Project	**IEEE 802.16 Broadband Wireless Access Working Group**
Title	Pilot-Assisted Frequency Domain Reciprocal Modulation for Microwave Channels with Dynamic Multipath - Rev.1
Date Submitted	**1999-12-24**
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Re:	Responsive to: 802.16 Physical Layer Task Group Call for Contributions - Session #5 in accordance with the "Development Plan for the 802.16.1 Air Interface Standard" Item number IEEE802.16p-99/01
Abstract	This paper describes a new modulation type that is called Frequency Domain Reciprocal Modulation (FDRM). FDRM is well-suited for operation over channels afflicted with dynamic multipath distortion. FDRM uses two blocks of data that are frequency domain reciprocals of each other. The blocks may be sent sequentially or concurrently in an interleaved fashion so the same channel distortions are acquired by each block When the blocks processed together all linear distortion is automatically canceled. The addition of out-of-block pilot signals to the transmissions allow the FDRM signal to tolerate the high levels of phase noise and frequency error encountered at microwave frequencies.
Purpose	For consideration as physical layer technology for inclusion in the proposed 802.16 standard
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Pilot-Assisted Frequency Domain Reciprocal Modulation for Microwave Channels with Dynamic Multipath - Rev. 1

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Introduction

This document is a revision of an earlier document with the same title that was offered to the 802.16 task group in Hawaii on Nov. 9, 1999.

Frequency domain reciprocal modulation (FDRM) is a new digital transmission technique that offers an advantage in microwave frequency channels afflicted with dynamic multipath. Multipath is a linear distortion that is also known as echoes or ghosts. Adaptive equalizers allow high-speed bandwidth-efficient communications through channels with multipath. However, when the multipath is dynamic, bandwidth-efficient digital transmission is very difficult because the adaptive equalizers frequently can not adapt fast enough. At short wavelengths the problem is particularly acute if multipath is being created by foliage and wind is moving the foliage. This new modulation technique employs two blocks of correlated data to cancel the effects of all linear distortion. In a first implementation the 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 a special type of orthogonal frequency division multiplexing (OFDM) and the second block may be described as reciprocal OFDM. 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. Cancellation of all linear distortion is an intrinsic property of this new modulation technique. The effects of rapid fades is also canceled 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 similar implementation the two blocks are interleaved into one block.

The FDRM transmission is enhanced by the addition of one or more unmodulated out-of-block pilot signals that are surrounded by vacant spectrum. These pilots allow the phase noise and frequency error to be eliminated from the FDRM transmissions by a filtering and mixing process. This eliminates the weakness of FDRM to phase noise and frequency error created by the up and down frequency conversion processes.

FDRM offers several advantages in point to multipoint wireless services, but its strongest assets are its adaptability to rapidly changing channel conditions and its suitability to infrequent bursty transmissions.

The new information in this revision to the original paper is:
1. a further discussion of the set of physical layer problems that challenge the construction of a successful point to multipoint distribution system
2. a discussion of dynamic multipath distortion and the channel capacity that must be expended to characterize the channel
3. details about how antenna diversity can be used to great advantage with both OFDM and FDRM modulation.
4. further details about Holtzman's proposal for a physical layer for the IEEE 802.16 task group.

Some generic information has been dropped from the earlier revision.

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.

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:

$$E(t) = A_1 ?\cos(\omega t + \phi_1) + A_2 ?\cos(2\omega t + \phi_2) + A_3 ?\cos(3\omega t + \phi_3) + A_4 ?\cos(4\omega t + \phi_4) \qquad (1)$$

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.
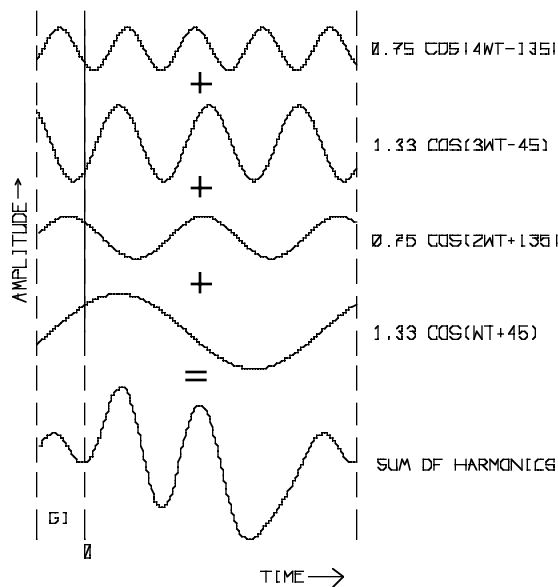

Figure 1 A Normal (N) Waveform Comprised of 4 Harmonics in the Time Domain

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 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.
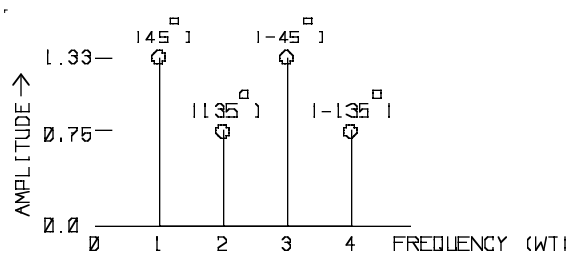

Figure 2 The Four Harmonics of Figure 2 Viewed in the Frequency Domain

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 frequencies. A set of pilot HCs may be viewed as a training or reference signal for OFDM.

Frequency Domain Reciprocal Modulation
Holtzman's new FDRM modulation is based on two consecutive blocks of data that contain the same information but use different encoding. The first 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.

