Title: HS-FH and IR proposed FQPSK based standards for 1.4Mb/s to 4.2Mb/s

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For the High Speed Frequency Hopped (HS-FH) standard a 1.4Mb/s, 2.8Mb/s and 4.2Mb/s rate FQPSK based PHY solution (in 1MHz) is proposed. Bit rates for the proposed 1st generation Infrared (IR) standards are the same as for the HS-FH. Gear shift "up/down" and Clear Channel Assessment (CCA) method with the proposed 1Mb/s GFSK is also presented. FQPSK is the only technique which satisfies the IEEE 802.11 Higher Data Rate FH-SS and infrared "EXIRLAN" PHY requirements and agreed-upon standardized specifications [39].

A brief comparison of essential requirements of the final HS-FH proposals is listed below. As of March 3, 1994 nine (9) European and American companies (including some of the largest ones) and several American, Asian, Australian, Canadian and European Universities [42] have already stated their intentions to support the wireless FQPSK based radio and/or EXIRLAN infrared standardization process. Terms of technology transfer/license/FQPSK consortium/tranining course open invitation letters were mailed on February 3, 1994 to IEEE 802.11 and to TIA-JTC standardization committee members. To obtain copies of this letter and additional information please contact K. Feher.

Essential Requirements per Adopted Specifications [1]	FQPSK	π/4-DQPSK	4-FSK
1 Compliance with regulatory agencies	✓	?	?
2 Compliance with 802.11 PAR (data rate at least 1Mb/s)	✓✓	✓?	✓?
3 Minimum area coverage	✓	?	? ?
4 Suitable for low power consumption implementations	✓	No	No
5 Cost effective	✓	No	No
6 Support a number of stations per cell	✓	No	No
7 Suitable for small size implementation	✓	No	✓
8 Robust operation in narrow band and partial band interference as well as multipath fading	✓	No	No
9 Ensure interoperability between conformant 802.11 stations; CCA problems?	✓	?	?
10 Graceful degradation under load and interference	✓	No	No
Other Essential Criteria			
11 Forward compatibility to permit new emerging technologies	✓	No	No
12 Compatibility with related applications, e.g., JTC-TIA standards at 1.9GHz	✓	No	No
13 Linearized amplifiers enable increased bit rates	✓	No	No
14 Backward compatibility with FH-SS 1Mb/s GFSK	✓	No	No
15 IC chips trend/available components - VLSI - trend	✓	No	No
16 Higher bit rates limit (max) with proposed technology	✓✓	✓	✓
17 Faster throughput/reduced message delay in interference environment	✓✓	?	? ?
18 Maximal bit rate, including future extensions	4.2Mb/s	1.5Mb/s	2Mb/s

Table 1 Compliance with essential requirements of IEEE 802.11 higher data rate frequency hopping spread spectrum PHY standard "template" reference: (N. Silberman, Editor, IEEE P.802.11.93/210A, January 10, 1994, Ref. [39]). Comparison of FQPSK, π/4-DQPSK and 4-FSK proposed standards

Code: (✓) meets requirements (✓✓) exceeds requirements

1. FQPSK COHERENT DEMODULATION IS *MUCH* BETTER THAN NONCOHERENT 4-FM and π/4-DQPSK

- In [6; 13 and 35] it is demonstrated that the performance of coherently demodulated systems is about 10dB better than that of 4-FM noncoherent systems (noise; interference, delay spread).
- Change of FQPSK bit rate from 1.4 Mb/s to 2.8Mb/s and to 4.2Mb/s in 1 MHz could be achieved simply by changing software/DSP of baseband processor.
- Higher data rate, higher throughput and reduced message delay at least **10*** with coherent FQPSK
- π/4-DQPSK is not suitable for implementations in the 250mW to 1Watt range; cannot meet specifications and extension to higher data rates not known

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2. ARCHITECTURES TO ACHIEVE FLEXIBLE STANDARD RATES OF 1.4Mb/s, 2.8Mb/s and 4.2Mb/s (same rates as proposed infrared standards)

- Transmit and receive "QUAD" offset based quadrature/coherent structures as described in references [6, 7, 13, 18, 21, 31, 37].
- FQPSK with "Offset" QPSK - OQPSK - essential for nonlinear (NLA) operation; extension OQAM linear operation (16-state) could be required for 2.8Mb/s and 4.2Mb/s.
- FQPSK family of nonlinearly amplified modems (C-class) is fully compatible with OQPSK [6 to 21].
- Offset QPSK and offset QAM (OQAM) achieves 1.4 Mb/s, 2.8 Mb/s and 4.2 Mb/s; same symbol rate of 700k Baud.
- Gear shift "up/down" by user control "vendor" bits
- CCA (Clear Channel Assessment) with 1Mb/s rate proposed GFSK standard is simple and feasible with FQPSK

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3. JUSTIFICATION OF 1.4 Mb/s, 2.8 Mb/s AND 4.2 Mb/s, EXTENDIBLE FLEXIBLE (MULTIPLE) RATE STANDARD

- Most "ROBUST" low power proposals are at 1.4 Mb/s. FQPSK could transmit 1.5Mb/s.
- Robust performance is essential [Silberman, Ref. 39].
- Robust performance as BER = $f_1(E_b/N_0) = f_2(C/I)$ is a must.
- Robust performance in **DELAY SPREAD** essential for higher speed FH-SS systems.
- NLA (nonlinear amplifier) - a practical requirement for standardized PCMCIA card for 1 Watt at 2.4 GHz with present technology. In future linear or nonlinearly amplified FQPSK (4*4) or 16-OQAM and FQPSK (8*8) or 64-OQAM with 4.2b/s/Hz will become practical.

4. GEAR SHIFT TO AND FROM 1Mb/s, 1.4Mb/s, 2.8Mb/s or 4.2Mb/s

PREAMBLE CONTENT: EXACT BIT PATTERNS WITHIN FRAMES TBD LATER

Solution could be very similar to adopted draft standard (IEEE 802.11) DS-SS and of proposed infrared (IR). Reference J. Boer ATT, Editor No. [41].

A : Synchronization field 128 bits of 'ones'

B : Unique word : 16 bits (octal 2717)

C : 802.11 SIGNAL BITS ILLUSTRATIVE EXAMPLES - HS-FH

16 bits are here assumed instead of 8. Could reduce number of signal bits if required by MAC. See Item 35 in Silberman [39].

