IEEE 802.11

WIRELESS ACCESS METHODS AND PHYSICAL LAYER SPECIFICATIONS

FQPSK: A modulation-power efficient RF amplification proposal for increased spectral efficiency and capacity GMSK and π/4-QPSK compatible PHY standard

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PROPOSAL: Adopt FQPSK for the PHY standard. Some of the most important advantages, reasons and justifications of this proposal include:

1. FQPSK is 50% more spectrally efficient than GMSK and 4CPM-FM. For example, in a 1 MHz RF channel, it could have an approximate 1.5 Mb/s bit rate instead of the previously proposed maximum of 1 Mb/s.
2. Constant envelope nonlinearly amplified FQPSK increases battery lifetime/power efficiency and reduces peak radiation of QPSK and of π/4-QPSK by 5dB to 8dB.
3. FQPSK is 1.5dB more robust in a C/I and ACI Rayleigh system than coherent GMSK and 5.5dB more robust than noncoherent GMSK and 4CPM-FM.
4. Capacity of FQPSK-PHY standard is 80% to 90% higher than that of other constant envelope systems (combined power [BER = $f(E_b/N_0) = f(C/I)$]/spectral efficiency advantage).
5. Compatible operation between FQPSK and GMSK, π/4-QPSK and conventional offset QPSK is feasible.
6. Simpler implementation and more robust in delay spread environment than GMSK.
7. Products using FQPSK family operate over radio-satellite links. Several manufacturing and operating companies have experience.
8. FQPSK processor/modulator patents can be licensed from the inventor, K Feher – Digcom, Inc., "on a reasonable and nondiscriminatory basis" and other standard terms stipulated by IEEE and other national/international standardization committees.
9. Performance of FQPSK compared to that of GMSK, QPSK, and 4CPM-FM in a complex wireless ACI and CCI controlled environment has been extensively evaluated and documented in various IEEE papers.

This contribution describes the FQPSK modulation technique. Enclosed references provide additional in-depth material.

1. SUMMARY

A coherent FQPSK modem/radio nonlinear amplification (NLA) technique is proposed for future generations of WLAN, cellular high-capacity mobile and PCS systems. FQPSK [Feher 8-11] is a constant envelope modulation that is 6 to 8 dB more power efficient than non-constant envelope signalings like the π/4-DQPSK as used in the US IS-54 digital cellular mobile radio and the Japanese Handyphone standards.

A comprehensive evaluation of Feher et al.'s patented QPSK or "FQPSK" ACI and CCI characteristics, spectral efficiency in b/s/Hz/m^2 and BER performance in a wireless cellular environment is presented. The results are compared with GMSK, which is the modulation format adopted as the current DECT, DCS1800, and the European digital cellular GSM PHY standards. We demonstrate the FQPSK has an attainable spectral efficiency of about 1.5 b/s/Hz, which is 50% higher than GMSK as used in DECT. The BER performance of FQPSK is also more robust in both Rayleigh fading and CCI controlled environments. Our study shows that the combined spectral efficiency, CCI and ACI advantage of FQPSK over GMSK leads to a significant 95% increase in system capacity over DECT and an 86% improvement over DCS1800. The implementation of FQPSK is simpler than that of $BT_b = 0.3$ filtered GMSK. FQPSK has been used for many years in satellite communications and has been evaluated in land mobile wireless systems. It is compatible with GMSK and offset QPSK systems. We conclude that FQPSK is an excellent modulation and power efficient RF amplification method for the future generations of high-capacity microcellular PCS and of WLAN.

2. CANDIDATE MODULATION/RADIO AMPLIFICATION TECHNIQUES AND ILLUSTRATIVE RADIO ARCHITECTURES FOR IEEE 802.11 PHY

2.1 MODEMS: GMSK; QPSK; Π/4-QPSK; DQPSK; BPSK; 4-CPM-FM; 16-QAM and FQPSK

Our objective has been to identify modulation-demodulation (modem) techniques which could be suitable for the emerging IEEE 802.11 PHY standard. Based on our literature survey and active involvement in several WLAN data and voice digital cellular, SMR, general mobile and PCS modem/radio designs, we summarize the performance and efficiency, in b/s/Hz, of 14 different modems and linearly or nonlinearly amplified (NLA) radio systems. See Table 1.1, Ref. [3]. All of these modems have been considered and/or are in use in several operational American and International (European, Japanese) systems. Selection of a "best modem", for particular applications, e.g., WLAN mobile radio is a challenging undertaking. The modem/radio has a significant impact on the overall Physical Layer Radio performance, cost, power requirement, size, coverage area and system capacity. In this section, we present a brief review of the pertinent, most important modem parameters which impact on the overall system and network design, while in the next section, we recommend our proposed PHY standard "F-QPSK" modem/radio architectures.

Frequently used modem and related abbreviations:

GMSK	-	Gaussian Minimum Shift Keying
QPSK	-	Quadrature Phase Shift Keying
FQPSK	-	Filtered QPSK (See Patents [8; 9; 10; 11] and Ref. [2-7])
4-CPM-FM	-	Continuous Phase Modulation 4-level FM; Ref. [35]

Modem/BER		Approx. b/s/Hz	E_b/N_o AWGN	Rayleigh Fading C/N = C/I								REFERENCES
				10^{-1}		10^{-2}		10^{-3}		10^{-4}		
	Amplif.	Pract.	10^{-4}	Th	Div	Th	Div	Th	Div	Th	Div	
1. FSK-MAN; Amps	nla	0.33		10		20		30		40		AMPS Spec. 1981; Arredon. BSTJ, Jan. 79
2. Digit. Cellular π/4-DQPSK	lin	1.7					17					New standard based on TIA Inputs
3. FSK-NRZ	nla	0.5?	11.4	8		20		30				Proakis p. 718 (2nd Ed)
4. BPSK	lin	0.7	8.4	3		14	8	24	14	34	19	Proakis p. 718 (2nd Ed) p. 727
5. BPSK w/ Pilot	lin	0.7	9	4		15		25		35		Hou, IEICE Japan, Jan. 87
6. BPSK w/ Pilot	lin	0.7	-	4		15		25		35		Hou, IEICE Japan, Jan. 87
7. QPSK Coher.	lin	1.6	8.4	5.5		17	12	27	17.5	37	22	Proakis p. 742, 727 (QPSK=BPSK + 3 dB)
8. π/4-DQPSK	lin	1.7	10.5			20	15	30	20	40	25	Liu/Feher (ICC-90?) SC-I-1 Proakis p. 742, 743 assume π/4-DQPSU-DQPSK
9. FQPSK	nla	1.5	9.4			17	12.5	27	16	37		
10. QPRS w/ Pilot	lin	2.1	11.2	14	17	20	15	29	30	40	25	Estimates Based on Note (a)*
11. C-GMSK (BT_b=0.5)	nla	0.9	9.3									
12. C-GMSK (BT_b=0.3)	nla	1.02	10.5	7.5		19	14	30	20	40	25	Hirade (Feher's book p. 545)
13. Noncoh. 4CPM-FM discrim.	nla	1.2	12.5			22?		32?		42?	?	Hirade (Feher's ADC book p 519 & 52_)
14. 16-QAM	lin	3.1	13 dB			22	15	32	21	42	25	Sampei theoretical 16-QAM questionable?? Sampei VTC-89 p. 645 D. Subasinghe Ph.D. 1992
15.												Sampei VTC-89 Laboratory f_d = 80

lin=linear
nla=nonlinear amplifier

Table 1 : Comparison of digital mobile radio modems/radio/diversity systems. Approximate values are indicated to establish trend and first-order estimates. Ref. [3]

IJF-OQPSK	-	Intersymbol-Interference and Jitter-Free Offset QPSK (same as F-QPSK, see [4; 6])
QPRS	-	Quadrature Partial Response [4]
DQPSK	-	Differential QPSK
PI/4-DQPSK	-	PI/4-rotated DQPSK-such as American Standard (ADC)
16-QAM	-	16-State Quadrature Amplitude Modulation
LIN	-	Linear Amplifier and Radio Chain
NLA	-	Nonlinear Amplifier
ECI	-	External Co-Channel Interference
SQAM	-	Superposed NLA-QAM [9 and 4]. Part of FQPSK family

2.1.1 Most Important System and Hardware Parameters

Threshold Sensitivity and Capacity Optimization

To optimize modem/radio performance we search for modem techniques which have the lowest, i.e., most robust, Carrier to Interference (C/I) and C/N or E_b/N_0 (bit energy to noise density ratio) in a Rayleigh faded and/or in an AWGN-stationary environment, i.e., best sensitivity or lowest threshold. In Rayleigh fading (only in Rayleigh) for a specified BER the

$$C/N = C/I \qquad \text{for BER} = 10^{-2} \text{ to } 10^{-5}$$

within 1db. The interference term here refers to Co-channel Interference (CCI) whether it is caused by interference (I) of our own cellular WLAN-system or by another Rayleigh faded External Interference which is in the co-channel band, i.e., External Co-channel Interference (ECI).

Spectral efficiency in terms of b/s/Hz with a defined integrated out-of-band ACI (Adjacent Channel Interference) is important from a capacity/spectral efficiency point of view. Spectral efficiency should be jointly maximized with C/I sensitivity to attain the largest capacity objectives, i.e., $b/s/Hz/m^2$.

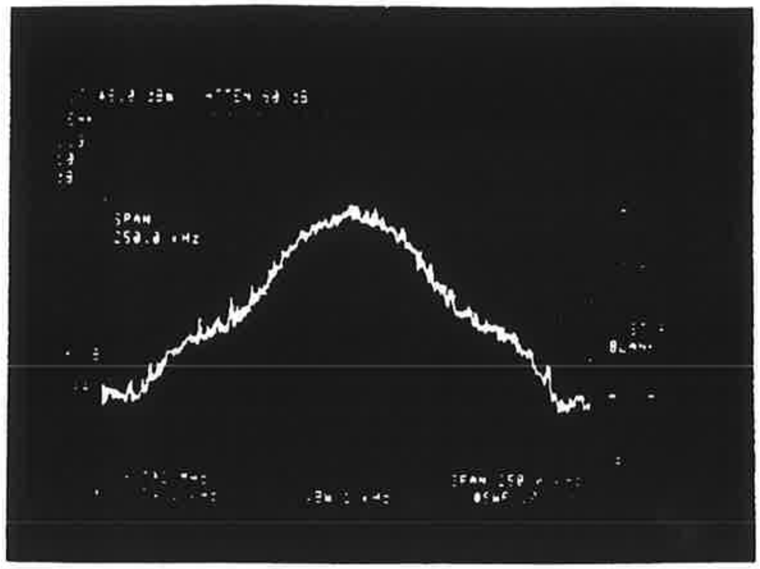
LIN-NLA Power Amplifier issues relate to hardware size, required power, regulations (FCC) and cost. In most systems NLA (nonlinear) amplifiers have a lower cost and size and are more RF power/dc battery efficient.

