IEEE P802.11
Wireless LANs
Compliance document for the 2.4 GHz CFO-SS PHY proposal

Date: March 9, 1998
Authors: H. Ishikawa and H. Shinonaga
KDD R&D Laboratories
2-1-15 Ohara, Kamifukuoka-shi,
Saitama, 356-8502, Japan
Phone: +81-492-78-7856
FAX: +81-492-78-7524
e-mail: ishikawa@lab.kdd.co.jp, shinonaga@lab.kdd.co.jp

1. Introduction

This document is submitted to clarify the compliance of the CFO-SS proposal in regard to Doc: IEEE P802.11-97/157r1, "Criteria for 2.4 GHz PHY Comparison of Modulation."

Features of the CFO-SS are shown below.

- The CFO-SS is an abbreviation of "Carrier Frequency Offset-Spread Spectrum", which is a kind of synchronous multi-carrier DS SSMA technique and utilizing a single PN (Barker) code commonly assigned to all the multiple carriers.
- Orthogonality among multiple carriers is achieved by specially selected carrier frequencies.
- The CFO-SS employs a receiver with surface acoustic wave (SAW) matched filters (alternatively, digital matched filters) to achieve rapid signal acquisition.
- Hardware is simple. A 10 Mbit/s CFO-SS transceiver basically consists of five units of the 2 Mbit/s 2.4 GHz wireless LAN transceiver.
- The CFO-SS is backward compatible with the current 2 Mbit/s 2.4 GHz PHYs. Furthermore, 1, 2, 4, 6, 8 and 10 Mbit/s rate can flexibly be set.
- One clock tracking circuit is only required, which is shared by the five units.
- The CFO-SS requires no special equalizing technique under typical multipath fading environments.

2. Overview

2.1 Principle of CFO-SS

The CFO-SS method employs the SAW matched filters to demodulate the SS signal. Figure 2.1 shows an example output signal of the SAW matched filter in association with the input SS signal. A correlation peak appears at every T_S period at the timing when the PN code patterns of both the input SS signal and the SAW matched filter coincide, where T_S indicates symbol duration. The correlation peak value is obtained by the following equation when a frequency offset exists between the carrier frequency of the SS signal and the nominal operating frequency of the SAW matched filter.

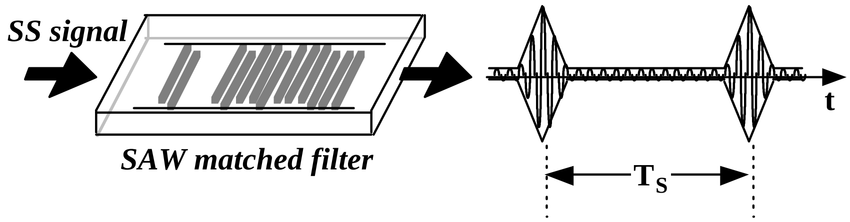


Figure 2.1 Operation of SAW matched filter

$$|Y| = \sin(\pi N T_C X)/\sin(\pi T_C X). \quad (1)$$

The parameters Y, X, N and T_C are an amplitude of the correlation peak, the frequency offset [Hz], the length of the PN code [chip] and the chip duration [sec], respectively. The correlation peak value decreases as the absolute value of the frequency offset X increases, and becomes zero at every specific value Δf [Hz] specified by the information symbol rate R [symbols/s] as shown in Fig. 2.2. Note that Δf is R [Hz], where R is the symbol rate of the system. The reason why the correlation peak becomes zero at specified frequency offset values is explained below.

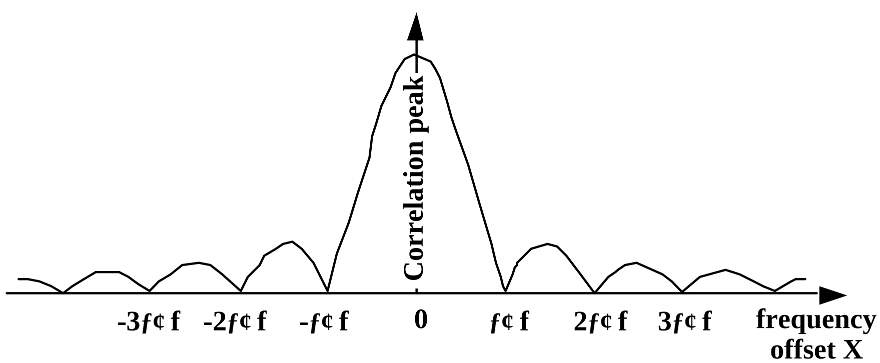


Fig. 2.2 Maximum correlation peak level as a function of the frequency offset X.

When there exists no frequency offset, all taps of the SAW matched filter sample the input signal in phase, leading to the maximum correlation peak. As the frequency offset increases, the difference between the relative phase of each tap and the input signal also increases. When the frequency offset becomes Δf, the phase difference between the adjacent taps becomes $2\pi/N$ [rad]. Therefore, the correlation peak value, which is the summation of the N tap output signals, becomes zero at every frequency offset of Δf. Since the correlation peak disappears at the above specified frequencies, multiple signals spread by a single PN code can be multiplexed without interfering one another if the following conditions (CFO conditions) are simultaneously satisfied.

1) The symbol timing and the PN code in each channel are synchronized.
2) The PN codes of all the channels are synchronized.

The desired channel is selected by changing the local frequency of the synthesizer at the receive side. So, the same receive unit can be used to demodulate any channel by changing the local frequency generated by the synthesizer.

Figure 2.3 shows the channel frequency plan of a five-channel CFO-SS system. The frequency offset is determined by the symbol rate R and is small as compared with the bandwidth of the spread signal. If the CFO-SS method is applied to the 2.4 GHz ISM band with a bandwidth of 26 MHz, up to nine 2 Mbit/s QPSK channels (symbol rate is 1 M symbols/sec) could be accommodated for a wireless LAN system, when the bandwidth of the single spread signal is 17 MHz and the length of the PN code is 11. However, the five channel CFO-SS employs the minimum channel separation of 2 MHz to make the system strong against the fading. The number of accommodated channels is subject to the bandwidth of the spread signal and the length of the PN code.

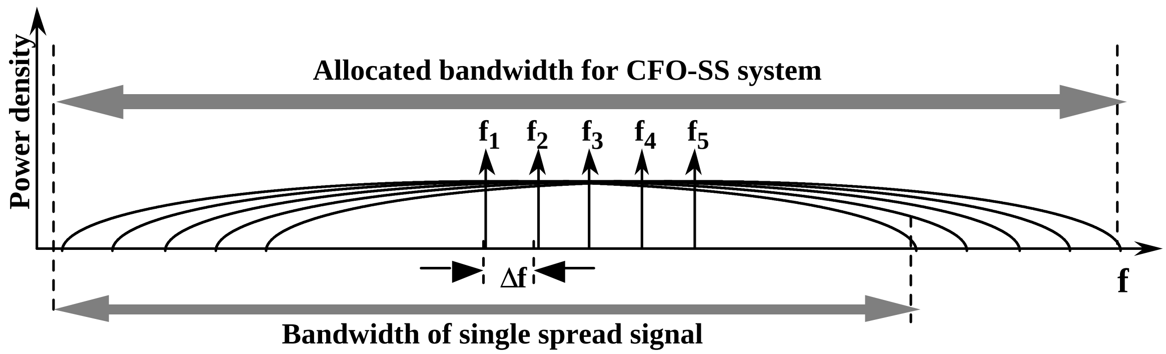


Fig. 2.3 Channel frequency plan for CFO-SS system.

2.2 CFO-SS system

An example configuration of the CFO-SS system is illustrated in Fig. 2.4.

In Fig. 2.4(a), five transmitters are illustrated, employing the same PN code with different carrier frequencies, each separated by Δf. Serial information data are transformed to parallel five data streams, and input to differential encoders. Differentially encoded data is multiplied with the common PN code, which then modulate the carrier in a QPSK format. In these procedures, PN code timings of all channels are synchronized. Bandpass filters are inserted to limit the transmit signal spectrum.

In Fig. 2.4(b), the receiver configuration is shown, employing five identical SAW matched filters together with down-converters and differential detectors, where T_S is one symbol duration. Received five radio frequency (RF) carriers with different frequencies are individually down-converted to the same intermediate frequency (IF), being the center frequency of the SAW matched filters, by the down-converters. In this operation, a local oscillator with an accuracy of +/-25 ppm is sufficient to maintain required orthogonality among multiple signals at the data decision timing. Details are described in clause 3.2.4. Finally, the differential detected parallel data sequences are transformed to a serial information data sequence.

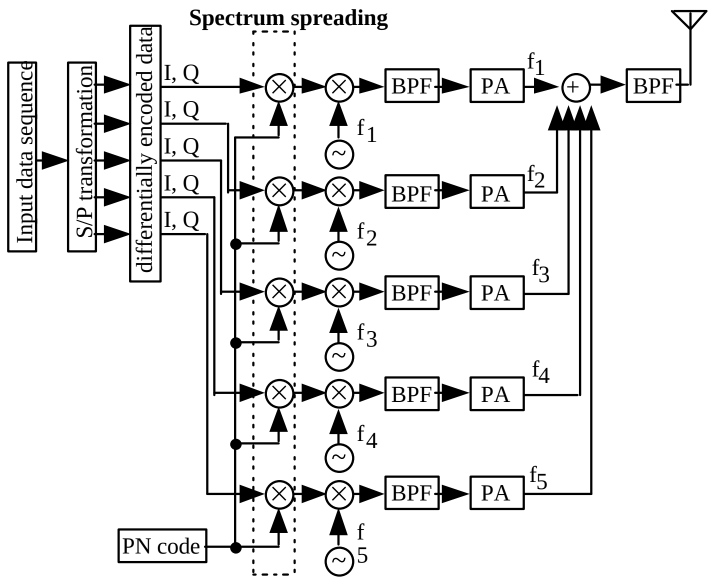


Fig. 2.4 (a) Example transmitter configuration of CFO-SS system.

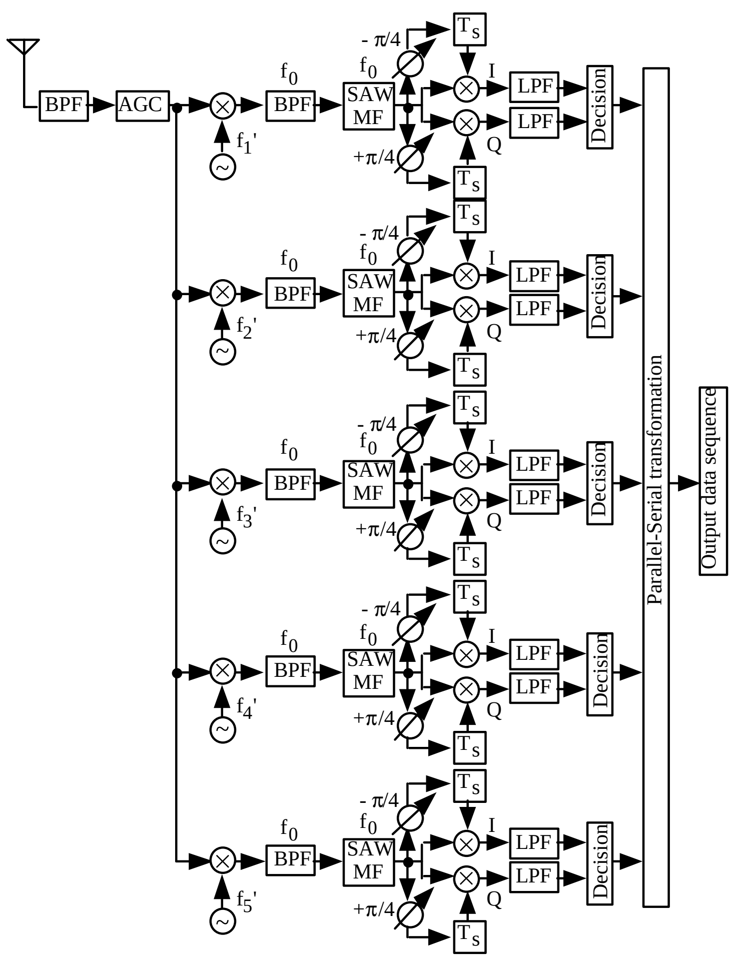


Fig. 2.4 (b) Example receiver configuration of CFO-SS system.

In the demodulation procedure, the correlation peak of the desired channel, i.e. the channel whose center frequency is down-converted to the operating frequency of the SAW matched filter, appears at the output of the SAW matched filter ideally without being affected by the other channels. An example output waveform of the SAW matched filter is shown in Fig. 2.5. The number of channels and the frequency offset between the CFO-SS carriers are five and 2 MHz, respectively, to achieve the transmission rate of 10 Mbit/s. In Fig. 2.5, vertical and horizontal scales show the relative amplitude and time, respectively. As seen in this figure, the correlation peak is not affected by the other four channels, though these channels use the same Barker code and their spectrum overlap each other. The other channels, however, make the sidelobe level higher.

