IEEE 802.11
Wireless Access Methods and Physical Layer Specifications

Proposal for a modulation technique for Frequency Hopping Spread Spectrum PHY Standard

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Introduction

This document represents an augmented submission to a previous proposal [5] for the modulation technique for the IEEE 802.11 Frequency Hopping PHY standard.

Proposal:

1. **Adopt 4 level CPFSK as the technique of choice for the frequency hopping PHY.**

2. **Select the baseband shaping separately in order to optimize for the agreed channel model impairments and also correct for known implementation imperfections. In addition to normal baseband shaping I also included in this category duobinary modulations, partial response modulations and / or limited Trellis coding.**

In the following there is supporting material for the submission.

Criteria for the selection of the modulation technique:

The following is a collection of criteria suggested in the PHY group meeting at the March 1993 IEEE 802 plenary meeting in Baltimore, MD. Though some of these criteria were not clearly defined nor fully agreed at the above mentioned meeting I will try to respond within reasonable assumptions. At this time no benchmark environments had been defined. Explanations to these criteria are in italic letters.

1. Compatibility with 802.11 PAR
   It means to us 1 Mbps nominal data rate.
2. Technical feasibility
3. Economic feasibility
4. Suitable for portable applications
   power consumption, size, power down/ sleep modes
5. Flexibility for technological growth
6. Compatibility with ISM environment

ISM environment is characterized by interference; there are several types of interference to be considered: similar networks (overlapping networks), dissimilar networks (using other SS transmission techniques), other users in the band, narrow band signals (such as microwave ovens), partial band such as other part 15 xxx users, other ISM devices and Amateur radio.

7. Ability to coexist with opposite PHY
   It should be covered under 6 above
8. Meets regulatory technical requirements
   Meets the in-band and out-of-band spectral requirements demanded by various agencies in different countries (e.g. FCC requires 20 dB bandwidth at channel edges, 1 MHz).
9. Minimum data rate
   Per 802.11 PAR is 1 Mbps included in 1. above. This is does not preclude fall-back data rates.
10. Bandwidth efficiency (at maximum data rate).
11. Impact on radio
    The modulation should not preclude low cost implementations while it is highly desirable to allow for improved performance implementations (which might be more expensive).
12. Impact on throughput (ACI)
13. Operation with overlapping networks
    These are similar networks utilizing a different hopping sequence. These networks create a certain degree of interference.
14. Robustness of transmission technique
    Operation in interference, multipath propagation and other channel impairments. Recommend to provide quantification such as : Probability of Acquisition, tracking, MSDU loss rate
15. BER vs. Eb/No in benchmark environment
    Benchmark environment not defined yet.
16. Lending itself for error correction codulation
17. Ability to operate in a Frequency hopping environment
    Frequency Hopping is characterized by discontinuity at hop time. The length of time for this discontinuity is determined by the hardware time to complete the frequency change and have the radio parts ready for operation. This is a reason why coherent modulations are less suitable for FH without increased hardware complexity
18. Ability to acquire vs. S/I
    a. in environments of its own
    b. in environments of opposite PHY
    c. in presence of ISM interference
19. BER vs. S/I
    a. in environments of its own
    b. in presence of opposite PHY
    c. in presence of ISM interference
20. Impulse noise response

Characteristics of 4CPFSK

Continuous phase FSK modulation is a sub-class of constant envelope "digital FM" signals with continuous phase functions. Phase continuity provides a more "compact" spectrum and also offers the opportunity to take advantage of phase trellis for higher performance receivers. It is suitable to digital ASIC implementation and to baseband digital shaping. CPFSK is a family of modulations which among others includes the MSK modulations. MSK modulation is defined as a full response CPFSK with a fixed deviation ratio of 0.5 (2 fdT = 0.5 fd = frequency deviation, T= bit rate).

