Project	**IEEE 802.16 Broadband Wireless Access Working Group**
Title	**Pilot-Assisted Frequency Domain Reciprocal Modulation** **for Microwave Channels with Dynamic Multipath**
Date Submitted	**1999-10-29**
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Re:	Responsive to: 802.16 Physical Layer Task Group Call for Contributions - Session #4 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 are sent sequentially so the same channel distortions are acquired by each block When the blocks processed together all linear distortion is automatically canceled. The addition of pilot signals to the transmissions allow the FDRM signal to tolerate the high levels of phase noise 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

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Introduction

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. 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.

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

FDRM offers several advantages in point to multipoint wireless services, but its strongest asset is its adaptability to changing channel conditions.

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. Likewise 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.

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:

$$E(t) = A_1 \cdot \cos(\omega t + \varphi_1) + A_2 \cdot \cos(2\omega t + \varphi_2) + A_3 \cdot \cos(3\omega t + \varphi_3) + A_4 \cdot \cos(4\omega t + \varphi_4) \qquad (4)$$

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.

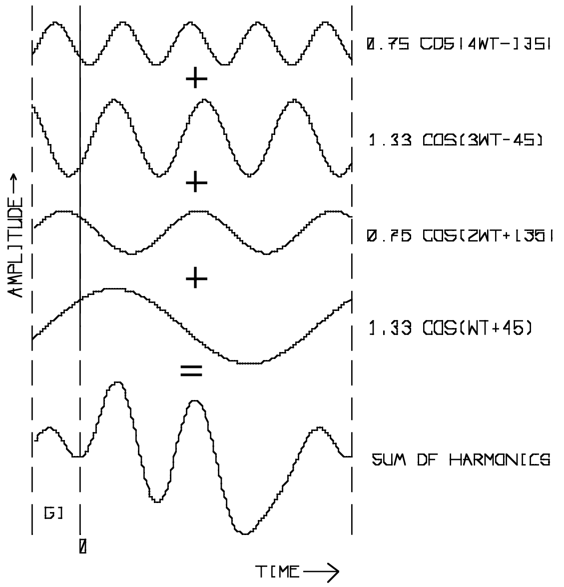

Figure 2 A Normal (N) Waveform Comprised of 4 Harmonics in the Time Domain

Figure 2 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 2 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 3 is a frequency domain (spectral) plot showing the 4 HCs of Figure 2 as 4 vertical spectral lines. The HC's magnitudes can be seen, and the HC's phases are printed above the HCs spectral lines.

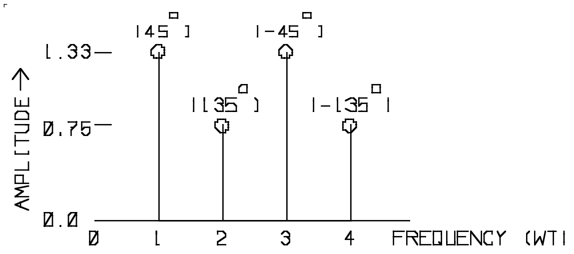

Figure 3 The Four Harmonics of Figure 2 Viewed in the Frequency Domain

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.

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.

De-ghosting with Two Data Blocks

Figure 4 features a reciprocal (R) data block to the OFDM transmission illustrated in Figure 2. Each HC comprising the reciprocal sum signal is the reciprocal of the HC with the same frequency in Figure 3. 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 2 for a given HC, it is smaller in Figure 4. Likewise, if the phase angle of a HC is positive in Figure 2, it is negative in Figure 4, and vice-versa. Figure 5 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 property of controlled magnitudes in the frequency domain.

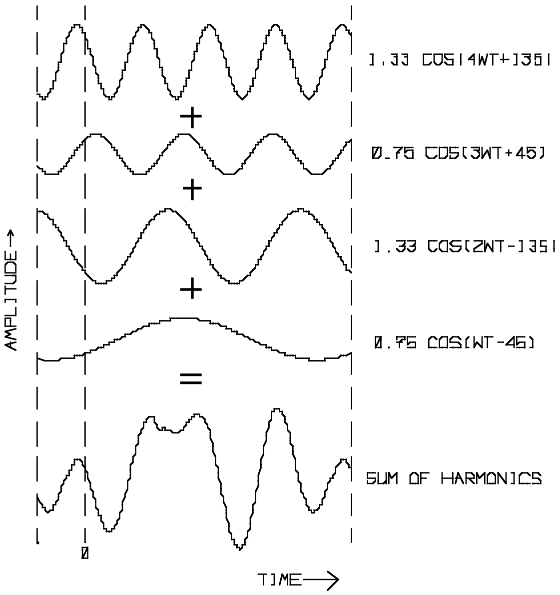

Figure 4 A Reciprocal (R) Waveform Comprised of Four Harmonics. The Harmonics are the Reciprocals of the Harmonics at the Same Frequency Illustrated in Figure 2