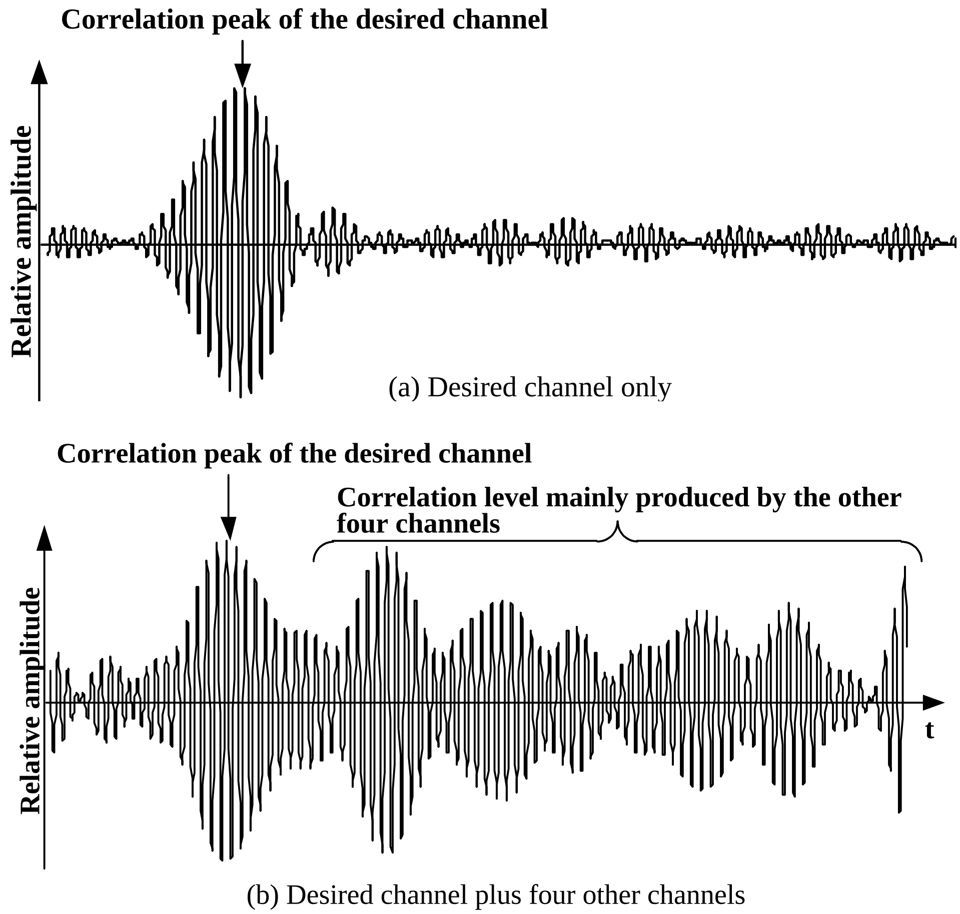


Fig. 2.5 Output waveform of SAW matched filter.

To evaluate the effects from the other channels, eye diagrams are calculated. Figure 2.6 shows an example eye diagram when five channels are multiplexed achieving 10 Mbit/s. The eye amplitude of the desired signal is slightly fluctuated by the intersymbol interference generated by the bandwidth limitation. The fluctuations in the sidelobe are mainly caused by the cross-correlation with the other channels. The eye of the desired channel was almost the same as that without the other channels, and enough to correctly decide the output data.

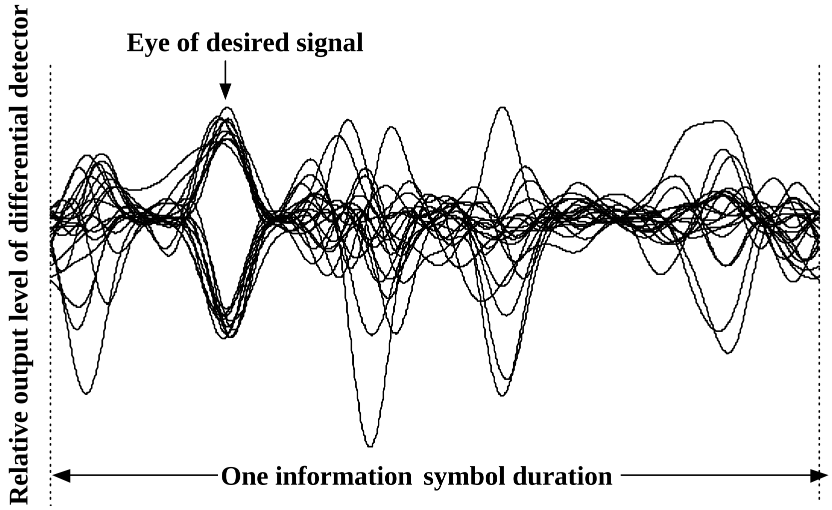


Fig. 2.6 Eye diagram of CFO-SS system when five channels are multiplexed.

3. Criteria for Comparison of Proposals

3.1 Implementation

3.1.1 RF/IF complexity relative to the low rate PHYs.

1) The front-end RF unit consists of an antenna, a divider, a combiner, a RX LNA and a TX power amplifier. In comparison with the current low rate PHY, a divider and a combiner are additionally required to treat five channels. (See Figure 3.1)

2) The RF/IF transceiver unit basically consists of five units of the low rate PHYs. Figure 3.2 shows an example block diagram of CFO-SS RF/IF unit. The first IF and second IF are selected to be 88 MHz and 280 MHz, respectively. In the first IF operation, each 2 Mbit/s SS/QPSK baseband signal is up-converted to 88 MHz and fed into a SAW bandpass filter for bandwidth limitation. Figures 3.3 and 3.4 indicate the frequency response of 88 MHz and 280 MHz SAW filters, respectively. Each RF/IF transceiver is basically the same as that of the low rate PHY.

3) Figure 3.5 shows an example structure of the SAW matched filter. Two independent output transducers coded with eleven chip Barker code are sequentially placed on crystal substrate. The output signal of the backward output transducer is delayed by one symbol duration as compared to the output of the forward output transducer. Differential detection is easily accomplished by multiplying these two output signals.

4) Only one clock timing acquisition and tracking circuit is required, which is shared by the five RF/IF transceiver units.

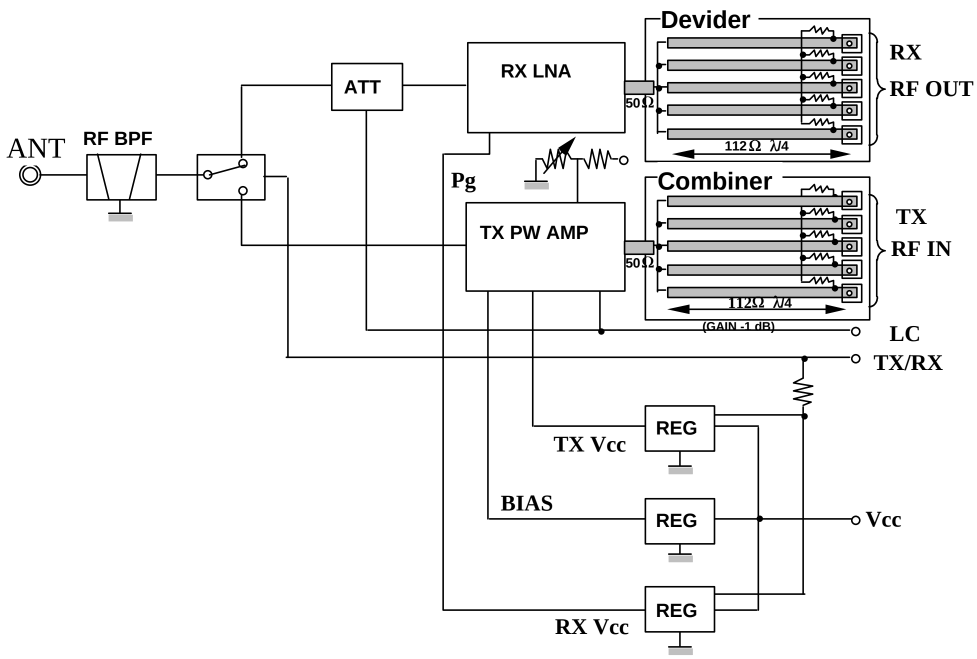


Fig. 3.1 Configuration of CFO-SS antenna and RF unit.

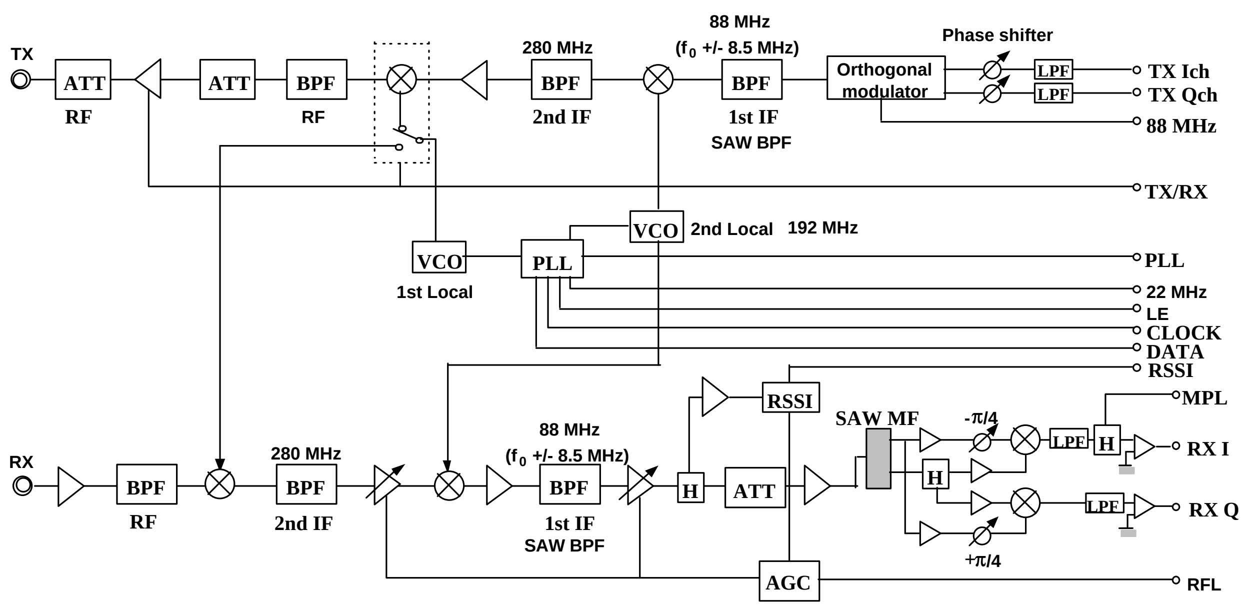


Fig. 3.2 Configuration of CFO-SS RF/IF unit.

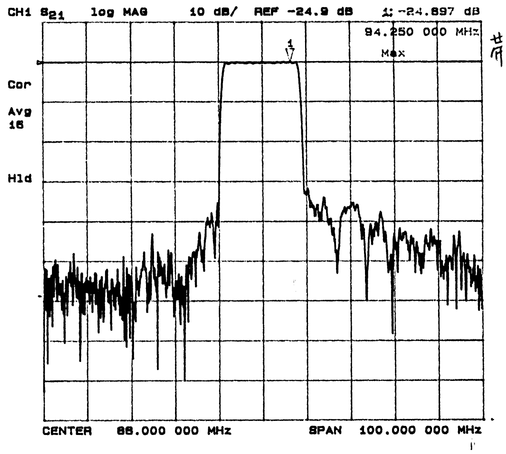


Fig. 3.3 Frequency response of 88 MHz SAW filter.

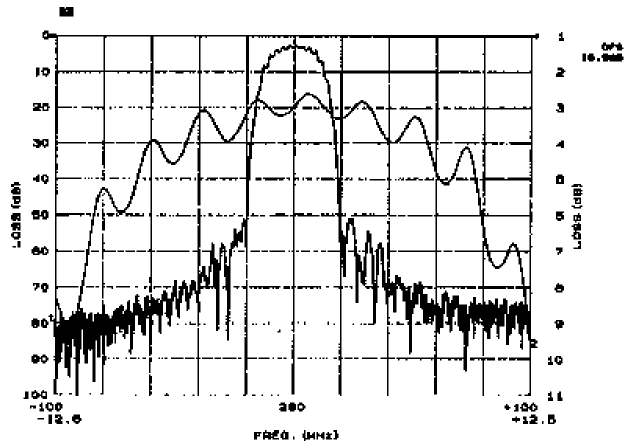


Fig. 3.4 Frequency response of 280 MHz SAW filter.

