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| Abstract | This paper describes a new modulation technique known as frequency domain reciprocal modulation (FDRM) that has a characteristic of high immunity to dynamic multipath distortion. FDRM is a multicarrier transmission technology that is related to orthogonal frequency division multiplexing (OFDM). FDRM uses frequency domain reciprocal harmonic carriers to allow automatic cancellation of all linear distortion, random noise reduction, and improved channel characterization. Holtzman also proposes a dynamic mix of FDRM harmonic carrier pairs with OFDM harmonic carriers to allow the PHY standard to adapt to changing channel conditions. |
| Purpose | For Consideration as a physical layer technology for inclusion in the proposed 802.16.4 standard |
| Notice |  |
| Release |  |
| Patent Policy and Procedures |  |

# Frequency Domain Reciprocal Modulation for Channels with Dynamic Multipath

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**Introduction**

Single frequency carrier transmission systems, such as QPSK and 8-VSB, typically perform poorly in channels with severe dynamic multipath distortion for a couple of reasons. First, for single frequency carrier transmission systems to perform without intersymbol interference (ISI) the channels must be accurately equalized or "flattened". Adaptive equalizers can usually perform the necessary equalization, but the channel's frequency response must first be accurately characterized to determine the correct coefficients for the adaptive equalizers, and the adaptive equalizers must then be rapidly re-programmed. However, when the multipath is highly dynamic, single frequency carrier transmission systems fail because the channel can not be characterized fast enough to yield an accurate solution for the channel condition. This problem is greatly aggravated by the presence of random noise in the channel. Second, in the case of multipath with deep spectral fades, there may be no practical equalizer solution that results in low ISI. For example, if the channel fades to near zero at some frequency the equalizer must provide a huge gain at that same frequency. If there is random noise present in the channel, the noise at that frequency will also receive a huge amplification, creating ISI.

Multicarrier transmission systems, such as OFDM, are block transmission systems that can solve these transmission problems. Multicarrier transmission systems transform blocks of high speed time-domain symbols into blocks of slow-speed frequency-domain harmonically-related carriers (HCs). If a guard interval (or cyclic extension) is formed on the block transmission, and if the guard interval is longer than the longest echo in the channel, all ISI between HCs can be eliminated. If there is a deep fade at some frequency, a few of the HCs may be lost, but forward error correcting codes (FEC) can be used to correct the errors caused by a small number of lost HCs. Although the ISI between HCs is eliminated, each HC must be multiplied by a single magnitude and phase correction coefficient to restore the HC's magnitude and phase to the correct values. Typically an interleaved subset of HCs are made into static pilots that are incorporated into the transmitted block to assist in the determination of the magnitude and phase correction factors that each HC should use. If the channel's frequency response changes relatively slowly in frequency between pilot HCs, the pilot's values can be interpolated for the correction factors.

OFDM is an excellent transmission system, but there are a few weaknesses with this system. First, if the channel is noisy, random noise will contaminate each HC as well as the pilot HC. The noise on the pilot HC will result in an incorrect correction coefficient for all of the HCs that rely on the accuracy of its value. Thus, if the pilot is at the same level as the HCs, there is a 3 dB random noise penalty on each HC because the pilot HCs is also affected by random noise. Second, use of a pilot represents lost bandwidth. Third, the guard interval also represents lost bandwidth. Fourth, relative to single frequency carrier systems, OFDM transmissions produce large voltage spikes that clip active devices. OFDM has a peak to average power ratio that is higher than equivalent single frequency carrier systems.

Frequency domain reciprocal modulation (FDRM) is a new multicarrier transmission system. FDRM is an OFDM-like technique that offers an advantage in microwave frequency channels afflicted with dynamic multipath. In a first implementation, a single block transmission is used. The odd-numbered HCs are unique symbols, and the even-numbered HCs are made into frequency-domain reciprocals of their adjacent odd-numbered HCs. This new modulation technique essentially employs correlated data on adjacent HCs to cancel the effects of all linear distortion. Cancellation of all linear distortion is an intrinsic property of this new modulation technique. The effects of rapid fades are also canceled automatically by FDRM. Additionally, FDRM is useful for transmission of bursty data packets because a demodulation process is simplified by using two blocks of data.

In a second two-block transmission implementation, a first block of data is immediately followed by a second block which is a reciprocal of the first block in the frequency domain. The first block may be viewed as simply a special type of OFDM, and the second block may be described as having all HCs that are reciprocals in the frequency domain of the corresponding-frequency HCs in the first block. By sending the blocks sequentially, approximately the same set of echoes are applied to both blocks and the echoes are canceled when the two blocks are processed together.

FDRM offers several advantages in point to multipoint wireless services, but its strongest assets are its adaptability to rapidly changing channel conditions, a 3 dB improvement in noise performance over OFDM, and its suitability to infrequent bursty transmissions.

References [1]-[4] are other publications on FDRM.

**OFDM Primer**

Before describing FDRM it is useful to explain orthogonal frequency division multiplexing (OFDM) which is a similar technology. If you are familiar with OFDM, you may want to read this section because it leads into to a discussion of FDRM.

Although OFDM was invented in the late 60's, it has been made a practical transmission method with the coming of the digital signal processor (DSP) which can perform a discrete FFT operation very quickly. OFDM is a block transmission method that is in wide use for a variety of services, such as digital terrestrial television and audio broadcasting in Europe, coaxial cable telephony systems, and high speed telephone modems.

The OFDM signal may be transmitted as a baseband signal through a baseband channel such as telephone lines. Alternately, the OFDM signal may be modulated onto a radio frequency (RF) carrier using single, double, or vestigial sideband modulation for transmission over a RF or microwave channel. When using double sideband modulation, the real components are used to modulate the inphase channel and the imaginary components are used to modulate the quadrature channel. This allows different information to be carried in the upper and lower sidebands.

A transmitted data block is made up of many harmonic carriers (HCs) at different frequencies that can be accurately distinguished from each other at the receive site because the HCs are orthogonal to each other. Orthogonality is achieved because the individual HCs (which are cosine waves) comprising the composite signal are integer multiples of a fundamental frequency. Information is conveyed by assigning different discrete values to the magnitudes and phases of the individual HCs. For example, if E(t) is an OFDM transmission with only four HCs, it may be represented as:

$$E(t) = A_1 \cdot \cos(\omega t + \phi_1) + A_2 \cdot \cos(2\omega t + \phi_2) + A_3 \cdot \cos(3\omega t + \phi_3) + A_4 \cdot \cos(4\omega t + \phi_4) \tag{1}$$

The magnitudes of $A_n$ may take on values such as 1.33 or 0.75 and the phase may take on values such as 45, 135, -45, or -135 degrees. The index variable n is the HC number. The magnitude and phase angle comprise the coefficient of a HC. In practice, hundreds or even thousands of individual HCs make up an OFDM transmission.