2.2 4-LEVEL FM, 16-QAM OR QPSK (FQPSK-GMSK)

A generic or "universal" Quadrature Coherent Modem Architecture is presented in Fig. 2.1 and 2.2. These illustrative block diagrams are suitable for QPSK, $\pi/4$-QPSK, 16-QAM, as well as FQPSK, GMSK implementations.

From Table 1.1, (a rough estimate of modem parameters) we note that:

C/N (of 4CPM-FM) = C/N (of 16-QAM) = C/N (of QPSK + 5dB



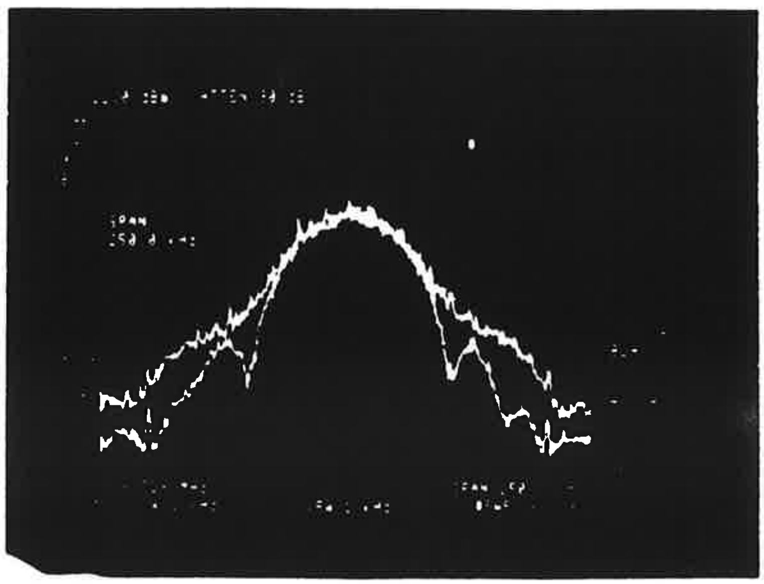


**Fig. 2.3. Power Spectral Density (PSD) of FQPSK and of GMSK signals.
(c) Experimental (hardware) of nonlinearly amplified spectrum of FQPSK at 100 kb/s; IF frequency 10 MHz.
Saturated Amplifier ZHL-32A: UC Davis**

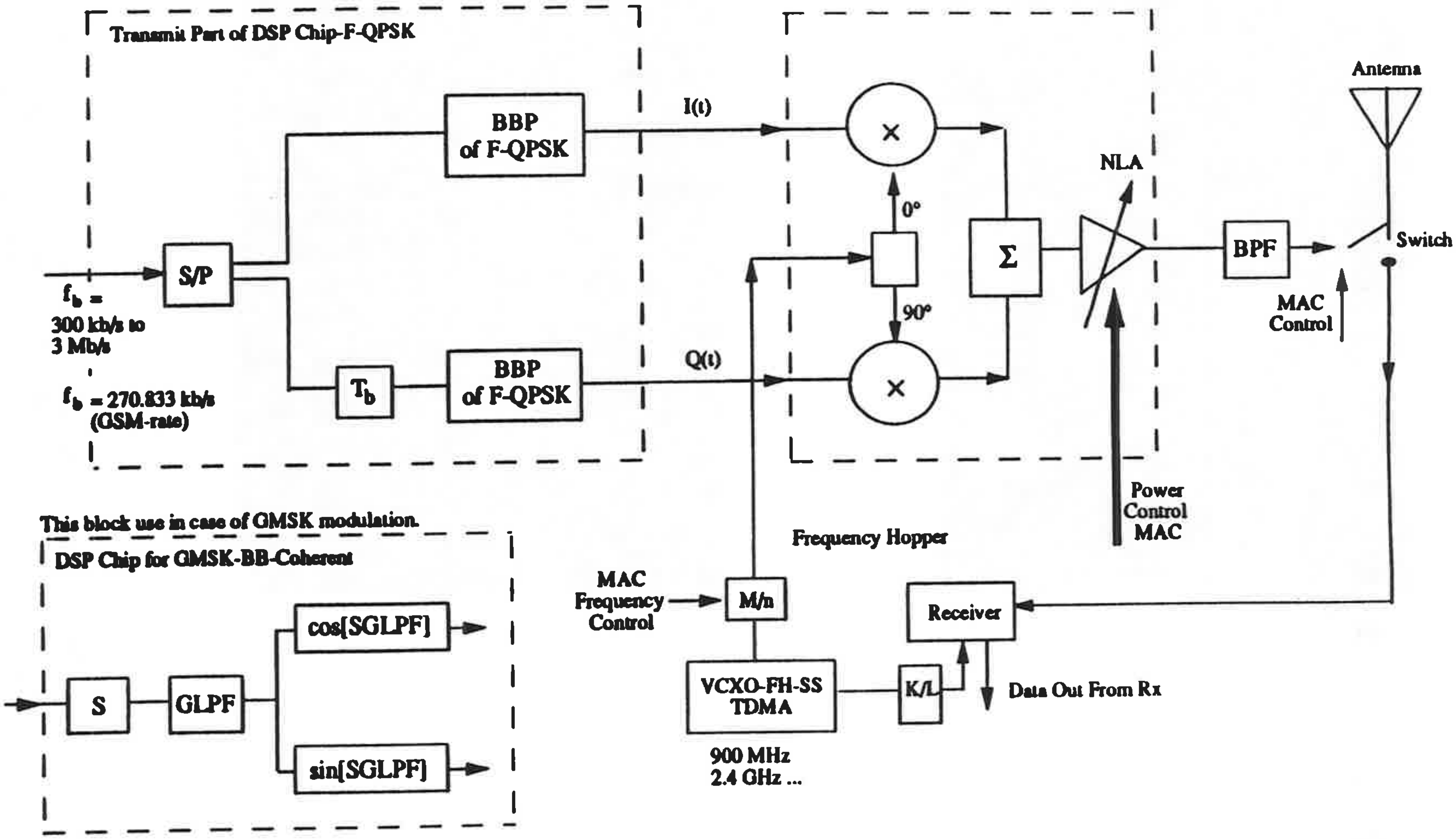


Figure 2.1 Transmitter of a BB to RF radio for F-QPSK or GMSK nonlinear amplifier applications (slow frequency hopping-spread spectrum SFH-SS-TDMA). The same generic diagram could be used for 16-QAM (linearly amplified) and for other modems Ref. [3; 24]. This system has been implemented at UC Davis.

For example for a BER = 10^{-2} in a Rayleigh faded environment coherent QPSK requires C/N = C/I = 17dB, while coherent 16-QAM requires C/I = C/N = 22dB for the same BER. In other words conventional QPSK is 5dB more robust than 16-QAM to co-channel interference (CCI) and/or to noise. Additionally, 16-QAM requires very linear amplifiers (Tx and Rx), AGC circuits, mixers . . . thus could lead to a low "efficiency" (RF power/battery efficiency). A potential advantage of 16-QAM is that it has a 3b/s/Hz practical spectral efficiency, as compared to linearly amplified QPSK's 1.6 b/s/Hz.

Four-level FM or 4CPM-FM, noncoherently detected, for 1.2 to 1.4 b/s/Hz has also an approximately 5dB worse BER = f(C/I) performance than QPSK-type systems; see Table 1.1.

2.3 GMSK: QPSK AND FQPSK

Gaussian-MSK or (GMSK) is the modulation standard of the European DECT and European GSM systems as well as other standards. This modulation technique has been used with coherent and non-coherent implementations and is well described in many references. In GMSK systems the BT_b product refers to the pre-modulation Gaussian filter cut-off frequency. A $BT_b = 0.3$ and $BT_b = 0.39$ will lead to an increased spectral efficiency, as compared to $BT_b = 0.5$, however, a more complex implementation and increased sensitivity to C/I and to radio propagation (e.g., delay spread) and equipment-caused imperfections [16; 34]. The power spectral density (PSD) of bit rate normalized GMSK systems is illustrated in Fig. 2.3. The Integrated ACI or out-of-band interference of GMSK is shown in Fig. 2.5.

The principle advantages of GMSK are: **Use of NLA - power amplifier efficiency**; reasonably robust performance (i.e., BER = 10^{-3}; C/N = 30 dB); coherent and noncoherent detection possible; chips (silicon VLSI) available European standards use GMSK; and potential for simplified (somewhat) CR - synchronization.

The principle disadvantages of GMSK are: relatively wideband main lobe is the cause of **lower spectral efficiency** than QPSK type modems; less robust (by 2dB) than FQPSK; baseband processor G-LPF and DSP more complex than for FQPSK; GMSK with $BT_b = 0.3$ more sensitive than QPSK to system-caused imperfections.

2.4 PI/4-DQPSK - MODULATION: STANDARDS USA AND JAPAN

The PI/4-rotated DQPSK has a somewhat reduced envelope fluctuation (as compared to conventional QPSK). In "quasi-linear" channels the reduced envelope fluctuations may lead to a reduced spectral spreading and BER degradation. The principal advantage of PI/4-DQPSK is that it can be coherently and/or noncoherently demodulated and is somewhat better than conventional QPSK in "linearized" or "quasi-linear" systems. Non-coherent detection was the preferred approach several years ago for fast moving, e.g., 100 km/hour large Doppler shift systems. Later it was found that due to predominant delay spread coherent receivers have to be used.

Filtered $\pi/4$-QPSK and conventional QPSK systems have an envelope fluctuation in the 3dB to 5dB range. Linear RF amplifiers have a gain and output power variation of 1dB to 3dB. Due to imperfect linearization an additional output backoff (OBO) of 2dB is common. For these reasons, the OBO of digital $\pi/4$-DQPSK cellular systems is

$$\text{OBO} = 6\text{dB to } 10\text{dB}$$

and the overall power efficiency is only 5% to 15%.

