GMSK	(d) GFSK	(e) FQPSK-1	(f) FQPSK-KF	(g) FQPSK-4x4	(h) FLOQAM	(i)	(j)
2	Organization and/or individual Originator Reference Number	California Microwave Silberman presently Wireless-1 [15]	Proxim ?? [24]	Motorola MacDonald [14]	Motorola MacDonald [9]	UC Davis Feher [1 to 6]	UC Davis Feher [1 to 7; 7-23]	UC Davis Feher [1 to 7; 7-23]	Lamair Chayat/ Rothenberg [24]		
3	In FCC-1 MHz Bit Rate for 99% Conservative -20 dB-PSD in [Mb/s]	1.4 Mb/s	1.92 Mb/s	1.0(-) Mb/s	1.0 Mb/s	1.1 Mb/s	1.5 Mb/s	2.048+ Mb/s	1.72 Mb/s		
4	Required E_b/N_o for BER = 10^{-5} in [dB]	17 dB	22.5 dB	18.5 dB	19.3 or 15.5 dB	10.5 dB	16 dB	15 dB	16 dB		
5	Degradation from linear amplified QPSK-AWGN theory (at 10^{-5} E_b/N_o = 9.4 dB Ref)	<-7.6>	<-13.1>	<-9.1>	<-9.9> or <-6.1>	<-1.1>	<- 6.3>	<-5.6>	<6.6>		
6	Degradation in Rayleigh and C/I-interference [dB]	??	??	??	??	<-0.5>	<-3>	<3?>	??		
7	Coherent/Differential (COH)/(DISCR)	DISCR	DISCR	DISCR or COH	DISCR	COH	COH	COH	COH		
8	other										
9	other										
10	Key Parameters	4-levels	4-levels	2-levels	2-levels	2-levels	2-levels	4-level	not disclosed		

Table 1 Nonlinearly Amplified (NLA) basic modulation/radio parameters of several proposed techniques. Preliminary estimated data based on the available/indicated references. Draft-1 Issue-1; suggested revisions requested from committee.

Table 2

Proposed Study for

Data File Transfer Time As a Function of PHY Bit Rate and BER Performance Single or Diversity?

At "fringe of area/cell?" coverage "geographic" area 80%? 90%?

Assume: Raw BER; no FEC
file length 400 bits to 12,000 bits
BER = 10^{-1}; 10^{-2}; 10^{-4}; 10^{-5}
random error distribution

Compare "file transfer time" for a given E_b/N_o and C/I as function of modem and bit rate.
Is it fair to proceed as follows?

Example:	Modem (A)	Modem (B)
(1)	$E_b/N_o = 10$ dB	$E_b/N_o = 10$ dB
	BER = 10^{-2} (?)	BER = 10^{-4}
	Average every 10,000 bit file in error?	Average 1 out of 10 files in error
	Retransmit time ??	Retransmit 10% only
(2)	$E_b/N_o = 15$ dB	$E_b/N_o = 15$ dB
	BER = 10^{-3} (?)	BER = 10^{-7}
	Retransmit N times N = 15?	Retransmit N = 1 time
	File transfer time 15 units (normalized)	Transfer time 1 unit

	Bits Required For:	Number of Bits (Range) ?? GFSK (noncoherent)	FQPSK or other (coherent)
1.	Turn "on-off" radio transmitter (to reduce spectral spreading)	10	10
2.	Radio receiver and BP filter ringing - other transients; AGC?	10	10
3.	STR (symbol timing recovery or bit timing recovery). For coherent joint CR and STR	20	15
4.	DC offset compensation-discriminator caused dc drift due to RF frequency	10	0
5.	CR-Carrier recovery synchronization	0	15
6.	Switch to higher (or lower) data rates	10	10
7.	Message delay (throughput) bits-indicator	5	5
8.	Other TBD	11	11
9.	TBD	?	?
10.	TBD	?	?
	Subtotal	76	76

Table 3 Preambles and PHY headers suggested for study. An illustrative example is shown. Total number of bits might have to be reduced.

Illustrative eye diagrams for various FQPSK and FQPSK-KF parameters are shown in Fig. 6. Measured eye diagrams on several **production units** have been the same as the computer generated results. The FQPSK-KF simple processor leads to very easy change of modulation parameters (could be software controlled and changed during operational conditions of WLAN equipment in the field). This is illustrated by several constellation diagrams of Fig. 7.

In Fig. 8 to Fig. 10, several hardlimited NLA power spectral density (PSD) data are shown. In Fig. 11 to Fig. 14, BER curves as a function of E_b/N_0 and interference, i.e., BER = f(C/I), of coherently and noncoherently demodulated systems is illustrated. Stationary AWGN (Additive White Gaussian Noise) and mobile Rayleigh faded data are presented.

In Fig. 15 to Fig. 18, block diagram, power spectral density (PSD), and BER performance of several NLA FQPSK 4*4 systems is illustrated.

4. DATA FILE TRANSFER TIME/MESSAGE DELAY AND THROUGHPUT: A PROPOSED INVESTIGATION

For standardized 1 Mb/s rate GFSK as well as for higher bit rate systems, e.g., 2 Mb/s-FQPSK, we propose to the committee to investigate the "data transfer time" or "message delay time" and throughput and its relation to the robustness of the demodulated radio signal. An oversimplified, however interesting, example is illustrated in Table 2. Geographic coverage "fringe of area/cell" 80%, 90% ... ? should be addressed. Initially perhaps the retransmit time or message delay and throughput of two modem/radio systems should be compared, in a nondiversity mode, as indicated in Table 2. Evidently, more realistic and complex scenarios and architectures could be developed later.