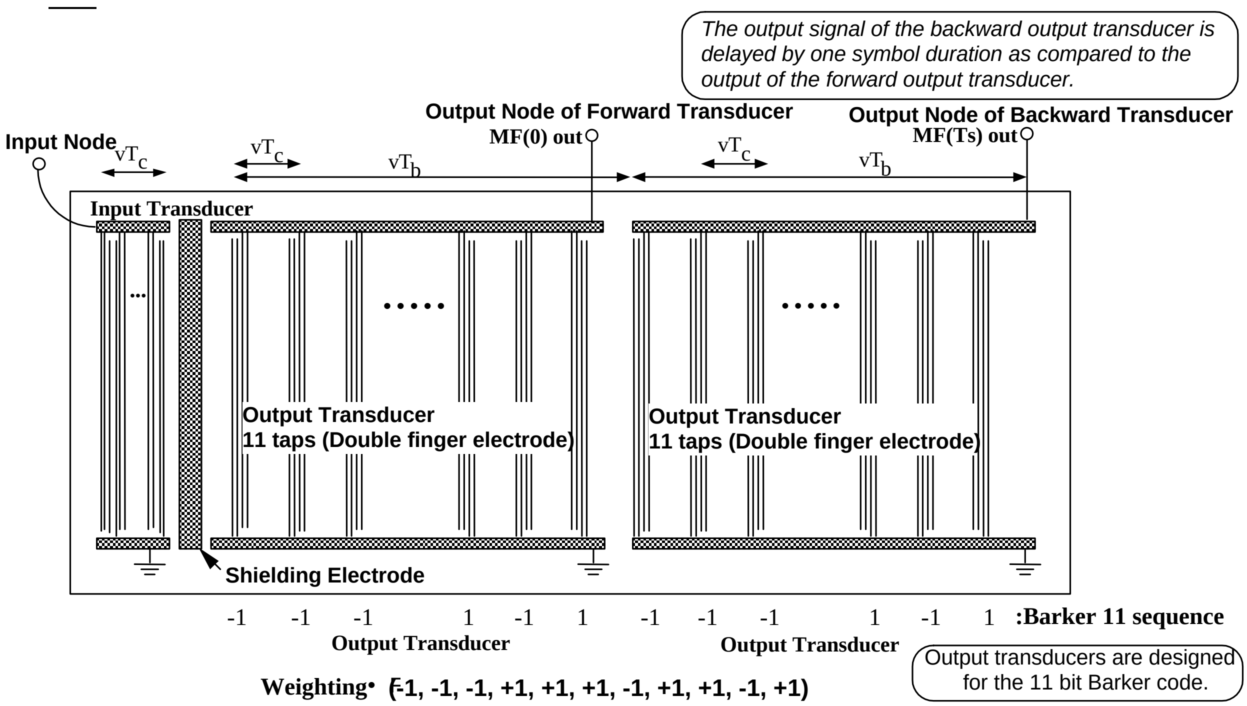


Fig. 3.5 Structure of SAW matched filter.

3.1.2 Baseband processing complexity relative to the low rate PHY, give gate counts if applicable.

1) Figure 3.6 shows an example configuration of the 10 Mbit/s CFO-SS baseband unit which are mainly consists of a CPU, a MAC processor, TX/RX buffers, a five-port serial-parallel converter, an A/D converter, a baseband differential encoder, a preamble pattern generator, an oscillator and a clock recovery and a tracking circuit. Selection of 2 Mbit/s, 4 Mbit/s, 6 Mbit/s, 8 Mbit/s and 10 Mbit/s transmission rate is easily controlled by the

CPU. The transmission rate of 1 Mbit/s is also easily supported. Clock recovery and tracking method is based on a conventional method. Details are given in Doc:IEEE P802.11-98/01.

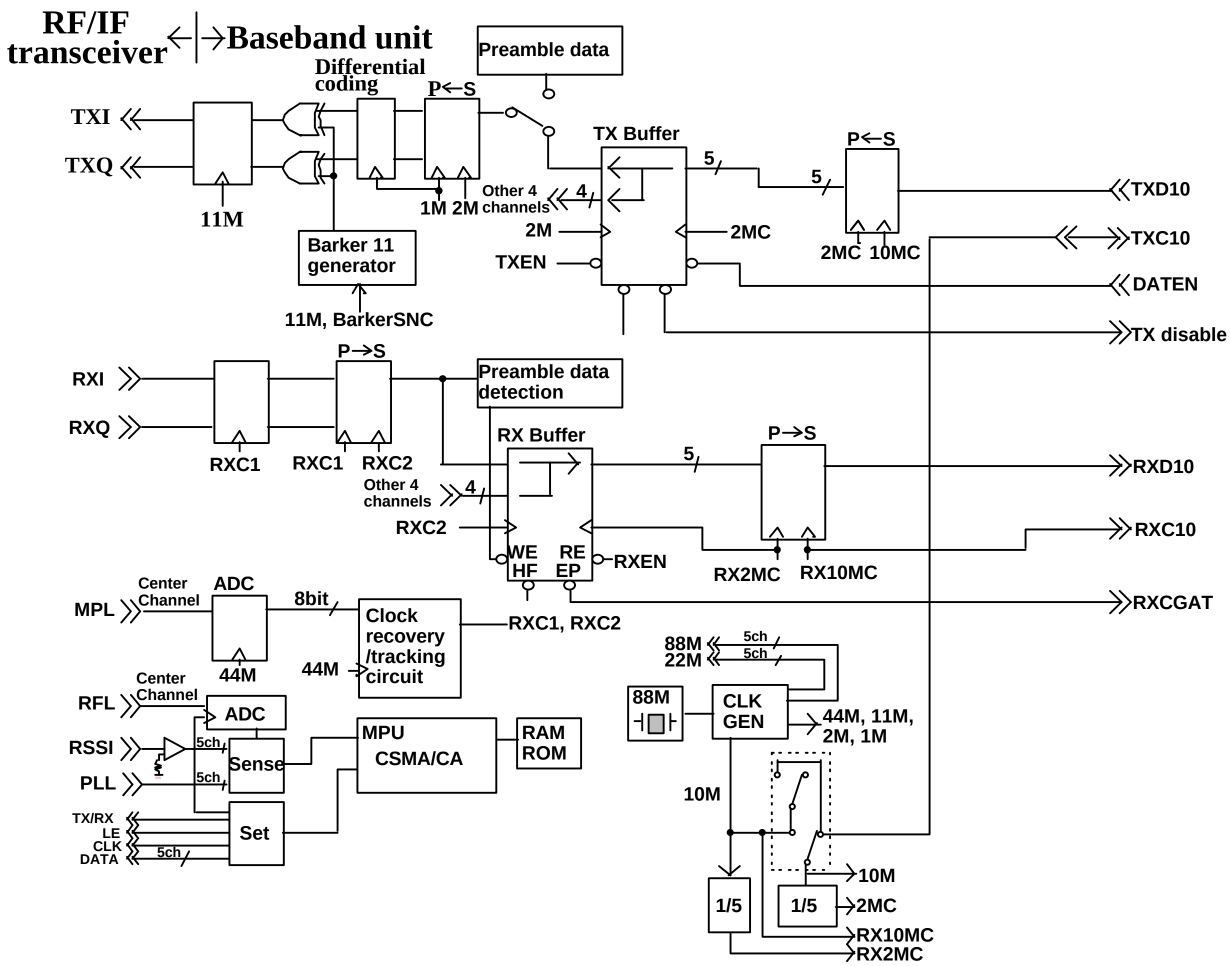


Fig. 3.6 Example configuration of CFO-SS baseband unit.

3.1.3 Equalizer complexity

1) The CFO-SS does not require a special equalizer. The 10 Mbit/s CFO-SS can achieve almost the same BER and PER performance under the AWGN environment as the low rate PHY.

2) Under severe multipath fading conditions, a RAKE receiver configuration is appropriate to improve the performance. Some preamble data (20~30 symbols) are required for the RAKE receiver to estimate the channel characteristics. A path estimate function of the RAKE receiver precisely obtains the delay profiles by observing the output waveform of the SAW matched filter during the preamble data duration. The RAKE combiner selects up to N paths and combines their signals coherently. These

procedures are basically the same as the RAKE receiver employed by the DS/CDMA cellular systems.

3.1.4 Diversity implementation

1) A conventional selection diversity technique is adequate, if employed. The current IEEE 802.11 preamble and slot time are adequate.

3.2 Immunity to multipath and noise

3.2.1 Simulation parameters:

Table 3.1 Computer simulation parameters.

Number of multiplexed channels	3 and 5
Total transmission rate	6 Mbit/s & 10 Mbit/s
Channel separation	2 MHz
Frame length	64 Byte & 1000 Byte
PN code	11 chip Barker code
Chip rate	11 Mchip/s
Modulation technique	SS/QPSK
Transmission rate per channel	2 Mbit/s
Demodulation technique	Differential detection as prescribed by the 2.4 GHz low rate PHY
Band pass filter	8th order Butterworth filter
3 dB bandwidth of BPF	17 MHz (per channel)
Preamble length	128 bits (64 μsec)
Timing recovery and acquisition scheme	As described in Doc:IEEE P802.11-98/01
Multipath fading model	11 wave exponentially decaying Rayleigh fading channel

3.2.2 Multipath without noise:

1) Under the exponentially decaying Rayleigh fading channel, the CFO-SS shows good performance when the RMS value of delay spread (T_{RMS}) is 20~60 nsec, which are typical values for indoor use. The lowest T_{RMS} at which PER=10% with a frame length of 64 Byte is approximately 20 nsec for the five channel multiplexed 10 Mbit/s CFO-SS, and 60 nsec for the three channel multiplexed 6 Mbit/s CFO-SS. The lowest T_{RMS} at which PER=10% with a frame length of 1000 Byte is approximately 15 nsec for the 10 Mbit/s CFO-SS, and 50 nsec for the 6 Mbit/s CFO-SS.

2) The lowest delay spread T_{RMS} at which the PER=10% could be extended up to several hundreds nsec by employing a 2~3 finger RAKE receiver.

3) The detailed simulation results are summarized in Table 3.2.

Table 3.2 Maximum T_{RMS} at which the PER=10%

Frame length	64 Byte	1000 Byte
10 Mbit/s CFO-SS without RAKE	up to 20 nsec	up to 15 nsec
6 Mbit/s CFO-SS without RAKE	up to 60 nsec	up to 50 nsec
10 Mbit/s CFO-SS with RAKE (two fingers)	up to 50 nsec	up to 40 nsec
6 Mbit/s CFO-SS with RAKE (two fingers)	up to 300 nsec	up to 200 nsec
10 Mbit/s CFO-SS with RAKE (three fingers)	larger than 300 nsec	up to 300 nsec
6 Mbit/s CFO-SS with RAKE (three fingers)	larger than 300 nsec	larger than 300 nsec

3.2.3 Multipath with noise:

1) Under the exponentially decaying Rayleigh fading channel with thermal noise, the CFO-SS also shows good performance for indoor use. The lowest T_{RMS} at which PER=20% with a frame length of 64 Byte is 15~20 nsec for the 10 Mbit/s CFO-SS, and 40~50 nsec for the 6 Mbit/s CFO-SS when the E_b/N_0 is 20 dB. The lowest T_{RMS} at which PER=20% with a frame length of 1000 Byte is 10~15 nsec for the 10 Mbit/s CFO-SS, and 30~40 nsec for the 6 Mbit/s CFO-SS, when the E_b/N_0 is 20 dB. The simulation results are shown in Fig. 3.7 (a)~(b).

2) The lowest delay spread T_{RMS} at which the PER=20% is dramatically extended up to several hundred nsec by employing a 2~4 finger RAKE receiver when the E_b/N_0 is less than 20 dB. The simulation results are shown in Fig. 3.8 (a)~(c).

3) The results are summarized in Table 3.3.

Table 3.3 Maximum T_{RMS} at which the PER=20% when E_b/N_0=20 dB

Frame length	64 Byte	1000 Byte
10 Mbit/s CFO-SS without RAKE	15~20 nsec	10~15 nsec
6 Mbit/s CFO-SS without RAKE	40~50 nsec	30~40 nsec
10 Mbit/s CFO-SS with RAKE (two fingers)	50~60 nsec	40~50 nsec
6 Mbit/s CFO-SS with RAKE (two fingers)	up to 300 nsec	up to 150 nsec
10 Mbit/s CFO-SS with RAKE (three fingers)	larger than 300 nsec	up to 300 nsec
6 Mbit/s CFO-SS with RAKE (three fingers)	larger than 300 nsec	larger than 300 nsec

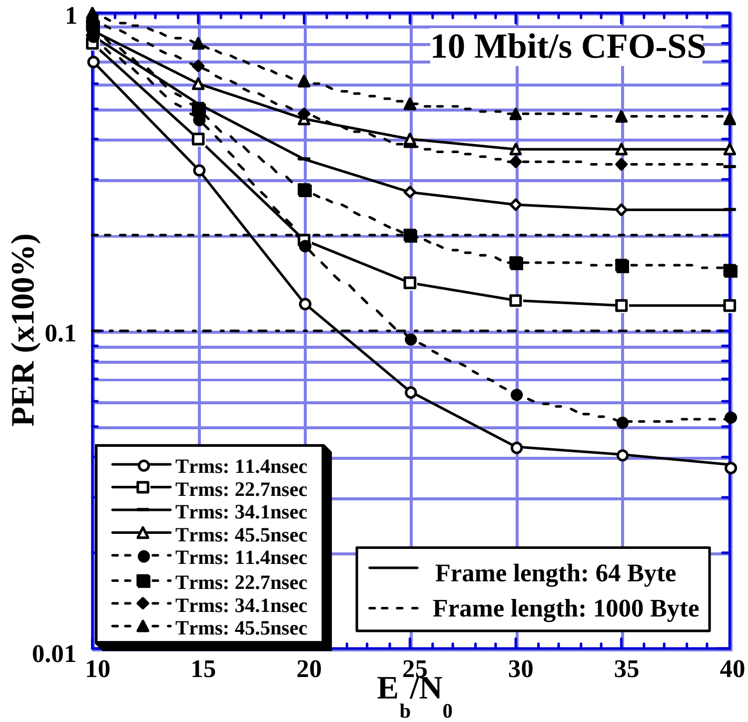


Fig. 3.7 (a) PER performance of 10 Mbit/s CFO-SS under multipath fading environment.