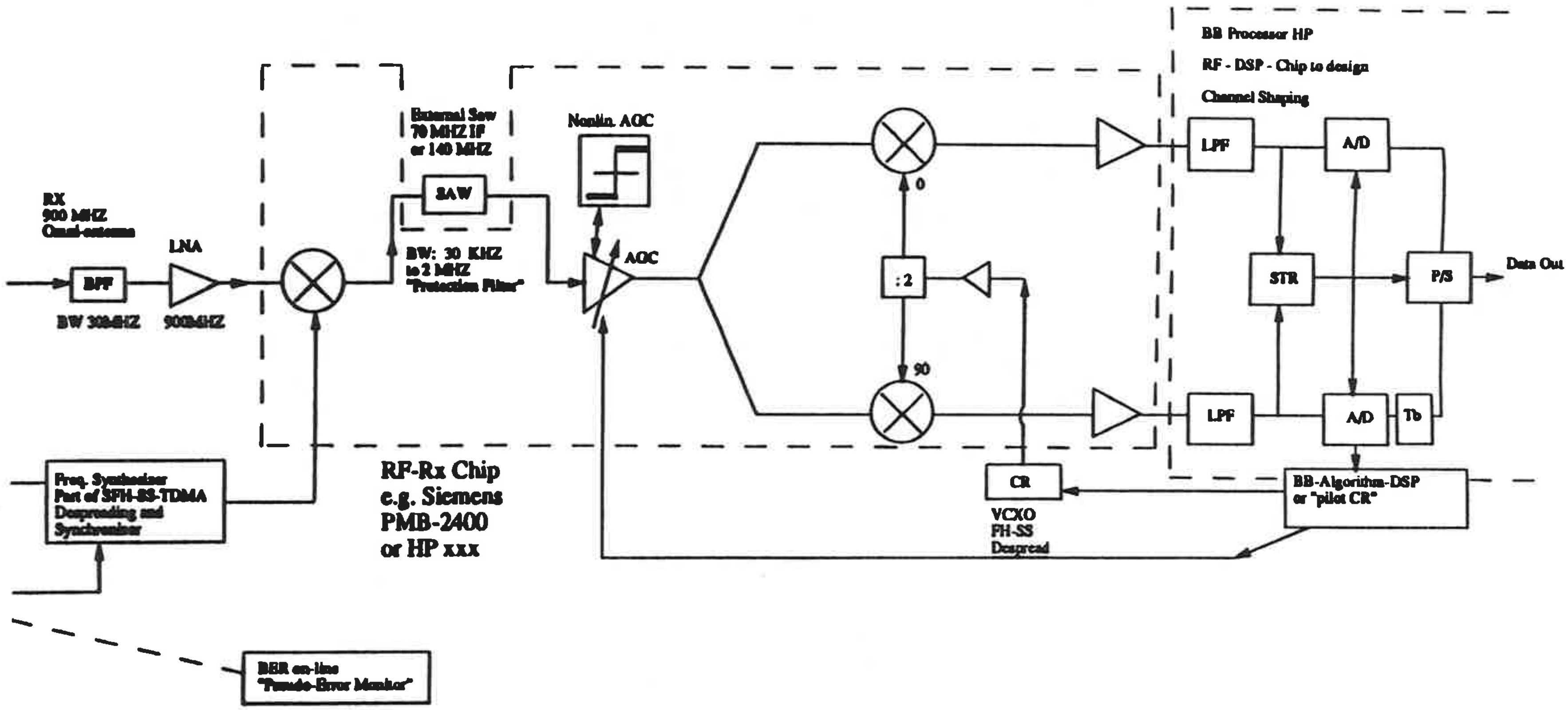


Figure 2.2 Receiver with one IF stage for Coherent F-QPSK or GMSK systems (TDMA-TDD-SFH-SS); Ref. [3; 24].

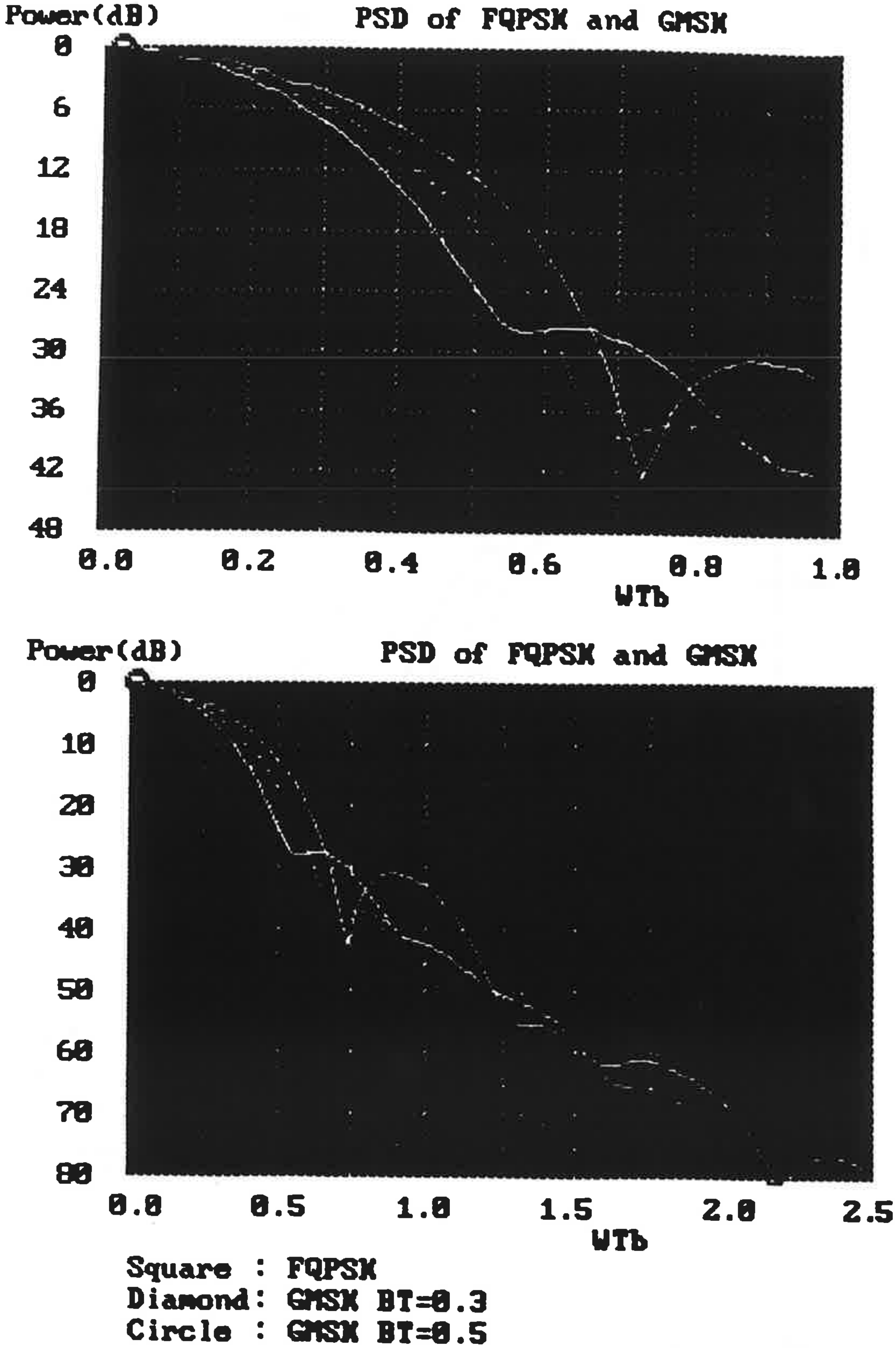


Fig. 2.3. Power Spectral Density (PSD) of FQPSK and of GMSK signals.
(a) to –48 dBr (b) to –80 dBr (c) Experimental (hardware) of nonlinearly amplified spectrum of FQPSK at 100 kb/s; IF frequency 10 MHz.
Saturated Amplifier ZHL-32A; UC Davis

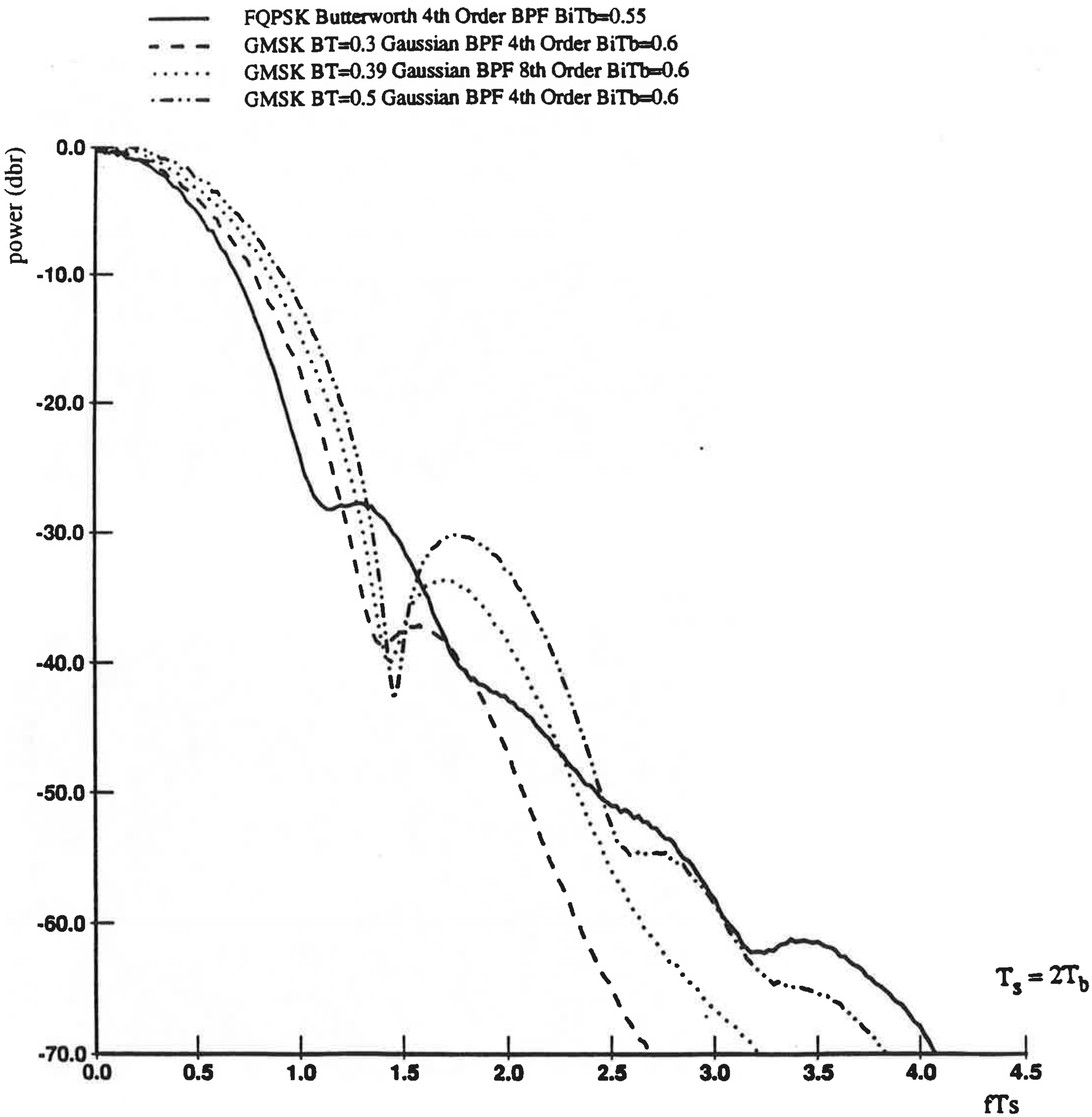


Fig. 2.3. Power Spectral Density (PSD) of FQPSK and of GMSK signals.
(a) to –48 dBr (b) to –80 dBr (c) Experimental (hardware) of nonlinearly amplified spectrum of FQPSK at 100 kb/s; IF frequency 10 MHz.
Saturated Amplifier ZHL-32A; UC Davis