In one implementation 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, if all HCs have the same amplitude, the reciprocal 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.
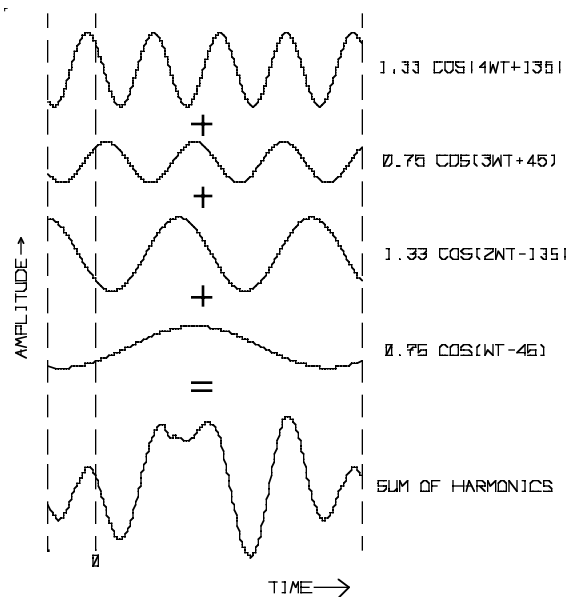

Figure 3 A Reciprocal (R) Waveform Comprised of Four Harmonics. The Harmonics are the Reciprocals of the Harmonics at the Same Frequency Illustrated in Figure 2
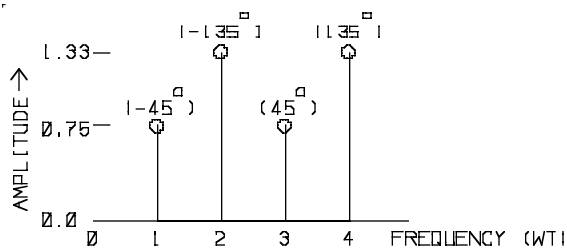
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Figure 4 The Reciprocal of the Four Harmonics of Figure 3 Viewed in the Frequency Domain. Also the Four Harmonics of Figure 3 Viewed in the Frequency Domain

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:

$$X(f) = S(f)?H(f) \tag{2}$$

If a reciprocal signal block is created:

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

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

$$Y(f) = R(f)?H(f) = \frac{H(f)}{S(f)} \tag{4}$$

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

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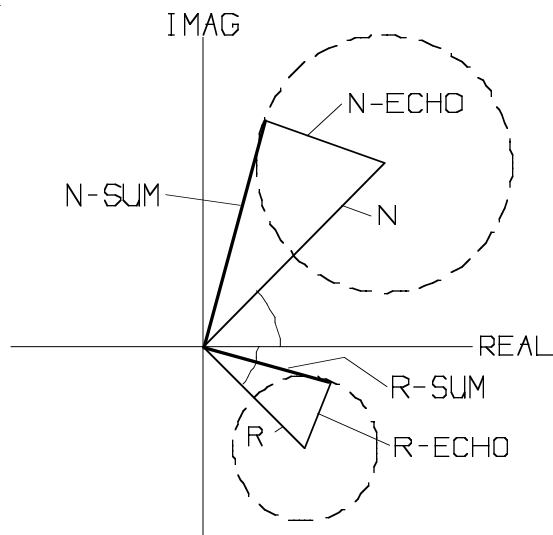

Figure 5 A Carrier, Its Reciprocal, and an Echo Distorting Both

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

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

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

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

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

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

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

$$H = 0.909@29.88\deg.$$

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']

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']

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

$$X_N\,?\frac{1}{Y_R} = S_N{}^2 = 1.777@90\deg.$$

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.

$$S_N = 1.333@45\deg.$$

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

$$X(f)\,?Y(f) = S(f)\,?H(f)\,?\frac{H(f)}{S(f)} = H(f)^2 \qquad (6)$$

so the channel's frequency response is:

$$H(f) = \sqrt{H(f)^2} \qquad (7)$$

Continuing with the earlier example,

$$H(f) = \sqrt{U_N(f)\,?U_R(f)} = 0.909@29.88\deg$$

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 neighboring frequencies. This commonly occurs in practical channels, depending on the nature of the echoes (number, delay, amplitude).
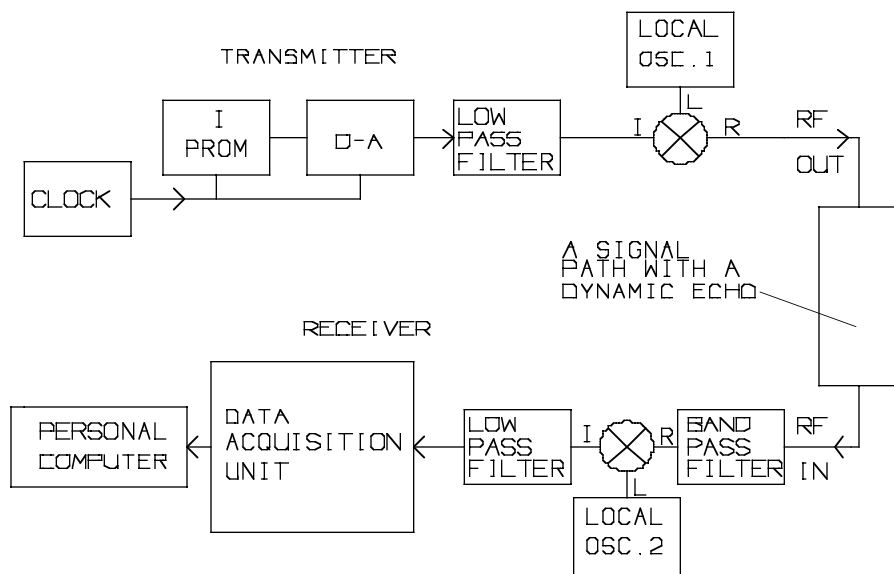

Figure 6 Hardware Block Diagram

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

Test Results from Hardware: Figure 6 is a hardware block diagram of prototype hardware that has been used for demonstrations and tests. 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. 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 7 is a screen plot showing the results of an analysis of a burst transmission of a FDRM burst using a 10 point constellation. The second row down illustrates the transmitted normal and reciprocal signals as a time-domain trace. The bottom trace is a spectral plot showing the effect 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 upper sideband received normal constellation points (NUSB) and the upper sideband received reciprocal constellation points (RUSB) are processed together to produce the USB plot. Likewise, the lower sideband received normal constellation points (NLSB) and the lower sideband received reciprocal constellation points (RLSB) 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 probably Ricean fading and Raleigh fading. More research is