Bit Patterns* in Frame (HS-FH)					Bit Rate	Modulation
11	00	00	00	00	1Mb/s	GFSK
00	11	00	00	00	1.4Mb/s	FQPSK
00	00	11	00	00	2.8Mb/s	FQPSK (4*4)
00	00	00	11	00	4.2Mb/s	FQPSK (8*8)
00	00	00	00	11	Spare TBD	?? TBD
		TBD			TBD	TBD
		TBD			TBD	TBD

Table 2

* Better more robust bit patterns could be chosen/selected by PHY for HS-FH; IR and MAC.

C : 802.11 SIGNAL BITS INFRARED EXAMPLES

Details TBD by Committee Later

Bit Patterns* in Frame (HS-FH)					Bit Rate	Modulation
10	10	00	00	00	19.2kb/s	? PPM baseband
10	01	00	00	00	115.2kb/s	16 PPM baseband
00	00	10	00	00	1Mb/s	16 PPM baseband
00	00	01	00	00	1Mb/s	FQPSK (in 3MHz)
00	00	00	10	01	1.4Mb/s	FQPSK (in 3MHz)
		TBD			2Mb/s	FQPSK (in 3MHz)
		TBD			2.8Mb/s	FQPSK (in 3MHz)
		TBD			4.2Mb/s	FQPSK (in 3MHz)
		TBD			5.6Mb/s	2nd generation IR
		TBD			8.4Mb/s	2nd generation IR
		TBD			12.6Mb/s	2nd generation IR

Table 3

D : Service bits: 8 bits used at vendors discretion; all zeros for 802.11

5. 4dB LESS ROBUST LEADS TO 100 TIMES RETRANSMISSION OR COMPLETE FAIL INSTEAD OF A SINGLE TRANSMISSION WITH FQPSK [20;27;6]

<u>Modem (A)</u>	<u>Modem (B)</u>
(less robust)	(more robust by 4 dB)
BER = 10^{-2} (?)	BER = 10^{-5}
On average every file in error ?	Average 1 out of 10 files in error
Complete fail	Almost every file transmission is a "success"
Retransmit time ? Infinity ?	Retransmit 10% only

If modem 6dB more robust = file transfer time 1000 times shorter

6. IC CHIPS FOR FQPSK*

For FQPSK and compatible quadrature mod/coherent demod OQPSK, GMSK VLSI/ASIC's/ technologies/components for IEEE 802.11 (2.4GHz) and TIA-JTC(1.9GHz) chips in the 300kb/s to 12Mb/s range, numerous companies have solutions and are suggested including (in some cases product or group):

300kb/s++	**1Mb/s to 60Mb/s**
Siemens	Oki
Ericsson/GE	INTEL (iFX740); Ref. [40] FPGA
Motorola	TRW MCDD Technology Group
Alcatel	UNISYS
Northern Telecom	NTT
	TELEDYNE (MMIC) TFE 1050 transceiver
	Digcom/Dr. Feher Assoc.
	HP-CCD
	Andromeda
	Xilinx XC-4003 (1C-DSP prototypes)

* Several of these companies (including some of the largest ones) already joined the FQPSK Consortium

7. FQPSK REVIEW/DEFINITIONS

The FQPSK family of linearly and nonlinearly amplified (NLA) radio modem techniques have been invented by Feher et al. and described in numerous references. See List of References.

FQPSK-1 = IJF (Intersymbol Interference and Jitter free) simplest baseband processor of OQPSK; Patent No. [1] two-level eye diagrams

FQPSK-kf = FQPSK (xx ... yy) parameters of crosscorrelated and baseband filtered (after correlator) Kato/Feher patented, Ref. [2] method 2-level eye diagram, increased spectral efficiency

FQPSK-4*4 = extended FQPSK to 4 and 8 level baseband signaling states in the I and Q
FQPSK-8*8 = channels

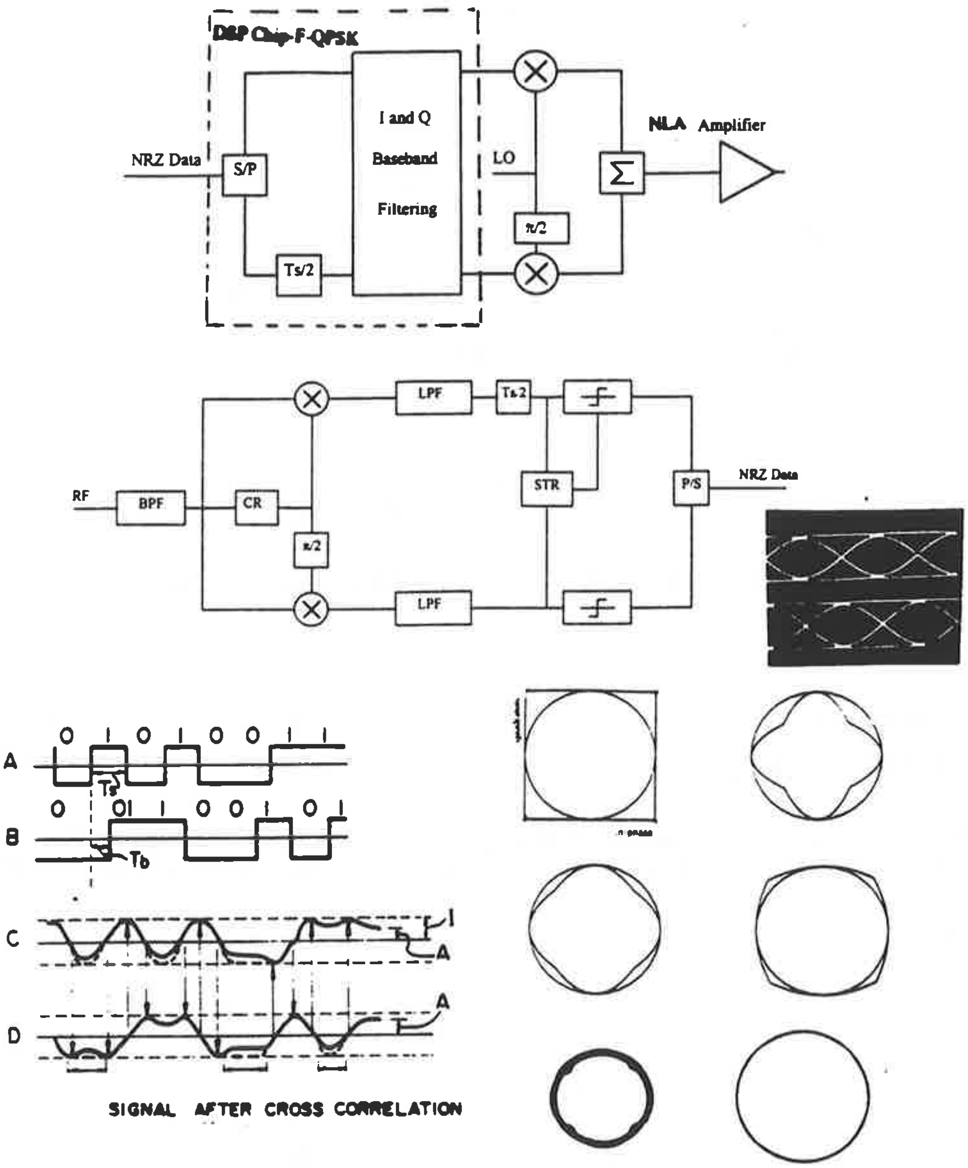
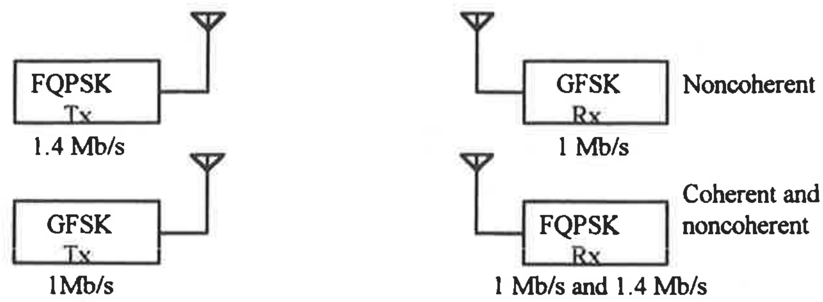
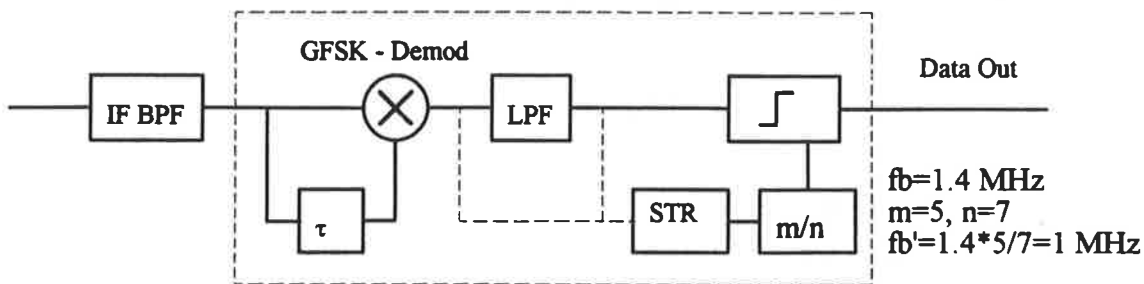