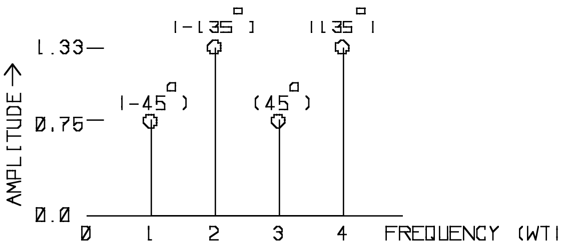

Figure 5 The Reciprocal of the Four Harmonics of Figure 3 Viewed in the Frequency Domain. Also the Four Harmonics of Figure 4 Viewed in the Frequency Domain

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:

$$X(f) = S(f)?H(f) \qquad (5)$$

If a reciprocal signal block is created:

$$R(f) = \frac{1}{S(f)} \qquad (6)$$

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

$$Y(f) = R(f)?H(f) = \frac{H(f)}{S(f)} \qquad (7)$$

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

$$S(f) = \sqrt{\frac{X(f)}{Y(f)}} = \sqrt{\frac{S(f)?H(f)}{\frac{H(f)}{S(f)}}} = \sqrt{S(f)^2} \qquad (8)$$

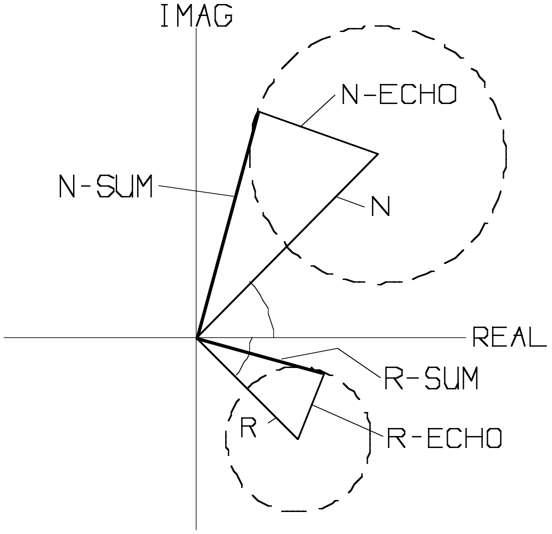

Figure 6 A Carrier, Its Reciprocal, and an Echo Distorting Both

A Processing Example

Refer to Figure 6 for a vector diagram of illustrating how an echo is canceled using two HCs.

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

$S_N(t) = 1.333\cos(\omega t + 45)$ [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= $S_R(t) = 0.75\cos(\omega t - 45)$ [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.

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

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

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:

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

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.

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

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

$$X(f)\,?\,Y(f) = S(f)\,?\,H(f)\,?\,\frac{H(f)}{S(f)} = H(f)^2 \qquad (9)$$

so the channel's frequency response is:

$$H(f) = \sqrt{H(f)^2} \qquad (10)$$

Continuing with the earlier example,

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

which is the frequency response when contaminated with an echo.

If the channel has slowly-moving echoes, reciprocal blocks can be sent infrequently. The channel's frequency response data 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).

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.

Square Root at Transmitter FDRM

Another way to use FDRM is to perform the square root function at the transmitter prior to transmission:

$$S(f) = \frac{\sqrt{S(f)}H(f)}{\frac{1}{\sqrt{S(f)}}H(f)} \qquad (11)$$

This technique unfortunately suffers a penalty in the presence of severe random noise, as will be discussed later. This technique is called "SR-FDRM".

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).