Figure 1 is a time domain plot of a 4-HC waveform with each of the individual HCs plotted, as well as the sum of the 4 individual HCs. This waveform, comprised of 4 summed HCs, is referred to as a normal (N) data block.

Figure 1 has another feature: a guard interval (GI) has been formed by copying a number of microseconds from the end of the transmission block and attaching the samples onto the beginning. The guard interval is also described as a 'cyclic extension'. If the time duration of the guard interval is slightly longer than the duration of the longest echo that afflicts the channel, the echo can be completely canceled in a noise-free channel. With conventional OFDM, an equalizer is still needed to cancel the effects of an echo, but it needs only to perform a single complex multiplication on each received HC's coefficient to correct the effect of the linear distortion.

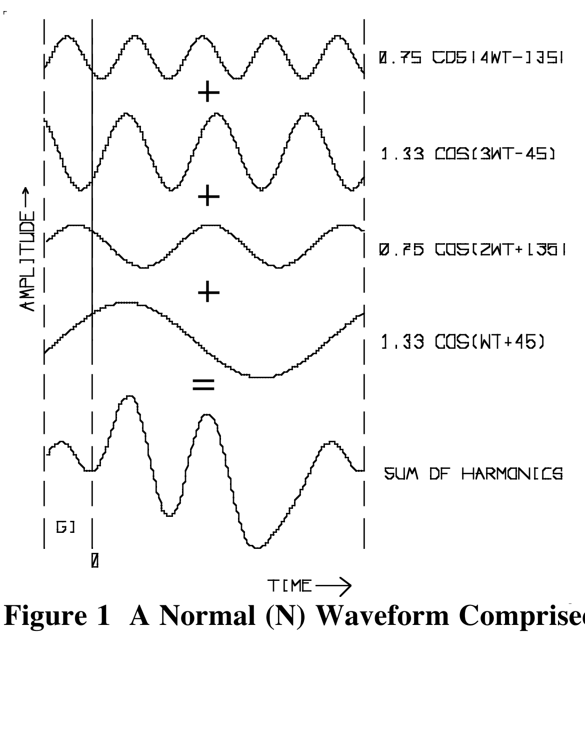



**Figure 1 A Normal (N) Waveform Comprised of 4 Harmonics in the Time Domain**

Figure 2 is a frequency domain (spectral) plot showing the 4 HCs of Figure 1 as 4 vertical spectral lines. The HC's magnitudes can be seen, and the HC's phases are printed above the HCs spectral lines.

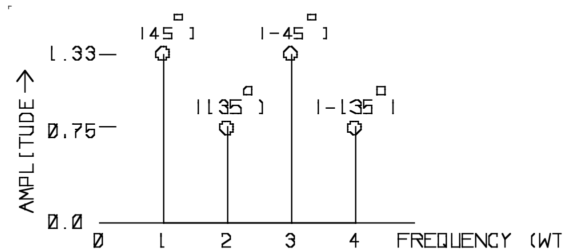



**Figure 2 The Four Harmonics of Figure 2 Viewed in the Frequency Domain**

As mentioned above, each HC needs to be multiplied by a single complex coefficient to cancel any echoes. To assist in determining each correct coefficient, a set of pilot HCs with predetermined magnitude and phase values is typically used. An estimate of the linear distortion on each HC can be computed by measuring linear distortion on the pilot HCs and interpolating for the data HC frequencies. A set of pilot HCs may be viewed as a training or reference signal for OFDM.

**Frequency Domain Reciprocal Modulation**

As mentioned in the introduction section, there are two implementations of FDRM: a single block with interleaved reciprocals HCs, and two block implementation with the reciprocal HCs all located in the second block. For clarity, the following explanation first describes the two-block implementation. The discussion of the single block implementation, with its advantages and disadvantages follows later.

**Two-Block FDRM**

Holtzman's new FDRM modulation is based on two consecutive blocks of data that contain the same information but use different encoding. The first block is similar to normal (N) OFDM with the restriction that low-valued magnitudes are not used for HCs. The second block is a "reciprocal" (R) in the frequency domain to the first block. A reciprocal block is formed by a complex division of the magnitude and phase of each HC in a normal OFDM block into 1.0 at an angle of 0 degrees. The computed reciprocal coefficients are used for the corresponding same-frequency HCs in the reciprocal block.

The two blocks are sent out in adjacent time slots so that approximately the same echo is applied to both blocks. At the receive site each HC from a reciprocal block is divided into the corresponding HC in the normal block, and a square root is performed on the quotient. This process yields the transmitted data without linear distortion, as will be explained. Thus, echo cancellation is an inherent property of FDRM.

**A Reciprocal Example**

Assume a 127th HC in a first normal block with a frequency of 127,000 Hz is sent with a magnitude of 2.0 at a phase of +60 degrees. A corresponding 127th HC, also with a frequency of 127, 000 Hz, in the reciprocal block will have a magnitude of 0.5 at a phase of -60 degrees. In general a reciprocal block has a similar noise-like appearance to the normal block from which it is derived. In a special case, when all HCs have the same amplitude, the reciprocal block appears to be the normal block played backwards in time.

**De-ghosting with Two Data Blocks**

Figure 3 features a reciprocal (R) data block to the OFDM transmission illustrated in Figure 1. Each HC comprising the reciprocal sum signal is the reciprocal of the HC with the same frequency in Figure 2. Remember that the reciprocal of a complex number is computed by dividing the magnitude component into 1.0 and changing the sign on the phase angle component. Note that if the magnitude was larger in Figure 1 for a given HC, it is smaller in Figure 3. Likewise, if the phase angle of a HC is positive in Figure 1, it is negative in Figure 3, and vice-versa. Figure 4 is a frequency response plot of the reciprocal data block.

Note that to avoid a division by zero problem, it is necessary that the coefficients in the normal block not have zero or near-zero magnitudes. If a signal such as a burst transmission of conventional single carrier frequency 16 QAM were examined in the frequency domain, some of the coefficients would likely have very low valued magnitudes. Thus, some of its reciprocal coefficients would be huge, making an impractical signal for transmitting over physical channels. OFDM has the necessary property of controlled magnitudes in the frequency domain.