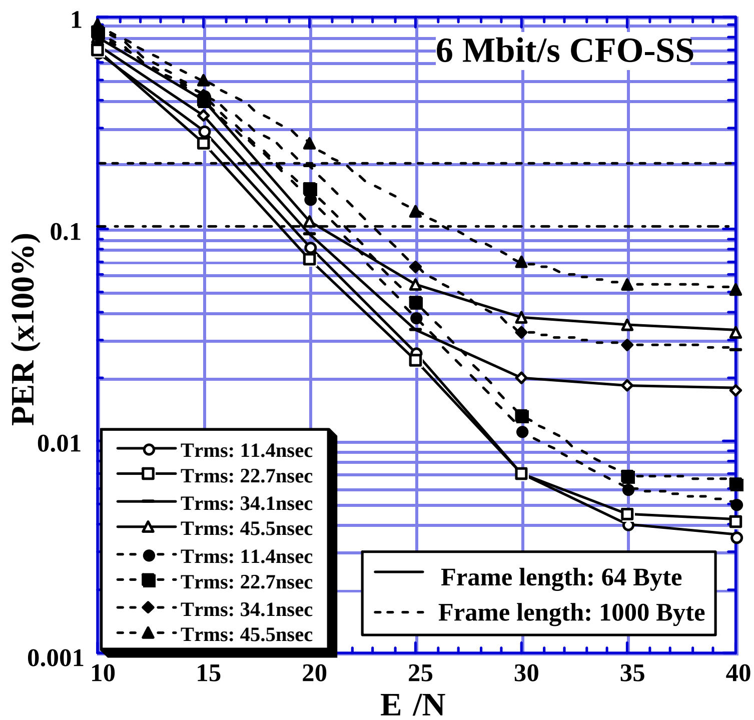


Fig. 3.7 (b) PER performance of 6 Mbit/s CFO-SS under multipath fading environment.

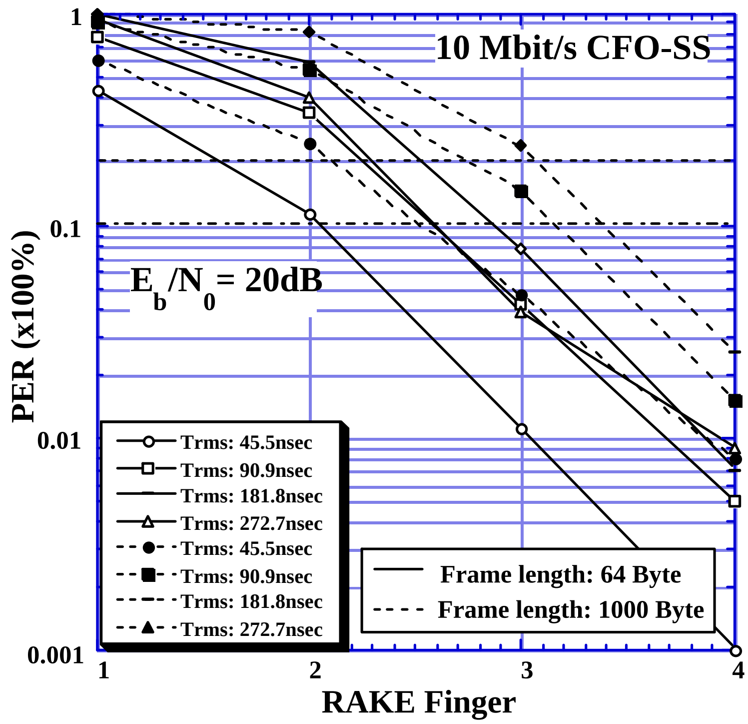


Fig. 3.8 (a) PER performance of 10 Mbit/s CFO-SS vs. the number of RAKE finger.

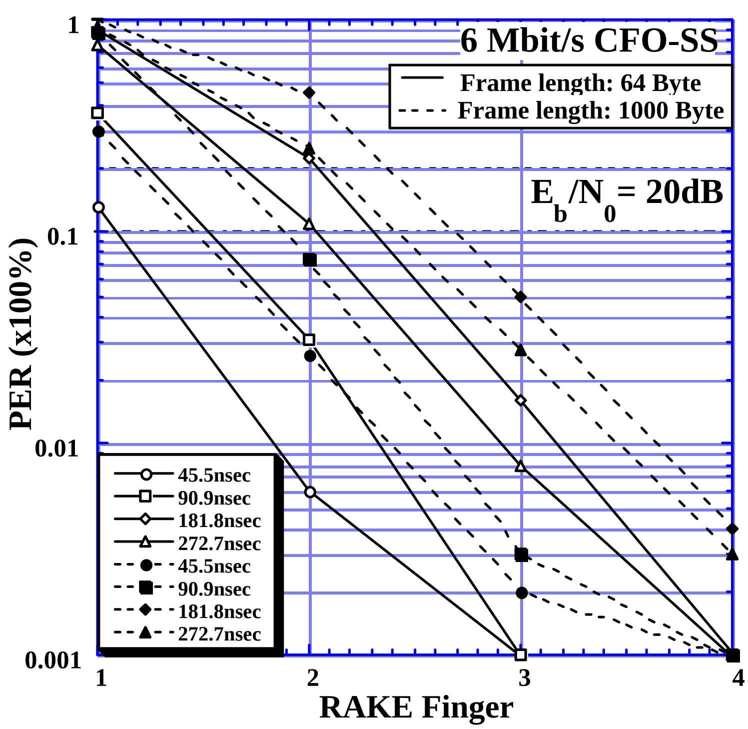


Fig. 3.8 (b) PER performance of 6 Mbit/s CFO-SS vs. the number of RAKE finger.

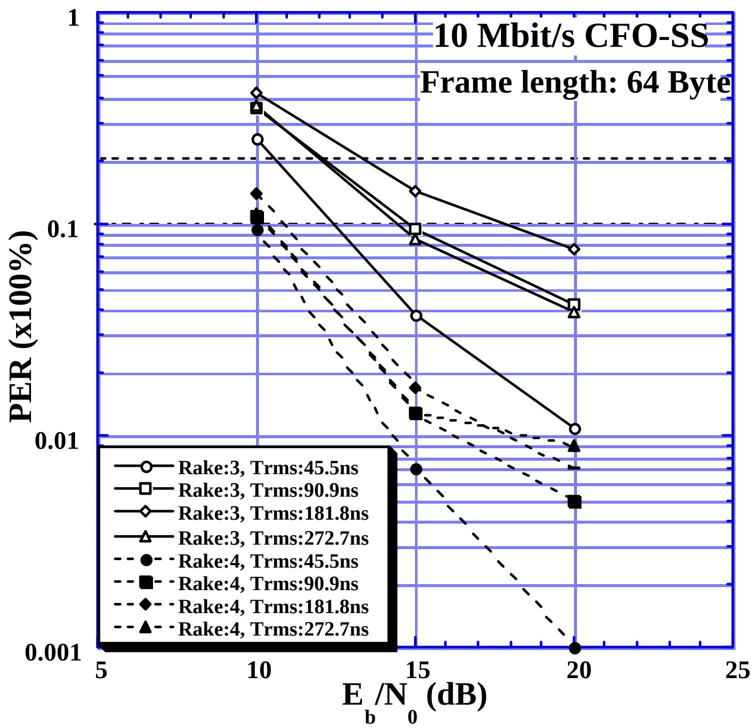


Fig. 3.8 (c) PER performance of 10 Mbit/s CFO-SS with RAKE receiver.

3.2.4 Thermal noise only:

1) BER and PER performance of the 6 Mbit/s and the 10 Mbit/s CFO-SS are shown in Fig. 3.9. The E_b/N_0 at which the PER=10% is summarized in Table 3.4. For the 10 Mbit/s CFO-SS, the degradation from the ideal case is only 1.5 dB, which is caused by the intersymbol interference generated by the strict bandwidth limitation to less than 17 MHz.

Table 3.4 E_b/N_0 at which the PER=10%

Frame length	64 Bytes	1000 Bytes
6 Mbit/s CFO-SS without RAKE	9.8 dB	11.4 dB
10 Mbit/s CFO-SS without RAKE	10.0 dB	11.6 dB

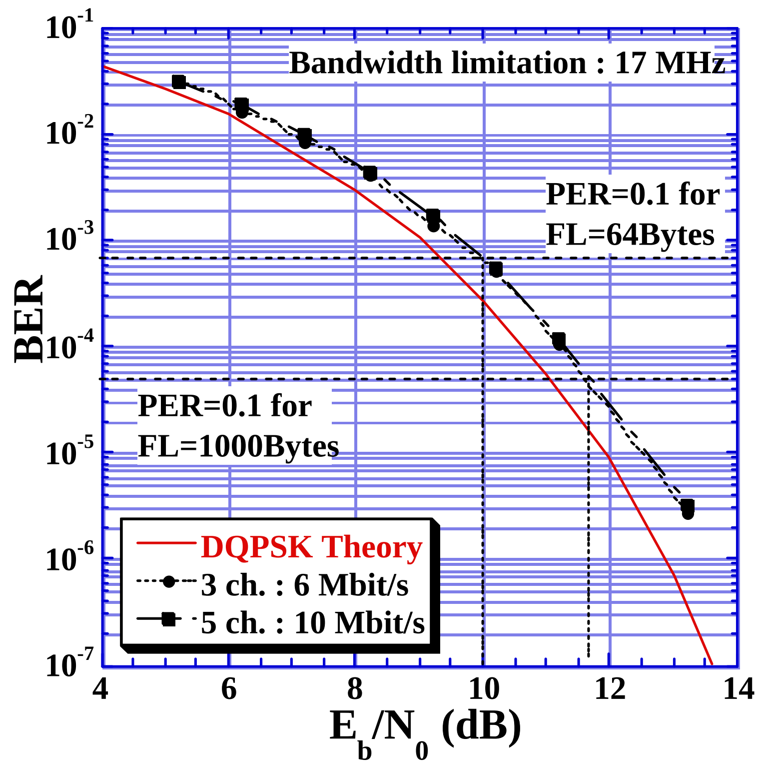


Fig. 3.9 BER performance of 6 Mbit/s and 10 Mbit/s CFO-SS under AWGN environment.

3.2.4 Center frequency accuracy

1) Figure 3.10 shows the C/I performance calculated using equation (1). I is the interference from the other four channels generated by the degradation in orthogonality due to the frequency offset. C/I of 20 dB is achieved if the frequency offset Δf is less than 60 kHz (+/-25 ppm) for the 10 Mbit/s CFO-SS case. C/I of 20 dB is achieved with the 6 Mbit/s CFO-SS case if Δf is less than 100 kHz (+/-40 ppm).

2) Figure 3.11 shows the simulated BER performance of the 6 Mbit/s and 10 Mbit/s CFO-SS systems when the frequency offset exists under a noise free condition. The simulation results take into account the band limitation in each channel. From this figure, BER of 10^{-5} is achieved for Δf of less than 75 kHz (+/-30 ppm) in the 10 Mbit/s CFO-SS and for Δf of less than 90 kHz (+/-37 ppm) in the 6 Mbit/s CFO-SS, respectively. When Δf is less than 60 kHz, no error bit was observed in the 10 Mbit/s CFO-SS. From these simulation results, it is concluded that the required center frequency accuracy is +/- 25 ppm for the 10 Mbit/s CFO-SS, which is +/- 60 kHz for the 2.4 GHz case.

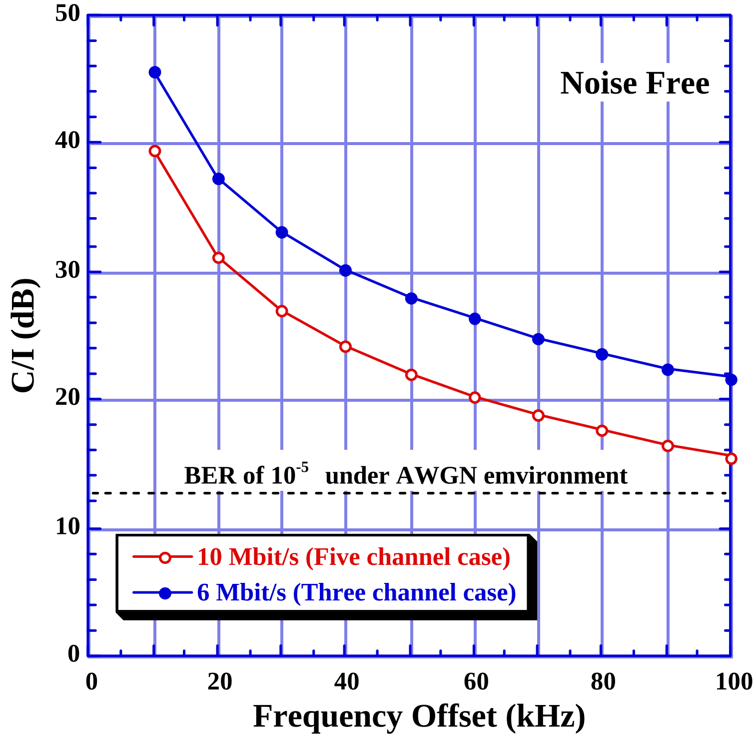


Figure 3.10 C/I performance vs. frequency offset Δf.

