IEEE P802.11
Wireless Access Method and Physical Layer Specification

Comparison between 3-channel FDMA and CDMA Direct Sequence Spread Spectrum System.

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INTRODUCTION

This contribution deals with a comparison between 2 Direct Sequence Spread Spectrum Systems that can be defined for the 2.4 GHz ISM band.
In the 80 MHz broad band different DSSS systems can be defined within the FCC part 15 rules. For this comparison we choose a 3-channel Frequency Division Multiple Access system and a 3-channel Code Division Multiple Access system. The systems have the same modulation schemes having the same raw bitrate of 2 Mbits/s per channel and thus the same Baud rate. Also the occupied bandwidth of both systems is equal. The comparison is done on expected system throughput (medium reuse, performance) and also on complexity.

ISSUE ADDRESSED

For channel separation in a DSSS system there exists no issue in the IEEE 802.11 Issues Document. Therefor an issue can be raised:
How is channel separation in a Direct Sequence SS system to be accomplished?

DESCRIPTION OF THE SYSTEMS

3-channel FDMA system

The characteristics of the 3-channel FDMA DSSS are as follows. The used modulation is DQPSK. To cope with the minimum required processing gain of 10 dB the well known 11 chip Barker sequence is applied as spreading sequence. This gives a chiprate of 11 MHz for a 1 MBaud (2Mbit/s) system. The occupied bandwidth of such a channel is about 22 MHz. In a 80 MHz wide band (at least) 3 in frequency separated channels can be defined.
The sidelobs of one channel are supposed to lay more than 55 dB below an other channel.
The characteristic of the barker sequence is such that the auto correlation has a peak of 11, while the 10 other values are +1 or -1 depending on even or odd autocorrelation. ($11, \pm 1^{10}$). For the comparison other characteristics of the FDMA system are not important.

3-channel CDMA system

To make a fair comparison the occupied bandwidth of the CDMA system should be the same as for the three FDMA channels together. So the length of the spreading sequence is about three times the 11 chip Barker. Optimal choice are 31 length m-sequences over GF[32]. In GF[32] there are six primitive polynomials, three of which are the reciprocal of the other three. A set of three codes are considered an optimal set because the even autocorrelation function of the m-sequence generated by these polynomials, $(31, -1^{30})$, is two valued and because of these 6 codes, a chosen set of three has a three-valued cross-correlation function(-1,7,-9). Any set of three codes which does not belong to this chosen set of sets will either have "worse" crosscorrelation functions or autocorrelaton functions.
Even (or periodic) means that there is no transition of the data. Half the time there is of course a transition and then the odd or a-periodic autocorrelation has more values in the sidelobs. Table 1 lists the values for the set we choose. This table also lists the even and odd crosscorrelation function values for the non-reciprocal primitive m-sequences.
The above described system defines a 31 MHz chiprate and the total bandwidth (about 62 MHz) is occupied by three overlaying channels separated by the code of there spreading sequence.

PERFORMANCE EVALUATION SET-UP

General

To compare the two systems it is interesting to evaluate how the medium reuse efficiency is effected by both FDMA and CDMA .Therefor a triangular cellular covering is assumed. Each cell is centred on the vertices of the equilateral triangles. Six such triangles form a hexagon - consequently the cells are centred on each vertex of the hexagon. See figure 1.