NLSB / RLSB = LSB ; NUSB / RUSB = USB
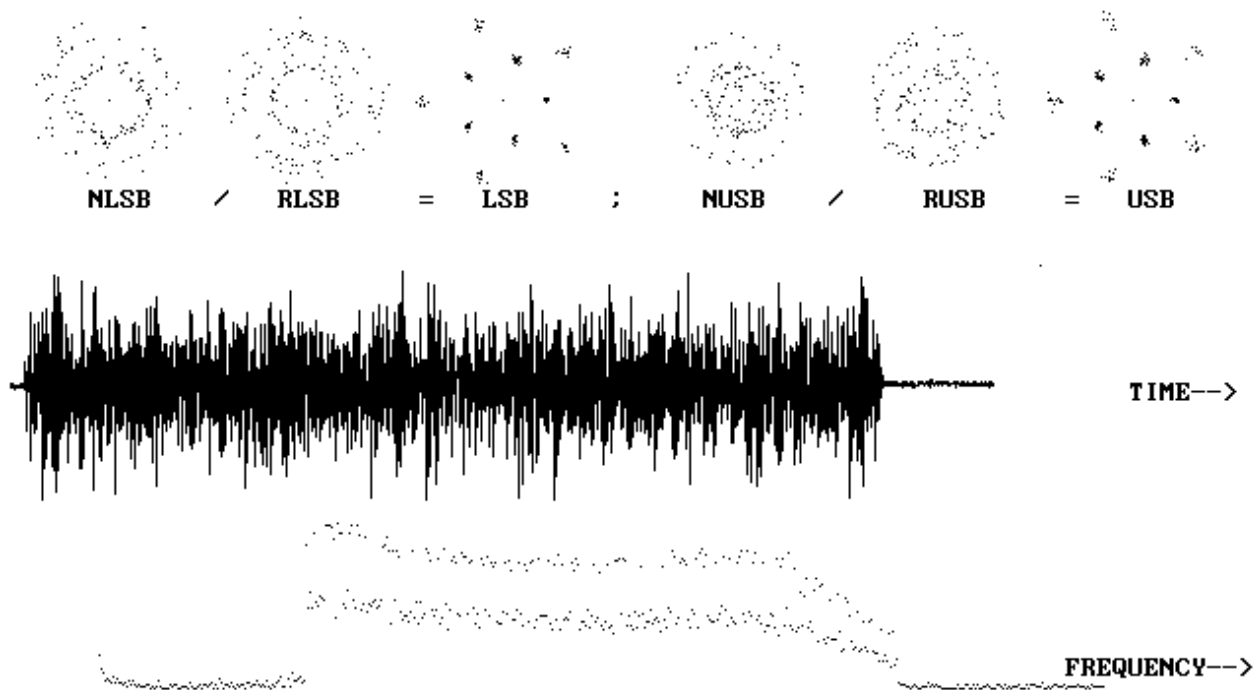
TIME-->

FREQUENCY-->

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

necessary to determine exactly what echo environment will be encountered for typical deployments. A likely scenario is that deployments will push the limits of the performance of the final standard and the implementation.

For a channel with rapid flat fading, FDRM works very well because the fade affects both the normal and reciprocal blocks. 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.

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 that will be discussed later.

Performance Near Threshold: One might think that sending the same signal twice in a different form would reduce the channel capacity by one-half. However the information in both blocks of 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:

$$S(f) = \sqrt{\frac{S(f)\,?H(f) + N_n(f)}{\frac{H(f)}{S(f)} + N_d(f)}} \tag{8}$$

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. However, for a cancellation to occur, the noise energy must be at an equal magnitude and opposite phase simultaneously, which is less probable than just a magnitude match. 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. More will be said on this subject later.

Easier Processing: There are a number of advantages associated with the demodulation of FDRM that OFDM does not enjoy.
1. Equalization is automatic.
2. Phase locking is not required. With 2 block FDRM, if the transmitter's local oscillator (LO) is running at a different rate than the receiver's LO the received constellation will still be tight, but rotated. A simple angular correction will correct the frequency error. The rotation angle can also be calculated and used as an automatic frequency control (AFC) for the next received burst.
With single block (interleaved) FDRM the constellation will not be rotated, but excessive frequency error will cause intersymbol interference. When FDRM is supplemented with an out-of-block pilot, the pilot can be used to remove both the phase noise and any frequency error. One of the largest problems implementing conventional OFDM is sensitivity to phase noise.
3. No accurate automatic gain control (AGC) is required. As mentioned earlier, FDRM works well in environments with fast fades.

Because it is easy to demodulate a single burst of data, FDRM modulation is an efficient technique for single infrequent bursts of data, such as are encountered in internet packet traffic, such as ack transmissions. Likewise, FDRM is ideally suited for a TDMA (time division multiple access) system with multiple subscribers transmitting in their respective time slots.

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° with a reciprocal at $+135^o$ is ambiguous: it could have also been

transmitted as a carrier at +45° with a reciprocal at -45° and suffered a 180° 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° rotational symmetry. This works for channels with Raleigh fading. Also, a small DC offset in a constellation point will locate the positive in-phase axis.

Patents are pending.

Applications in General
A personal computer (PC) or hand-held device may be used to do the necessary digital signal processing associated with FDRM. This lowers the cost of the receiver circuitry and avoids the cost of a dedicated digital signal processing chip if the data is being generated or used by the PC or hand-held device.

FDRM can be used to improve the demodulation of conventional OFDM by transmitting reciprocal HCs in the next block for only a fraction of the total number of HCs. In essence, reciprocal HCs can replace the static pilot carriers used in conventional OFDM with a noise reduction for both the pilot and the carrier with an accompanying reciprocal.