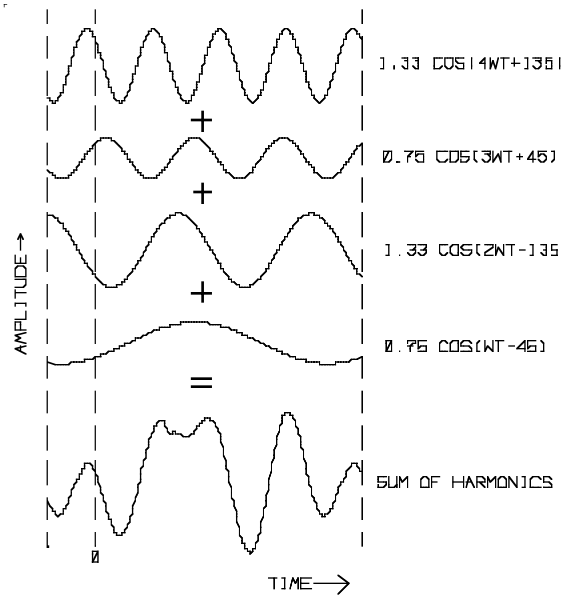



**Figure 3 A Reciprocal (R) Waveform Comprised of Four Harmonics. The Harmonics are the Reciprocals of the Harmonics at the Same Frequency Illustrated in Figure 2**

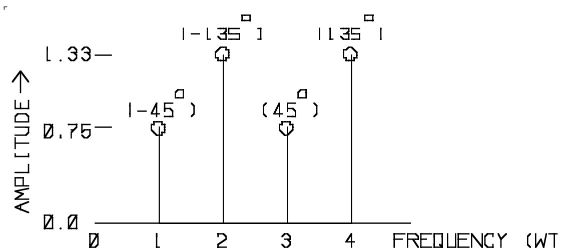



**Figure 4 The Reciprocals of the Four Harmonics of Figure 3, Viewed in the Frequency Domain.**

**Operation**

Assume a transmitted signal block is S( $f$ ) in the frequency domain and a channel's frequency response is H( $f$ ). The variable $f$ represents discrete frequency steps. The transmitted signal block may be a burst of OFDM (orthogonal frequency division multiplex) modulation which is comprised of multiple harmonically-related carriers (HCs). The normal received signal is:

$$X(f) = S(f) \cdot H(f) \qquad (2)$$

If a reciprocal signal block is created:

$$R(f) = \frac{1}{S(f)} \qquad (3)$$

and sent through the same channel the received reciprocal signal will be:

$$Y(f) = R(f) \cdot H(f) = \frac{H(f)}{S(f)} \qquad (4)$$

The undistorted signal can be found by dividing the received reciprocal block into the normal block and performing a square root on the quotient:

$$S(f) = \sqrt{\frac{X(f)}{Y(f)}} = \sqrt{\frac{S(f) \cdot H(f)}{\frac{H(f)}{S(f)}}} = \sqrt{S(f)^2} \qquad (5)$$

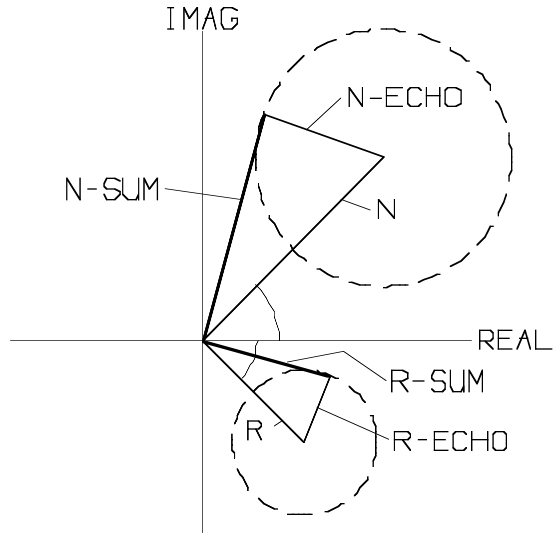



**Figure 5 A Carrier, Its Reciprocal, and an Echo Distorting Both**

**A Processing Example**
Refer to Figure 5 for a vector diagram of illustrating how an echo is canceled using two HCs.

Assume a N harmonic carrier at some frequency is transmitted with a magnitude of 1.333 at an angle of +45 degrees.

$$S_N(t) = 1.333\cos(\omega t + 45) \quad \text{[labeled as 'N']} \tag{6}$$

Therefore, the R harmonic carrier at that same frequency will have a magnitude of 0.75 at an angle of -45 degrees.

$$R = S_R(t) = 0.75\cos(\omega t - 45) \quad \text{[labeled as 'R']} \tag{7}$$

Assume an echo with amplitude 0.5 at an angle of 115 degrees identically contaminates both the N and R harmonic carriers.

$$H = 1.0@0\,\text{deg} + 0.5@115\,\text{deg.} \quad \text{or} \tag{8}$$

$$H = 0.909@29.88\,\text{deg.} \tag{9}$$

After reception, the received N harmonic carrier will be the vector sum of the $S_N(t)$ and its echo signal (labeled as N-ECHO). N-ECHO is the product of $S_N(t)$ and the echo. Therefore the received N harmonic carrier's coefficient is:

$X_N$=1.212@74.88 deg. [labeled as 'N-SUM'] (10)

The received R harmonic carrier will be the vector sum of the $S_R(t)$ and its echo signal (labeled as R-ECHO). R-ECHO is the product of $S_R(t)$ and the same echo. Therefore, the received R harmonic carrier's coefficient is:

$Y_R$=0.682 @-15.12 deg. [labeled as 'R-SUM'] (11)

The received N harmonic carrier's coefficient divided by the received R harmonic carrier's coefficient is:

$$X_N \cdot \frac{1}{Y_R} = S_N{}^2 = 1.777@90\,\text{deg.} \tag{12}$$

The originally transmitted harmonic carrier's coefficient was therefore 1.33 (square root of 1.769) at 45 degrees (half of 90), which is the correct answer.

$$S_N = 1.333@45\text{deg.} \tag{13}$$

Likewise, the channel's frequency response can be determined by multiplying X(f) by Y(f):

$$X(f) \cdot Y(f) = S(f) \cdot H(f) \cdot \frac{H(f)}{S(f)} = H(f)^2 \tag{14}$$

so the channel's frequency response is:

$$H(f) = \sqrt{H(f)^2} \tag{15}$$

Continuing with the earlier example,

$$H(f) = \sqrt{U_N(f) \cdot U_R(f)} = 0.909@29.88\,\text{deg} \tag{16}$$

which is the frequency response when contaminated with an echo.