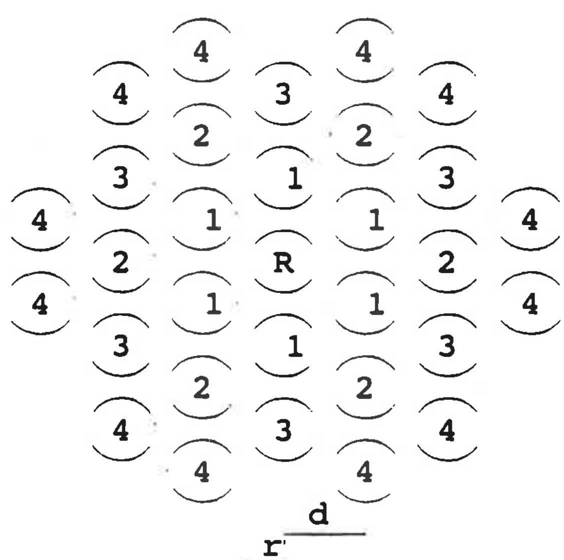

Figure 1. Cell topography; R is the reference cell

The coverage radius of a cell is *r*. The cell separation, *d*, is the length of the size of the hexagon. Note that *d* can be less than *r*. The reference cell is the cell at the centre, and we consider the effect of 30 cells around it: 6 at distance *d*, $\sqrt{3}d$, and 2*d* respectively, and 12 at distance $\sqrt{7}d$.
For calculation of interference levels the channels attenuation coefficient is 3.5 for distances over 10 meters and 2 within this distance. The SIR requirement is set to 10 dB.
Simulations were carried out to evaluate the medium reuse, which can be expressed as the effective number of channels per cell. Simulated is this number as function of the *normalised cell separation*, defined by *d/r*, that is the separation between the midpoints of the cells divided by the coverage radius of each cell.
The purpose is to study the performance of ***one*** cell , surrounded by a group of neighbouring cells which are behaving in a certain predefined manner. No protocol or sharing mechanisms are assumed. The aim is not to estimate throughput but to calculate the instantaneous capacity available to a single cell.
Two configurations have been evaluated: In the first transmitter and receiver are randomly placed in the cell, in the second a basestation (half the time as transmitter, half the time as receiver) is placed in the middle of the cell.
For each instant the spots of a transmitter and receiver are chosen in the centre cell(randomly if not a basestation). In each surrounding cell the spot of a transmitter is chosen. The activity of such a transmitter is dependent of the offered load, a parameter for the simulation. In the centre cell two events may happen:
1. The transmitter in the centre cell has to defer. The level of the signal from each active transmitter at the receiver in the centre cell is calculated. All crosscorrelation functions between the spreading sequence of the centre receiver and the transmitting stations (if applicable) are summed (note that the phases of these correlation functions are subject to a probability function, see below). If a peak of the summed crosscorrelation function (in any instant) comes, compared to the autocorrelation peak, above the *defer threshold*, which is a parameter of the simulation, the centre cell transmitter is supposed to defer.
2. The SIR of the centre cell receiver is worse than 10 dB. In the same way the crosscorrelation functions are added. If the ratio of the peak of the autocorrelation function and the value of the summed crosscorrelation function at that instant is worse than 10 dB there is no correct reception.
So in these two cases reception fails, while in all other cases there is a good transmission.

3-Channel FDMA

Each neighbouring system (interferer) is assigned one of the three channels. Interferers on other channels then the one used by the centre cell are disregarded. If an interferer on the same channel is transmitting, then the interference level is 11 with probability 1/11, and 1 with probability 10/11. The autocorrelati on peak of the received sequence at the centre receiver is assumed 70% of the best actual peak due to timing mismatches (other values :50%,100% have also been used; the effect on the comparing results was negligible) .

3-Channel CDMA

Neighbouring system are assigned one of three codes. If an interferer is using a code different from that being used by the centre cell, then the probability of the interference level is dependent on the even or odd (each half the time)crosscorrelation function: e.g. for even CCF[0,1] (see table 1) the level is 1 with probability 15/31, 7 with probability 10/31 and 9 with probability 6/31.
If a interferer is using the same code then half the time (for the periodic correlation) the interference level is 31 with probability 1/31 and 1 with probability 30/31. The other half of the time the probability of the interference level is deduced from the odd autocorrelation function (again see table 1).
Also here the autocorrelation peak is assumed 70% of the best actual peak.

Amplitude →	-1	3	-5	7	-9	11	-13	31
Even ACF[0]	30							1
Even ACF[1]	30							1
Even ACF[2]	30							1
Odd ACF [0]	12	4	6	6	2			1
Odd ACF [1]	12	6	6	6				1
Odd ACF [2]	16	2	6	4	2			1
Even CCF [0,1]	15				10	6		
Even CCF [0,2]	15				10	6		
Even CCF [1,4]	15				10	6		
Odd CCF [0,1]	7	6	5	6	7			
Odd CCF [0,2]	8	7	5	5	3	2	1	
Odd CCF[1,2]	9	7	5	6	4			

TABEL 1 Correlation Function Values for One Maximal Connected Set of Preferred *m* -sequences over GF[32]:

Polynomial[0]: $1+x^2+x^5$
Polynomial[1]: $1+x^2+x^3+x^4+x^5$
Polynomial[2]: $1+x+x^2+x^4+x^5$

SIMULATION RESULTS

Simulation were run for the different parameters described above: defer threshold, offered load, coverage radius, base station or random placement.
The results are presented in figures where the Effective Number of Channels per Cell (also referred to as cell capacity) is a function of the normalised cell separation *d/r*. In each figure the parameter is defer threshold.