Four level **CPFSK** has the following advantages:

- Provides a **compact spectrum** meeting the FCC 20 dB bandwidth requirements with margin. Per Lourens' Van Der Jagt simulation it occupies only 750 Khz at 1 Mbps. This matches both the theory and the practical experience. See attached measured spectrum of California Microwave's implementation.
- **Provides good bandwidth efficiency.** Bandwidth efficiency is defined as the ratio between the available bandwidth and bit rate.

$$(\frac{Rs}{W} = \frac{\log_2 M/T}{M/T})$$

Rs= symbol rate
Rb= bit rate
The units are cycles /bit
For M-ary modulations , $R_b = (\log_2 M) R_s$, where M represents the number of modulation levels. Based on theory, Rs/W for 4CPFSK is 1 which is the same as for **2CPFSK**. Therefore **4CPFSK** occupies the same bandwidth as **2CPFSK** . In order to compensate for the spectrum expansion associated with higher levels of FSK modulations, the deviation ratio is reduced accordingly. Based on maximum Euclidean distance (i.e. minimum BER) between signal vectors **4CPFSK** optimal deviation ratio is approximately 0.3. This in turn means more bits / Hz. Based on an existing implementation a 1 Mbps data rate can be obtained in approximately 800 Khz bandwidth.

- **Provides improved Eb/No .** An increase in M reduces the energy requirements. The improvements shown in literature indicate approximately 3 dB difference between **2CPFSK** and **4CPFSK** while maintaining the same bandwidth efficiency (in practice this number is closer to 2.5 dB).

- Resistance to Fading
- Resistance to Interference
- No sensitivity to Phase impairments:
  - Signal phase glitches
  - Signal Phase flips (propagation impairment)
- **Constant Envelope**

Constant envelope schemes have the advantage of simplicity in the transmitter and in the front end stages of the receiver in that these stages don't have to be linear. The use of class C amplifiers would be a definite advantage for small scale implementations which have limitations in power consumption and power dissipation. The use of limiters in the demodulator has definite advantages as compared with. AGC linear amplifiers required for other modulations. Furthermore, in a packetized environment fast AGC is required (power consumption, complexity !)

- **Robustness to propagation impairments:**
  - Mulitpath fading
  Studies indicate that 4CPFSK modulations are well behaved in a fading environment.
  - Delay Spread
  Four level CPFSK provides better delay spread performance than DQPSK and DPSK and with similar performance to BPSK.
- **E_b/N_0 performance**: Theoretical is between 9.8 to 10.7 dB for 10^{-5} BER, practical is less than 13.7 dB with 3 dB allocated for implementation imperfections.

Other modulations characteristics:

Phase Modulations: Among the numerous modulations in this family I elected to refer to the most popular ones: PSK, DPSK, QPSK,OQPSk (or $\pi/4$ QPSK). While they seem to have definite advantages in Gaussian or well defined channels (such as point to point microwave links) not subjected to the kind of impairments in existence in our environment: multipath fading , delay spread, interference (narrow band, partial band, and wide band), they perform poorly in the described environment, mainly because of sensitivity to phase glitches existent in the equipment and phase flips due to propagation. When these occur, these modulations may loose synchronization and need to reaquire. Robustness in time varying channels (Phase and amplitude) and in portable applications are questionable. Phase modulations don't have constant envelope and are sensitive to amplitude variations. Theoretically, Phase modulations have good bandwidth efficiency, but as can be seen in the literature [4] the occupied bandwidth is fairly wide and they will have difficulty in meeting the FCC spectrum bandwidth requirements in 1 MHz channels.
For example, it was shown in the literature [3] that MSK has lower sidelobes than QPSK and OQPSK in a prescribed bandwidth; Since MSKs sidelobes do not meet FCC requirements for the allocated channel neither will QPSK. Phase modulations require linear amplifiers at the transmitter and in the receiver plus AGC control. All these in addition to fast AGC required in a Frequency Hopping packetized data environment does not lend itself to low cost low power implementations.

QAM: is the result of the linear addition of two quadrature DSB-SC signals and has all the characteristics of an AM modulation. Therefore it requires linear amplifiers and fast AGC like the phase modulations. It has the same BER performance as QPSK. It has very poor performance in an interference controlled environment. In order to

achieve bandwidth efficiency, multilevel QAM has to be used. It's theoretical bandwidth efficiency is 2 bps/Hz. QAM implementation is fairly complex and expensive. It is sensitive to phase stability to impairments and to crosstalk between quadrature channels.