Echoes
Echoes on a signal present a severe problem to the transmission of digital information, and with conventional technology, linear distortion must be accurately characterized to enable adaptive equalizers to flatten the channel. 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 either the echo is slowly-moving and/or because the echo changes relatively slowly with frequency. That is, adjacent 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 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 channel characterization, the noise on the pilots will result both in a poor channel model and in noise enhancement in the corrected signal. That is, a perfect channel characterization can never improve the receiver's carrier to noise ratio, but it a poor characterization can hurt it.

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 Pilot-Assisted FDRM to Microwave Point to Multipoint for IEEE 802.16
and Physical Layer Problems in 10-60 GHz Frequency Band

The primary intent of the IEEE 802.16 task group is to create a system with the following key characteristics:
1. 2-way communications from a base station to a plurality of subscriber stations will be primarily line of site. Subscriber stations that are close to the base station will be able to tolerate some additional attenuation due to foliage.
2. A point-to-multipoint architecture will be employed. This implies that a wide beam transmit/receive antenna will used at the base station site and narrower beam antennas will be used in the subscriber stations.
3. The downstream transmissions will be continuous while upstream transmissions will be bursty in nature.
4. Frequency reuse will be employed with directional antennas and sectorization.

Some of the severe problems facing the IEEE802.16 task force in defining a system operating in the 10-60 GHz are as follows:

1. Multipath distortion may be present on some percentage of the signal paths and furthermore, if present, it may be dynamic. The very short wavelengths associated with these high frequencies (10 mm. at 30 GHz) insure that a very short change in echo delay time will produce a large phase rotation in the echo. For example, a single echo that changes delay by only one hundredth of one nanosecond will cause a phase rotation in the echo of 108 degrees! This can be caused by a reflector moving a fraction of an inch. (Skyscrapers can sway greater than one foot on windy days.)

A single echo will produce ripples in the frequency response with a frequency that is the reciprocal of the delay. That is, a 100 ns. echo will produce a ripple in the frequency response with a period of 10 MHz. If the delay of the echo is short relative to the signal's occupied bandwidth, then the frequency response will have a ripple response that either appears relatively flat or as a channel tilt. If there is a minor dynamic variation in the time delay of any echoes on the signal path, the channel's response can be expected to have rapid changes in both channel tilt and signal level.

2. Rain attenuation is expected to cause an extremely large variance in attenuation levels, such as 20-30 dB. over a 2 km. link. Additionally, the attenuation may change at a rate of several dB per minute. Because the upstream bandwidth will probably be shared on a time basis, many subscriber units with different lengths signal paths must be maintained in a "continuously connected" state. This rapid changes in attenuation levels from rain will put an additional burden on the MAC to keep all stations calibrated.

3. Phase noise levels for cost-effective transmitters and receivers will be extremely high. Phase noise will increase above some reference frequency by a ratio of 20 log (f / f_{ref}).

4. Frequency accuracy present a challenge to system deployment. An oscillator that can hold frequency accuracy to five parts per million over temperature is considered to be a very good one, but this frequency accuracy will result in a 150 kHz error at 30 GHz..

5. High levels of transmitter power will be expensive due to the high frequencies. The high frequencies will force the use of GaAs technology, which will be particularly expensive at high power levels until mass production levels are achieved on active devices.

Holtzman's Proposal

For upstream transmissions Holtzman is proposing that FDRM, accompanied by pilot carriers, be used at the start of every burst transmission and for short transmissions, such as mini-slots. Although the multipath may not be dynamic, the reciprocal burst will improve the probability of successfully decoding a packet by improving the signal to noise ratio (after processing) and simplifying the necessary processing associated with the reception of a single packet. If additional reciprocal HSs or full-time reciprocal HCs are needed, the receiver will send a message to the MAC to request that the transmitter on the other side of the radio link comply.

In the downstream direction, reciprocal block transmission will be done on an as-needed. Packets that are not accompanied by a reciprocal burst will be de-ghosted by stored coefficients. A continuously-transmitted downstream pilot will accompany the continuous transmission of back-to-back blocks.
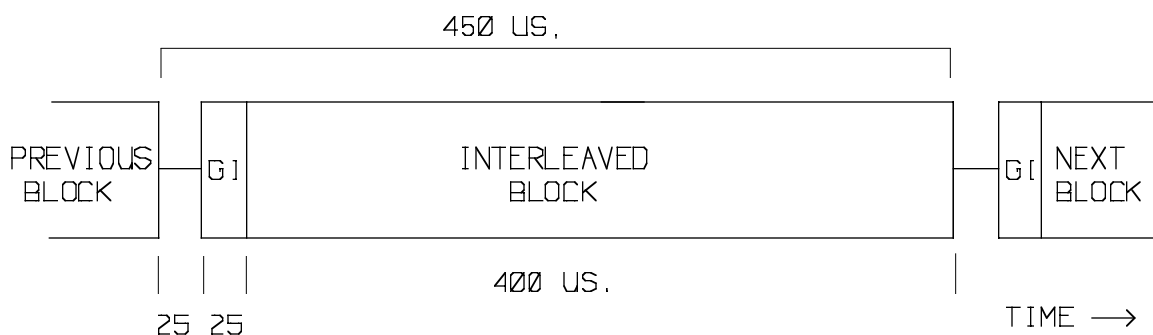

Figure 8 Temporal Plot of Single Block Interleaved FDRM Transmission

Furthermore, Holtzman recommends the use of adaptive transmissions on both the upstream and downstream paths. Adaptive transmissions mean that the number of constellation points, the number and amplitude of HCs, the FEC code strength, the optional use of a reciprocal HCs and possibly the duration of the guard interval all be considered to be adjustable. COFDM allows the broadcaster to adjust of many of the same parameters. The base station, if transmitting downstream data destined for a single subscriber station, can change its modulation format for that particular base station to use the highest data rate possible for a given signal path. Downstream packets that will be received by multiple subscriber stations (e.g. broadcast entertainment) will be broadcast with the same type modulation. On days with high attenuation due to high precipitation, the transmissions will continue at a lower speed.