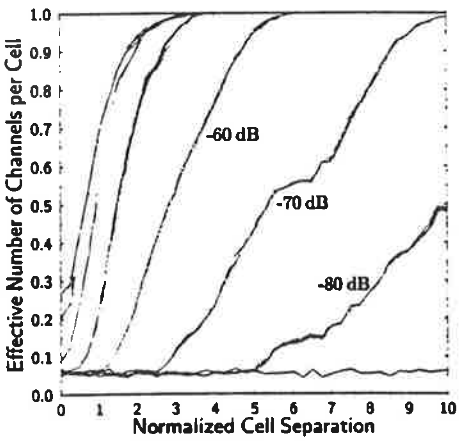

Figure 2a: FDMA , Random station config.
r =20m, offered load 25%

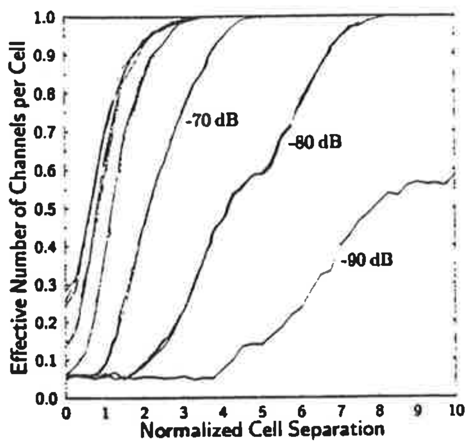

Figure 2b: FDMA Random station config.
r =50m, offered load 25%

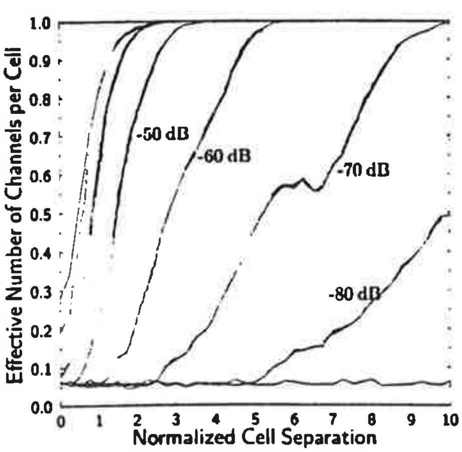

Figure 2c: FDMA , Base station config.
r =20m, offered load 25%

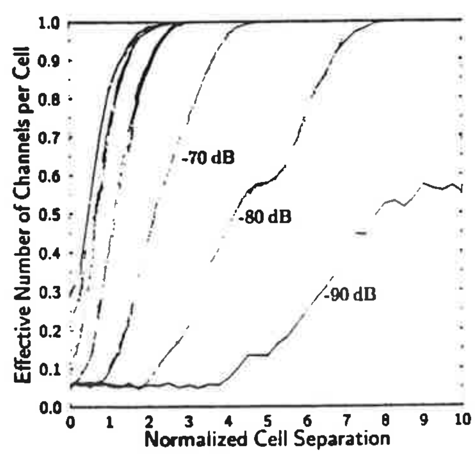

Figure 2d: FDMA, Base station config.
r =50m, offered load 25%

Figure 2 shows results for FDMA at a offered load of 25%. In figure 1a e.g. can be seen that at a high defer threshold when the cell are fully overlapping at d/r=*0* the capacity is 25%, while, when the cells are touching each other *(d/r=2)* the capacity is 90%. These figures improve for a higher coverage radius (fig 1b) or for a base station configuration (fig 1c and 1d).