PI/4-DQPSK could be a reasonable choice for systems which require coherent and/or noncoherent reception, a spectral efficiency of 1.6 b/s/Hz, and battery lifetime, power efficiency (linearly amplified RF power/dc power ratio) and peak radiation, e.g., health hazard, is not critical. The receiver BB processor of $\pi/4$-DQPSK is slightly more complex than that of conventional QPSK or Offset QPSK (OQPSK). In nonlinearly amplified systems Offset-QPSK with specific filtering (BB processing) has significant spectral advantages. For this reason we investigate in further detail O-QPSK systems which we will also call "Filtered QPSK" or "F-QPSK."

2.5 FQPSK: FILTERED OFFSET QPSK

A baseband processor nonlinear filter in an Offset QPSK quadrature structure leads to an **IJF** = Intersymbol Interference and Jitter Free eye diagram. This type of QPSK modulator we call IJF-OQPSK or for short F-QPSK ("F" for filtered QPSK based on Feher's filter patent) [8; 9; 10; 11]. The I and Q baseband F-QPSK signal generation concept was described in many references, including [4-10; 17; 35]. From Fig. 2.6(a) we note that it is a very simple concept and has a simpler "smooth" baseband drive signal. The implementation of FQPSK is practically identical to that of a Quadrature GMSK modulation except that FQPSK has a simpler baseband processor; see Fig. 2.1.

2.5.1 FQPSK: Illustrative Field Proven Products, Operational Experience and Rayleigh Faded WLAN Demonstrations at UC Davis

In this section the description of two typical modem/radio products which have made use of our FQPSK related patents [8; 9; 10; 11] are highlighted.

(A) IDC-Internat. Data Casting Corp., Ottawa, Canada: The SR500 and DM500 series modems and radio systems have been in use for more than five years as satellite TX/RX for digital audio and data broadcast applications. Nominal data rate 512 kb/s; variable rate system using so-called SQAM (our patented modems which are practically the same as the proposed FQPSK nonlinearly amplified system. IDC measurements indicate a 0.3dB deviation from theory in the 10exp(–2) to 10exp(–5) range, i.e., an excellent agreement. Ref. [33], Seo et al., provides a detailed description of the IDC modem.

(B) SPAR Aerospace Ltd., St. Anne de Belevue, P.Q. Canada: The SPARCOM satellite terminals operate in a fully saturated mode in an FDM true SCPC mode. Nominal bit rate is 64 kb/s. These nonlinear amplified satellite systems have a performance of within 1dB of theoretical predictions. A description is given in Ref. [17] and Feher's book [4, pp. 368-369]. SPARCOM terminals used the name IJF OQPSK instead of the shorter name FQPSK.

(C) UC Davis WLAN-Rayleigh Faded Demonstration of Frequency Hopped 200 kb/s rate (in 133 kHz RF band): Nonlinearly amplified FQPSK radio in the ISM 902-928 MHz band demonstrates computer generated results and confirms robust performance of Frequency Hopped FQPSK [22; 24].

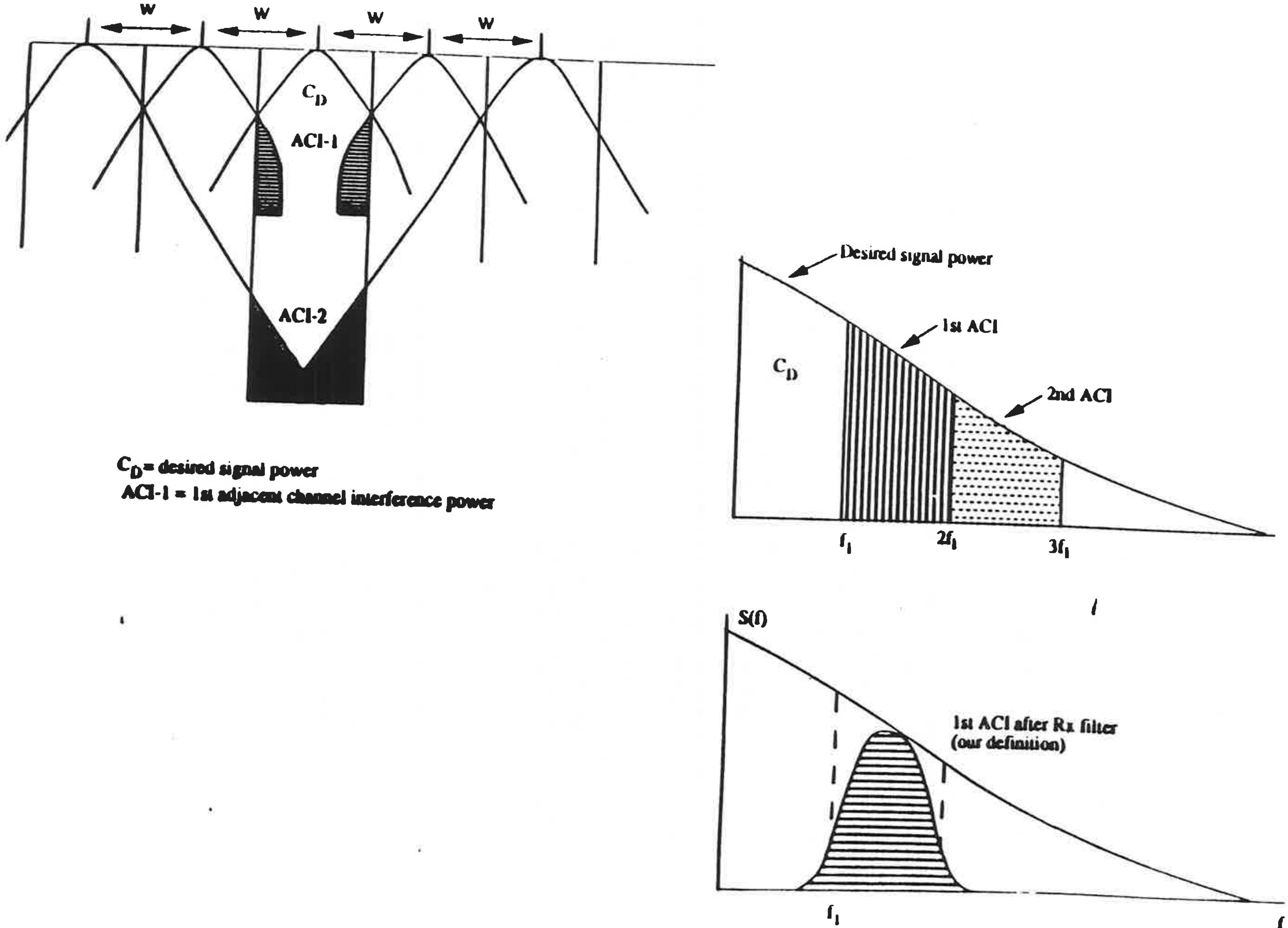
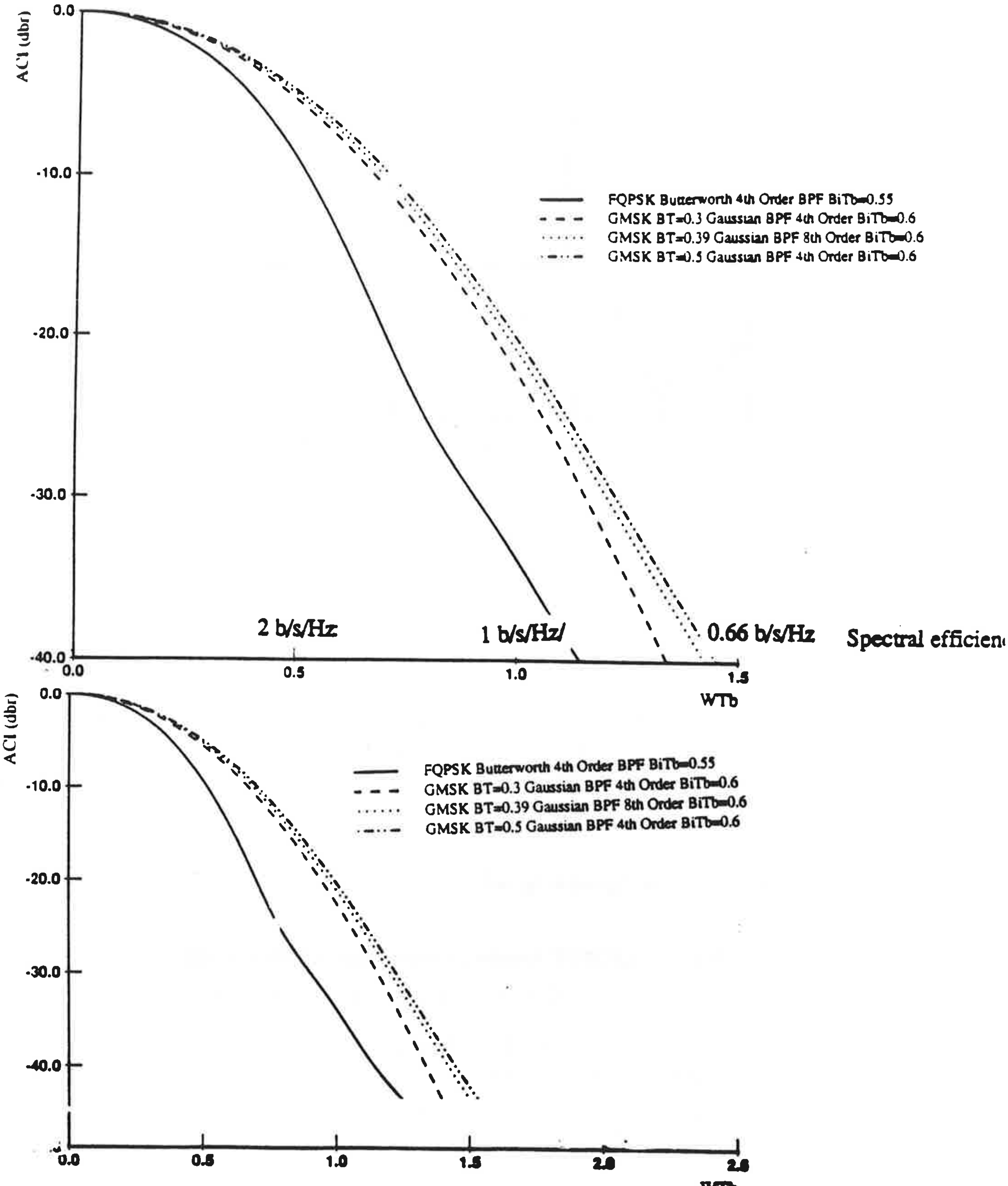


Fig. 2.4. Integrated ACI definition in 1st ACI with "brick wall" and with practical bandpass or equivalent lowpass filters. We use the definition with practical filters



Spectral efficiency and ACI (integrated)

Fig. 2.5.