Figure 8 is a temporal plot of single block FDRM burst that may be used for upstream 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 25 microseconds is probably more than is needed for terrestrial transmissions, but the additional time allows the pilot bandpass filter(s) to stabilize. The transmission time of 450 microseconds is the duration over which an echo would be expected to change very little. A 25 microsecond buffer zone is allowed for timing inaccuracies to neighboring blocks which may originate at other subscriber stations. The need to re-range transmit power frequently in a rain storm is alleviated because the interleaved normal block and reciprocal block are acquired into a same buffer with a continuous clock and the attenuation factor cancels out when the interleaved blocks are processed.

The decision of whether a single interleaved block is superior to two separate sequential blocks depends on the channel characteristics, especially whether or not 2 adjacent HCs are receiving approximately the same echo (which is very probable).
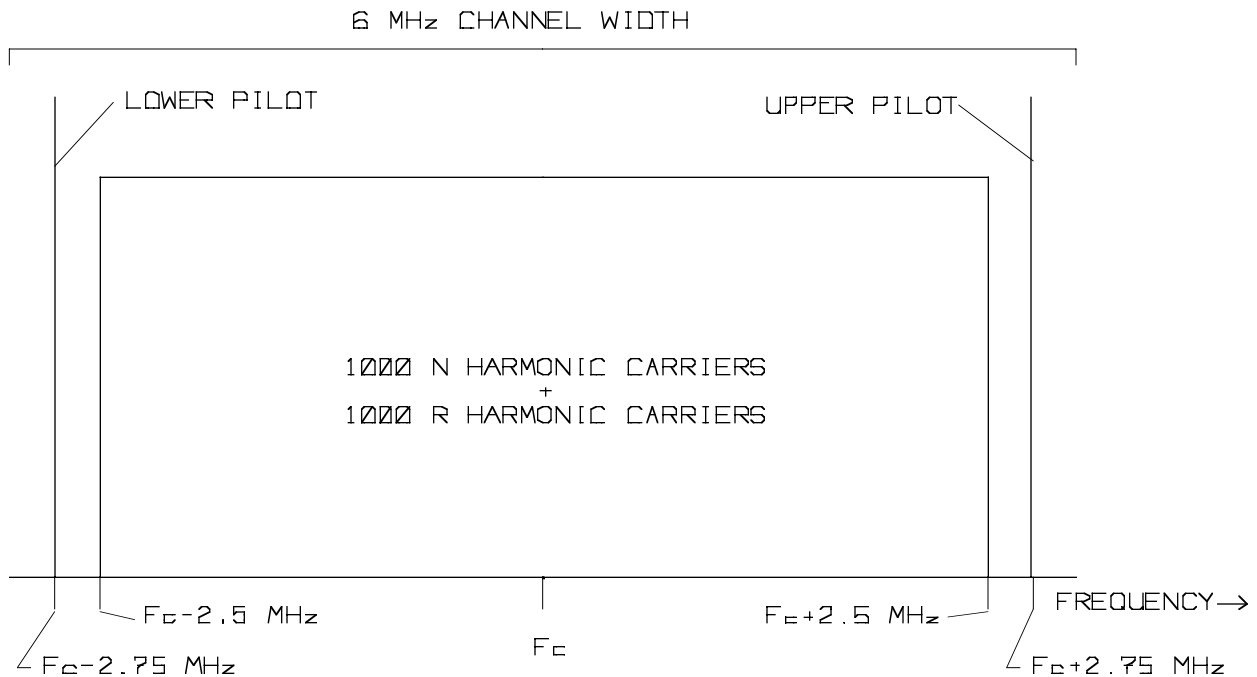

Figure 9 Spectral Plot of FDRM with Two Pilots

Figure 9 is a spectral diagram of the Figure 8 burst with a 6 MHz channelization plan. The separation between harmonic carriers is 2.5 kHz and 1000 N HCs reside between 1000 R HCs in 5 MHz. A pair of pilots are provided at +/- 2.75 MHz above and below the center of the channel. The pilots are 250 kHz away from either the band edges or the HCs. If the channel is experiencing Raleigh fading it is unlikely that both carriers will be in a deep notch. The pilots are harmonically related carriers and are several dB above the other modulated carriers to avoid random noise pickup causing false phase noise modulation.
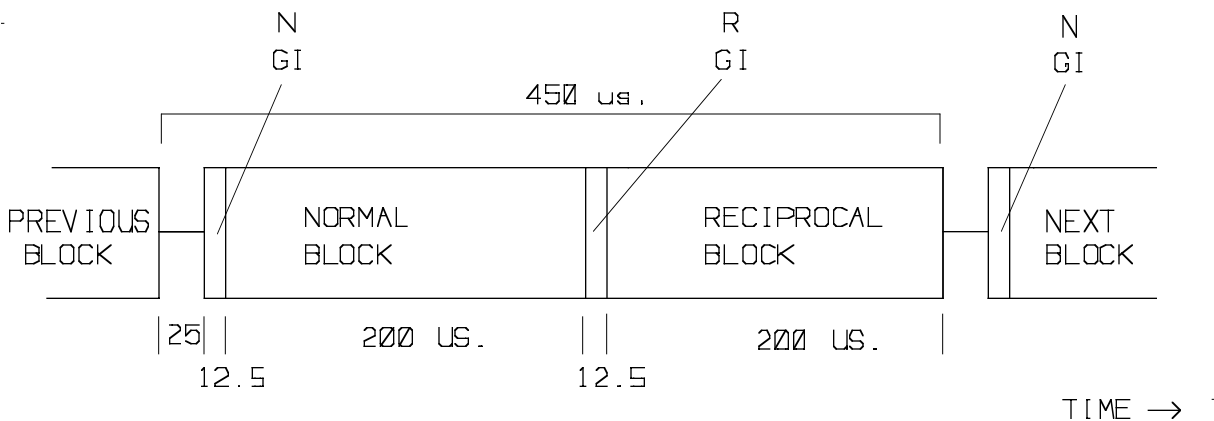

Figure 10 A Temporal Plot of a Two-Block FDRM Transmission

Figure 10 is a temporal plot of an alternate two-block FDRM burst that may be used for upstream transmissions. The normal and reciprocal blocks are sent sequentially without a pause. Both blocks have their own guard interval. The spectral plot associated with Figure 10 is similar to Figure 9.