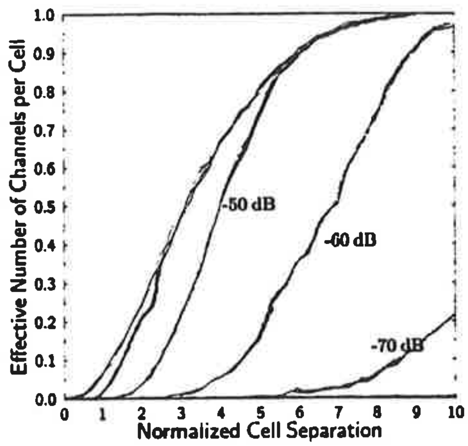

Figure 3a: CDMA , Random station config.
r =20m, offered load 25%

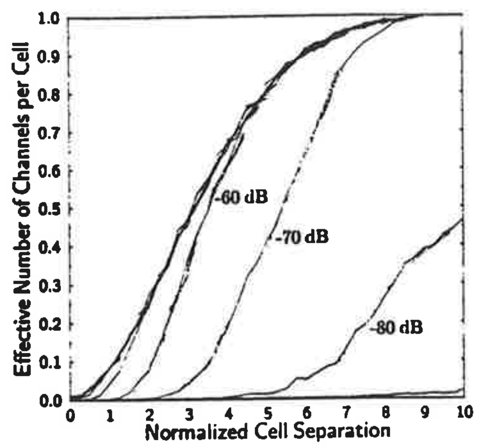

Figure 3b: CDMA Random station config.
r =50m, offered load 25%

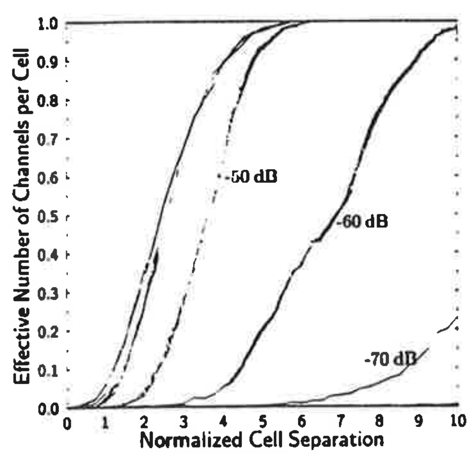

Figure 3c: CDMA , Base station config.
r =20m, offered load 25%

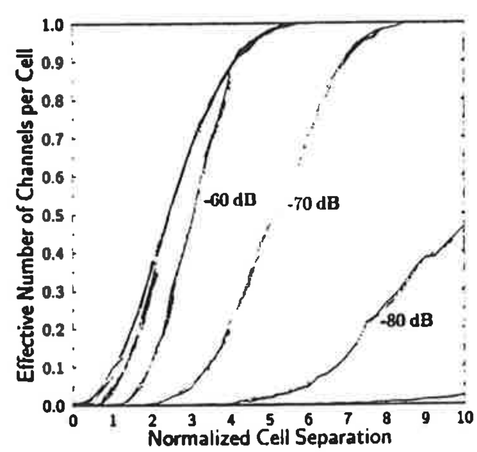

Figure 3d: CDMA, Base station config.
r =50m, offered load 25%

Figure 3 shows the same for 3-code CDMA. For the different parameters the same improvements can be seen, but this CDMA system behaves worse then FDMA. At touching cells *(d/r=2)* at high defer thresholds for example the capacity is only about 20% against the more then 90% in the FDMA case.