Fig. 1 FQPSK NonLinearly Amplified (NLA) transceiver/modem. Compatible architecture already adopted by the DS-SS committee of IEEE 802.11. Same FQPSK architecture with NLA proposed for the Higher rate/Speed Frequency Hopping (HS-FH) standard and by an international user group for the infrared (IR) standardization committee. Several I and Q signals and constellations of the FQPSK family are illustrated. Insert with black background is experimental DSP-IC chip 1Mb/s binary eye.

7. CCA (Clear Channel Assessment) - Illustrative Method.



Rx - GFSK [see Ref. 34]



Experimental CCA :

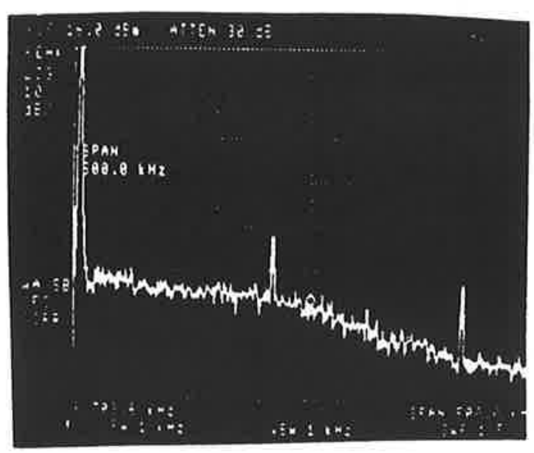
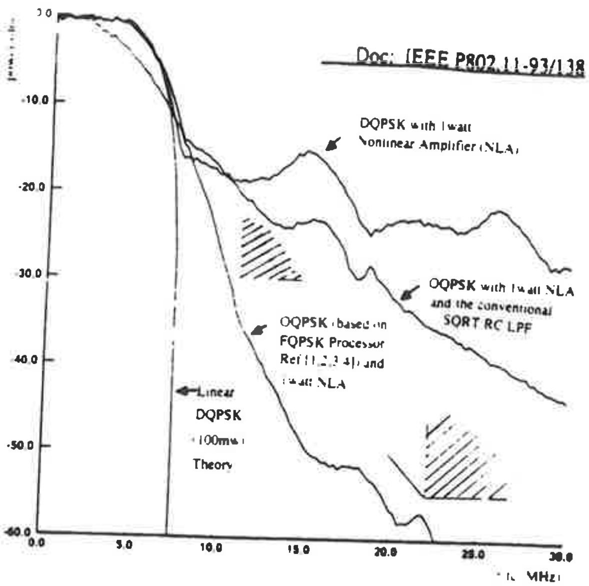
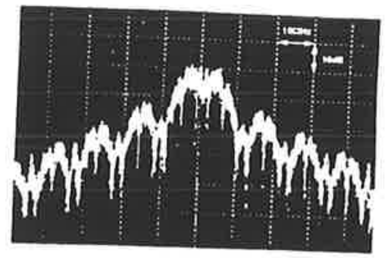


Fig. 2 Experimental result of CCA (Clear Channel Assessment) concept/solution. GFSK discriminator generates discrete spike at 1.4 MHz. Symbol Timing Recovery (STR) recovers by 5/7 multiplication (available in most chips) the 1MHz clock. Alternatively pseudo error monitor CCA could be implemented [13].