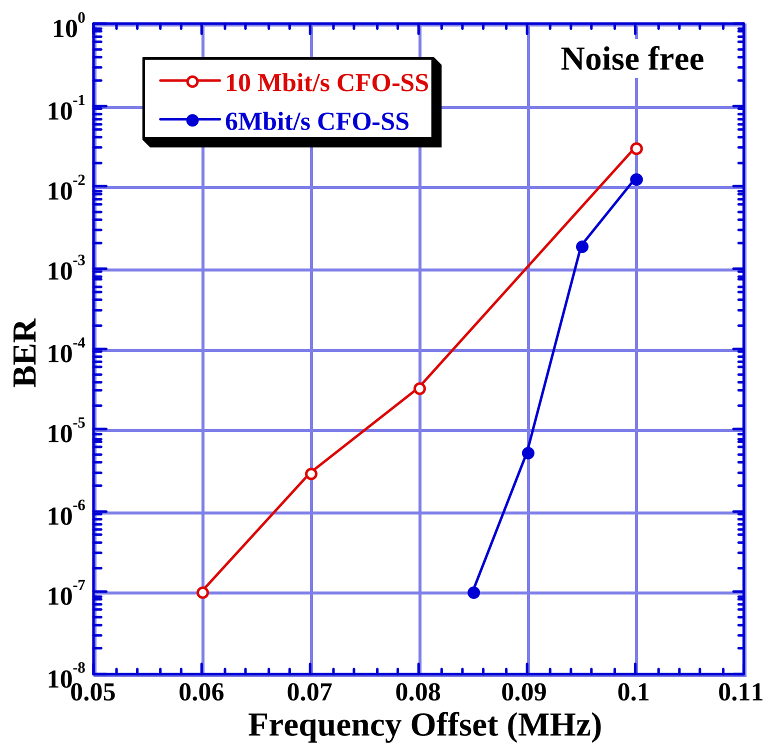


Figure 3.11 BER performance of CFO-SS when frequency offset exists.

3.3 Overhead related parameters

3.3.1 Preamble length:

1) 128 bits for synchronization is sufficient for the CFO-SS under typical indoor multipath fading environments, the length being the same as the current low rate 2.4 GHz PHY.

2) Rapid acquisition can be achieved by adopting a specially selected preamble pattern. The preamble pattern in the backward compatible channel is the same as the current low rate PHY.

3) Additional preamble data (20~30 symbols) are required for the RAKE receiver to precisely estimate the multipath conditions. Furthermore, it is required to transmit the preamble data by a single channel to derive the delay spread distribution with high accuracy. Approximately 15 μsec is required before transmitting the PLCP (Physical Layer Convergence Protocol) header by multiple channels to adjust the AGC.

3.3.2 Slot size:

1) The slot size for the backoff algorithm is the same as the current low rate 2.4 GHz PHY. Figure 3.12 shows a frame format of the CFO-SS system.

2) A CCA (Clear Channel Assessment) mechanism and associated timing is the same as the current low rate 2.4 GHz PHY.

3) Transmission data rate of 1, 2, 4, 6, 8, 10 Mbit/s is informed by “SIGNAL” field.

4) Time to detect signal from when it appears at the antenna and turnaround time to transmit (at the antenna) are the same as the current low rate 2.4 GHz PHY.

5) The slot size is extended when the RAKE receiver is applied to the CFO-SS terminal. Figure 3.13 shows an example frame format when the RAKE receiver is adopted. Additional 20 bits are required for the channel estimation, and 30 bits are for AGC training.

6) As mentioned in clause 3.1.4, it is required to transmit preamble symbols only by a single channel when the RAKE receiver is employed.

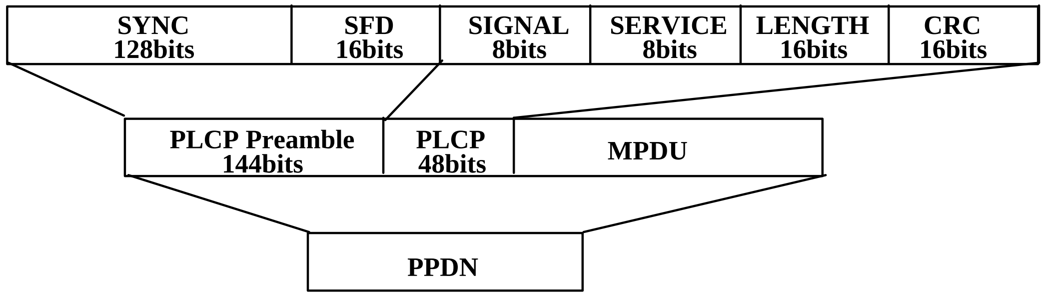


Figure 3.12 PLCP frame format for CFO-SS

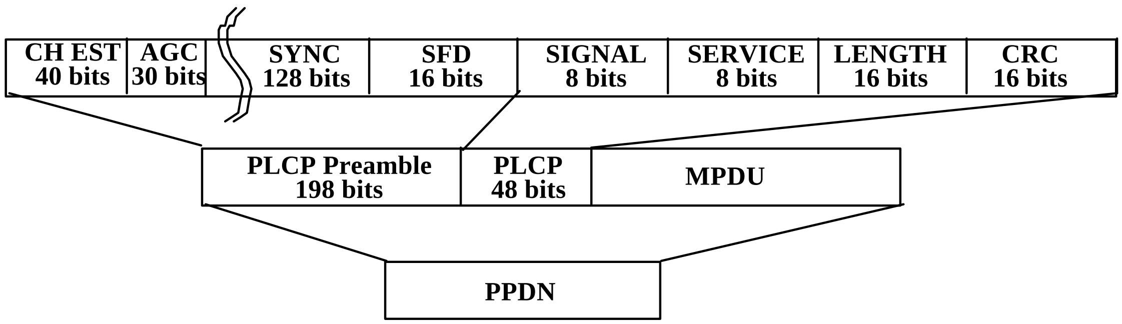


Figure 3.13 PLCP frame format for CFO-SS with RAKE receiver

3.3.3 SIFS (Short Inter-Frame Space) time:

1) The CFO-SS consists of multiple low rate 2.4 GHz transceivers with a RF divider, a combiner and a Serial-Parallel converter. The RF divider and the combiner will not affect the delay at RF level. The TX/RX turn-around time is the same as the current low rate 2.4 GHz PHY. The Serial-Parallel converter will not affect the operation delay of the MAC protocol. From the above, the current Short Interframe Space (SIFS) time of 10 microseconds can be maintained for the CFO-SS.

3.4 Spectral Efficiency and Cell Density related parameters

3.4.1 Channelization:

A) Rigid channelization plan

1) In the US ISM band, three channels can be defined for the CFO-SS system at maximum. Figure 3.14 shows an example channelization plan for the five channel multiplexed 10 Mbit/s CFO-SS system. The center frequencies of three channels are selected to be 2.414 GHz, 2.442 GHz and 2.470 GHz.

2) The separation between the channels are 28 MHz. ACI is sufficiently suppressed by the sharp SAW filters at the transmit side. Figure 3.15 shows an RF output signal

spectrum of the five channel multiplexed 10 Mbit/s CFO-SS equipment. 30dB attenuation is achieved at the points at f_c +/- 13 MHz.

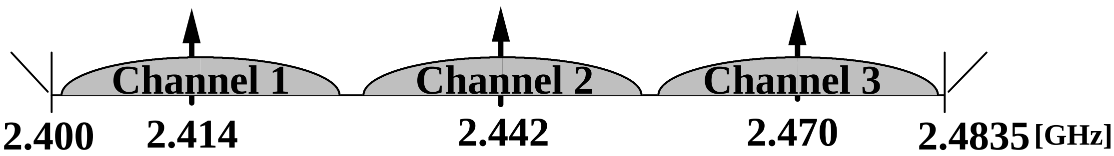


Figure 3.14 Channelization plan for CFO-SS system.

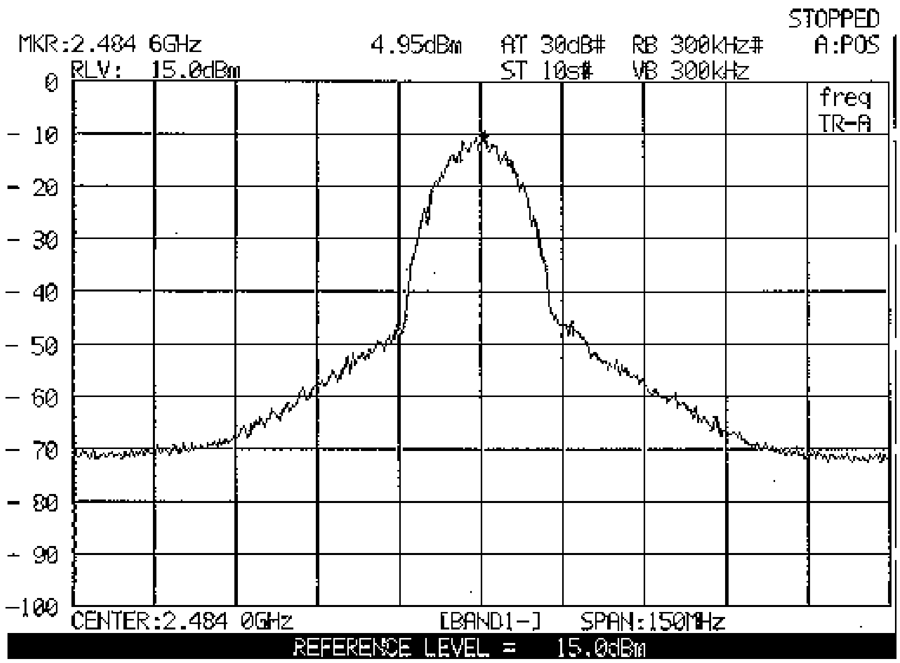


Figure 3.15 Output signal spectrum of the five channel multiplexed 10 Mbit/s CFO-SS equipment.

3) Figure 3.16 shows the overlapped spectrum of the three CFO-SS signals when the rigid channelization plan is adopted. It is clearly understood that ACI will not affect the performance of the CFO-SS.

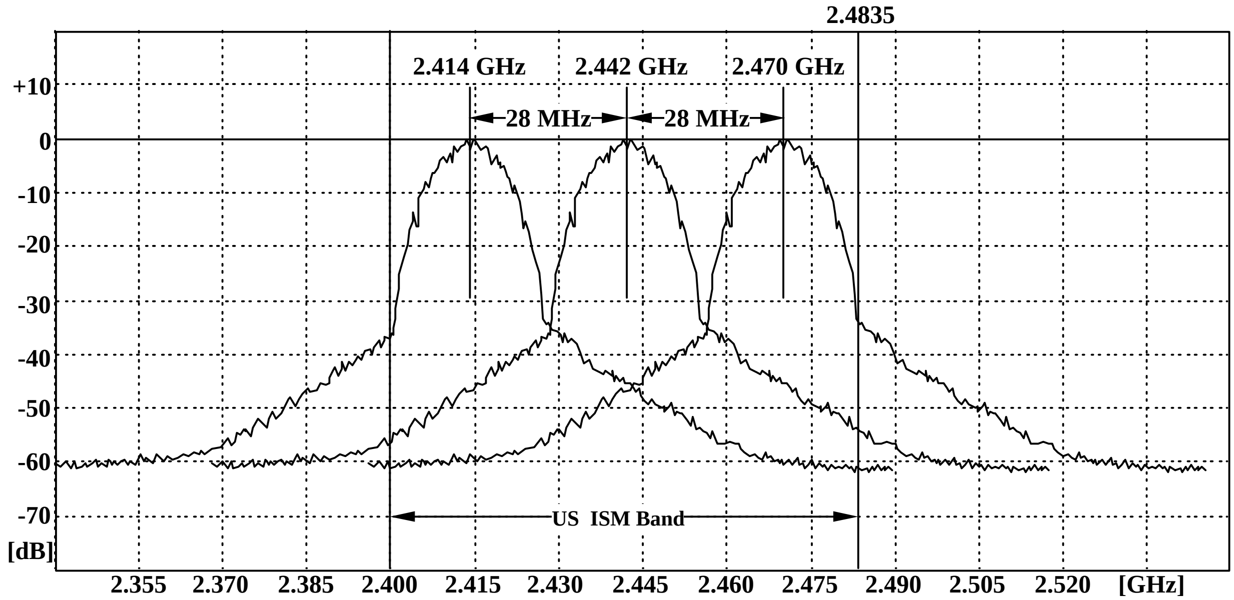


Figure 3.16 Overlapped spectrum of the three CFO-SS signals when three 10 Mbit/s CFO-SS carriers are allocated in the US ISM band.

B) Flexible channelization plan

Alternatively, channel center frequencies of the current low rate PHY can also be supported by the CFO-SS. In this case, the separation between CFO-SS signals should carefully be coordinated to avoid interference among them as described in clause 3.4.2.