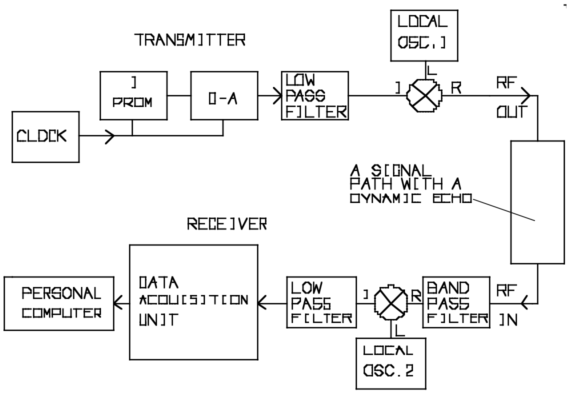

Figure 7 Hardware Block Diagram

Table 1 Details of Demonstration Hardware

Parameter	Value
Sample Rate	10.0 M Samples/sec.
Each Block's Duration	102.8 microseconds +GI
Guard Interval (GI)	10.28 microseconds
Total Burst Duration	226.16 microseconds

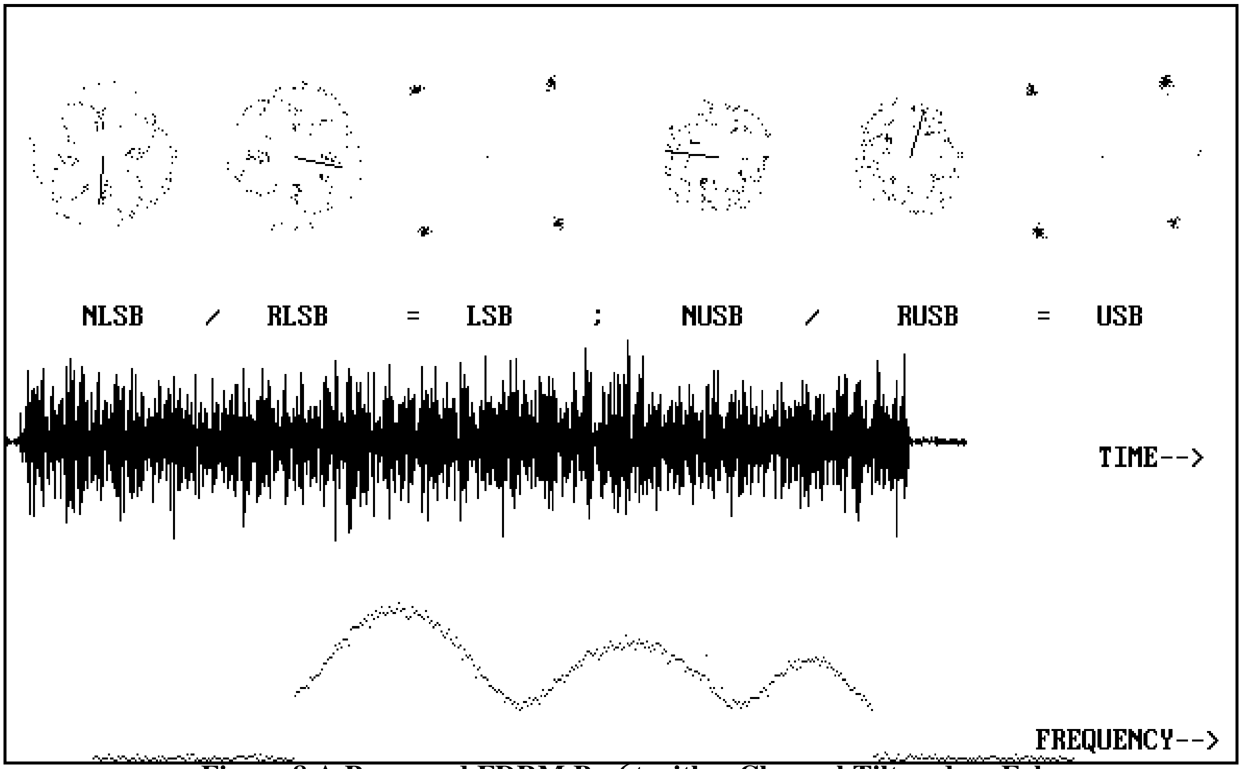

Figure 8 A Processed FDRM Burst with a Channel Tilt and an Echo

Parameter	Value
HC spacing	9.766 kHz.
Occupied Bandwidth	2.93 MHz.
Size of Fourier Transform	2048 points
Number of HCs	300

Test Results from Hardware: Figure 7 is a hardware block diagram of prototype hardware that has been used for demonstrations and tests. A normal burst signal and a trailing 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 (8) in a personal computer. Table 1 lists the parameters used for the demonstration hardware.