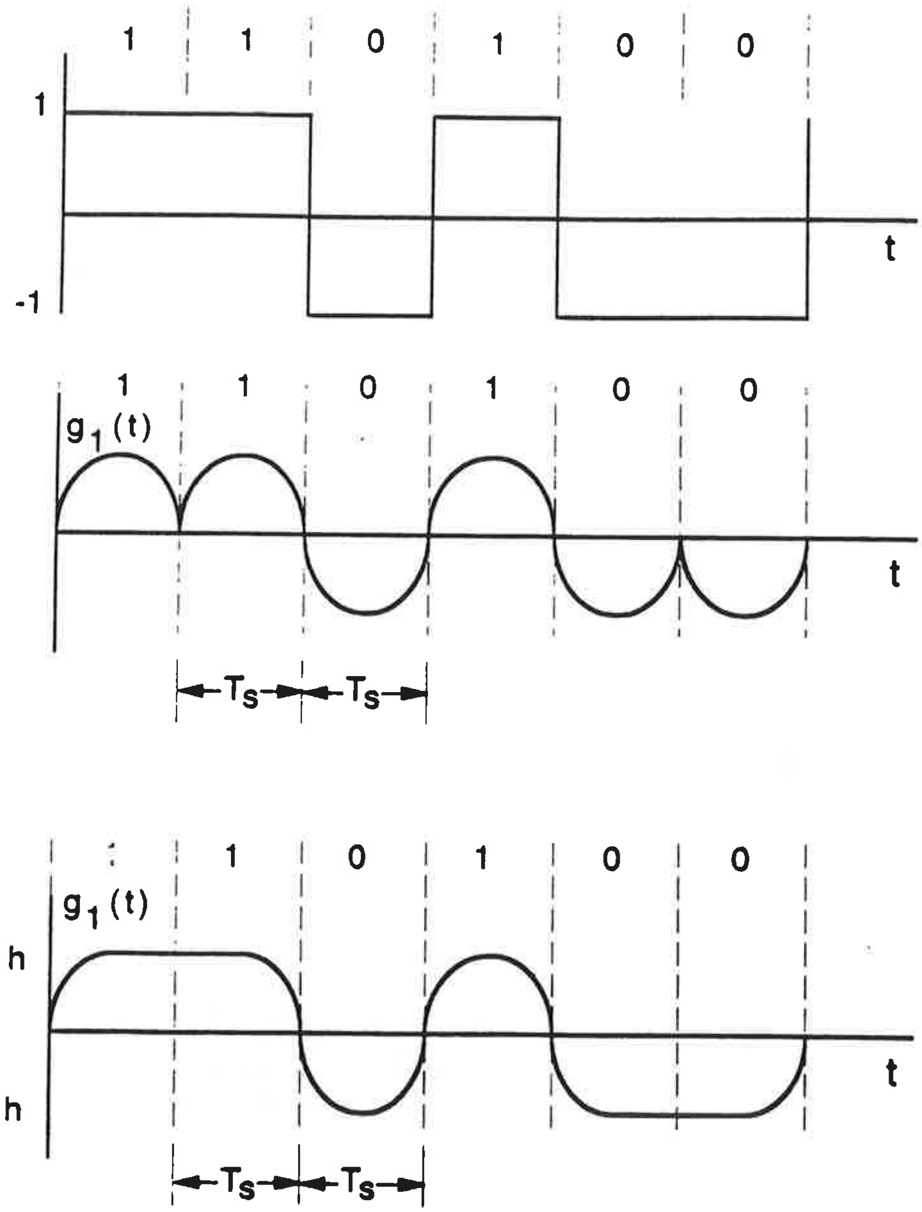
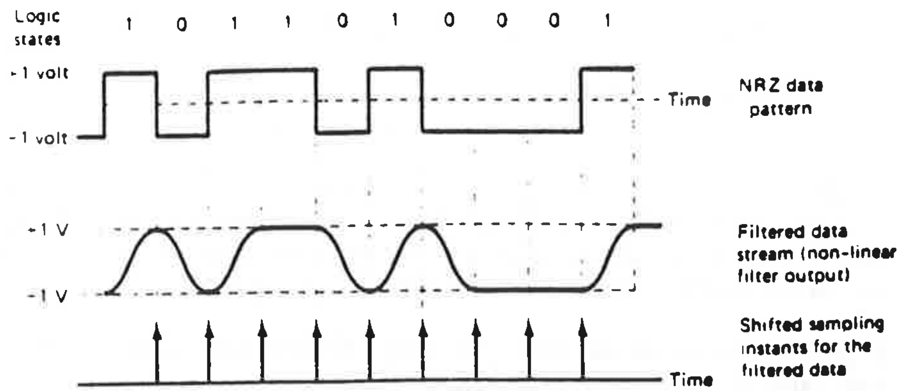
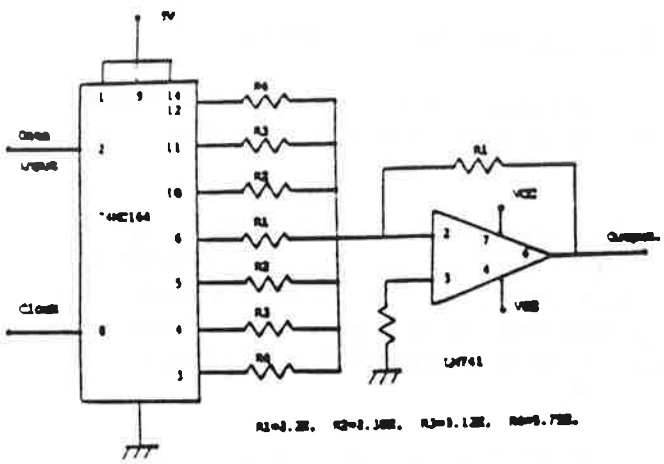


Fig. 2.6. aFQPSK baseband signal generation concept

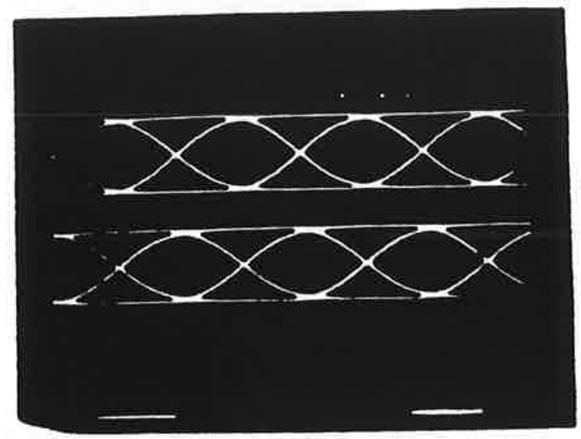
Baseband Signal Patterns for

(a) Unfiltered Non-Return to Zero (NRZ)
(b) MSK (Minimum Shift Keying)
(c) F-QPSK (Feher's filtered) QPSK modulated systems

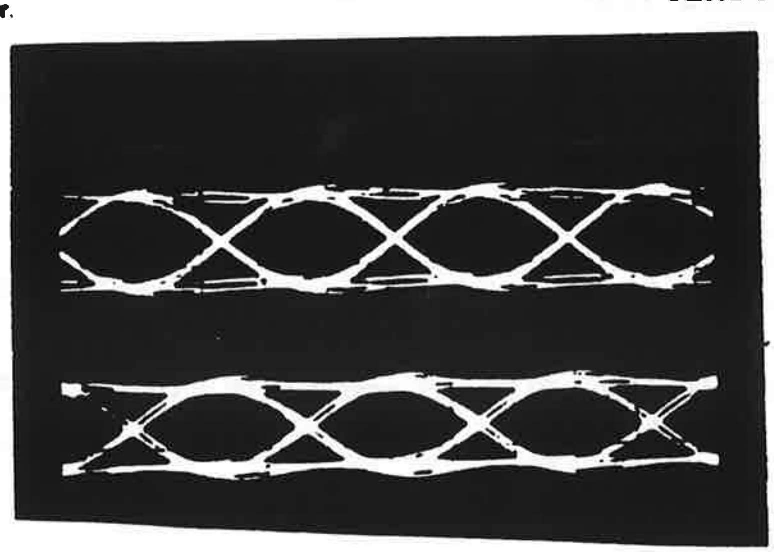




Circuit Diagram of the Filter for F-QPSK Modulator.



Baseband Eye-diagrams of F-QPSK Signal.



Coherently demodulated 100kb/s rate hardlimited FQPSK experimental eye diagrams

Fig. 2.6.b, FQPSK baseband signal generation concept [4] and circuit diagram—digital/analog transversal implementation and resultant FQPSK eye diagrams (I and Q channels) as published in Ref. [36]. The FQPSK baseband processor could be implemented by software DSP and by other techniques [8-11].

2.6 F-QPSK COMPARISON WITH QPSK AND GMSK

- F-QPSK is suitable for power efficient low cost nonlinear amplification and our proposed radio/modem architecture; see Figs. 2.1 and 2.2.

- F-QPSK has a somewhat simpler baseband transmit processor than Conventional QPSK with SRC (Square Root raised Cosine [3-7] filtering), thus the DSP is simpler and the design time shorter than for SRC-QPSK and/or for GMSK, and in particular for BT = 0.3 GMSK.