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.
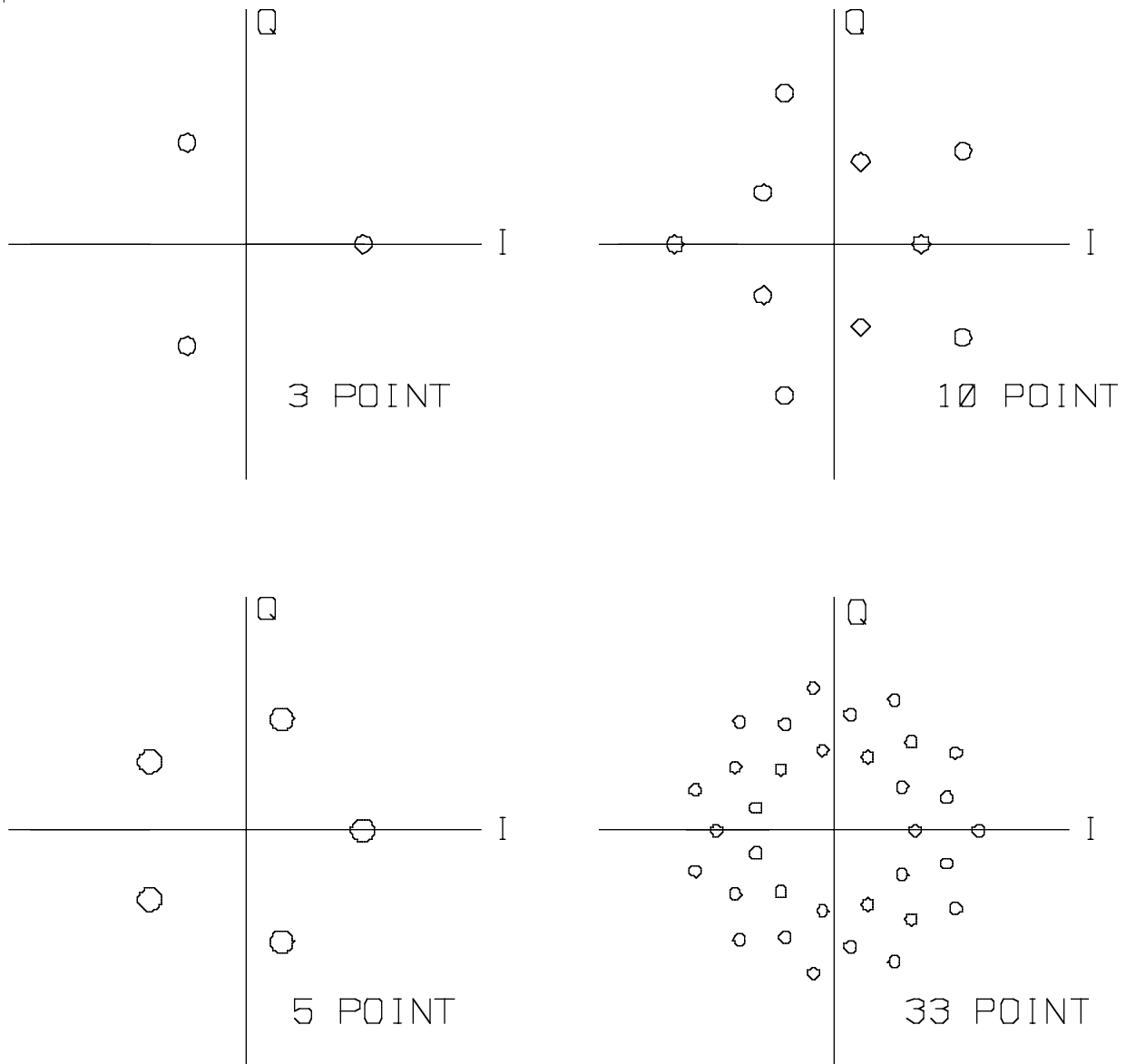

Figure 11 Four Normal Constellations for Use with FDRM. Note that Constellations do not have 180 Degree Rotational Symmetry

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 angle to use 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's to noise ratio by an additional 3 dB, even when no echo is present. Reference [5] 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).

Criterion and Discussion

1. Meets system requirements.

Adaptive FDRM with pilots should excel at meeting system requirements, particularly the multipath and rain fade requirements. For the upstream path, FDRM should be used at the start of a message, for short messages and as often as necessary (e.g. on windy days). The rest of the time, FDRM without reciprocals (i.e. OFDM) will be used with stored coefficients. For downstream, FDRM should be used as frequently as channel conditions require. Both upstream and downstream paths will experience dynamic multipath which will vary from subscriber station to subscriber station. The MAC will carry messages about the need for a power adjustment, a capacity adjustment (number of points in the constellation), or more immunity to dynamic multipath (more reciprocal HCs).

2. Spectrum Efficiency.

Spectral efficiently should be comparable to widely-deployed OFDM systems, unless the channel conditions turn bad. Holtzman proposes that the downstream system use reciprocal blocks on an as-needed basis with pilots assisting the demodulator in the presence of phase noise and frequency offset. Stored adaptive equalization coefficients, derived from earlier normal-reciprocal block pairs, will be used to correct the normal blocks sent without reciprocals.

In general, a single interleaved block is preferred over the two block version of FDRM because the guard interval time percentage may be reduced by half.

Upstream transmission of reciprocal blocks will nominally occur at the start of each transmission.