Figure 8 is a screen plot showing the results of an analysis of a burst transmission. The third row down illustrates the transmitted normal and reciprocal signals as a time-domain trace. There is no dead time between the two blocks. The bottom trace is a spectral plot showing the effect of an echo and a channel tilt. The processed upper and lower sidebands are separated for illustration.

The upper sideband received normal constellation (NUSB) and the upper sideband received reciprocal constellation (RUSB) are processed together to produce the USB plot. Likewise, the lower sideband received normal constellation (NLSB) and the lower sideband received reciprocal constellation (RLSB) are processed together to produce a LSB plot.

Changing Echoes

Two models of fading that are most applicable are probably Ricean fading and Raleigh fading. More research is necessary to determine exactly what echo environment will be encountered for typical deployments.

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 2-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.

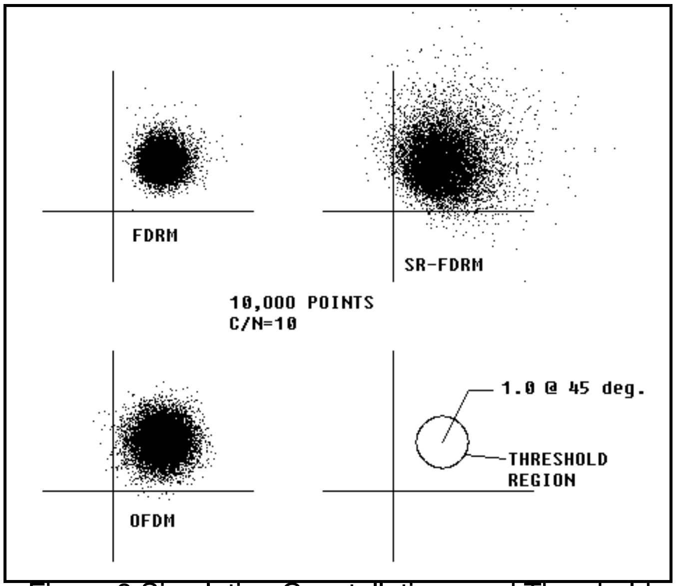

Figure 9 Simulation Constellations and Threshold Region

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.

A received processed signal in the presence of noise is:

$$S(f) = \sqrt{\frac{S(f)\,?H(f) + N_n(f}{\dfrac{H(f)}{S(f)} + N_d(f)}} \tag{12}$$

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.

Figure 9 is a set of four simulated constellation plots of a single harmonic carrier. These plots compare FDRM, normal OFDM and SR-FDRM.

A single HCs with a magnitude of 1.0 at 45^0 (after processing) are contaminated with equal levels (-10 dB) of randomly-distributed noise. FDRM is plotted in the upper left corner, OFDM in the lower left corner, and square-root-at-transmitter FDRM (SR-FDRM) in the upper right corner. SR-FDRM employs equation (11). The fourth plot in the lower right corner is noise-free and illustrates an arbitrary circular threshold region that was used to make the three sets of symbol error rate (SER) curves illustrated in Figure 10. Note that FDRM has a tighter constellation than conventional OFDM, although this advantage came at a price of sending the data twice. Notice that the square-root-at-the transmitter (SR-FDRM) suffers a noise performance penalty relative to both OFDM and FDRM since the noise is not reduced by performing the square-root function at the receive site. Only OFDM has a "round" point distribution.

Figure 11 is comparative plot of error vector magnitude (EVM) for FDRM, OFDM, and SR-FDRM. EVM is a measure of the average deviation of the constellation point from its ideal location due to an impairment, such as random noise. Note that FDRM still maintains its advantage over OFDM at carrier to noise ratios less than 5 dB, although the margin is reduced.

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 frequency error will cause intersymbol interference.

When FDRM is supplemented with a pilot, the pilot can be used to remove both the phase noise and any frequency error.

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 burst of data, FDRM modulation is an efficient modulation technique for single bursts of data, such as are encountered in internet packet traffic. Likewise, FDRM is ideally suited for a TDMA (time division multiple access) system.

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. 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. (Note that the square-root-at-the-transmitter case is unambiguous.) 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. 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) may be used to do the necessary digital signal processing associated with this transmission method. This lowers the cost of the receiver circuitry and avoids the cost of a dedicated digital signal processing chip.