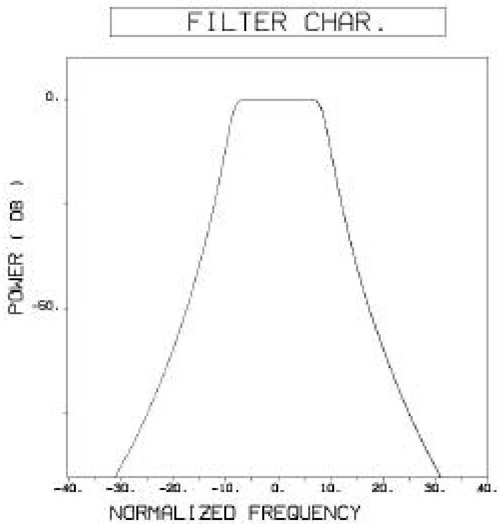
3.4.2 Cell Planning:

1) A terminal connected with an AP shall first search a vacant channel among candidate center frequencies as specified. When a scanned channel is busy, then the CFO-SS terminal searches a vacant channel among the other candidate channels. If all the candidate channels are occupied, the same channel is shared among cells on a CSMA/CA basis. Channel selection can also be made manually. Minimum separation between CFO-SS signals shall be 28 MHz for the rigid channelization plan, 30 MHz for the flexible channelization plan.

2) Typical range is 50 meters in an indoor operation, and 1 km for an outdoor point-to-point use. Typical dynamic range of the 10 Mbit/s CFO-SS receiver is designed to be 80 dB.

3) Throughput for both single cell and multiple cells are approximately five times those of the current low rate 2.4 GHz PHY. Aggregate throughput of 7 Mbit/s is achieved by 10 Mbit/s CFO-SS equipment.

3.4.3 Adjacent Channel Interference:



1) ACI is sufficiently suppressed by the sharp SAW filters at the transmit side as referred in clause 3.1.1. Figure 3.17 shows a filter response of an 8th order Butterworth filter assumed for the computer simulation. The SAW filters employed in the CFO-SS hardware is much sharper than this model used in the simulation.

Figure 3.17 Filter response of 8th order Butterworth filter.

2) Figure 3.18 shows the spectrum when three channels are simultaneously used. The channel separation is selected to be 28 MHz and the difference in the received signal levels is 0 dB. Figures 3.19 and 3.20 show the signal spectrum at the output of the SAW filter at the receive side and the eye diagram, respectively. Degradation caused by ACI can hardly be recognized.

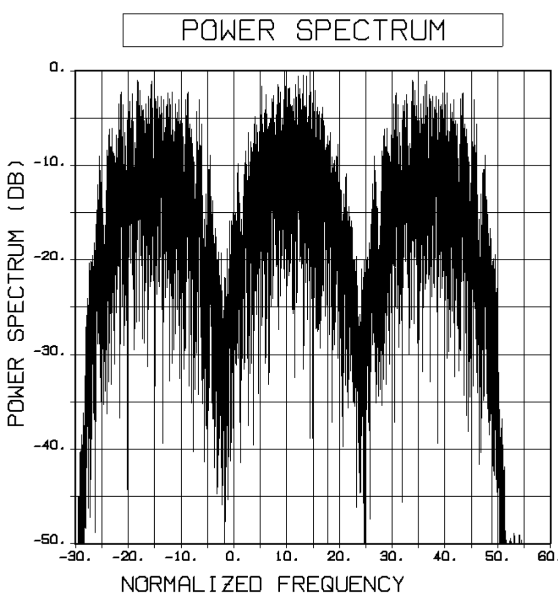


Figure 3.18 Received spectrum of three 10 Mbit/s CFO-SS signals when the signal level of the center channel is the same as those in the adjacent channels.

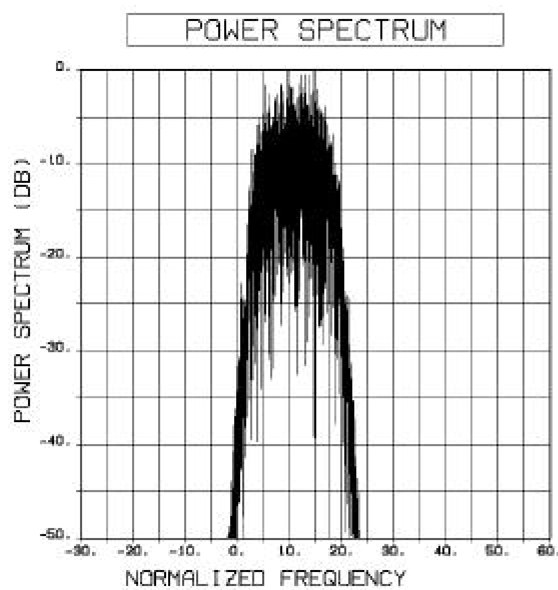


Figure 3.19 Signal spectrum of the signal in the center channel at the output of the RX filter

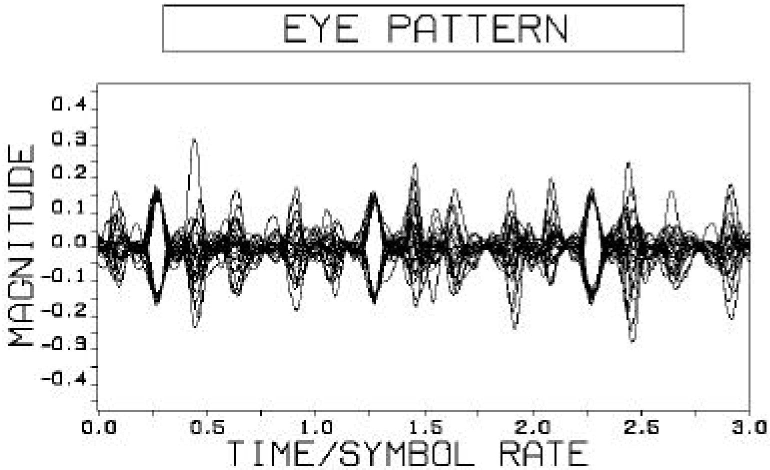


Figure 3.20 Eye diagram performance of 10 Mbit/s CFO-SS with ACI (C/C_A= 0dB).

3) Figure 3.21 shows a RX spectrum of three channels when the signal in the center channel is received 30 dB below as compared to the signals in the other two channels. Figures 3.22 and 3.23 show a spectrum at the output of the SAW filter at the receive side and the eye diagram, respectively. Signals from the adjacent channels affects the center channel spectrum as in Fig. 3.22, however, degradation in the eye diagram is hardly recognized in Fig. 3.23.

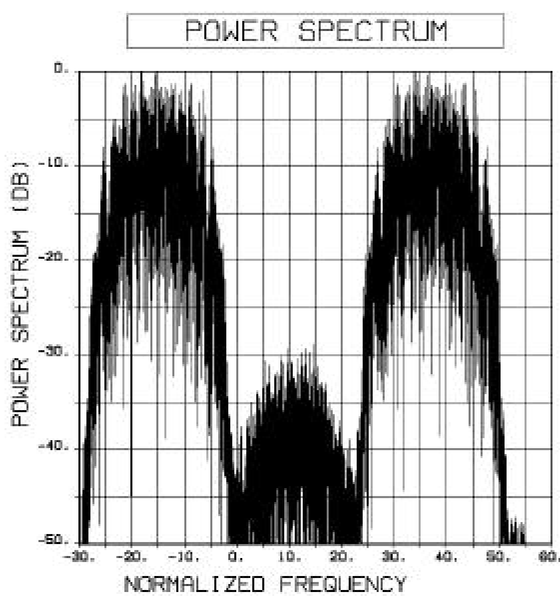


Figure 3.21 Received spectrum of three 10 Mbit/s CFO-SS signals when the signal level of the center channel is 30dB lower than those in the adjacent channels.

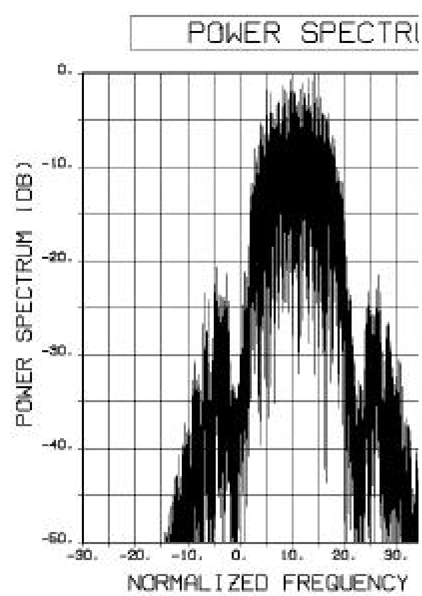


Figure 3.22 Signal spectrum of the signal in the center channel at the output of the RX filter.

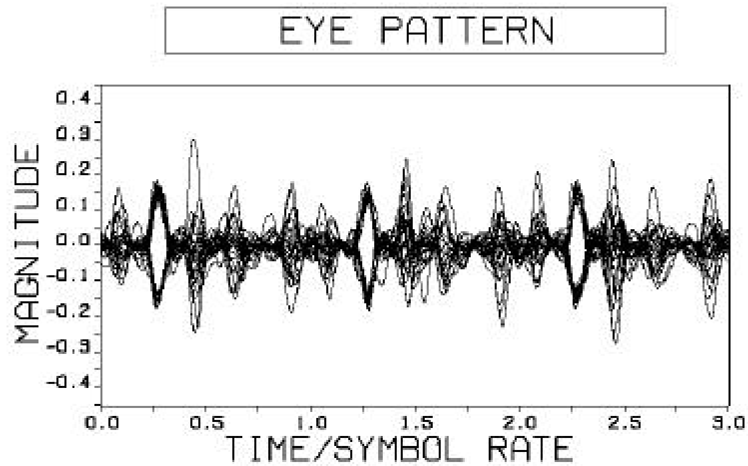


Figure 3.23 Eye diagram performance of 10 Mbit/s CFO-SS with ACI (C/C_A= 30dB).

5) Figure 3.24 shows a RX spectrum of three channels when the signal in the center channel is received 40 dB below as compared to the signals in the other two channels. Figures 3.25 and 3.26 show a spectrum at the output of the SAW filter at the receive side and the eye diagram, respectively. The center channel spectrum and the eye diagram are degraded by ACI as seen in Fig. 3.26.

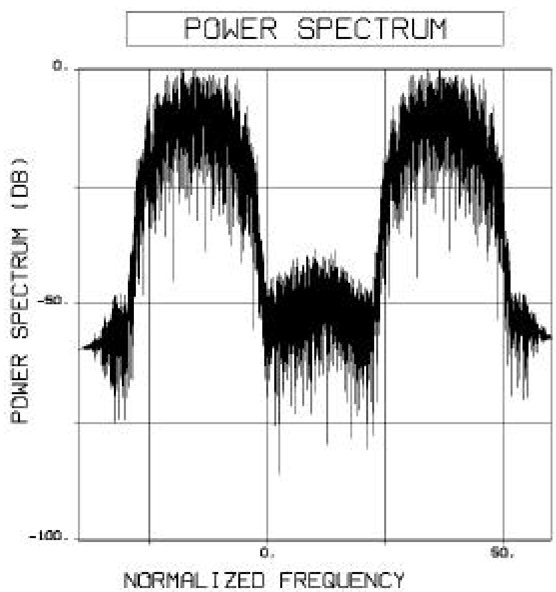


Figure 3.24 Received spectrum of three 10 Mbit/s CFO-SS signals when the signal level of the center channel is 40dB lower than those in the adjacent channels.

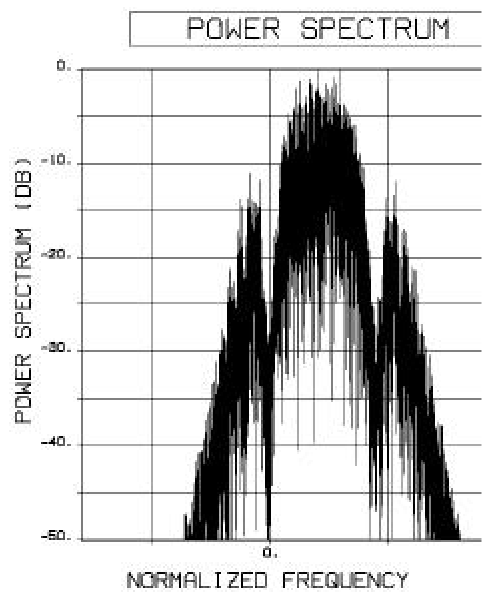


Figure 3.25 Signal spectrum of the center channel at the output of the RX filter.

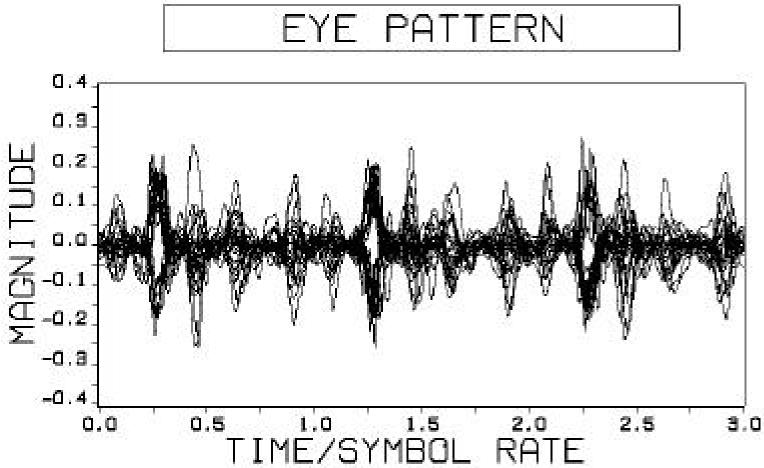


Figure 3.26 Eye diagram of 10 Mbit/s CFO-SS with ACI (C/C_A= 40dB).

6) With the above, it is concluded that the 10 Mbit/s CFO-SS system can tolerate at least +30 dBc higher level signals at the adjacent channels.