- F-QPSK is more about 50% spectrally efficient than GMSK; see Fig. 2.3-2.5 and Table 2.2.

- GMSK capacity could be about 50% lower than that of F-QPSK.

- F-QPSK has had some production and operational experience while GMSK chips are being manufactured in the millions for various cellular/PCS standards.

- QPSK (conventional QPSK) has the best performance and highest b/s/Hz efficiency and is more robust (by 1 dB), however requires linear amplifiers. Overall power efficiency, from a hardware designer's point of view (not radio system theory) of QPSK, could be very low due to Linear Power Amplifier requirements. Typical output backoff (OBO) is in the 6dB to 10dB range and overall amplifier efficiency is about 10%.

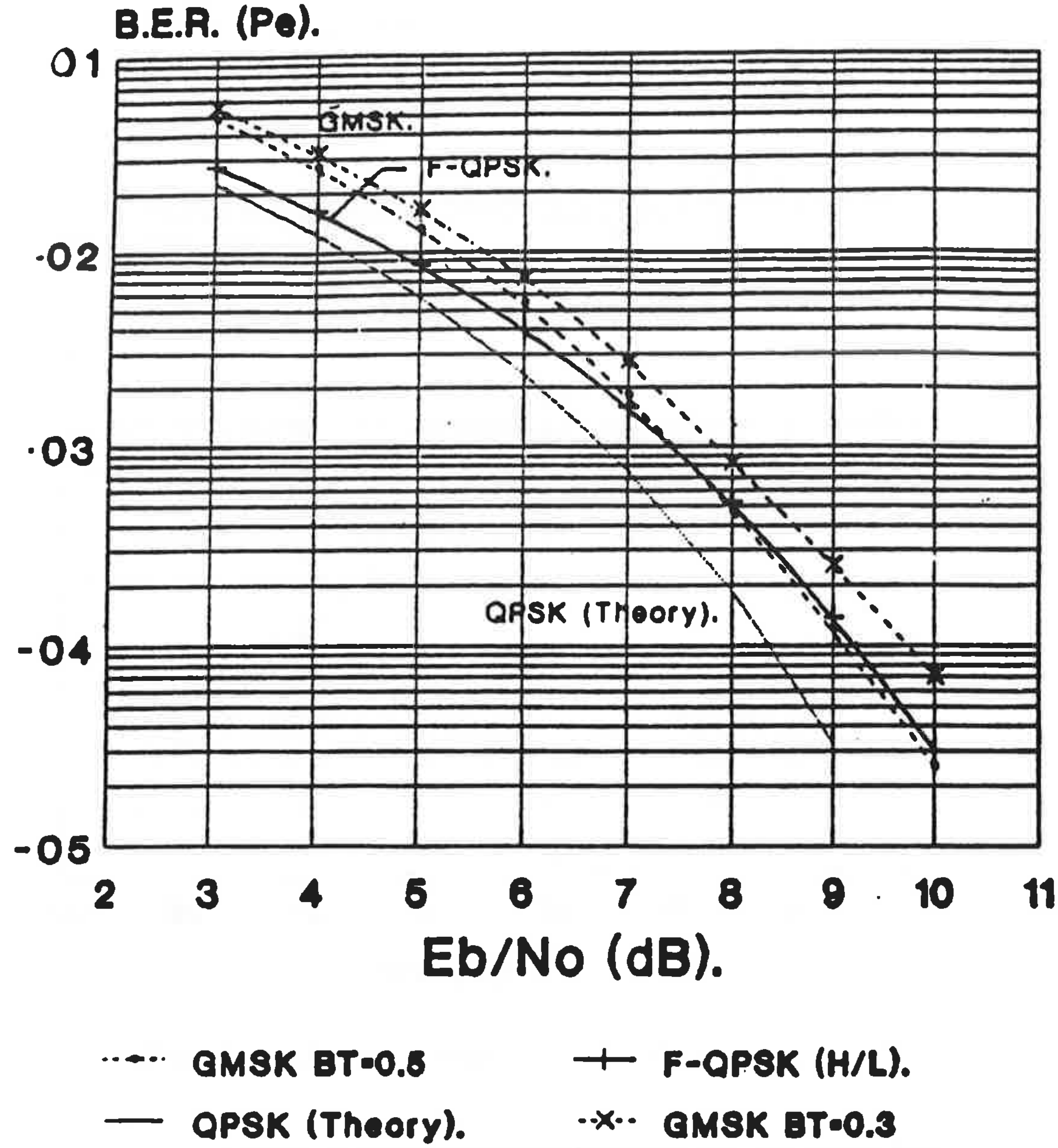
2.7 BER PERFORMANCE OF FQPSK AND OF GMSK MODEMS: STATIONARY AND RAYLEIGH FADED NOISE/INTERFERENCE CONTROLLED SYSTEM PERFORMANCE

The BER performance of ideal linearly amplified coherent QPSK and of practical nonlinearly amplified (NLA) F-QPSK and of GMSK modems is described in this section.

In Fig. 2.7, BER = $f(E_b/N_o)$ results are presented for a stationary Additive White Gaussian Noise Environment, [2]. Linear QPSK, NLA-F-QPSK and GMSK computer generated predictions are shown. In the BER = 10^{-1} to 10^{-2} range F-QPSK is significantly better than GMSK. In the simulations practical 4th order Butterworth filters are used for F-QPSK. For GMSK, a BT = 0.3 ideal "infinite order" Gaussian filter is used.

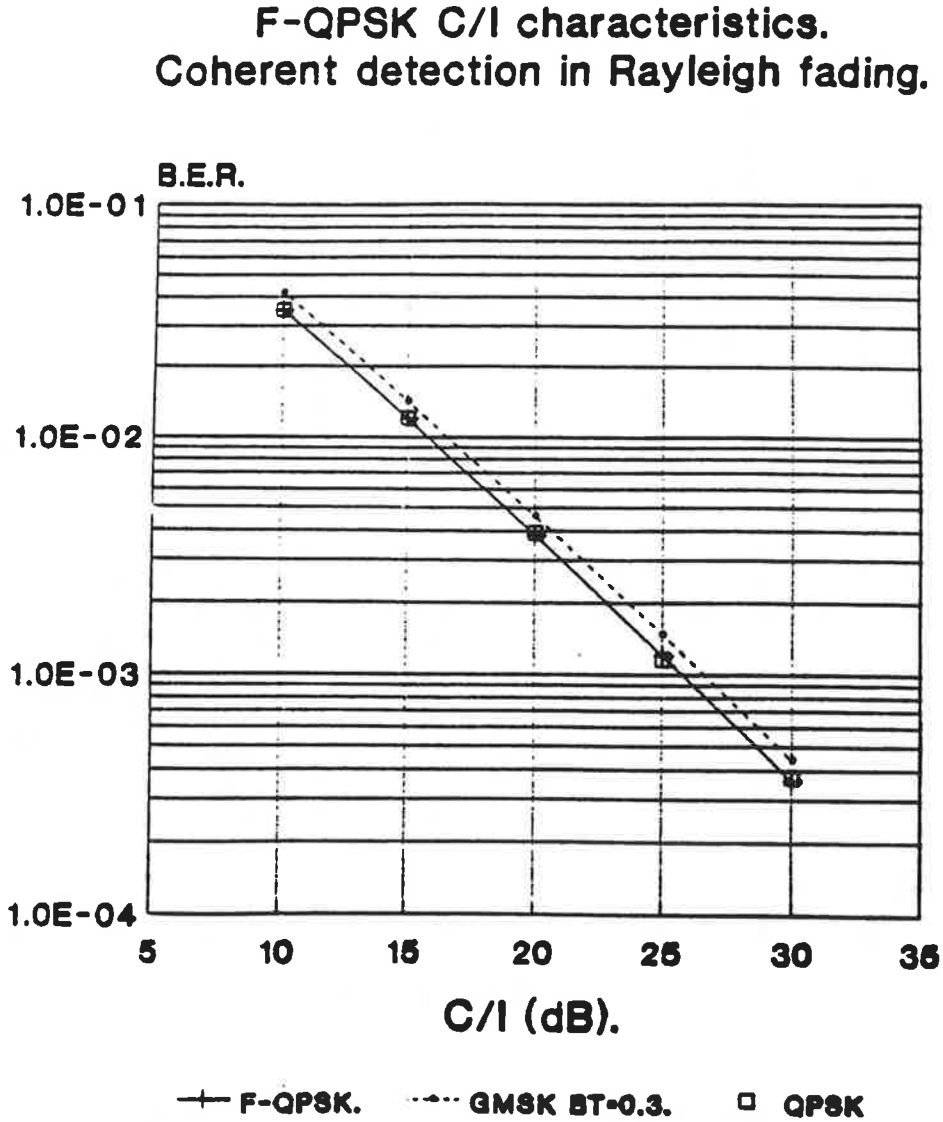
The Rayleigh faded BER = f(C/I) performance of NLA coherent FQPSK and of GMSK radio systems is shown in Fig. 2.8. Note that the E_b/N_o to C/I conversion is about 1.8dB (instead of 3dB), due to the noise bandwidth of the receive filter. We also note that **the FQPSK system in a C/I environment is about 1.5dB more robust than the coherent GMSK system.**

From Fig. 2.9 we note that the performance of **coherent FQPSK is 5.5dB more robust than noncoherent GMSK with BT = 0.5**. Very similar performance advantages (in the 5dB range) are obtained when compared to 4CPM-FM noncoherent systems [32].