If the channel has slowly moving echoes, reciprocal blocks can be sent infrequently, or sent sparsely in the time domain. The channel's frequency response data, H(f), may be used to provide echo correction for normal blocks that do not have reciprocal blocks accompanying them. Echo cancellation is accomplished by dividing each normal block HC by H(f). Likewise, if neighboring HCs have nearly the same echo, reciprocals HCs can be used sparsely in the frequency domain.

The frequency response data can also be used to compute an impulse response of the channel by performing the inverse fast Fourier transform (IFFT) on the set of coefficients, H(f). The impulse response then may be used to program a conventional adaptive equalizer. If the channel's frequency response is slowly changing and the level of random noise is high, time averaging of coefficients can be used to improve the accuracy of the characterization of the channel.

**Single Block FDRM**

Another way to use FDRM is to interleave normal and reciprocal harmonic carriers within the same block. Thus the reciprocal value to a harmonic carrier can be located at the next adjacent harmonic carrier frequency. With this technique odd numbered HCs could use normal coefficients and the even numbered HCs could use reciprocal coefficients. In other words, instead of transmitting a N data block followed by a R data block, a single data block comprised of alternating N and R harmonic carriers is transmitted. For example, the spectral order of the first 10 HCs in a single block transmission may be:

N1, R1, N2, R2, N3, R3, N4, R4, N5, R5 ......

where N1 is the first N HC and R1 is the first R HC, N2 is the second N HC and R2 is the second R HC etc.

This variant of the basic idea can be successfully used if approximately the same echo is applied by the signal path to two HCs that are at adjacent frequencies. This commonly occurs in practical channels, and depends on the duration of the echoes relative to the frequency separation between adjacent HCs. One advantage of the single block FDRM over two block FDRM is that rapidly changing multipath will change less over a one block duration than over a two block duration, making the assumption that the echo did not change over the relevant capture period twice as valid. Another advantage of single block FDRM is that total guard interval time is halved.

**Test Results from Hardware:** Figure 6 is a hardware block diagram of prototype hardware that has been used for demonstrations and tests in the past. The bandwidth is lower than for the present proposal, but the number of HC is roughly similar. The hardware illustrates the principle of operation. A normal burst signal interleaved with a reciprocal burst signal were created using random data and stored in a programmable read-only memory (PROM) as 300 discrete harmonic carriers (HC) situated between 1 and 4 MHz. To create a transmitted burst, data are clocked through a digital-to-analog converter (D-A converter) and up-converted to 51-54 MHz. RF frequency. After passing through a dynamic multipath impaired channel with 500 deep fades/sec, the bursts were down converted back to the 1-4 MHz band. The samples were converted back into digital format by a data acquisition unit (A-D converter) and processed according to equation number (5) in a personal computer. Table 1 lists the parameters used for the demonstration hardware.

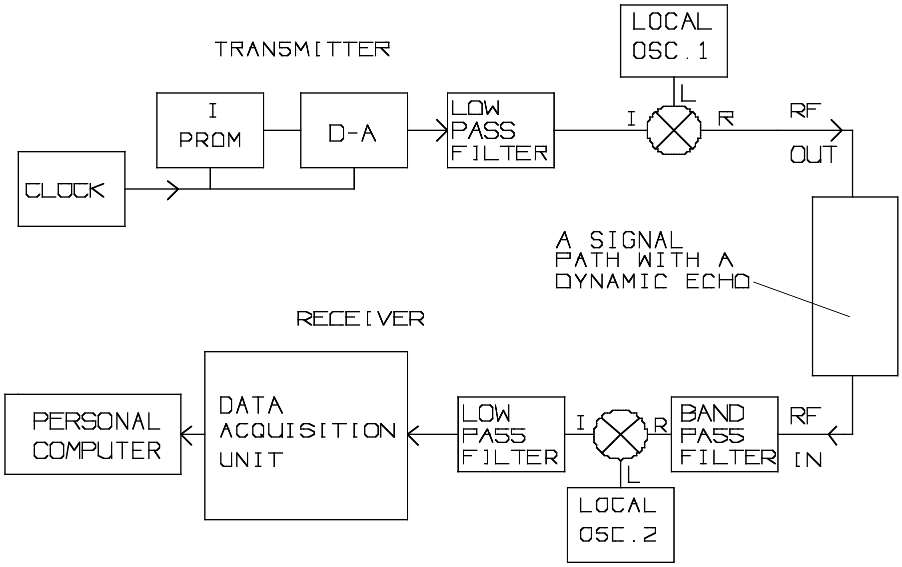



**Figure 6 Hardware Block Diagram**

**Table 1 Details of Demonstration Hardware**

| Parameter | Value |
|---|---|
| Sample Rate | 10.0 M Samples/sec. |
| Each Block's Duration | 204.8 microseconds +GI |
| Guard Interval (GI) | 10.24 microseconds |
| Total Burst Duration | 215 microseconds |
| HC spacing | 4.883 kHz. |
| Occupied Bandwidth | 2.93 MHz. |
| Size of Fourier Transform | 2048 points |
| Number of HCs | 300 |