This transmission method is readily adaptable to use diversity antennas. Diversity is a technique using multiple antennae and multiple signal paths. The signal path with the best signal is commonly used. The receiver could use the best signal from either of 2 antennas on a HC-by-HC basis. Alternately, the received energy could be summed after it is phase-rotated so that signals from the 2 antennas added constructively (using vector addition).

This technique can be used to simplify the demodulation of conventional OFDM by transmitting reciprocal HCs for only a fraction of the total number of HCs. This technique can replace the static pilot carriers used in conventional OFDM. Likewise, pilot carriers can be made to be reciprocals to the HCs located at adjacent frequencies.

The Application of Pilot-Assisted FDRM to Microwave Point to Multipoint for IEEE 802.16

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. At frequencies around 30 GHz. the attenuation due to foliage will be very large and variable and the attenuation due to rain fading will also be large and variable. Subscriber stations that are close to the base station will be able to tolerate some additional attenuation due to foliage. Subscriber stations that are distant from the base station will not be able to tolerate any additional attenuation due to foliage.

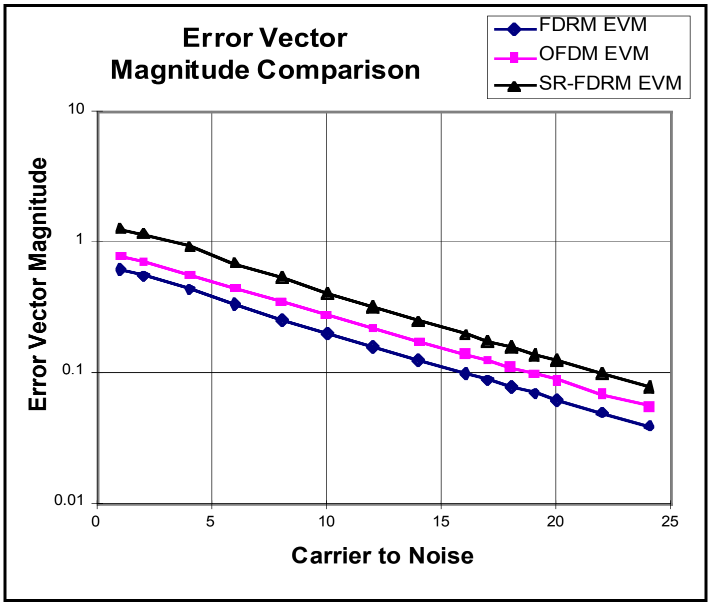

Figure 11 Comparative Error Vector Magnitude vs. Carrier to Noise

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 antennae will be used in the subscriber stations.
3. At microwave frequencies phase noise and frequency error will be large.
4. The downstream transmissions will be continuous while upstream transmissions will be bursty in nature.
6. Frequency reuse will be employed with directional antennae and sectorization.

Holtzman's Proposal

This proposal is for reference and discussion and illustration purposes. It is expected that it will be refined and adjusted.

For upstream transmissions Holtzman is proposing that FDRM, accompanied by pilot carriers, be used for every burst transmission. 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 reception of a single packet.

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 coefficient. A continuously-transmitted downstream pilot will accompany the continuous transmission of back-to-back blocks.

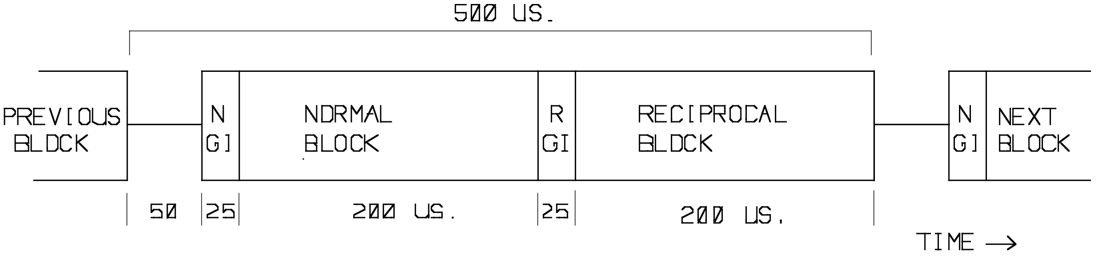

Figure 12 A Temporal Plot of a Two-Block FDRM Transmission

Furthermore, Holtzman recommends 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 trailing reciprocal blocks (FDRM), and possibly even the duration of the guard interval all be considered to be adjustable. 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 12 is a temporal plot of an interleaved FDRM burst that may be used for upstream transmissions. The bursts are shown in outline form, but the actual waveform will have a noisy appearance simiar to the temporal plot in Figure 8. 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 50 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 rapidly in a rain storm is alleviated because the normal block and reciprocal block are acquired into a same buffer with a continuous clock and the attenuation factor cancels out.