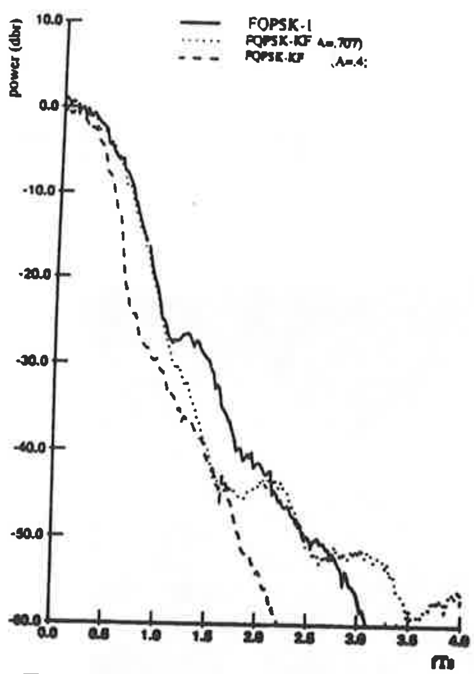
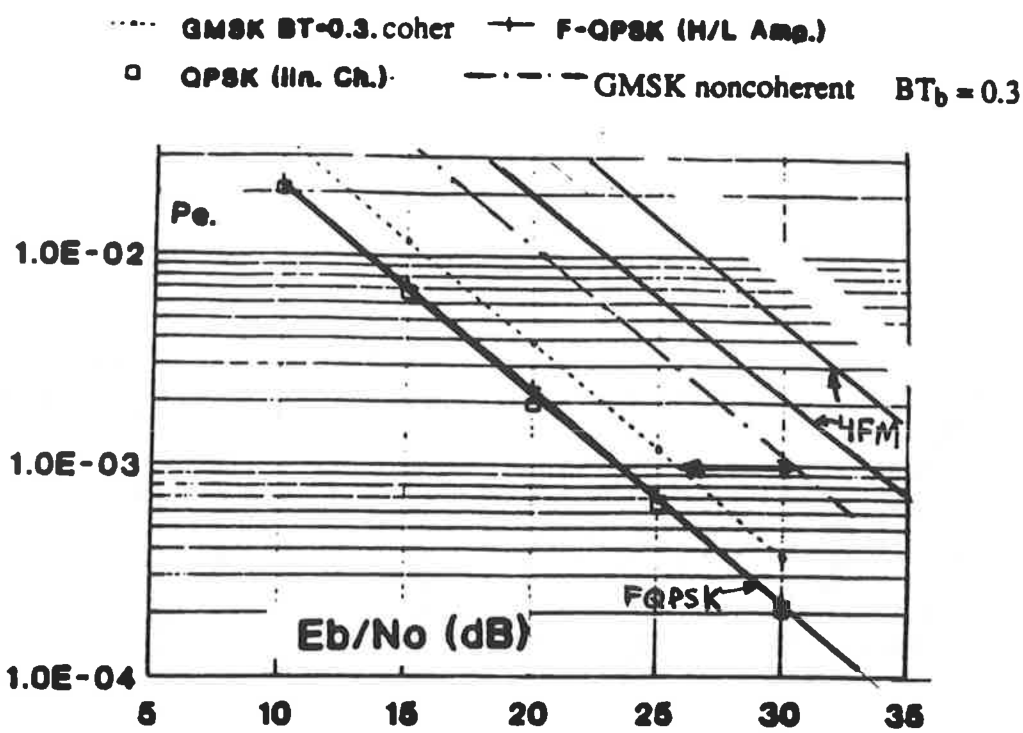


Fig. 3 Experimental hardware and computer generated power spectra

Top: DQPSK and π/4-DQPSK spectrum is fully restored after nonlinear amplification

Center: Nonlinearly amplified DQPSK restored (spread) sidelobes; experimental result measured at NTT, Japan

Bottom: FQPSK-1 and FQPSK-kf nonlinearly amplified spectra



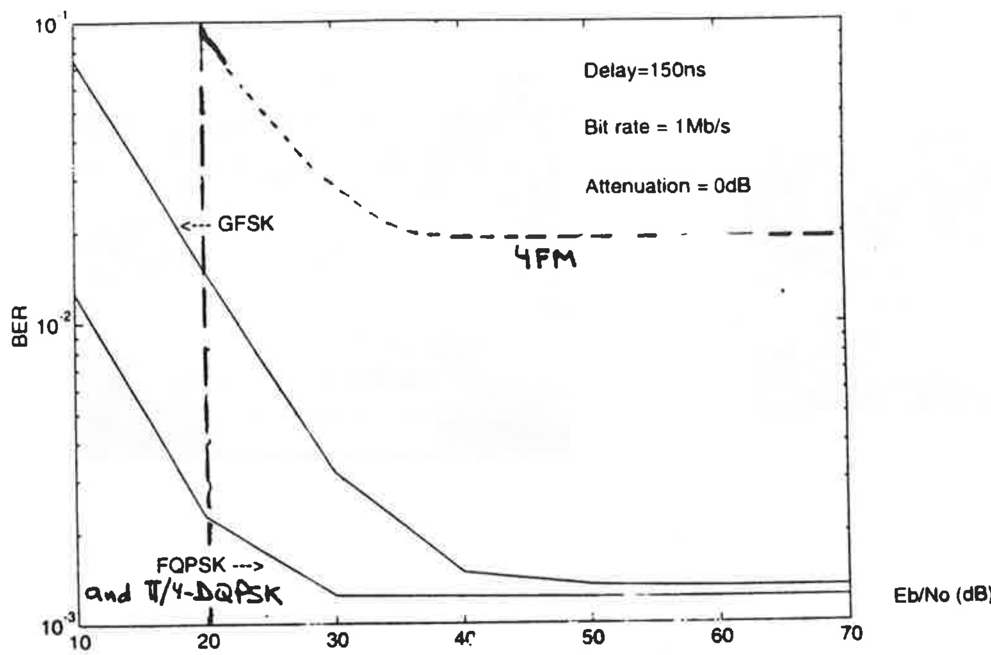
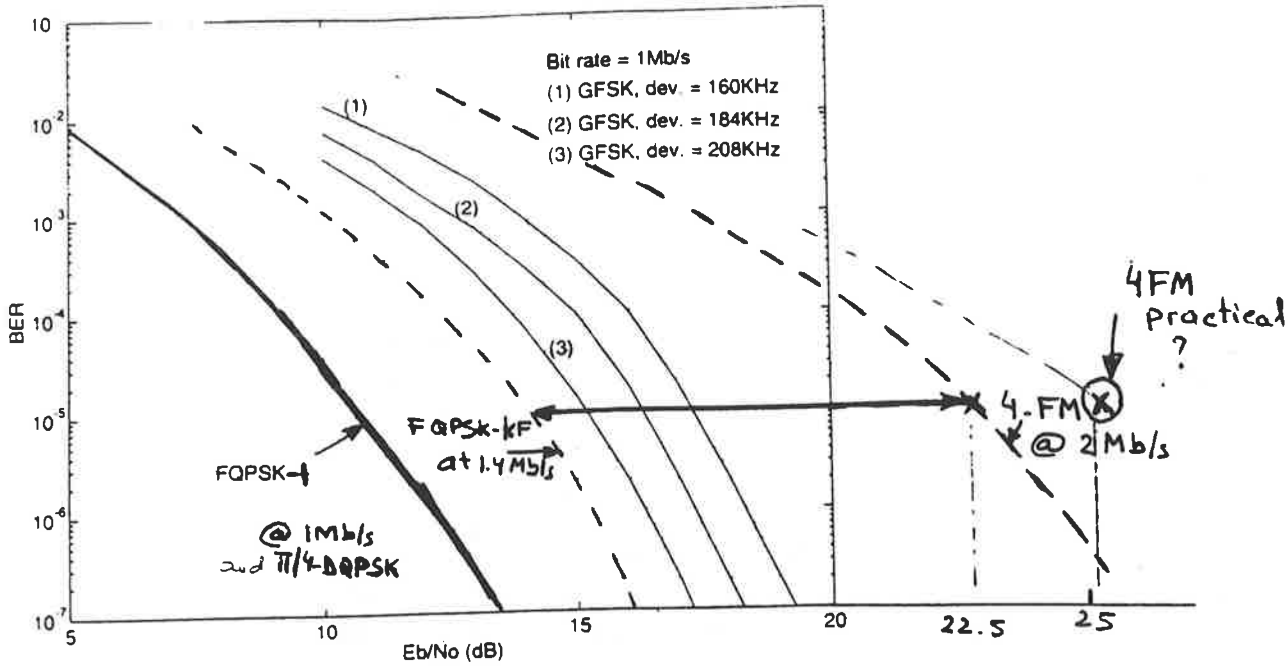
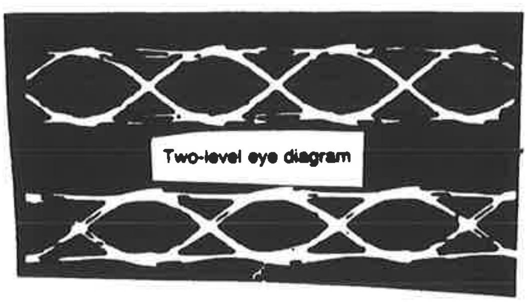