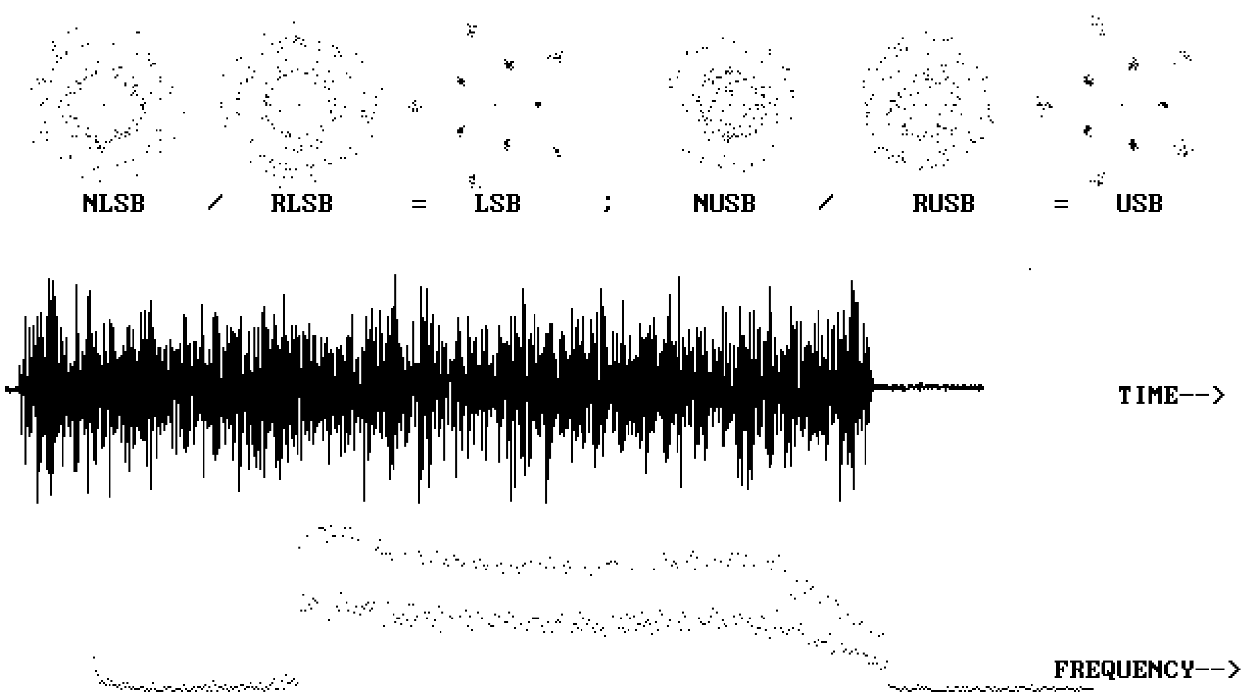



**Figure 7 A Processed 10 Point Constellation FDRM Burst with Linear Distortion and Noise**

Figure 7 is a screen plot showing the hardware results of an analysis of a burst transmission of a FDRM burst using a 10 point constellation. The second row down illustrates the interleaved transmitted normal and reciprocal signals as a time-domain trace. The bottom trace is a spectral plot showing the effects of noise and a channel tilt. The higher magnitude HCs can be distinguished in the spectral plot. The processed upper and lower sidebands are separated for illustration.

The NUSB points (upper sideband normal constellation points) and the RUSB points (upper sideband reciprocal constellation points) are processed together to produce the USB plot. Likewise, the NLSB points (lower sideband normal constellation points) and the RLSB points (lower sideband reciprocal constellation points) are processed together to produce a LSB plot. Each point in a N constellation is divided by the same frequency point in the R constellation to produce the corrected constellation. Note that point spread in the constellation due to noise is higher when the amplitude of the HC is lower.

**Changing Echoes**
Two models of fading that are most applicable are typically Ricean fading and Raleigh fading. FDRM works well for both. For a channel with rapid fading, FDRM works very well because the fade affects both the normal and reciprocal HCs. Hence the affect of the fade is canceled automatically. Thus an automatic gain control circuit does not have to have a fast response or an accurately set level. A good practice for AGC circuits receiving FDRM bursts is to allow a change in gain in steps that coincide with the end of a block sequence. The function of the AGC is to use as much of the dynamic range of the analog to digital converter without overloading it.

**Deep Fades**
It is possible for the combination of echoes in a channel to produce a deep fade over some portion of the frequency band. The HCs that are unfortunate enough to be located in the portion of the spectrum that is deeply faded will be hopelessly contaminated by any noise in the channel, and must be discarded. In this case, the use of well-known forward error correction techniques will allow the transmitted data to be received without error. What constitutes a "deep fade" depends on the level of the noise floor in the channel. Antenna diversity is another excellent solution because it is improbable that a particular frequency will be deeply faded on the same frequency on two antennas that are physically separated by an appreciable distance.

**Performance Near Threshold**: One might think that sending the HC twice in a different form would reduce the channel capacity by one-half. However the information in both HC's data is the same, and when the two blocks are processed together the signals add on a voltage basis (20 $\log_{10}$) while the noise contaminating each block of data is uncorrelated and adds on a power basis (10 $\log_{10}$). Thus the signal to noise ratio of the processed signal should be 3 dB better that either the signals in the N block or R block. Furthermore, since the two HCs form a virtual pilot per equation (6), the energy of the pilot signal is doubled, resulting is a 3 dB more accurate channel characterization relative to a static pilot signal without the energy doubling feature.

A received processed signal in the presence of noise is:

$$S(f) = \sqrt{\frac{S(f) \cdot H(f) + N_n(f)}{\frac{H(f)}{S(f)} + N_d(f)}} \qquad (8)$$

where $N_n$ is the random noise disturbing the first block and $N_d$ is the uncorrelated random noise disturbing the second block. Near threshold one might expect that the performance of FDRM may be poor because the $N_d$ term could cancel the signal from the second reciprocal block. Simulation shows that the 'division by almost zero problem' at low carrier to noise ratios is not a severe problem. This characteristic is common with other transmission systems using pilots: when noise gets on the pilot, the adaptive equalizer receives inaccurate programming.

**Phase Ambiguity**
One of the problems associated with performing the square root function at the receiver is ambiguity about the correct phase, since a square root has two possible solutions. Equation (5) employs the square root function. The phase may be incorrect because of an inexact start of sampling time, or because of transmitter's frequency or phase being unlocked relative to the receiver's, or because of group delay (which is a linear distortion). For example, a harmonic carrier received at $-135^{O}$ with a reciprocal at $+135^{O}$ is ambiguous: it could have also been transmitted as a carrier at $+45^{O}$ with a reciprocal at $-45^{O}$ and suffered a $180^{O}$ rotation. One solution is to transmit a single pilot frequency and track HC phase change versus frequency. This works for channels with Ricean fading. Another solution is to employ a constellation without $180^{O}$ rotational symmetry. This works for channels with Raleigh fading. Differential encoding between adjacent HC pairs may also be used.

Patents granted and pending. See [7]

**Replacing Pilots with Reciprocals**

FDRM can be used to improve the demodulation of conventional OFDM by converting OFDM pilots into reciprocal Hcs of adjacent carriers. This means that only a fraction of the total number of HCs will have reciprocals. The FDRM signal processing technique reduces the noise on the adjacent carrier by 3 dB and also reduces the noise on the channel characterization by 3 dB. The noise-reduced pilot can be used to deghost the other HCs that do not have an accompanying reciprocal

**Echoes**

Echoes on a signal present a severe problem to the transmission of digital information. The challenge from a technical standpoint is to determine how much energy must be expended to have accurate current information about the channel's response. Fortunately, the amount of energy that must be expended in many stationary wireless applications is a relatively small percentage of the total transmitted power because the echo is slowly-moving in time and/or because the echo changes relatively slowly with frequency. That is, neighboring frequency samples have nearly identical echo distortion. One may speak of the information rate that is associated with the channel's dynamic frequency response, although it is unlikely that anyone would understand what they were talking about. Two factors complicate this idyllic slow-moving situation for wireless signal paths: wind, which makes foliage reflectors/diffusers into sources of dynamic multipath, and infrequent or bursty transmissions, which allow slowly moving echoes to produce large relative changes in the frequency response during the long times between bursts.