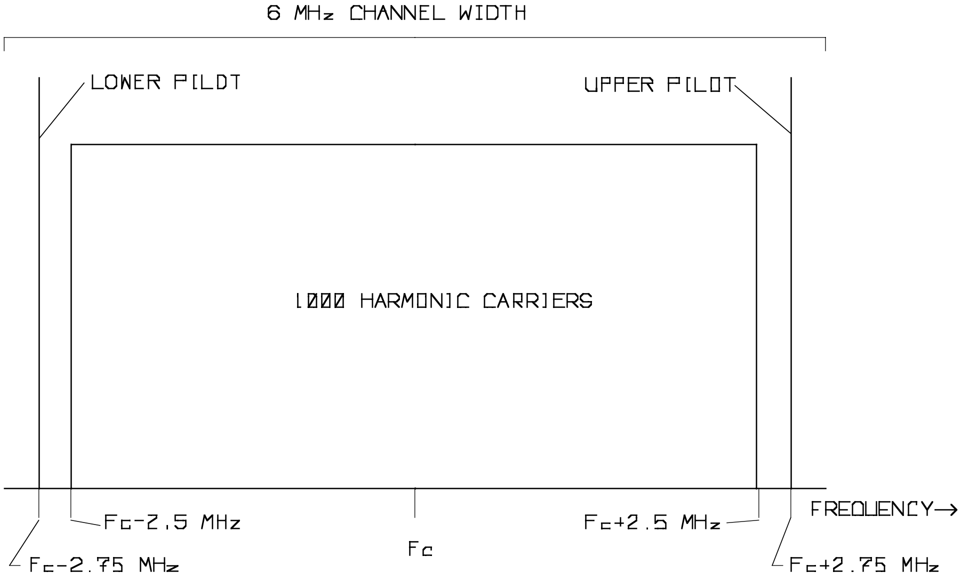

Figure 13 Spectral Plot of FDRM with Two Pilots

Figure 13 is a spectral diagram of the Figure 1 burst with a 6 MHz channelization plan. The separation between harmonic carriers is 5 kHz and 1000 are contained 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.

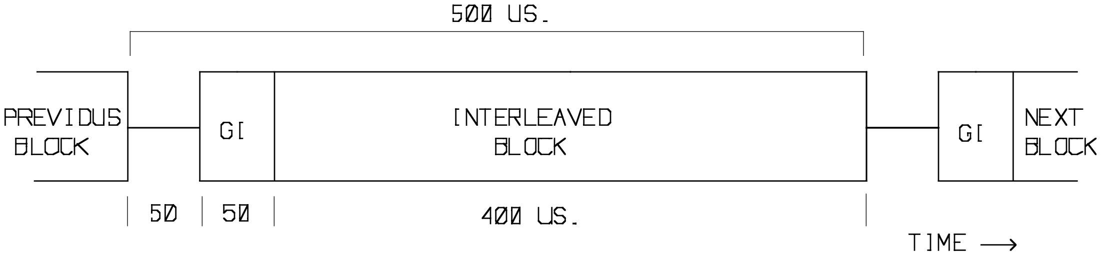

Figure 14 Temporal Plot of Single Block Interleaved FDRM Transmission

Figure 14 is a temporal plot of a interleaved 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 spectral plot associated with Figure 3 is identical to Figure 2. The decision of whether a single interleaved block is superior to two blocks depends on channel characteristics, especially whether or not 2 adjacent carriers are receiving approximately the same echo.

Figure 15 is an 8 point "arrowhead" constellation plots that exhibits desirable properties with FDRM. Note that this is one of many possible constellations and is probably not optimal. The reciprocal constellation plot corresponding to this normal constellation is not illustrated. This plot has 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 above. 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.