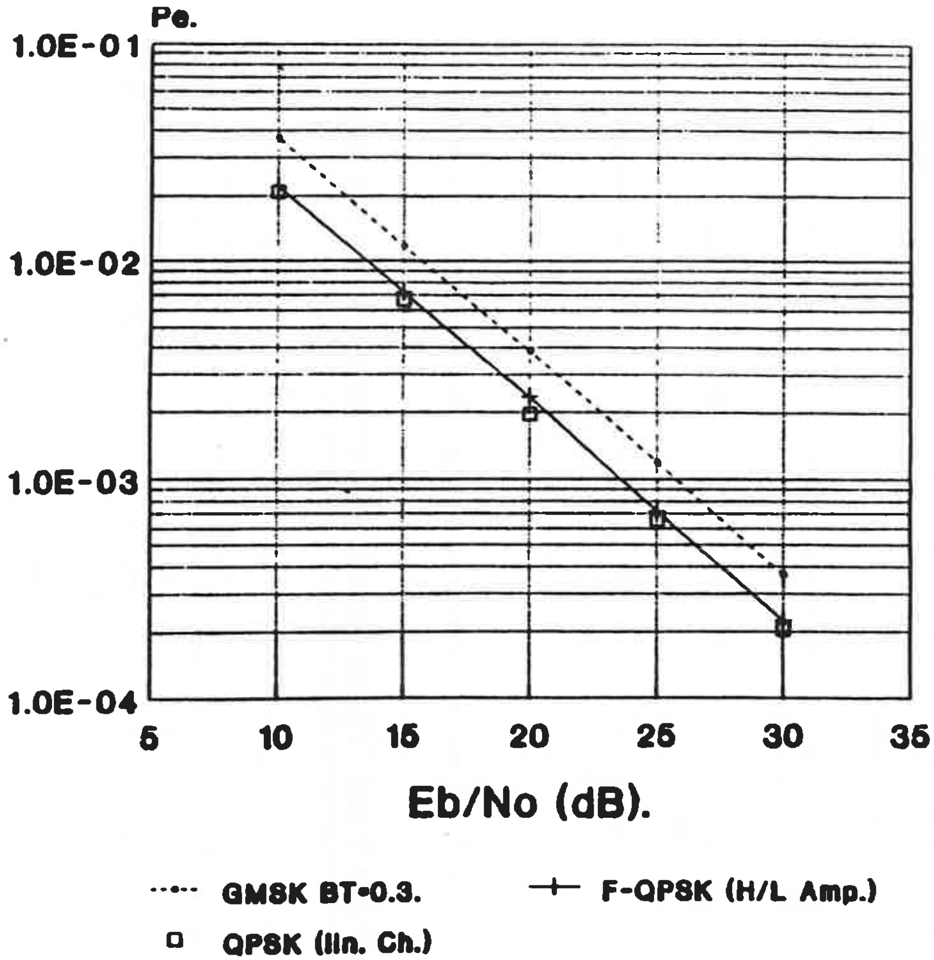
Butterworth 4 BPF (BiTb=0.55) for F-QPSK
Gaussian BPF (biTb=0.6) for GMSK.

Fig. 2.7. Theoretical BER = f(E_b/N_o) performance of nonlinearly amplified FQPSK, GMSK and of linearly amplified QPSK in an Additive White Gaussian (AWGN) channel

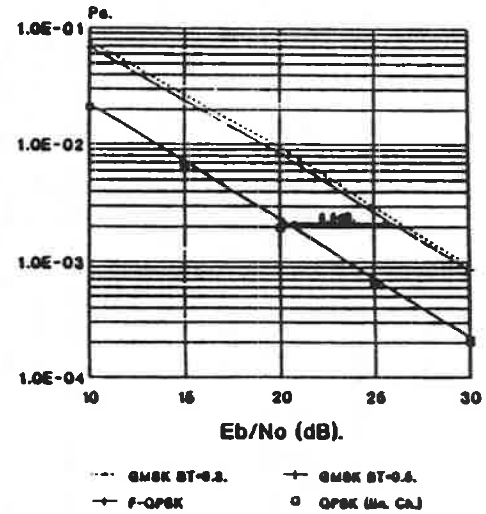


. BER performance of F-QPSK and GMSK in cochannel interference (CCI) controlled environment with Rayleigh fading. F-QPSK employs Butterworth (4th. order) receive BPF with BiTb=0.55. GMSK employs Gaussian receive BPF with BiTb=0.6.

Fig. 2.8. BER = f(C/I) in Rayleigh faded systems [1; 2]. Coherent GMSK and FQPSK. Note: 1.5dB advantage of FQPSK.



performance of F-QPSK and GMSK as function of Eb/No in fading channels. F-QPSK employs Butterworth (4th. order) receive BPF with BiTb=0.55. GMSK employs Gaussian receive BPF with BiTb=0.6.



BER performance of F-QPSK and non-coherent GMSK in Rayleigh fading. F-QPSK is 5.5dB better than GMSK BT=0.5 as in DECT.

Fig. 2.9. Rayleigh faded BER = $f(E_b/N_o)$ performance of GMSK, FQPSK and QPSK. Note: 5.5dB advantage of FQPSK over noncoherent GMSK.

2.8 COHERENT DEMODULATION: A BETTER DESIGN STRATEGY THAN INCOHERENT

In this section we highlight the advantages of coherent demodulation, as compared to noncoherent discriminator/differential detection. This section is included to answer the questions raised in relation to performance/cost/power consumption trade-offs, as well as to flexible/changeable RF frequency and bit rate tradeoffs [23]

Coherent systems have numerous advantages, including the following:

Capacity advantage of coherent QPSK (or FQPSK) could be about 30% to 100% larger than that of the noncoherent, based on the CCI or ECI cellular cell reuse factor K = 7 to 9 or WER (Word Error Rate of 10^{-4}). Similar advantages could be obtained for WLAN.

ACI (due to BB LPF versus IF BPF) could lead to an additional capacity, coverage and reliability advantage.

Bit rate: About 30% to 100% higher with coherent than noncoherent due to delay spread. With simple adaptive equalization bit rate could be about 4*(400%) increased over incoherent systems which have **unknown** adaptive equalizer complexity and performance (relative to coherent). Research at UC Davis indicates that F-QPSK is 50% more robust to delay spread than conventional CQPSK with a = 0.3.

Performance: Better/more controllable.

Synchronization: Time about same as noncoherent if we take into account the need of frequency synthesizer/RF drift caused DC drift adaptation time for DC compensation.

Tools: (computer design/analysis) much simpler; no known (to me) threshold/impulse noise problems in coherent systems.

IF BPF not so critical for coherent, as channel shaping noise/interference limitation is performed by the baseband processor in DSP/software control instead of physically large inaccurate IF band pass filters. This filter consideration alone could save a full additional stage of downconversion.

IC global chips: global trends are mostly in the new I-Q QUAD, that is coherent demod, direction.

Block demod in which all CR and STR and demod functions are performed after an A/D would not require any extra hardware for a superior performance coherent demod.

Summary: Coherent demodulation offers significant advantages in the design, manufacturing and marketing/sales of new generations of high speed (high data rate of more than 10 kb/s... and probably up to several Mb/s or even 10Mb/s++ systems), when compared to noncoherent reception. Increased capacity, coverage, improved performance, simpler and known computer and analytical tools to predict and practically to optimize performance, increased reliability, higher bit rate possibility, relatively simple addition of adaptive equalization, simpler hardware/less power, simpler IF filters combined with one IF instead of two, IC global trends, possible extension/simple modification. **Same architecture/product** subsystems for subscriber units and for base stations, etc., are among the most significant advantages of coherent demodulation. Perhaps the most significant **disadvantage** of the coherent approach is the requirement to

Maximal bit rate and delay spread τ_{rms} issues	**COHERENT QPSK OR F-QPSK** (or GMSK-similar, however worse performance.)	**DIFFERENTIAL DQPSK** (or DGMSK)
τ_{rms} "worst case" 1μs		
τ_{rms} = 200 ns		
BER = 10^{-2} floor due to τ_{rms}/T_s	$\tau_{rms}/T_s = 0.2$	$\tau_{rms}/T_s = 0.15$
$P_{(e)}$ = C/I degrad(addit) of 1dB due to τ_{rms}/T (4*more sensit. than for "floor"	$\tau_{rms}/T_s = 0.075$ QPSK F-QPSK is higher abut 50%	$\tau_{rms}/T_s = 0.05$
Maxim. bit rate f_b		
for 10^{-2} Error Floor 1μs[200ns]	600 kb/s [3 Mb/s]	300 kb/s [1.5 Mb/s]
for 1dB τ_{rms} caused degr. 1μs[200ns]	150 kb/s [750 kb/s]	75 kb/s [375 kb/s]
CAPACITY ISSUES BASED ON C/I = 3 dB (CCI advantage)	BER=10^{-2} C/I-15dB (Rayleigh)	BER=10^{-2} C/I=18dB
NORMALIZED RELAT. CAPACITY		
Based on k = 9 to k = 7 reuse	100%	70% (30% loss)
Based on WER and throughput	100%	20% (80% loss)
Spectral efficiency ACI and BPF versus LPF caused advantage, i.e., lower noise BW-coherent receiver (normalized to coherent)	100%	60%
Increased Bit Rate or Cell Coverage/Adaptive Equalization	Relatively simple/low cost DSP/SW adaptive equalizer could increase rate (coverage)	Very costly if at all feasible adaptive equalization technology (theory not well understood-requires original new research).
Bit rate (PHY) change, without loss of performance (within range)	Automatic SW (software controlled) in BBP	Very difficult could require change of IF-BPF
Spectral Efficiency for ACI=-20dB nonlinearly amplified radio	F-QPSK = 1.42 b/s/Hz GMSK = 0.94 b/s/Hz $BT_b = 0.5$ and 0.98 b/s/Hz for $BT_b = 0.3$	Approx. 0.7 b/s/Hz depending on BPF complexity

Table 2 Coherent/Noncoherent Comparison of GMSK, FQPSK and QPSK Systems, Reference [23]

Table 2 (continued) Coherent/Noncoherent Comparison of GMSK, FQPSK

	COHERENT QPSK	DIFFERENTIAL DQPSK
Synchronization Time (CR) (relative to no CR - differential loss of frame efficiency for 1000 or 10,000 bit word (packet)	50 bits:1000 = 5% (max 100 bits = max 10% 50 bits:10,000 = 0.5% max 100 bits for CR=max.1% - a disadvantage. Parallel CR and STR design could eliminate this drawback.	Potential of 1% to 10% packet/synch time advantage(?). However, could be lost due to BPF transient ringing. Synch. Time advantage could be lost due to DC comp. to sat. time requirement.
Threshold capture effect (discriminator-impulse noise)	No problem	Potential problem in the critical BER = 10^{-2} range with discriminator.
Tools (prediction)	Well known.	Much more involved as IF-BPF imperfect; impact of frequency tolerance GMSK $BT_b = 0.3$ very difficult.
RF-oscillator drifts include synthesizer - impact on BER - DC restoration.	Simple.	Very costly - potential danger like in DECT.
Additional down conversion/filters	Not required.	Very costly, extra stage could be required due to lower IF and BPF problems.
Carrier Recovery Requirements	Yes. Simple pilot in band and other Costas ... well-known techniques. No Doppler problem. Low power solution. GSM, ADC other cellular have it.	No need for CR. Advantage
DC power-extra for CR	Could be marginally higher for demand alone.	Discriminator power requirement is smaller than coherent. However, DC battery power advantage could be lost due to LO or synthesizer-DC compensation requirement.
IC Chips-Trend	Most manufact. companies developing QUAD (coherent struct.)	Noncoherent discrim. today cheaper however overall radio extra IF, BPF, DC compensation not evident.
Overall Cost/DC Power estimate	About same as noncoherent receiver (total radio) with new technology.	About same.
RF Frequency 900MHz 1.9GHz, 2.4GHz Bit Rate Variation	Same architecture for both RF frequencies Flexible bit rate	Could require in some applications extra expensive IF stage (space/cost) does not lead to software driven bit rate change