If pilots or training signals are employed, and insufficient energy is used for pilots, the noise on the pilots will result both in a poor channel model, which gives noise enhancement in the corrected signal. <u>That is, a perfect channel characterization can never improve the receiver's carrier to noise ratio, but it a poor characterization can hurt it.</u>

As mentioned above, FDRM is an adaptable technology that allows HCs with accompanying reciprocal HCs to be spread thickly or thinly through the channel's passband. Reciprocal HCs can also be spread thickly or thinly through time. The thick use of reciprocals would be a reciprocal accompanying every normal HC in every block. A thin or sparse use of reciprocals would be a reciprocal in every 20th harmonic carrier in frequency and every 10th block in time. Holtzman is proposing the adaptive use of reciprocals depending on the dynamics of an individual subscriber's signal path.

**The Application of FDRM to Microwave Point to Multipoint for IEEE 802.16.4 and Physical Layer Problems in the 5 GHz Frequency Band**

**Holtzman's Proposal**

Holtzman proposes the incorporation of FDRM into the PHY layer of 802.16.4. If the problem of longer and dynamic echoes is attacked by adding more and more pilot carriers to a conventional OFDM transmission, additional capacity will be lost. Furthermore, if an OFDM harmonic carrier with a pilot at the same power is replaced with FDRM normal and a reciprocal carrier pair, the FDRM pair would have a 6 dB advantage with a random noise impairment. A three dB advantage would be achieved because of the FDRM voltage addition of the normal and reciprocal carriers, and another 3 dB advantage would be realized from the FDRM noise reduction in the channel characterization.

Specifically:

1. Holtzman recommends a mixed system where some of the HCs use OFDM modulation and some of the HCs are paired up to use FDRM modulation. Channel conditions determine a mix.

2. Holtzman recommends that the duration of the block be increased from 3.2 plus a 0.8 microsecond guard interval to 25.6 microseconds plus a 2.4 microsecond guard interval, as shown in Table 2. The longer guard interval should allow for outdoor operation up to several kilometers. The closer spacing of harmonic carriers is necessary to improve performance with longer echoes (which produce closer ripples in the frequency response).

3. Holtzman also recommends the use of adaptive transmissions on both the upstream and downstream paths. Adaptive transmissions mean that the number of points in a constellation, the number and amplitude of reciprocal HCs, the FEC code strength, possibly the duration of the guard interval all be made adjustable by the MAC layer. (COFDM allows the broadcaster to adjust many of the same parameters.) On days with high attenuation due to wet foliage, the transmissions will continue at a lower speed. On windy days with more dynamic multipath, FDRM pairs can be used until an OFDM transmission is completely converted into a FDRM transmission.

4. When channel fade is extremely severe, the total number of HCs can be reduced to allow more power to be transmitted in the remaining HCs.

**Table 2 Details of Holtzman Inc. Proposal**

| Parameter | Value |
|---|---|
| Sample Rate | 20.0 M Samples/sec. |
| Useful Block Duration | 25.6 microseconds +GI |
| Guard Interval (GI) | 2.4 microseconds |
| Total Block Duration | 28 microseconds |
| HC spacing | 39.0625 kHz. |
| Spacing Between Two Outermost HCs | 16.25 MHz. |
| Size of Fourier Transform | 512 points |
| Number of HCs | 208 USB + 208 LSB |

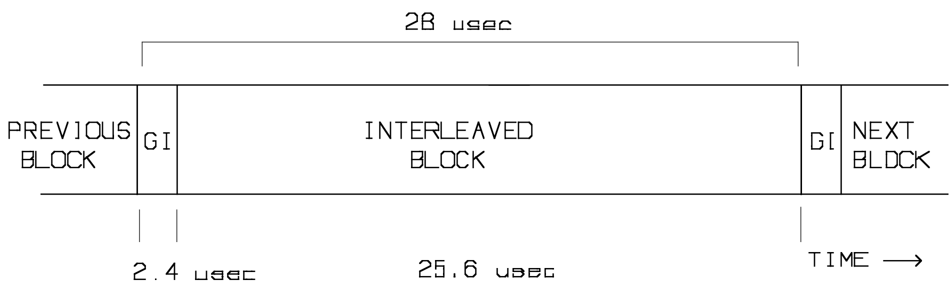



**Figure 8 Temporal Plot of Single Block Interleaved FDRM Transmission**

Figure 8 is a temporal plot of single block FDRM burst that may be used for transmissions. The normal and reciprocal harmonic carriers are interleaved with each other whereby each harmonic carrier has its reciprocal at an adjacent frequency. The burst is shown in outline form, but the actual waveform will have a noisy appearance similar to the temporal plot in Figure 7. A guard interval of 2.4 microseconds represents less than a 10% overhead. The transmission time of 28 microseconds is the duration over which a dynamic multipath will change very little.

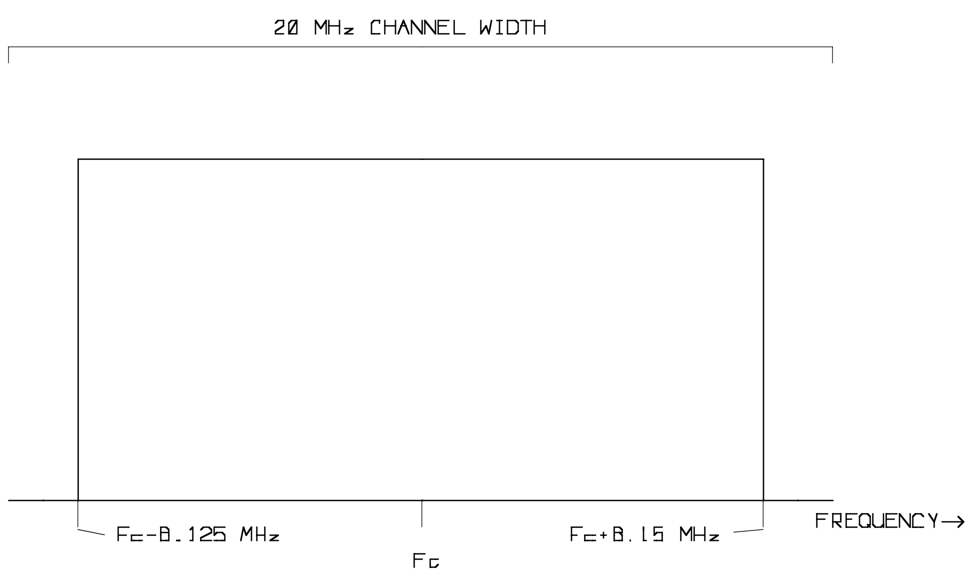



**Figure 9 Spectral Plot of FDRM**

Figure 9 is a spectral diagram of the Figure 8 burst with a 20 MHz channelization plan. The separation between harmonic carriers is 39.06 kHz and 208 N HCs reside between 208 R HCs in 16.25 MHz. The harmonic carrier at $F_c$ (DC) is not used.