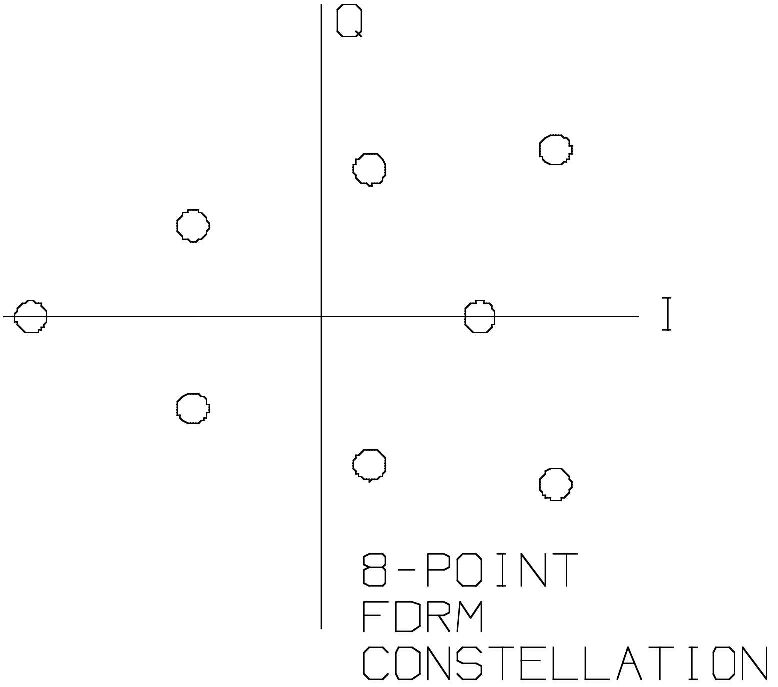

Figure 15 A Normal Constellation Illustrating Desirable Properties for FDRM

Criterion and Discussion

1. Meets system requirements.

Adaptive FDRM with pilots should excel at meeting system requirements particularly the multipath and rain fade requirements. FDRM should be continually used for the upstream path. 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.

2. Spectrum Efficiency.

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.

Holtzman proposes that the downstream system use reciprocal blocks on an as-needed basis with pilots assisting the demodulation 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.

Upstream transmission of reciprocal blocks will nominally occur with 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 block by block 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 clean affurate-frequency 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.

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 tall antenna mast will not be required.

One disadvantage of FDRM (and OFDM for that matter) is the transmitter needs to be linear 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 linear operation is a requirement, regardless of which modulation used. 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 transmit and receive frequencies are similar.

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.

7. Protocol Interfacing Flexibility

The greater tolerance on upstream to dynamic levels will alleviate the need to frequently re-range power levels in bad weather, simplifying the MAC protocol.

8. Implication on Other Network Interfaces

Holtzman has not yet specified adaption layers to map MPEG or IP packets into FDRM blocks.

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 within the wider upstream channel.

9. Reference System Gain

TBD. Downstream will be slightly lower than OFDM due to the use of pilots. 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 long guard intervals will also reduce upstream capacity.

10 Robustness to Interference

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

OFDM and FDRM can 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 DMT (discrete multi-tone) and in COFDM when a PAL video carrier is operating co-channel.

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.

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 [4] discusses the merits of OFDM relative to 8-VSB for broadcast applications. Reference [5] is the standard for terrestrial COFDM.

Conclusion and Summary

Holtzman proposes:

1. Downstream use of pilot carriers and intermittent use of FDRM depending on the individual echoes.

2. Upstream use of pilot carrier and full-time use of FDRM.

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, co-channel interfence, amplifier non-linearity, rapid fades and dynamic multipath.

The adjustable parameters include:
a. Sending reciprocal blocks only fast enough to keep up with the channel's changes and using the multipath solution on blocks that do not have accompanying reciprocal blocks. (upstream only)
b. Transmit power adjustment
c. Number of points in a constellation (change 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.

References:

[1] Thomas H. Williams, “A Digital Transmission System with Very High Immunity to Dynamic Multipath”, IEEE Transactions on Broadcasting, March 1999, Vol. 45, No. 1
[2] Thomas H. Williams, “Frequency Domain Reciprocal Modulation (FDRM) for Bandwidth-Efficient Data Transmission Over Channels with Dynamic Multipath”, 1999 NAB Broadcast Engineering Conference Proceedings, pp. 71-82
[3] Thomas H. Williams, “Frequency Domain Reciprocal Modulation (FDRM)”, 1999 IEEE Radio and Wireless Conference Proceedings, pp.129-132
[4] 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”
[5] DVB-T Standard ETSI EN 300 744 V1.2.1 (1999-07) available at www.etsi.org

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