From preliminary Table 2 we note that a less robust modem, e.g., modem (A), would require a file transfer time **15 times longer** than that of the more robust modem (B). In this illustrative non-diversity case for an $E_b/N_0 = 10$ dB, we assumed that the less robust modem has a BER = 10^{-2} while the more robust modem has a BER = 10^{-4}. Evidently the complete PHY and MAC study group could investigate whether it is really true that a **few dB's** of C/I or C/N **difference in robustness could have a tremendous impact on message delay and on throughput**. I believe that in the digital cellular industry 1 dB to 2 dB difference in BER = f(C/I) has a tremendous impact on data throughput, capacity, and delay. Is this also true in the WLAN case?

5. SUGGESTED PREAMBLES AND PHY HEADERS

In this suggestion, we address the issue of bit preambles/PHY headers which are required.

(a) Synchronization of the GFSK standard demodulator at 1 Mb/s rate.

(b) "Switch to higher (or lower?) data rates from the data rate defined above in (a).

(c) Synchronization of other than GFSK modems which could require coherent demodulation for higher bit rate systems such as FQPSK, 4-FSK, FLOQAM or others.

We anticipate that the following preamble bits will be required (a very rough estimate of the approximate number of bits is indicated). Number of bits and functions of bits to be studied and modified by the committee.

Frequent switching due to receive diversity switching is assumed. A study of the partial list of illustrative number of bits is recommended, see Table 3. It is assumed that the PHY and MAC committee's will complete, update and modify this table.

In the illustrated example, **76 bits are required for both systems**: the standardized noncoherent 1 Mb/s rate GFSK and for the coherent higher rate modems, e.g., FQPSK or FLOQAM [15; 24]. Joint carrier recovery (CR) and symbol timing recovery (STR) design could reduce the overall synchronization time [7]. Note: A "gear-up" as well as "gear-down" could be useful. In a poor transmission environment controlled by interference and/or delay spread, it might be advantageous to **reduce the transmission rate from 1 Mb/s to 500 kb/s**. A reduced transmission bit rate or PHY rate in such a propagation environment could lead to **faster data file transfer** as illustrated in Table 2.

In particular for GFSK with variable deviation or modulation index (minimum deviation of 160 kHz was standardized) a lower bit rate could lead to a substantially increased deviation and considerable improvement in the robustness and BER of the system. Reduced (improved) BER could lead to **much shorter data file transfer time**. The number of preamble and header bits could be too long (or too short?) for some applications. A study is recommended

6. FCC SUGGESTED CLARIFICATION FOR "99% POWER" TERM AND REQUEST FOR WIDER THAN 1 MHz FH ASSIGNMENT

The FCC rule in regards to the 99% power in a maximal bandwidth of ±500 kHz has been so far interpreted on a **conservative** and **aggressive** manner [9]. I have the impression that the current interpretation of the 802.11 committee is based on the conservative side. It is my understanding that this interpretation requires that the power spectral density or PSD be 20 dB attenuated at 1 MHz (±500 kHz). In Fig. 19, two interpretations based on the integrated ACI (Adjacent Channel Interference) power concept are shown.

Perhaps the committee could raise this issue with the FCC. In several related systems, e.g., IS-54, digital cellular TDMA integrated ACI has been specified. Integrated ACI is (in my opinion) more meaningful because it is the integrated ACI that causes most of the harm. Interpretation based on integrated ACI = −20 dB could lead to substantially increased bit rates [6; 9].

We might also wish to study the potential advantages of obtaining larger than 1 MHz assignment for FH in the 2.4 - 2.48 GHz band.

7. "CREATE" SOFTWARE PROGRAM

The "CREATE" software program has been developed for analysis and design of GMSK, QPSK and a large class of FQPSK, FQPSK-KX as well as self created-designed FQPSK signals. Offset QPSK (QAM) is the basic structure. Linearly and nonlinearly amplified devices are modeled.

It is anticipated that this program could become available, free of charge, within several months (probably January 1994). If interested, please write to K. Feher. CREATE has been developed at several universities, under the direction of Dr. Feher. Upgraded, more user-friendly software is currently being developed at the University of California, Davis (UC Davis).

8. SUMMARY

In Table 1 a performance comparison of various modulation NLA techniques is presented. This Table illustrates that the nonlinearly amplified "FQPSK 4*4" technique offers a 2 Mb/s (or even higher rates) in 1 MHz RF bandwidth and for an $E_b/N_o = 15$ dB has a BER = 10^{-5}. It is more robust to noise than any of the listed lower bit rate alternatives, with the exception of FQPSK-1.

The most robust performance in a faded interference and noise controlled environment, is attained by FQPSK-1 which requires only an $E_b/N_o = 10.5$ dB for 1.1 Mb/s at BER = 10^{-5} (as compared to others with at least 15 dB). If binary eye diagrams/simplest decision threshold receivers are of interest, then FQPSK-KF offers a 1.5 Mb/s rate with a robust performance and simple implementation. For further potential bit rate increases clarification, study and interpretation of the FCC rules (integrated ACI) and wide bandwidth is suggested.

A detailed "data file transfer time/message delay" investigation is recommended. Initial data indicates that more "robust" (lower E_b/N_o and C/I requirement) systems could have **much shorter delays and increased throughput**. Preamble and PHY header bits for the recently standardized 1 Mb/s rate GFSK-FH system and for PHY or MAC bits to negotiate a switch to higher (or lower) data rates are also suggested.

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