0.39 GMSK: is an MSK modulation with 0.39 Gaussian baseband shaping. This modulation has lower sidelobes than straight MSK at the expense of increased Inter Symbol Interference and higher E_b/N_0 requirements. With a discriminator implementation in the receiver GMSK has similar performance to non coherent FSK discriminator implementation. The main concerns with this modulation are its ability to meet the FCC bandwidth requirements . It shows a theoretical occupied bandwidth of 1065 Khz [6], and there are unanswered concerns about its sensitivity to interference and delay spread due to its already high ISI. It is popular in telephony radio systems (e.g. GSM) and in the European DECT system, which operate in dedicated licensed channels unlike the "open for all" ISM bands.

Degradations due to implementation imperfections in various modulations

The following is a list of additional implementation imperfections whose effect on the performance of various modulations should be considered. Most of them have a greater impact on phase modulations:

1. Phase and amplitude imbalance in BPSK, QPSK, QAM.
2. Imperfect or noisy reference at a coherent demodulator.
3. Power loss due to filtering of the modulated signal.
4. Degradation due to non ideal detection filter.
5. Degradation due to predetection filtering.
6. Degradation due to bit synchronization timing errors.
7. Local oscillator phase noise and spurious.
8. Envelope amplitude variations.
9. Stability and slope of Quadrature circuits in discriminator detectors.

The following table summarizes some of the most popular modulations characteristics. In places where there was not enough information or the information is questionable I placed a question mark.

Parameter	4CPFSK	2CPFSK	MSK	0.39 GMSK	xPSK	xQPSK	4 QAM
Sensitivity to Envelope variations	no / limiter used	no; limiter used	no; limiter used	no; limiter used	yes / linear amplifier required	linear amplifier required	linear amplifier required
Sensitivity to Phase Impairments	no	no	yes	?	phase flips phase glitches osc. phase noise	phase flips phase glitches osc. phase noise	-phase flips -phase glitches osc. phase noise
Interference performance	A-	A	B	B-	C	C	C
Suitability to Frequency Hopping	A	A	B	A	?	?	?
Demodulation	non coherent	non coherent	non coherent	non coherent	coherent preferred differential possible/ not suitable	coherent preferred differential possible/ not suitable	coherent preferred differential ?
ISI / Delay spread sensitivity	A	B	B	B	C	C	C
Robustness to Cochannel Interference	Excellent	Excellent	Excellent	Good	Good	Good	Poor
Digital ASIC Implementation (low power, low cost)	Excellent	Excellent	Possible	Excellent	?	?	?
E_b/N_o @ 10^{-5} BER ???	9.8 dB coherent 10.7 dB non coh	12.5 coherent 13.3 dB non coherent	10.4 dB 11.4 dB differential	16 dB discrimnator	10.4 BPSK 11.6 DPSK	10.9 QPSK 11.6 DQPSK	10.5 dB
BW efficiency bps /Hz	1	1	1.9	~0.75	0.8 0.8	1.9 QPSK 1.8 DQPSK	1.7
20 dB BW	750 Khz	1.4 MHz @ 0.7 deviation	~1.2 MHz	~1.1 MHz	> 1 MHz ?	8 / Tb?	>1 MHz ?
E_b/N_o @ CW Interference	TBD	TBD	TBD	TBD	TBD	TBD	TBD

Conclusions:

Based on both theoretical and practical results **4CPFSK** offers an optimal trade-off solution for wireless networks in the ISM band utilizing Slow frequency Hopping. It provides the spectral and error performance and the robustness required for a SFH PHY in the ISM environment. Based on reference [7], it also offers the opportunity for optimized performance through baseband shaping, which can outperform BPSK, QPSK types of modulations performance.

At least one existing implementation, uses this type of modulation with multiple bits baseband shaping and digital implementation of the modulator and demodulator (demonstrates the performance (robustness, spectral efficiency) the physical and economic

feasibility of the proposed technique. With additional baseband shaping and or partial response the performance can be further enhanced.

References:

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