Spectrum efficiency will depend on the channel's signal to noise ratio, the need for long guard intervals, and needs for heavy FEC. Under stable path, low-noise conditions, the channel capacity should be similar to COFDM (DVB-T) digital television modulation. Like COFDM, the transmission parameters, including coding gain, constellation size, and guard interval duration can be adapted for severe channel characteristics. The type of downstream transmission may be tailored to the signal path on a subscriber-by-subscriber basis if the data is intended for a single subscriber station.

3. Simplicity of Implementation.

One advantage of FDRM is that it is a sister technology to OFDM which is well-understood by technical professionals and well on its way to become the most popular broadcast digital television technology in the world.

Use of FDRM for upstream greatly simplifies computation of equalizer coefficients, since echoes are canceled automatically. A price paid is the FFT (fast Fourier transform) must be performed twice. AGC (automatic gain control) is greatly simplified since it neither has to be fast or accurate.

The use of pilots to assist demodulation with high phase noise should occur on both upstream and downstream transmissions until mankind discovers a way to produce low-cost, low phase noise carriers at microwave frequencies. Pilots will be continuously transmitted on downstream channels. The pilots may also be useful to the MAC layer as a method of monitoring rain fade and carrier activity such as collisions and interference. Upstream transmissions should use downstream pilots as frequency references to increase the accuracy of the carrier frequency. Subscriber stations will transmit at an offset frequency derived from downstream pilots.

4. CPE Cost Optimization

The use of pilots should allow much lower cost in the subscriber station since phase noise and frequency error requirements can be eased, lowering the cost of the CPE. The ability to live with dynamic multipath is also an advantage if it alleviates the line of site requirement for nearby subscriber stations. That is, a tree-trimming or a tall antenna mast will not be required.

One disadvantage of FDRM (and OFDM for that matter) is the transmitter needs to be backed-off or operated in a linear region. Downstream composite signals will likely be a composite high power (relatively) transmission of many frequency domain multiplexed carriers over a low-gain broad beam antenna. Thus downstream linear operation is a requirement, regardless of which modulation selected. In the upstream direction, only one channel will be transmitted at a time, but the narrow beam antenna gain will be high. Thus FDRM requires an amplifier with higher dynamic range than a competing technology, such as offset QPSK. This power limitation will probably force FDRM to transmit upstream at a slower relative rate in a rain storm or force a more expensive power amplifier to be used. **Fortunately, many of the applications that require low cost also require low upstream bandwidth (e.g. telephony, internet browsing, pay-per-view ordering).**

There is technology under development that will limit the peak transmit power for OFDM, but this not part of Holtzman's proposal at this time.

Note that the loss between the input to a transmit antenna and the output of a receive antenna should be about the same for either upstream or downstream. This assumes the same beam width for transmit and receive functions at the base station and subscriber station. This also assumes that the upstream and downstream frequencies are similar enough to have comparable loss ratios.

On rainy days, subscriber stations should monitor the downstream received power levels to estimate changes in path loss prior to transmitting. This reduces the burden on the MAC layer. This comment applies to other proposals as well.

5. Spectrum Resource Flexibility
Good for Upstream, Excellent for Downstream. The spectrum efficiency depends on co-channel interference, transmit power, low noise amplifier noise figure, and precipitation.

6. Spectrum Diversity Flexibility
Excellent, especially if concepts of software-defined radios are employed to reconfigure DSP functions from the base station.
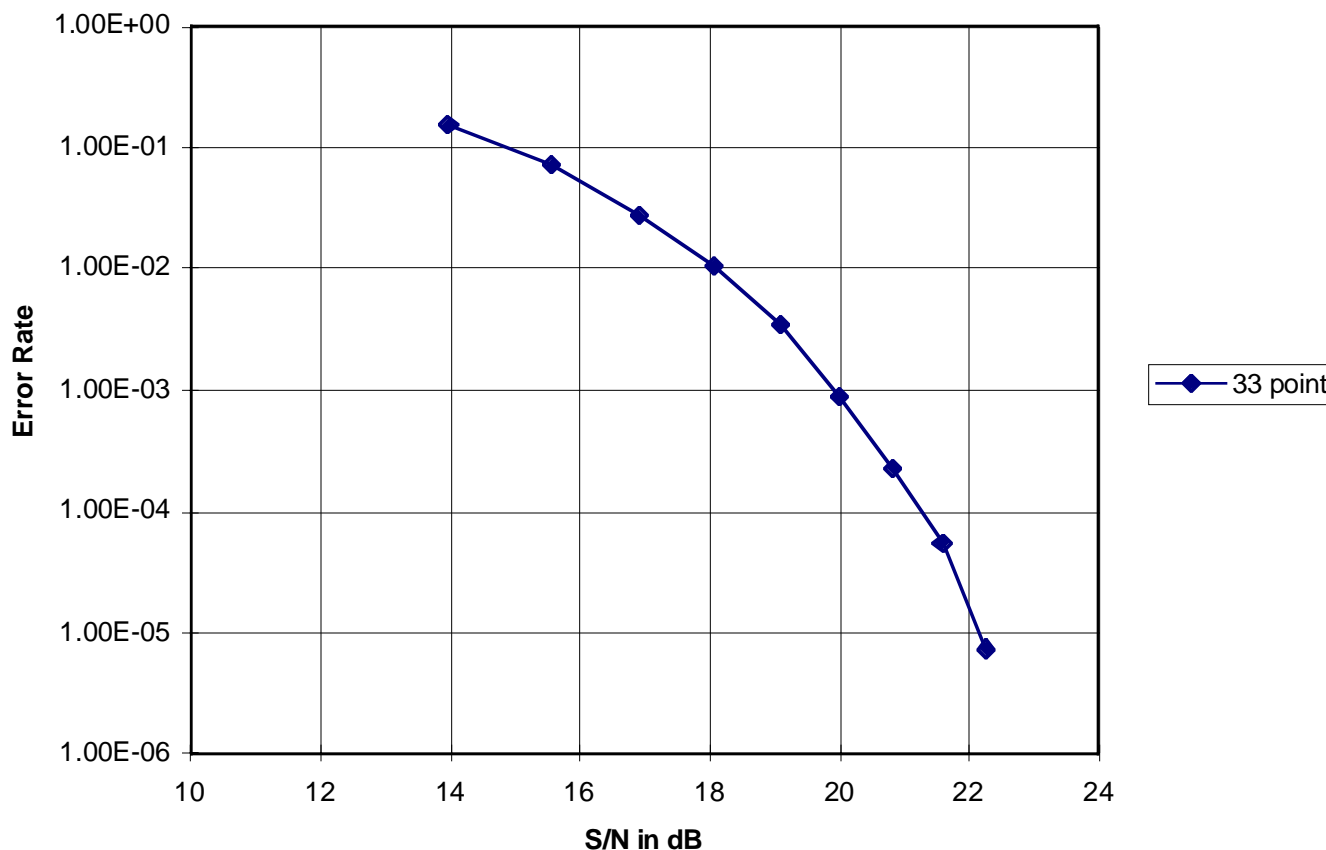
Graph 1   Symbol Error Rate vs. BER for 33 Point Constellation