Fig. 4 BER = $f(E_b/N_0)$ performance of FQPSK, GMSK and 4-FM constant envelope systems in Rayleigh (top) and Rayleigh/delay spread environment with IEEE 802.11 measured/quoted 150ns delay. 4-FM is estimated. GFSK, GMSK and FQPSK computed/experimentally verified. Note: Based on Dr. P. Leung, Ref. [50] of Australia the delay spread robustness of FQPSK is better than that of coherent QPSK and thus of π/4-DQPSK.





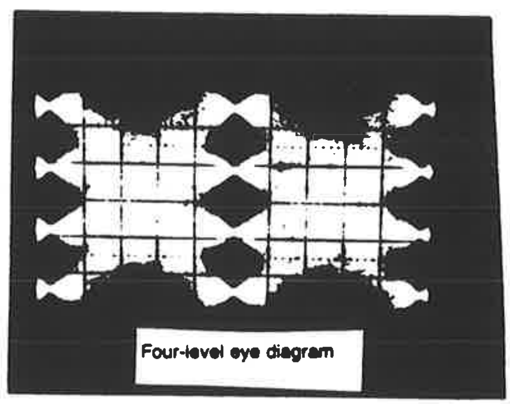


Fig. 5 Performance comparison in a stationary Gaussian noise environment

FQPSK and 4-FM measured (experimental hardware) and computer generated.
The 4-level (4-FM) eye diagram indicates the sensitivity of this multilevel system to delay spread (see Fig. 4). Also it requires an expensive 4-level decision device, previously rejected by the PHY committee.