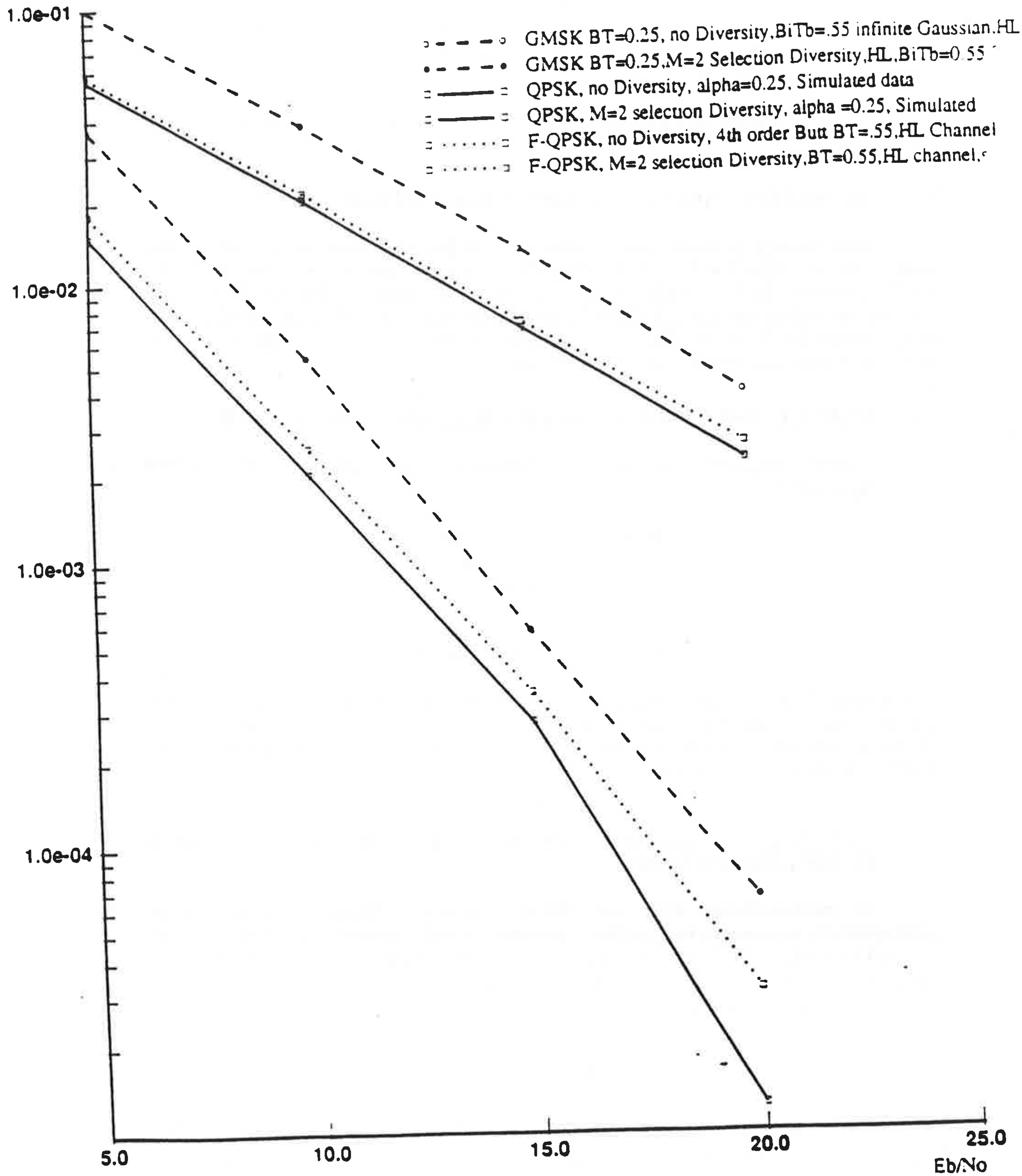


Fig. 2.10. Diversity (selection diversity) prelimin.

design a carrier recovery (CR) subsystem, a CR which could compensate for the relatively high Doppler shift. This is an initial **development** cost and potentially scheduling disadvantage. The predicted production quantities justify the initial added effort of a CR design. This would lead to better, more robust, higher capacity systems.

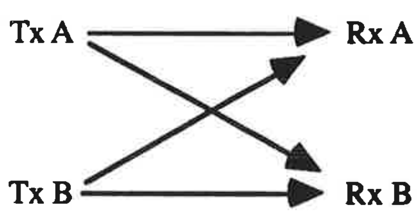
A more detailed comparison of coherent/noncoherent modems is given in Table 2.3, Ref. [23].

2.9 DIVERSITY – SELECTION SWITCHED PERFORMANCE

Preliminary performance results of two branch switched selection diversity systems are illustrated in Fig. 2.10. (Results were generated at UC Davis in Dr. Feher's R&D laboratory by H. Mehdi—a forthcoming publication.) The results indicate that linearly amplified theoretical QPSK and nonlinearly amplified practical FQPSK are within about 0.5dB while GMSK is degraded by about 2dB. The significant diversity gain is expected based on Hirade's chapter in [7].

2.10 FQPSK COMPATIBILITY WITH GMSK AND OFFSET QPSK

A fully compatible and backwards compatible system concept is illustrated by the following diagram:



In this case TxA or TxB could be either GMSK, FQPSK or a conventional OQPSK system. All Transmit (Tx) and Receive (Rx) combinations have to work. Research at UC Davis indicates that full compatibility (within 0.5dB degradation) is attained between FQPSK and GMSK and filtered offset QPSK.

3 CAPACITY IN CELLULAR AND WLAN ENVIRONMENTS: FQPSK COMPARED TO GMSK

In microcellular PCS and WLAN systems, frequencies are reused in geographically separate cells to achieve greater network capacity [4]. In this environment we need to include the frequency reuse factor K when comparing modulations. Suzuki and Hirade's definition of the overall spectral efficiency η_T(b/s/Hz/m^2) of a modulation in a cellular environment is given by [4]:

$$\eta_T = \eta_f \times \frac{1}{K} \times \frac{1}{S} \tag{1}$$

where η_f is the modulation's spectral efficiency with respect to frequency (in b/s/Hz) and S is the coverage area of a cell (m^2). The frequency reuse factor K (cells/cluster) is an integer [4]:

	ACI = -15dB	ACI = -20dB	ACI = -26dB	ACI = -30dB
FQPSK	1.63 (147%)	1.42 (151%)	1.23 (156%)	1.10 (155%)
GMSK BT = 0.3	1.16 (105%)	0.98 (104%)	0.83 (105%)	0.74 (104%)
GMSK BT = 0.5	1.11 (100%)	0.94 (100%)	0.79 (100%)	0.71 (100%)

Table 3 Spectral efficiency η in b/s/Hz.
Note FQPSK is 51% more efficient than GMSK (at 20dB) [1; 2]

	η_f	λ for $P_e = 10^{-2}$	K	η_T
F-QPSK	1.42	15.7 dB	7	0.203 (195%)
GMSK BT = 0.5	0.94	18.2 dB	9	0.104 (100%)

Table 4 Capacity comparison of F-QPSK and non-coherent GMSK as in DECT [1; 2]

	η_f	λ for $P_e = 10^{-2}$	K	η_T
F-QPSK	1.42	15.7 dB	7	0.203 (186%)
GMSK BT = 0.3	0.98	16.7 dB	9	0.109 (100%)

Table 5 Capacity comparison of F-QPSK and coherent GMSK as in DCS1800 [1; 2]

	DECT	DCS 1800
F-QPSK	195%	186%
GMSK	100%	100%

Table 6 Capacity improvement of F-QPSK over GMSK as in the current PCS standards DECT and DCS 1800 [1; 2]

	Power efficiency	Capacity [12]
F-QPSK	0 dBr	100%
π/4-DQPSK	-6 to -8 dBr	100%

Table 7 Comparison between F-QPSK and π/4-DQPSK [1; 2]

$$K = \frac{1}{3}[1 + (M_f\lambda)^{1/7}]^2 \quad (2)$$

where λ is the C/I ratio required for a given BER performance. γ is the propagation constant whose value ranges between 2 and 4, and M_f is the C/I margin. K = 1, 3, 7, 9, 12, etc. [4].

In this analysis we assume (i) a BER of 10^{-2} for acceptable quality voice and/or raw data in Rayleigh faded environment (at threshold), (ii) $\gamma = 3.5$ and (iii) a fade margin of M_f = 3dB. This margin corresponds to a geographical outage probability of approximately 10%. Furthermore, without loss of generality, we let S = 1 m^2. The total spectral efficiency η_T of the proposed F-QPSK scheme and GMSK in a microcellular mobile PCS communications environment are compared in Table 4 and Table 5. These comparisons serve as indicators of the system capacity [1; 2]. Table 4 shows that the combined spectral efficiency η_f of FQPSK and its CCI advantage over the noncoherent GMSKBT = 0.5 leads to a 95% increase of the overall spectral efficiency η_T in a cellular mobile environment. This indicates that our proposed F-QPSK modem radio solution can nearly double (95% increase) the capacity of DECT. Likewise Table 5 shows that FQPSK can improve the capacity of the current PCS standard DCS1800 by 86%. The advantages of FQPSK are further summarized in Table 6 and Table 7.

4 REFERENCE PUBLICATIONS AND PATENTS

All modulation techniques referenced in this proposal for IEEE 802.11 PHY standards have been extensively described in the open literature. For example, Hirade [in Ref. 4, K. Feher's 1987 book] has about 100 pages related to GMSK. A classic/most frequently referenced GMSK paper is [16]. Numerous references including [4; 6; 7; 12] describe QPSK, DQPSK, and π/4-QPSK systems.

The proposed FQPSK family of modems is described in more than 30 IEEE publications, including [3; 4; 6; 13; 22; 23; 32]. We use most extensively Ref. [1* and 2*]. Reference [1] is enclosed with our proposal. FQPSK related patents are Refs. [8-11].

FQPSK processor modem patents can be licensed by contacting the inventor (owner) of the patent (Dr. K. Feher, Digcom Consulting Group, Inc.). In accordance with IEEE standard committee (and other national and international committee) practice, "licenses will be provided on reasonable and nondiscriminatory basis". All other established, reasonable standard terms stipulated by the standardization committees will also be agreed upon.

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