Figure 11 is a set of constellation plots that exhibits desirable properties with FDRM. Note that as the number of points in a constellation decreases, immunity to random noise increases. The reciprocal constellation plots corresponding to these normal constellations is not illustrated, but can be easily created. These plots have two characteristics that should be pointed out. The first is that there are no constellation points near to the origin. This would create a high value point in the reciprocal constellation, which requires high dynamic range to transmit as mentioned earlier. The second feature is that 180 degrees opposite each point is a vacant area. This feature was employed to allow an easy resolution to the problem of two possible solutions to a square root function as discussed above.

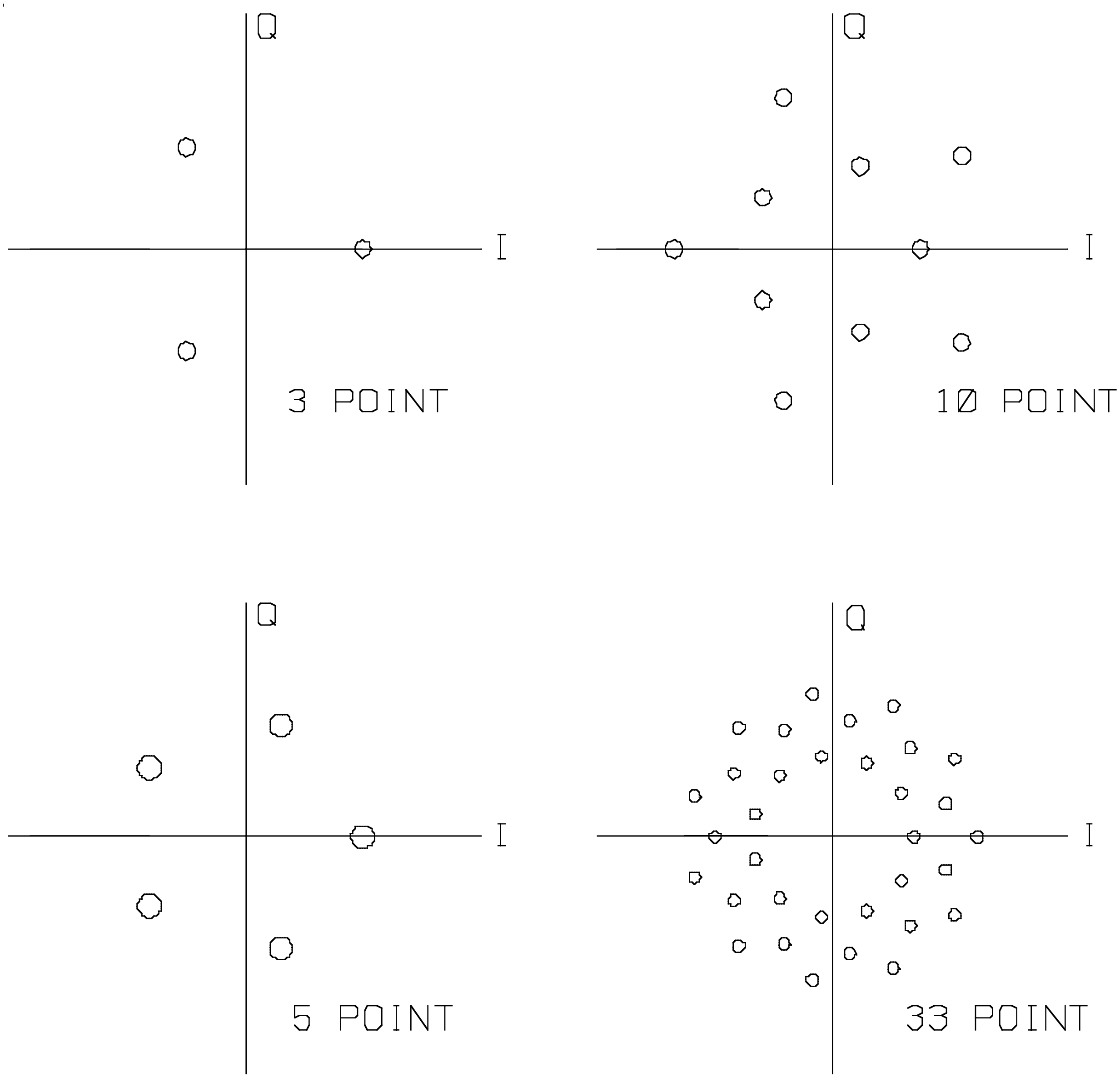



**Figure 11 Four Normal Constellations for Use with FDRM. Note that Constellations do not have 180 Degree Rotational Symmetry**

| Number of points in constellation N | Number of Bits / Symbol = log2(N) | Number of Symbols grouped for a binary conversion | Number of Bits per Conversion |
|---|---|---|---|
| 3 | 1.58 | 2 | 3 |
| 5 | 2.32 | 4 | 9 |
| 10 | 3.32 | 4 | 13 |
| 33 | 5.04 | 1 | 5 |