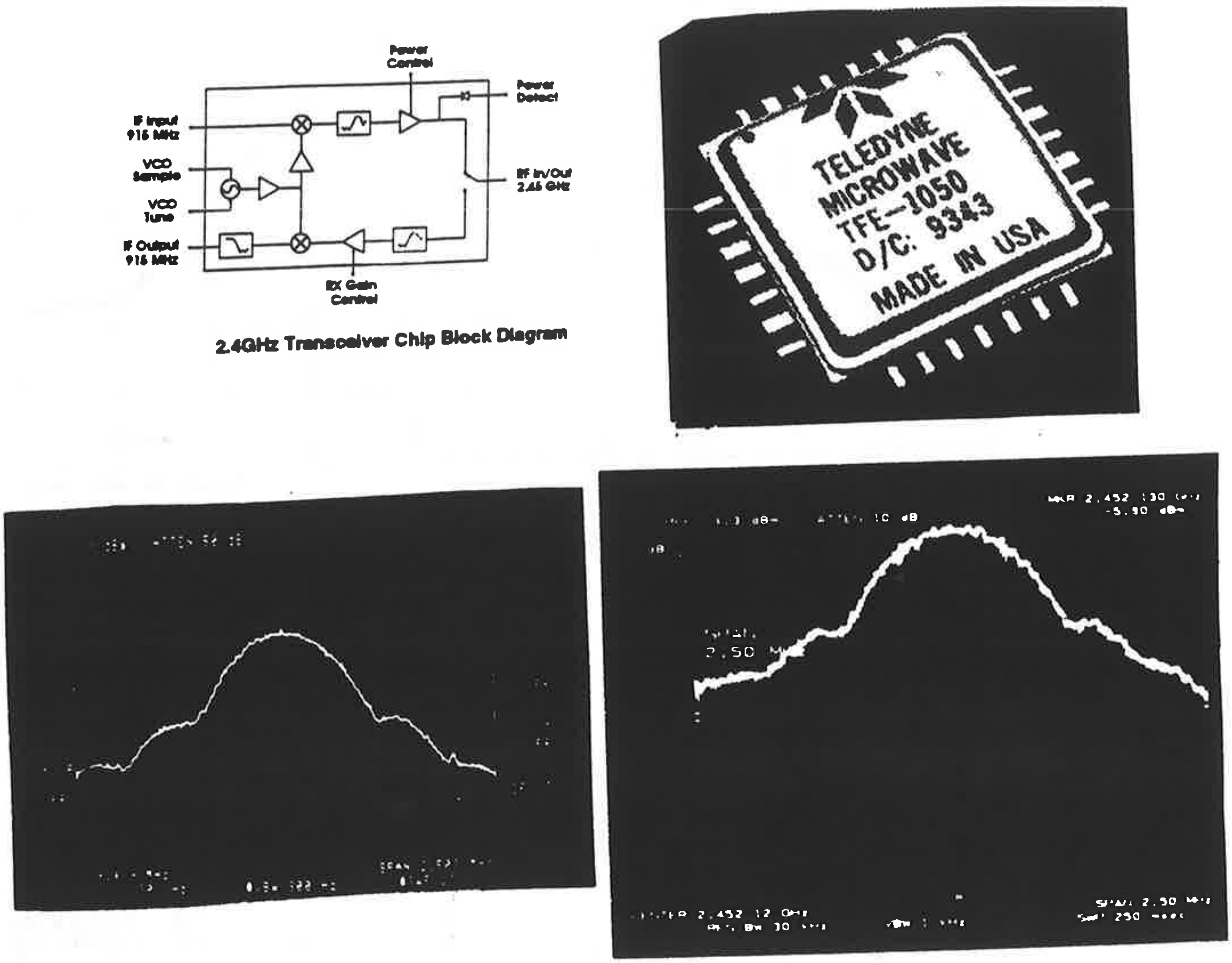
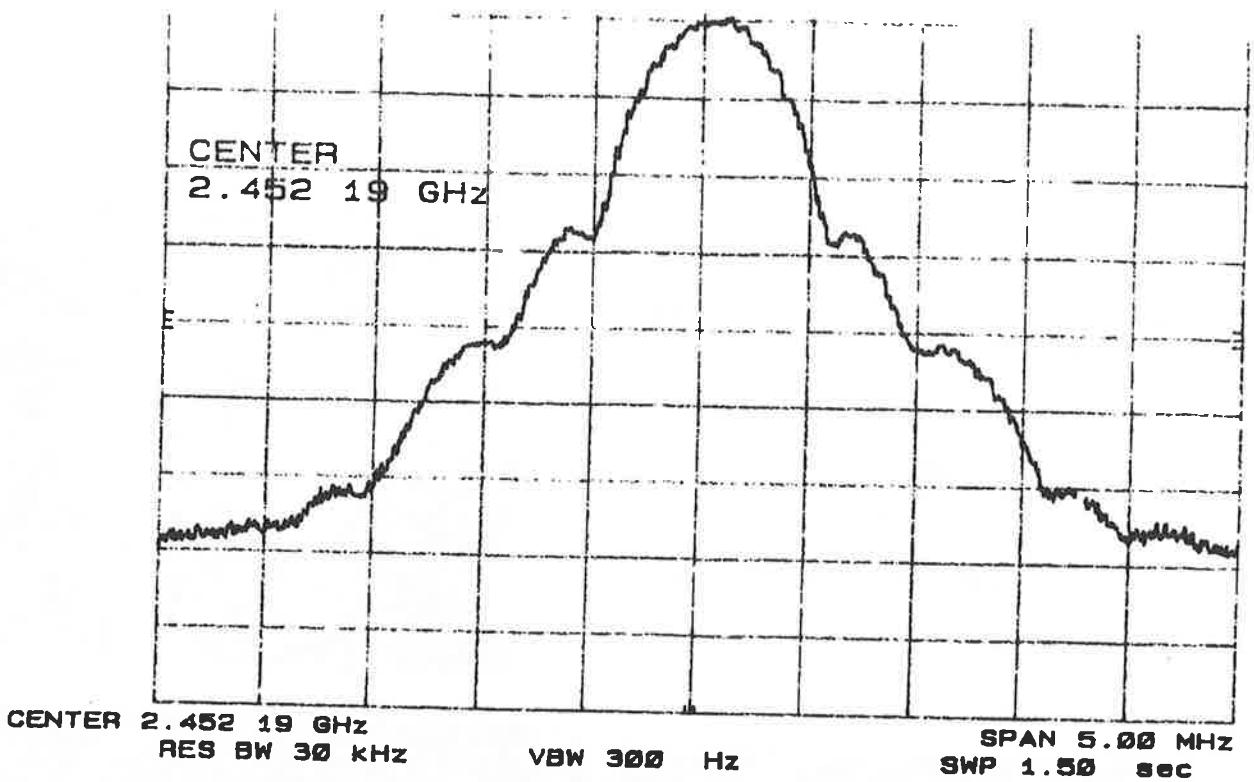


Fig.6 2.4 GHz experiments on Teledyne's TFE-1050 900MHz to 2.4GHz transceiver and TAE-1010 RF amplifier chip. At 915MHz and 2.452GHz we used fully saturated amplifiers (+28dBm power) with FQPSK-1 - DSP chips (see transmit and demodulated eye diagrams) at f_b = 1Mb/s. IEEE 802.11 requirements with DQPSK a 4dB output-backoff to 6dB is required.



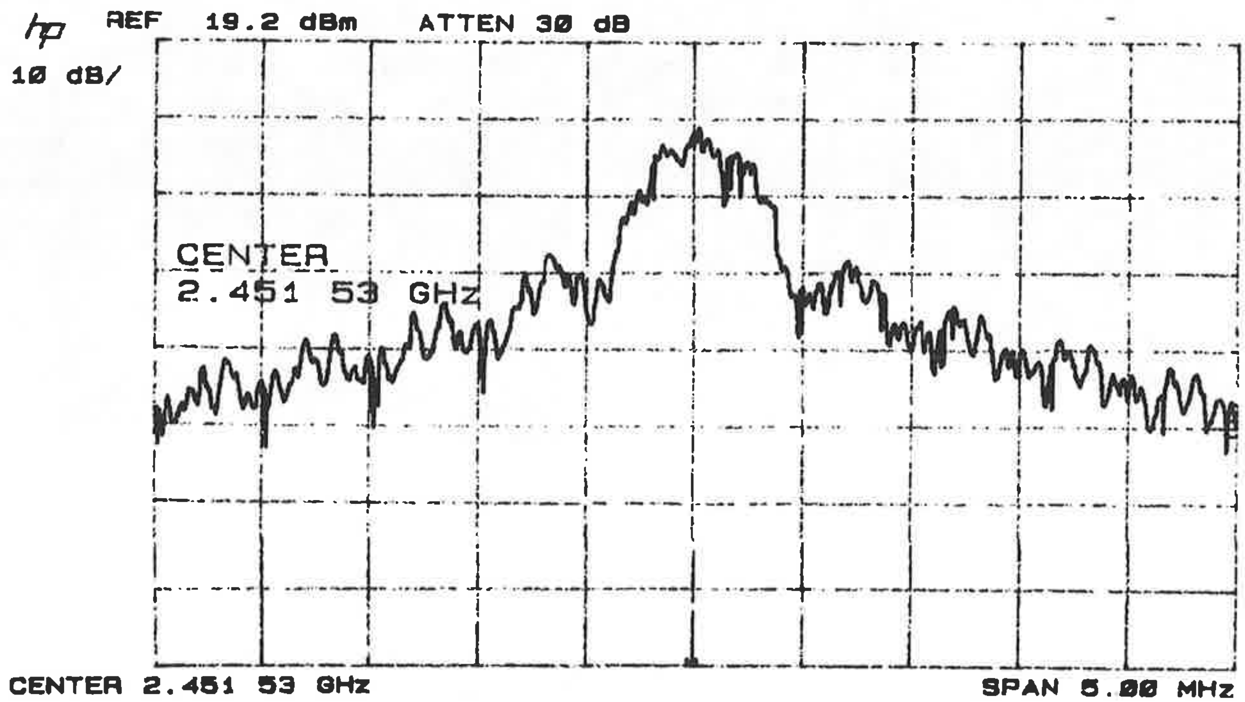


Fig. 7 GaAs 2.4GHz MMIC - TELEDYNE TAE-1010A
Newest RF amplifier chip and TAE-TFE transceiver FQPSK and DQPSK modulated spectrum measurement result. The FQPSK spectrum 28.5dBm with 5V) meets the requirements while the linearly (24.3dBm output DQPSK spectral spreading does not meet standard specifications.