3.4.4 Co-Channel Interference:

1) The CSMA/CA protocol is to be adopted by the CFO-SS, currently prescribed for the low rate PHY. By the CSMA/CA protocol, co-channel interference is basically avoided. However, co-channel interference would occur when hidden terminals exist in the same area.

2) Figure 3.27 shows the BER performance versus CCI level (dB) for the three channel multiplexed 6 Mbit/s CFO-SS and the five channel multiplexed 10 Mbit/s CFO-SS. BER of 10^{-5} is accomplished when C/I is larger than 12 dB for the 10 Mbit/s CFO-SS and C/I is larger than 8.5 dB for the 6 Mbit/s CFO-SS, respectively.

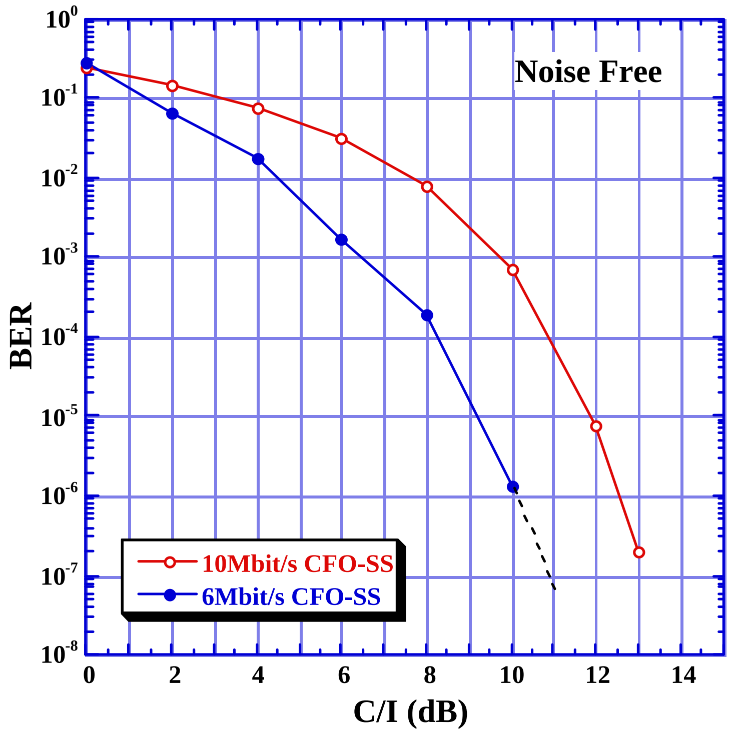


Figure 3.27 BER performance versus CCI level (dB) for three channel multiplexed 6 Mbit/s CFO-SS and five channel multiplexed 10 Mbit/s CFO-SS are employed.

3.4.5 Interference immunity:

1) Immunity to CW jamming is investigated in this clause. Figures 3.28 and 3.29 show the spectrum and eye diagram of the 10 Mbit/s CFO-SS with a CW jamming, respectively. The CW jamming is located at the center frequency of the CFO-SS signal with relative power of 0 dB at the relative frequency of 11 MHz. The total signal to CW power ratio is set to be 7 dB. The degradation in the eye diagram is negligible.

2) Figure 3.30 shows the simulation results when the C/I is changed from 1 dB to 4 dB. BER of 10^{-5} is maintained when the C/I is larger than 2.8 dB and 3.5 dB for the 6 and 10 Mbit/s CFO-SS, respectively.

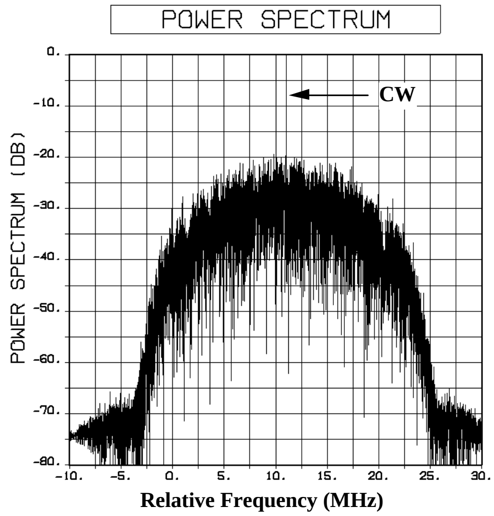


Figure 3.28 Spectrum of the 10 Mbit/s CFO-SS signal with a CW jamming (C/I=7 dB).

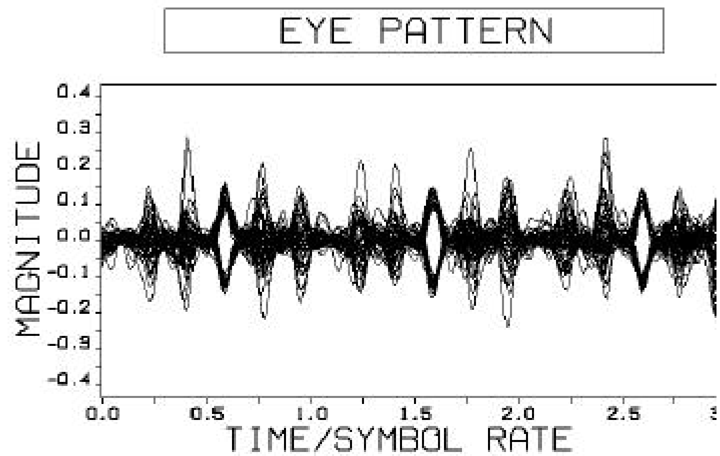


Figure 3.29 Eye diagram of the 10 Mbit/s CFO-SS with a CW jamming in the center frequency (C/I=7 dB).

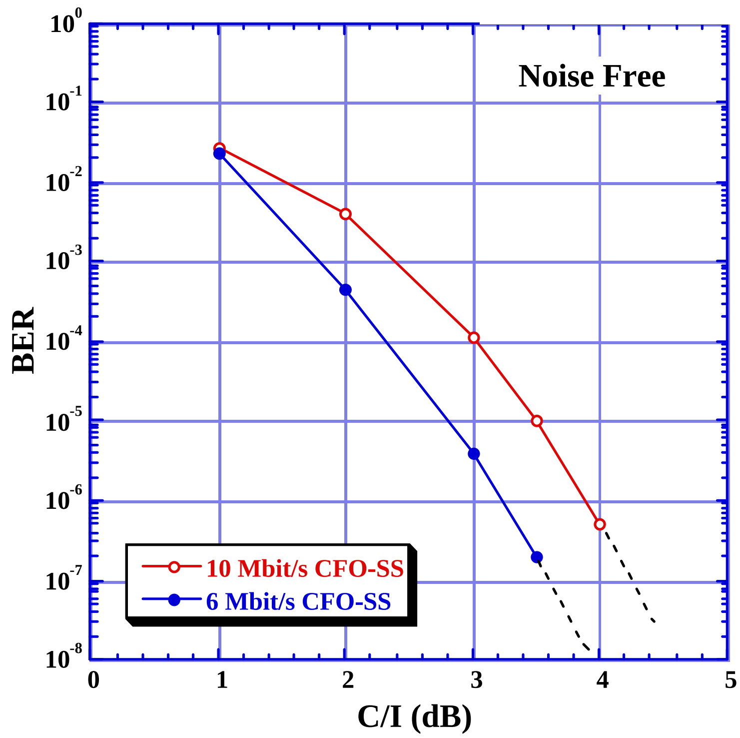


Figure 3.30 BER performance of the 10 Mbit/s CFO-SS with a CW jamming in the center frequency.

3.5 Critical Points

3.5.1 Extreme sensitivity to phase noise:

1) Phase noise generated by a conventional hardware is not critical for the CFO-SS.

3.5.2 Power consumption (DC) relative to the low rate PHYs:

1) DC power consumption of the five RF/IF transceivers are less than five times that of the current low rate transceiver, since one clock acquisition and tracking circuit is shared by five transceivers.

3.5.3 Complexity:

1) Hardware architecture is simple.

2) An oscillator with an accuracy of +/-25 ppm is sufficient.

3) AGC_s with a wide dynamic range (~ 80 dB) is required.

3.5.4 RF PA backoff:

1) Each 2 Mbit/s RF/IF transceiver shall employ an independent PA to avoid intermodulation problems.

2) Alternatively, a PA amplifying all the carriers with sufficient back-off can be employed, ensuring a linear operation.

3) Hybrid of 1) and 2) is also available as shown in clause 3.1.1.

3.5.5 Dependence on antenna diversity/directivity:

1) A conventional antenna diversity shall be adequate to improve the channel quality.

2) Directive antennas shall be used for long range point-to-point systems.

3.6 Intellectual property

3.6.1 KDD's position:

KDD follows the IEEE Patent Policy set forth in Clause 5 of the IEEE Standards Board Bylaws.

3.6.2 Applicable patent numbers:

1) US Patent number: 5,319,672. M. Sumiya and H. Shinonaga, "Spread Spectrum Communication System.", Jun. 7, 1994.

2) One Japanese patent had been authorized.

3) Three Japanese and two (soon three) US patents are pending.

3.6.3 Point of contact:

Shouzou Hikasa, Network Planning Department, Network Headquarters, KDD.
(TEL:+81-3-3347-5371/FAX:+81-3-3347-6362)
(E-mail:sh-hikasa@kdd.co.jp)

3.7 Interoperability / coexistence

3.7.1 Interoperability at the data level:

1) The CFO-SS system is backward compatible with the current low rate PHY at the data level, since the CFO-SS transceiver basically consists of five transceivers of the current low rate PHY_s.

2) The CFO-SS can work with the data rate of 1, 2, 4, 6, 8 and 10 Mbit/s. The data rate can be notified to the receive side through the "SIGNAL" field for the preamble. Additional cost associated with the interoperability at the data level is negligible.

3.7.2 Interoperability at the antenna level:

1) The CFO-SS system is backward compatible with the current low rate PHY at the antenna level, when the flexible channelization plan in clause 3.4.1 (B) is employed.

2) The CSMA/CA protocol need not to be changed. Additional cost for the interoperability is negligible, since the interoperability is inherent characteristics to the CFO-SS.

3.7.3 Identify low rate PHY(s)

1) The CFO-SS terminal identifies the transmission rate by recognizing the preamble data of each packet, and sets its transmission rate to be compatible with the transmit side.

3.7.4 Elaborate on migration path assumptions from the low rate PHY(s), include details on any dual schemes (i.e. fast vs. low rate preamble) .

1) A special migration scenario is not required, since the CFO-SS system sets its transmission rate among 1, 2, 4, 6, 8, and 10 Mbit/s by selecting the number of channels multiplexed.

2) When a CFO-SS terminal operated under the flexible channelization plan is used as an Access Point (AP), the CFO-SS terminal shall send control frames with a basic

transmission rate so that the current low rate PHY can receive and decode the control data. When a current low rate terminal makes an access to the CFO-SS terminal, the CFO-SS terminal sets its transmission rate down to 1 or 2 Mbit/s to communicate with the low rate terminal. Figure 3.31 shows the above procedure for interoperability.

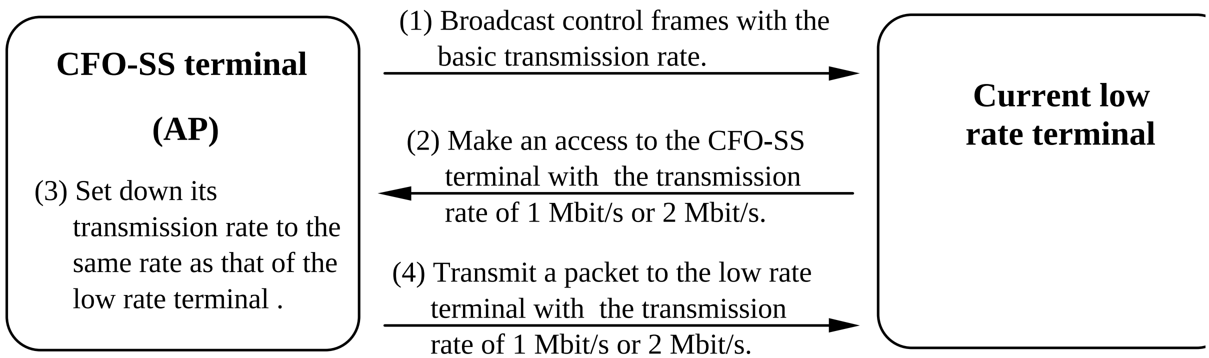


Figure 3.31 Procedure for interoperability when current low rate systems make an access to CFO-SS system.

3) When a low rate terminal is used as an AP, a CFO-SS terminal operated under the flexible channelization plan receives control frames, and sets its transmission rate to the 2 Mbit/s (alternatively, 1 Mbit/s). Figure 3.32 summarizes this procedure.