7. Protocol Interfacing Flexibility
One big advantage of FDRM is that each block pair or interleaved block can be demodulated as a stand-alone entity without referencing other blocks. The greater tolerance to upstream dynamic levels will alleviate the need to frequently re-range power levels in rainy and windy weather, simplifying the MAC protocol.

8. Implication on Other Network Interfaces
Holtzman has not yet specified adaptation layers to map MPEG or IP packets into FDRM blocks. In general, an MCNS/DOCSIS 1.1 type system may be used as a reference design.

The biggest problem with telephony is a need for low latency. If large packets are filled to capacity, large delay occurs. Therefore, it is advisable to employ shorter packets in the MAC for telephony applications. One way this can be accomplished by subdividing the wide upstream channel into multiple narrower upstream channels. Frequency domain multiple access (FDMA) can be employed to subdivide the wider upstream channel.

9. Reference System Gain
See Graph 1 for a plot of symbol error rate vs. noise levels for the 33 point constellation. These results were obtained by simulation using a circular threshold region half the distance to the nearest symbol, so results are slightly pessimistic. No FEC has yet been applied. FEC will both decrease the bit rate and decrease the probability of error Downstream will be slightly lower than OFDM due to the use of pilots and the hole in the constellation. Upstream capacity will be cut in half by using FDRM, but the carrier to noise should be improved by 3 dB. The use of pilots and longer guard intervals will also reduce upstream capacity. The 33 point constellation transmitting 2222 interleaved blocks per second with 2000 symbols per block and 5 bits per symbol has a capacity before FEC of 22.22 M bits/sec. If the channel has a rapidly changing echo and a reciprocal HC matches every normal HC, the capacity drops to 11.11 M bit/sec, and the threshold carrier to noise improves by 3 dB.

10 Robustness to Interference
If the downstream signals are all the same in multiple adjacent cells, as in broadcast applications, the broadcasts may be synchronized to use the same frequency, block timing and content as a method of interference rejection between cells. This is the single frequency network concept employed with COFDM in Europe. Because of phase noise

concerns associated with multiple independent oscillators, this technique may be best employed with reflectors and repeater amplifiers. The long guard interval on Holtzman's signal and the inherent robustness to long echoes allow signals to be received from multiple antennas if the antennas are radiating identical signals.

If a similar but delayed broadcast signal is received by a subscriber's terminal from another sector, systems using FDRM or OFDM should be able to tolerate the energy. This assumes the second path's delay time is less that the guard interval duration.

In the presence of upstream co-channel uncorrelated interference, FDRM will drop to a lower transmission rate with more distance between symbols, or use a higher gain FEC, or jump to a different frequency. The primary method of eliminating interference will be with antenna pointing or choosing an antenna with lower side-lobes. Adaptive beam-forming technologies will probably be useful.

OFDM and FDRM can both use the technique of abandoning multiple harmonic carriers to create a hole in the spectrum to avoid being interfered with or creating interference. This technique is used in telephony DMA (discrete multi-tone) and in COFDM when a PAL video carrier is operating co-channel.

11. Robustness to Channel Impairments
FDRM, when used with FEC, has excellent immunity to echoes and dynamic multipath distortion. Like OFDM, FDRM will be relatively susceptible to impulsive noise, which is not expected to be an issue at microwave frequencies. Reference [6] discusses the merits of OFDM relative to 8-VSB for broadcast applications. Reference [7] is the standard for terrestrial COFDM.

Conclusion and Summary

Holtzman proposes:

1. Downstream: Use of pilot carriers and use of reciprocal HCs as needed.

2. Upstream: Use of pilot carriers for the start of a transmission, short transmission, and reciprocals as needed.

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

3. Antenna diversity as an option.

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

The adjustable parameters include:
a. Sending reciprocal HCs fast enough to keep up with the channel's changes and using the stored multipath solution on normal blocks that do not have accompanying reciprocal blocks.
b. Transmit power adjustment
c. Number of points in a constellation (change the Euclidean distance between symbols)
d. Adjustable strength of the FEC (code rate)
e. Dropping some of the harmonically related carriers and using the saved power in the remaining carriers.
f. Duration of a guard interval

Pilot assisted FDRM should be able to provide the features and flexibility needed to make the IEEE 802.16 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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[5] "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.

[6] Special Rapporteur's Group International Telecommunications Union Radiocommunications Study Group "GUIDE FOR THE USE OF DIGITAL TELEVISION TERRESTRIAL BROADCASTING SYSTEMS BASED ON THE PERFORMANCE COMPARISON OF ATSC 8-VSB AND DBV-T COFDM TRANSMISSION SYSTEMS"

[7] DVB-T Standard ETSI EN 300 744 V1.2.1 (1999-07) available at www.etsi.org

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