TAE-1010A TELEDYNE GaAs MMIC

Experimental data with FQPSK and DQPSK

Measured at Teledyne, Mountain View, California; February 28-March 1, 1994; Ref. [33, Creviston, TELEDYNE and UC Davis]

Modems: DSP XC-4003 Xilinx for FQPSK-1
Conventional analog for DQPSK bit rates 1Mb/s for both cases

With 5V dc power (battery)	Maximum RF output power
FQPSK saturated (NLA)	28.5dBm maximum
DQPSK linearly amplified	26.5dBm maximum
FQPSK output power advantage	2dB

With 3V dc power (battery)	Maximum RF output power
FQPSK saturated (NLA)	24dBm maximum
DQPSK linearly amplified	21dBm maximum
FQPSK output power advantage	3dB

In experiments, DQPSK power gradually increased until spectral spreading increased specifications limits (both DS-SS and FH-SS) evaluated

Add temperature gain variation coefficient 3dB and change in AM/AM and AM/PM

Net FQPSK power output advantage 5dB to 6dB

* DQPSK and π/4-DQPSK technology limited power!
* Increased peak radiation of π/4-DQPSK over FQPSK also about 6dB to 8dB, not desired for "health/environmental hazard."
* Standard 1Mb/s-GFSK and PHY rejected some time ago; nonconstant envelope, e.g., π/4-DQPSK. A good decision.

Table 4 Comments and compliance with essential requirements of IEEE 802.11 higher data rate frequency hopping spread spectrum PHY standard "template" reference: (N. Silberman, Editor, IEEE P.802.11.93/210A, January 10, 1994, Ref. No. [39]). Comparison of FQPSK, π/4-DQPSK and 4-FSK proposed standards

Code: (✓) meets requirements (✓✓) exceeds requirements

Essential Requirements per Adopted Specifications [1]	FQPSK	π/4-DQPSK	4-FSK	Reference Template Specific Number and Comments
1 Compliance with regulatory agencies	✓	?	?	Specification No. 6 and No. 11 in template; peak radiation of π/4-DQPSK for 0.25W to 1Watt range; exceeds regulatory limits (?) π/4-DQPSK spectral regrowth marginal compliance; is 4FSK at proposed 2Mb/s marginal or does it meet 20dB FCC limit?
2 Compliance with 802.11 PAR (data rate at least 1Mb/s)	✓✓	✓?	✓?	Specification No. 14 FQPSK architecture; forward compatibility up to 4.2 MB/S minimizes danger of obsolescence including adaptive equalization. 4-FSK prevents use of new technologies; leads to obsolescence π/4-DQPSK not suitable for bit rates higher than 1.5Mb/s
3 Minimum area coverage	✓	?	? ?	Spec No. 27 for 99.5% coverage or channel availability. With maximum 100mW - π/4-DQPSK operated in a 1Watt IEEE 802.11-GFSK-1Mb/s environment and 1Watt DS-SS -10dB loss and 4-FSK 10dB less robust to interference than FQPSK the channel availability criteria would not be met with these less robust (4-FM and π/4-DQPSK) systems.
4 Suitable for low power consumption implementations	✓	No	No	Spec No. 4(a) and No. 6 for π/4-DQPSK having a nonconstant envelope peak/rms factor of 6dB to 8dB No suitable amplifiers exist which could meet the USA-FCC up to 1Watt permitted transmit power and radiation? Other IEEE standard and nonstandard systems operate in the same band with 1Watt power. Lower power, e.g., 100mW systems (π/4-DQPSK) could be wiped out or "killed" by the stronger 1Watt transmitters. Four-level very narrow eye diagrams of 4-FM require expensive A/D devices and were rejected by overall PHY.
5 Cost effective	✓	No	No	Spec No. 4(a) In the foreseeable future there are no 1Watt linear (RF power) amplifiers for π/4-DQPSK for PCMCIA cards. Many committees most recently rejected any non-constant envelope systems, including the IEEE 802.11 GFSK, FH-SS and DS-SS for higher power specificaitons. All major corporations for the JTC-TIA 1.9GHz PCS standard propose constant envelope nonlinearly amplified (NLA) binary systems. 4-FM-A/D expensive (see Item 4) and was rejected by PHY.

Table 4 (continued)

Essential Requirements per Adopted Specifications [1]	FQPSK	π/4-DQPSK	4-FSK	Reference Template Specific Number and Comments
6 Support a number of stations per cell	✓	No	No	Spec No. 6-FCC In a strong externally caused interference environment (FCC-15 2.4GHz band) a low power, e.g., 100mW π/4-DQPSK transmitter will support only a small number of stations. The 4-FSK system would crash due to its 10dB inferior performance in a C/I environment.
7 Suitable for small size implementation	✓	No	✓	Spec No. 4(a) and No. 6 There are no suitable PCMCIA small size linear amplifiers (not even on design boards or R&D) which could cover up to 4Watt peak for 1Watt RF power. Thus a fundamental specificaton (USA markets) could not be met with π/4-DQPSK high peak factors.
8 Robust operation in narrow band and partial band interference as well as multipath fading	✓	No	No	Spec No. 26 and 27 π/4-DQPSK does not have enough transmit power to survive in the strong 1Watt-caused interference environment. 4-FSK is about 10dB worse (less robust) than FQPSK, thus would correspond to a $BER=10^{-1}$ instead of $BER = 10^{-7}$ (illustrative no.) 4FM is extremely sensitive to multipath-caused delay spread. No known adaptive equalization for non-coherent 4-FM exists to meet specifications.
9 Ensure interoperability between conformant 802.11 stations CCA problems?	✓	?	No	Spec No. 15(a) The Clear Channel Assessment (CCA) between 1.4Mb/s FQPSK and 1Mb/s GFSK standard has been solved, see Ref [34]. For π/4-DQPSK, CCA solution not known. For 4-FM the four-level eye diagram is a problem for 2-level GFSK receivers. Per PHY committee decision of July 13, 1993, 2-level is essential.
10 Graceful degradation under load and interference	✓	No	No	Spec No. 26 and 7 The proposed 4-FM noncoherent systems crash, i.e., have a $BER=10^{-2}$ at the specified $E_b/N_o=19dB$. FQPSK has for same interference $BER \leq 10^{-6}$. 4-FM crashes for multipath-caused delay spread and ISI. FQPSK is the most robust π/4-DQPSK due to its 6dB or so lower transmit power (technology and FCC? limit) crashes 6dB earlier than FQPSK.