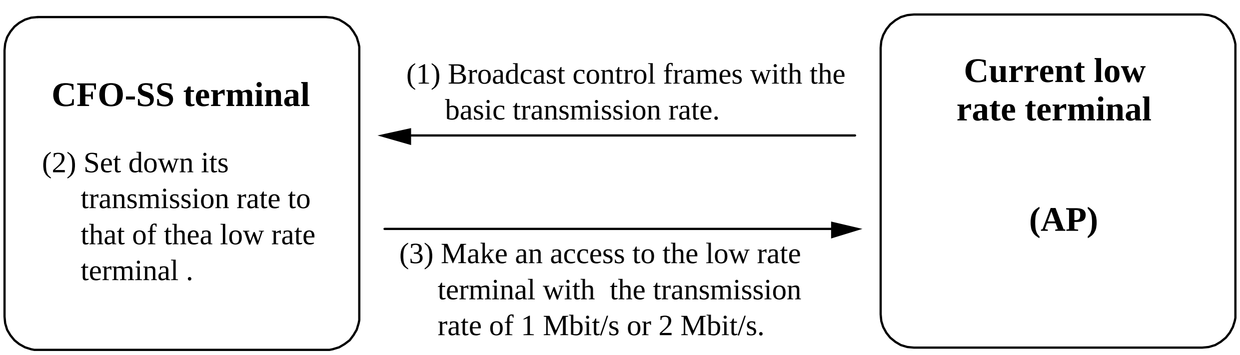


Figure 3.32 Procedure for interoperability when CFO-SS systems make an access to low rate system.

3.7.5 Co-existence:

1) The CFO-SS can coexist with the current low rate 2.4 GHz PHYs by detecting and setting the transmission rate.

2) The CFO-SS does not force any change of the current MAC protocol.

3) No additional cost is required for co-existence.

4. Summary

4.1 General description:

Modulation Technique	CFO-SS (Carrier Frequency Offset-Spread Spectrum): CFO-SS is a kind of multicarrier synchronous DS/SSMA, composed of orthogonaly multiplexed multiple current low rate carriers.
Data Rate(s)	• 1 Mbit/s (DBPSK) • 2 Mbit/s (DQPSK) • 4 Mbit/s (Two channel multiplexed CFO-SS) • 6 Mbit/s (Three channel multiplexed CFO-SS) • 8 Mbit/s (Four channel multiplexed CFO-SS) • 10 Mbit/s (Five channel multiplexed CFO-SS)
Sensitivity	• -80 dBm (Typical) for 10 Mbit/s CFO-SS @PER=10% • -82.2 dBm (Typical) for 6 Mbit/s CFO-SS @PER=10% • -87 dBm (Typical) for 2 Mbit/s CFO-SS @PER=10% • The above sensitivity can further be improved by adopting a LNA with lower NF.
Reference submissions	• Doc.:IEEE P802.11-98/01, "Carrier Frequency Offset-Spread Spectrum (CFO-SS) Scheme for Higher Speed 2.4 GHz PHY" • Doc.:IEEE P802.11-98/79, "Compliance document for the 2.4 GHz CFO-SS PHY proposal" • Doc.:IEEE P802.11-98/80, "Draft Specifications of Carrier Frequency Offset-Spread Spectrum Physical Layer for the 2.4 GHz ISM Band." • Doc.:IEEE P802.11-98/81, "Intellectual property statement of KDD."

4.2 Receiver structure:

Receiver structure description	• 10 Mbit/s CFO-SS transceiver basically consists of five RF/IF transceiver units of the current low rate PHY. One clock acquisition and tracking circuit is shared by the five RF/IF transceiver units. • SAW matched filters or digital matched filters are used to correlate the SS signal.
RF/IF complexity relative to current low rate PHYs.	• The RF/IF transceiver unit basically consists of five units of the low rate PHY_s.

	• Only one clock timing acquisition and tracking circuit is required, which is shared by the five RF/IF transceiver units. • The front-end RF unit additionally requires a power divider and a combiner to treat five channels.
Baseband processing complexity. relative to current low rate PHYs. (Gate Count, MIPS)	• Baseband processing is basically the same as the low rate PHY with the exception that up to 10 Mbit/s data rate should be treated. • Clock recovery and tracking method is based on conventional methods. Details were described in Doc:IEEE P802.11-98/01. • ASIC: 20k~30k gates
Equalizer Complexity and performance impact (if applicable).	• The CFO-SS does not require a special equalizer. • Under severe multipath fading conditions, a RAKE receiver is adequate to improve the performance.
Antenna Diversity and performance impact.	• A conventional selection diversity technique is adequate, if employed. The current IEEE 802.11 preamble and slot time are adequate.

4.3 Multipath and Noise performance:

Graph of PER vs. multipath rms delay spread (no noise). Delay spread @ 10% PER for 64 and 1000 byte packets.	**(without RAKE receiver: Graphs shown in Fig. 3.7 (a) (b) of Doc. :IEEE P802.11-98/79)** • 10 Mbit/s CFO-SS: 20 nsec for 64 Byte packet. 15 nsec for 1000 Byte packet. • 6 Mbit/s CFO-SS: 60 nsec for 64 Byte packet. 50 nsec for 1000 Byte packet. **(with three finger RAKE receiver: Graphs shown in Fig. 3.8 (a) (b) of Doc. :IEEE P802.11-98/79)** • 10 Mbit/s CFO-SS: larger than 300 nsec for 64 Byte packets. up to 300 nsec for 1000 Byte packets. • 6 Mbit/s CFO-SS: larger than 300 nsec for 64 Byte packets. larger than 300 nsec for 1000 Byte packets.
Graph of PER vs. thermal noise w/ multipath @ 10% PER. Eb/No @ 20% PER for 64 and 1000 byte packets.	**(without RAKE receiver: Graphs shown in Fig. 3.7 (a) (b) of Doc. :IEEE P802.11-98/79)** • 10 Mbit/s CFO-SS with T_{RMS}=15 nsec: 18 dB for 64 Byte packet 21 dB for 1000 Byte packet • 6 Mbit/s CFO-SS with T_{RMS}=45 nsec: 17.5 dB for 64 Byte packet 21 dB for 1000 Byte packet

	(With three finger RAKE: Graphs shown in Fig. 3.8 (c) of Doc. :IEEE P802.11-98/79) • 10 Mbit/s CFO-SS with T_{RMS}=300 nsec: 12~13 dB for 64 Byte packet up to 18 dB for 1000 Byte packet • 6 Mbit/s CFO-SS with T_{RMS}=300 nsec: up to 10 dB for 64 Byte packet up to 15 dB for 1000 Byte packet
Graph of PER vs. thermal noise (no multipath). Eb/No @ 10% PER for 64 and 1000 byte packets.	**(without RAKE receiver: Graphs shown in Fig. 3.9 of Doc. :IEEE P802.11-98/79)** • 10 Mbit/s CFO-SS: 10.0 dB for 64 Byte packet 11.6 dB for 1000 Byte packet • 6 Mbit/s CFO-SS: 9.8 dB for 64 Byte packet 11.4 dB for 1000 Byte packet

4.4 Carrier and Data frequency accuracy:

Required Carrier frequency accuracy.	• 10 Mbit/s CFO-SS: +/-25 ppm (Δf= +/- 60 kHz) • 6 Mbit/s CFO-SS: +/-35 ppm (Δf= +/- 85 kHz)
Degradation at worst case carrier frequency offset.	• 10 Mbit/s CFO-SS: BER of 10^{-7} @Δf= +/- 60 kHz • 6 Mbit/s CFO-SS: BER of 10^{-7} @Δf= +/- 85 kHz
Data clock frequency accuracy.	Same as the current low rate PHY
Degradation at worst case data clock frequency offset.	Same as the current low rate PHY

4.5 Overhead related parameters:

Preamble length	• 128 bits for synchronization is sufficient for the CFO-SS under typical indoor multipath fading environments, the length being the same as the current low rate 2.4 GHz PHY. • The RAKE receiver, if employed, requires additional preamble data (20~30 symbols) to precisely estimate the channel characteristics.
Does the preamble length include receive antenna diversity? Yes or no.	Yes (Antenna diversity does not affect the length of the preamble pattern.)
Does the preamble length include equalizer training? Yes or no.	No (No equalizer required)
Slot time.	Same as the current low rate PHY
CCA mechanism	Same as the current low rate PHY

description.	
Co-Channel signal detection time.	Same as the current low rate PHY
RX/TX turnaround time.	Same as the current low rate PHY
SIFS.	Same as the current low rate PHY (less than 10 microseconds)

4.6 Spectral efficiency, Cell density related parameters:

Channelization scheme	**(A) Rigid channelization plan** • For US ISM band, three channels are defined with the separation of 28 MHz. The center frequencies of three channels are selected to be 2.414 GHz, 2.442 GHz and 2.470 GHz. **(B) Flexible channelization plan** • Channel center frequencies of the current low rate PHY can also be supported by the CFO-SS for backward compatibility.
Cell planing scheme	• A CFO-SS terminal connected with the AP shall first search a vacant channel among candidate channels. When a scanned channel is busy, then the CFO-SS terminal searches a vacant channel among the other candidate channels. If all the candidate channels are used, the adjacent cells share the same channel on a CSMA/CA basis. • Channel selection can also be made manually.
Adjacent channel interference rejection.	• ACI is sufficiently suppressed by the SAW filters at the transmit side. 30dB attenuation is achieved at the points at f_c +/- 13 MHz. • 10 Mbit/s CFO-SS system can tolerate at least +30 dBc higher signal level at the adjacent channels.
Co-channel interference rejection.	• The CFO-SS employs the CSMA/CA protocol currently prescribed for the low rate PHY to avoid the co-channel interference. However, hidden terminals in the same area, if exists, would generate co-channel interference. • BER of 10^{-5} is maintained when C/I is larger than 12 dB for the 10 Mbit/s CFO-SS. • BER of 10^{-5} is maintained when C/I is larger than 8.5 dB for the 6 Mbit/s CFO-SS.
S/J where CW interference gives 10% PER.	• PER of 10% is maintained when S/J is larger than 3.0 dB for 10 Mbit/s CFO-SS. • PER of 10% is maintained when S/J is larger than 2.4 dB for 6 Mbit/s CFO-SS.
Other interference immunity tests.	None

Co-Channel signal detection time.	The same as the current low rate PHY
Total number of channels in 2.4GHz band.	Three
Aggregate throughput.	• 10 Mbit/s CFO-SS: Approx. 7 Mbit/s • 6 Mbit/s CFO-SS: Approx. 4.2 Mbit/s

4.7 Misc. critical performance factors:

Phase noise sensitivity	• Phase noise generated by a conventional hardware is not critical for the CFO-SS.
RF PA backoff	• Each 2 Mbit/s RF/IF transceiver shall employ an independent PA to avoid intermodulation problem. • A PA amplifying all the carriers, if employed, is required to be operated with sufficient back-off to ensure a linear operation.
DC power consumption	• DC power consumption of the five RF/IF transceivers is less than five times that of the current low rate transceiver, since one clock acquisition and tracking circuit is shared. • An A/D converter with a sampling frequency of up to 44 MHz is required for the clock timing acquisition and tracking circuit. This A/D converter and associated baseband processors might increase the DC power consumption as compared with the current low rate 2.4 GHz PHY.

.

4.8 Intellectual property:

Has the submission of the required IEEE letter covering IP been made? Yes or No	Yes
Applicable patent numbers	• US Patent number: 5,319,672. M. Sumiya and H. Shinonaga, “Spread Spectrum Communication System.”, Jun. 7, 1994. • One Japanese patent had been authorized. • Three Japanese and two (soon three) US patents are pending.
Point of contact	• Shouzou Hikasa, Network Planning Department, Network Headquarters, KDD. • TEL:+81-3-3347-5371/FAX:+81-3-3347-6362 • E-mail:sh-hikasa@kdd.co.jp

4.9 Interoperability and Coexistence:

Interoperability / Co-existence strategy with current low rate PHYs	• A special migration scenario is not required, since the CFO-SS is backward compatible with the current low rate PHY. • When a CFO-SS terminal operated under the flexible channelization plan is used as an AP, the CFO-SS terminal shall send control frames with a basic transmission rate so that the current low rate PHY can receive and decode the control data. After the low rate terminal makes an access to the CFO-SS terminal, the CFO-SS terminal sets its transmission rate down to 1 or 2 Mbit/s to communicate with the low rate terminal. • When a current low rate terminal is used as an AP, the CFO-SS terminal operated under the flexible channelization plan receives control frames from the low rate terminal, and sets its transmission rate to the 2 Mbit/s (alternatively, 1 Mbit/s). • The CFO-SS does not require any change of the current MAC protocol.
Is the proposal Interoperable at the data level?	• Yes • The CFO-SS data rate (1, 2, 4, 6, 8 or 10 Mbit/s) is notified to the receive side by the "SIGNAL" field of the preamble. • Additional cost associated with the interoperability at the data level is negligible.
Is the proposal Interoperable at the antenna level?	• Yes • The current CSMA/CA protocol need not to be changed for the CFO-SS 1, 2, 4, 6, 8, and 10 Mbit/s system.
Performance penalty due to Interoperability / Coexistence.	• A required frequency accuracy for the 10 Mbit/s CFO-SS is severer than that for the 6 Mbit/s CFO-SS. However, even for the 10 Mbit/s CFO-SS, the required frequency accuracy is +/- 25 ppm, which is the same requirement as the low rate PHY. • TX power of each multiplexed channel should be reduced as compared to the low rate PHY in accordance with the number of channels multiplexed. For example, the TX power of one multiplexed channel of the 10 Mbit/s CFO-SS should be reduced by 10 log 5 dB. However, nearly the same service area as the current low rate PHY is obtained, since the service area is mainly determined by the multipath environments not by E_b/N_0. • Additional cost for the interoperability or the co-existence is negligible, since the interoperability is inherent characteristics to the CFO-SS.