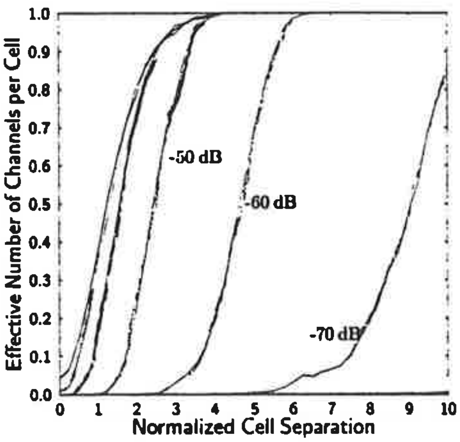

Figure 4: FDMA , Random station config.
r =20m, offered load 75%

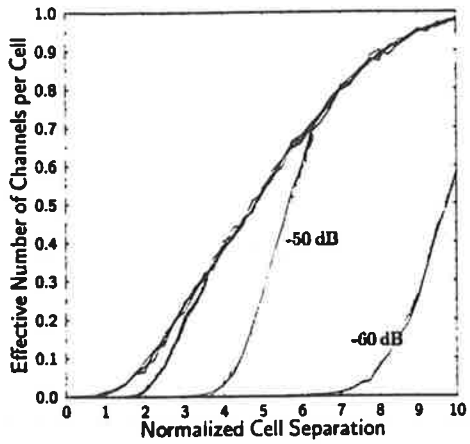

Figure 5: CDMA, Random station config.
r =20m, offered load 75%

At higher offered loads (fig 4 for FDMA and fig 5 for CDMA) the relative difference between the systems is not getting better.

From the figures: the 3-channel FDMA system offers a higher channel capacity in general. The actual throughput of any system is based on a number of other factors, such as the protocol being used, the defer threshold which is considered optimal, and the effective cell separation (walls, floors, attenuation coefficient). However the simulation approach is good for a comparison between the systems.

The better performance of the FDMA system is the result of the following characteristics:
- The separation between the 3 channels: the performance of the centre cell is only effected by a third of the other cells. Because of the high (odd or even) crosscorrelation in the CDMA system channel separation is much worse.
- The effect of transmission of other cells on the same cannel seems also to be less with FDMA : autocorrelation of the Barker sequence is 2-valued (11,1); The odd and even autocorrelation have the same effect! If there is no distortion (which spreads out the autocorrelation peak) then only 1/11 of the time the centre cell is effected. While the even autocorrelation function of the m-sequence CDMA code seems much better (31/1), which is the first reason why these codes are being studied, the odd autocorrelation is here destructive for channel separation. The sidelobs of the correlation with the neighbouring channel sum easily to corrupt the autocorrelation peak of the centre cell.

OTHER OR LARGER SET OF CODE SEQUENCES.

The maximum number of channels for the defined FDMA system is limited. However the number of code sequences can be enlarged. From the literature (reference 1) it is known that in order to expand our code set, it is necessary to suffer some degradation in either the autocorrelation or crosscorrelation function of the codes.

An example are Gold codes (reference 2). A set of 33 codes with length 31 (in general, N+2 length-N codes) with the same three-value even-crosscorrelation function of the set of preferred m-sequences, but with (on the average) larger autocorrelation sidelobs. Using average statistics of the code set simulations were carried out in a similar way as for the 3-code system.
The simulation show that the performance results do not differ much from the 3-code case. Based on this it is our believe that there might be a subsets of codes with a little better performance, but that they can not fill the gap that exists between the 3-channel FDMA and CDMA systems.

OTHER CRITERIA FOR SYSTEM COMPARISON

Interference robustness.

If there is a narrow band interferer somewhere in the band FDMA gives the possibility to react on that. If the system has provisions to detect and recognise such a interferer then there is the possibility to switch to one of the two other frequencies. Of course this requires a frequency management scheme. In the CDMA system, which occupies almost the whole band there are not such opportunities.

Multiple Baudrates.

When we want to use channels with different Baudrates, a FDMA system has that possibility by assigning the different frequencies a different rate. Channels with different rates will not effect each other. In a CDMA system it is much more difficult to have multiple Baudrates. The channels occupy the same frequency band an will effect each other. Thereby in a mixed Baudrate system other problems arise: detection/recognition of the rate.

Implementation/complexity.

The three times higher chiprate of the CDMA system makes it much more complex. Processing speed must be three times faster, but also the receiver correlators are three times longer. It is not clear how he resulting higher cost will pay back.

CONCLUSION

A 2 Mbit per second three channel FDMA Direct Sequence system with 11-chip Barker sequence has been compared with a 2 MBit per second 3-code CDMA system with codes with length 31. Simulations within a specific set-up show that the FDMA system is superior over the CDMA system. The differences are such that the conclusion is justified that this in general is true, as long as the systems use the same bandwidth.
Also on other criteria we think that the FDMA system under consideration is superior.
We recommend the commission to adopt for the DS Phy standard a system that is based on the in this contribution defined FDMA system.