Table 4 (continued)

Other Essential Criteria Proposed to be Added to "Requirements" of Ref. [39] Standards				
Essential Requirements per Adopted Specifications [1]	FQPSK	π/4-DQPSK	4-FSK	Reference Template Specific Number and Comments
11 Forward compatibility to permit new emerging technologies	✓	No	No	The expandable/flexible well-known generic OQPSK and compatible FQPSK architecture which has numerous IC chips enables the introduction of new higher bit rate technologies including 16-OQAM to 64-OQAM, a standardized product migration strategy to up to 4.2Mb/s. The π/4-DQPSK structure was never used in 16-QAM and is limited to about 1.6Mb/s. 4-FM excludes bit rate increase and due to noncoherent receivers adaptive equalization not practical. 4-FM is an obsolete technology which does not lead to new developments. In Motorola's submission [J. McDonald _____ July 1993] excellent reasons were listed why we should avoid 4-FSK even at 1Mb/s. The situation is even worse for 2Mb/s FSK.
12 Compatibility with related applications, e.g., JTC-TIA standards at 1.9GHz	✓	✓	No	Major corporations including AT&T, Alcatel, Ericsson, Siemens, NTT proposed constant envelope GMSK (FQPSK compatible solutions). Due to power inefficiency π/4-DQPSK was rejected by them. 4-FM is not robust; did not come even close to meeting most specifications.
13 Linearized amplifiers enable increased bit rates	✓	No	No	
14 Backward compatibility with FH-SS - 1Mb/s GFSK standard	✓	No	No	
15 IC chips trend available components VLSI, Trend	✓	No	No	Several large corporations as well as smaller organizations have tested VLSI chips suitable for FQPSK and equivalent OQPSK. These include TRW, Unysis, NTT and Teledyne. There are no chips/components which could meet the specifications with π/4-DQPSK and 4-FM. (See list in paper.)
16 Higher bit rates limit (max) with proposed technology	✓✓ 4.2Mb/s	✓ 1.6Mb/s	✓ 2Mb/s	
17 Faster throughput/ reduced message delay in interference environment	✓✓	?	??	
18 Maximal bit rate including future extensions	4.2Mb/s	1.5Mb/s	2Mb/s	

Item No.*	Parameter	Specification	FQPSK	π/4-DQPSK	4-FM	Comments
4a	Transmitted power levels	1000mW - max	1000mW	150mW	1000mW	Technology/size/power/cost limit of π/4-DQPSK to 150mW
6	Maximum radiated EIRP	FCC 15.247 USA ETS 300-328 Europe TBD Japan	✓	8dB peak disadvantage	✓	Peak radiation of π/4-DQPSK ? Regulation limits?
7	Receiver minimum input level sensitivity	-80dBm @10^{-5}BER	✓	✓	8dB problem no	4-FM has an 8dB higher C/N requirement than FQPSK and π/4-DQPSK. Requires an 8dB lower noise figure to meet specs. Could be very expensive.
10	Occupied bandwidth @20dB	±500kHz	✓	?	?	π/4-DQPSK marginal due to nonlinearity of amplifiers or mixers/modulators. 4-FM extremely sensitive to modulation index.
13	Modulation		FQPSK	π/4-DQPSK	4-FM	
14	Channel data rate and increments		1.4Mb/s 2.8Mb/s 4.2Mb/s	1.5Mb/s	2Mb/s	FQPSK could handle 1Mb/s, 1.5Mb/s, 2Mb/s, 3Mb/s and 4Mb/s. Best performance for indicated rates.
26	BER at specified E_b/N_o (Gaussian model assumed)	10^{-5}@E_b/N_o= 19dB	E_b/N_o = 15dB	15dB	23dB	4-FM does not meet specs.
26a*	BER with 150ns delay spread E_b/N_o requir.	10^{-2}@E_b/N_o= 21dB	15dB	17dB	50dB?	4-FM does not meet specs; extremely sensitive
27	Channel availability	99.5%	99.5% ✓	90% No	90% No	π/4-DQPSK lower availability due to low Tx power (1dB). 4-FM lower availability due to 10dB higher C/N required.

* Item number in Reference [39]

Table 5 Specifications and Critical Parameters [Ref. 39, Editor Silberman]

March 1994 Doc: IEEE P.802.11-94/51

	Standardized	Proposed Higher Speed			
	GFSK	FQPSK-1	FQPSK-KF	FQPSK 4*4	FQPSK 8*8
Maximum bit rate in 1 MHz	1 Mb/s	1.0 Mb/s	1.5 Mb/s	2.8 Mb/s+	4.2 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

	GFSK	FQPSK	QPSK	4-FM
Bit rate in 1MHz (-20dB)	1.0MB/s	1.6Mb/s	1.6Mb/s	2Mb/s
RF power@ 2.4GHz (max)	1 Watt (NLA)	1 Watt (NLA)	150 mW (Linear)	1 Watt (NLA)
Required C/I for BER = 10^{-2} Rayleigh	20dB	16dB	16dB	23dB
Increase in peak radiation	0dB	0dB	5dB to 10dB	0dB
Capacity (relative to GFSK)	100	300	300	50?

Table 6 BER = f(C/I) in Rayleigh fading and BER = f(E_b/N_o) in AWGN (stationary) for GFSK, FQPSK and 4-FM constant envelope NLA systems. The π/4-DQPSK BER performance is similar to that of FQPSK, however it requires linear amplifiers.

	Efficiency	**RF Out**
FQPSK saturated (NLA)	19.8%	+24dBm
DQPSK linear	8.6%	+21dBm

Table 7 GaAs MMIC - 2.4GHz power efficiency; newest generation of power amplifiers (Teledyne TAE-1010a) measurement result with 3V dc battery power. Amplifier measured at Teledyne during March 1994 to meet IEEE 802.11 spectrum mask. Details in Ref. [33] joint Teledyne/UCDavis paper.

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