**Table 2**

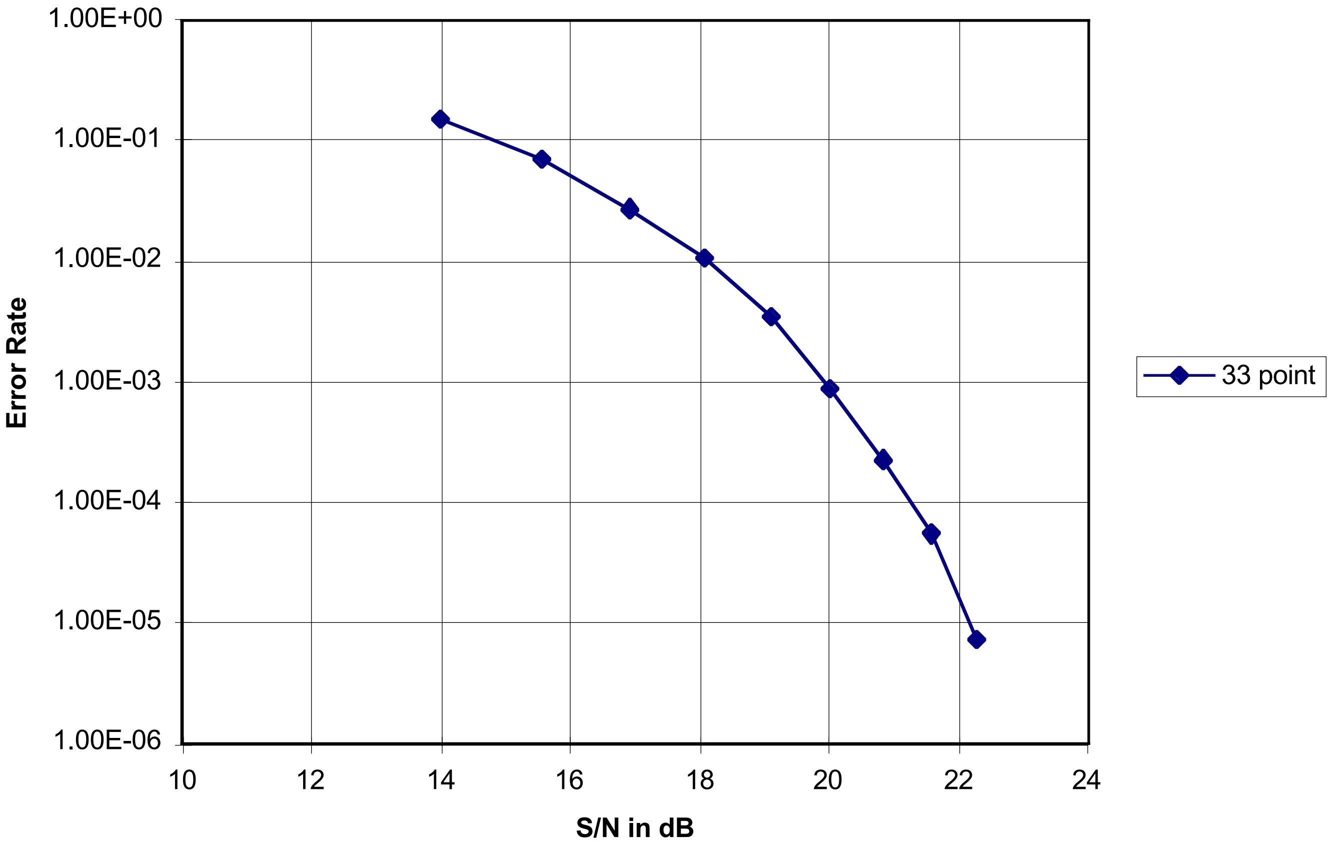
Because the number of symbols in a constellation is not a power of two raised to an integer power, the number of bits transferred by a single symbol is not an integer number. A solution is to read in multiple symbols until the fractional number of bits to be truncated is small. This is shown in Table 2. In the case of a 5 point constellation, the conversion from symbols to bits is done with a modulo 5 to binary conversion.

On the 33 point constellation, the hole in the center results in a closer symbol spacing that would be encountered with a conventional square 32 point constellation. The penalty is 2.3 dB.

**Antenna Diversity:**
If multipath distortion is present on a signal path, and the multipath components are sufficiently strong to cause a deep fading of the channel at some of the HCs, OFDM and FDRM modulation have two significant advantages over single frequency carriers, such as 16-QAM. First, if a forward error correcting code is used, the symbols lost in the deep fade are automatically corrected by the code, assuming the total number of lost symbols is below the maximum capability of the code. With FDRM, the channel characterization can be used to reliably mark the frequencies with deep fades. (If a Reed Solomon forward error correcting code is employed, and erasures are used for the deep fades instead accepting errors, the strength of the code is doubled.) Single frequency carriers are generally known to be inferior to multifrequency carriers in the presence of severe multipath distortion [6].

Second, another receive antenna can be placed near the first receive antenna, but approximately a half wavelength further away. This trick is known as antenna diversity. The transmitted spectrum seen by the second antenna is unlikely to have nulls at the same frequencies observed by the first antenna. Thus FDRM, using its channel characterization ability, can choose the best antenna to use on harmonic carrier by harmonic carrier basis. Likewise, if it is an advantage to vector add harmonic carriers from different antennas, that can also be done with FDRM because the channel characterization data yields the necessary phase angle to achieve an in-phase addition of HCs from two different antennas. Since noise adds on a power basis (10 log) and harmonic carriers from 2 antennas add on a voltage basis (20 log), the second antenna can improve the received signal to noise ratio by an additional 3 dB, even when no echo is present. Reference [6] discusses the use of antenna diversity for OFDM.

Antenna diversity is also used by single frequency carriers, such as QPSK, particularly at microwave. The conventional technique is to switch to the antenna that produces the lowest bit error rate (BER).




**Graph 1 Symbol Error Rate vs. BER for 33 Point Constellation**

**Conclusion and Summary**

Holtzman proposes:

1. A mixed OFDM / FDRM system.

2. Increasing the duration of a block from 3.2 microseconds to 25.6 microseconds.

3. Replacing pilots with reciprocal values to adjacent harmonic carriers. Use more HYPERLAN2 constellations when dynamic multipath is benign. Use more of the constellations of Figure 1 with FDRM when multipath is bad.

4. When the channel is experiencing dynamic multipath, convert more OFDM harmonic carriers into FDRM pairs.

5. Upstream and downstream: transmissions adapted to the characteristics of the signal path.

6. Antenna diversity as an option.

In both upstream and downstream paths, if channel conditions are bad, the modulation will be rapidly modified by the MAC to overcome the impairments. Dynamic impairments will include high attenuation due to rain, co-channel interference, rapid fades, and dynamic multipath.

Pilot assisted FDRM should be able to provide the features and flexibility needed to make the IEEE 802.16.4 standard successful. If channels are afflicted with dynamic multipath, OFDM will be at an advantage relative to single frequency carriers, and FDRM will be at an advantage to OFDM.

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[6] Performance of Frequency Domain Sub-band Diversity Combination Technique for Wide-band Mobile Radio Reception: An Application to OFDM (Orthogonal Frequency Division Multiplexing) Reception by Hiroyuki Hamazumi, Yasuhiro Ito and Hiroshi Miyazawa, Electronics and Communications in Japan, Part 1, Vol. 81, No 8, 1998.

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