REFERENCES

1. Dilip V. Sarwate, Bounds on Crosscorrelation and Autocorrelataion of Sequences, IEEE Transactions on Information Theory, Vol IT-25, N0. 6, November 1979.
2. R. Gold, Optimal Binary Sequences for Spread Spectrum Multiplexing, IEEE Transactions on Information Theory, October 1967.

PRESENTATION MATERIAL

Figures presented can be found in the document itself.

COMPARISON BETWEEN 3-CHANNEL FDMA AND CDMA DSSS SYSTEM

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* Issue addressed:

- How is channel separation in a DSSS to be accomplished?

* Comparison of two possible scenario's

- Frequency Division Multiple Access
- Code Division Multiple Access

* System Characteristics:

- 2.4 ISM band; 80 MHz wide
- 3 channels; each 2 Mbps

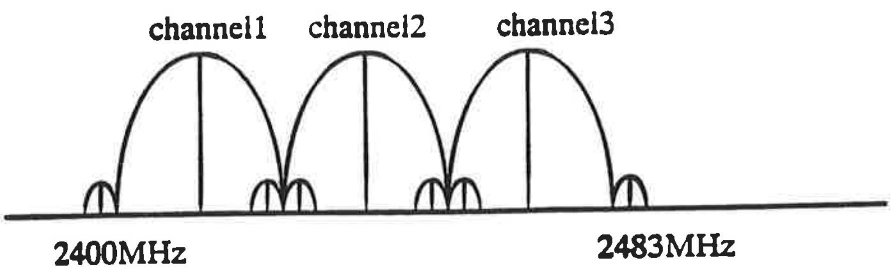
* Comparison criteria

- System Capacity, Performance
- Complexity

SYSTEM DESCRIPTIONS

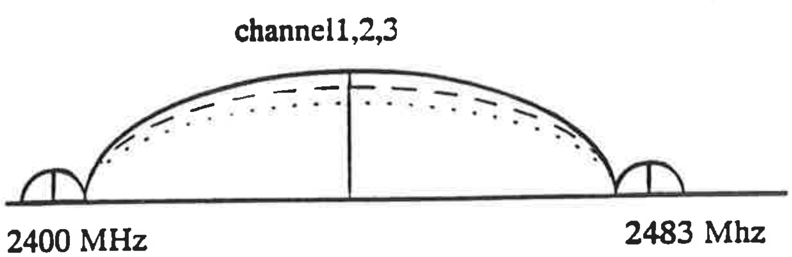
* 3-Channel FDMA

  - DQPSK
  - 11-chip Barker sequence
  - 1 MBaud symbol rate
  - 11 MHz chiprate
  - 2 Mbps
  - 3-channels: 3 frequency bands



* 3-Channel CDMA

  - DQPSK
  - 31-chip m-sequence
  - 1 MBaud symbol rate
  - 11 MHz chiprate
  - 2 Mbps
  - 3-channels: 1 frequency band, 3 spreading sequences



EVALUATION SETUP (CON'T)

* Interference of surrounding cells
  - Tx in center cell defers
  - SIR in center cell RX to high (worse then 10 dB)

* Parameters:
  - Defer threshold
  - Coverage radius r
  - Normalised cell separation d/r
  - Offered Load
  - station configuration in cell
    - random
    - base station in center

EVALUATION SETUP (CON'T)

* Interference calculation

* FDMA

  - Only autocorrelation of Barker sequence is of interest

  - Even and Odd autocorrelation is 2-valued:
    11 for the peak (at 1chipinstant)
    1 for the rest (at 10 chipinstants)

  - Interferer at **same** channel then interference level:
    11 with probability 1/11
    1 with probability 10/11

* CDMA

  - Interference levels based on odd and even autocorrelation and crosscorrelation.

Simulation results (con't)

* General result

  - 3-channel FDMA offers higher channel capacity:

    - separation between channels is better (no crosscorrelation)

    - interference level of cells in same channel is less:
      CDMA odd autocorrelation is high

OTHER CRITERIA

* Interference robustness

  - FDMA can make use of frequency managment

* Multiple Baudrates

  - Easily implementable with FDMA
  - More complex at CDMA

* Implementation / complexity

  - CDMA more complex:
    - Processing speed 3 times faster
    - correlator 3 time longer

CONCLUSION

Channel separation in a DSSS system is preferrably done by Frequency Division rather then Code Division.