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Title:

Pilot-Assisted Frequency Domain Reciprocal Modulation for Microwave Channels with Dynamic Multipath

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Purpose:

Consideration as physical layer technology for inclusion in the proposed 802.16 standard.

Pilot-Assisted Frequency Domain Reciprocal Modulation (FDRM) - Rev. 1

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Introducing FDRM

- Designed to deal with dynamic multipath distortion
- Uses two blocks that were encoded differently from the same information
- A multicarrier system that is related to OFDM
- Assumes that the same echoes distort each data block
- The two data blocks are processed together to find the unimpaired symbols
- The frequency response of the path can be measured and used for correcting future blocks or for averaging

Characteristics of FDRM

- First block is like OFDM, second is a frequency domain reciprocal to the first block, HC by HC
- Tolerant to dynamic multipath
- Operates in 0 dB echo environments
- Operates with dispersed echoes
- Tolerant to rapid fades
- Ideal for burst-mode
- Pilot assistance fixes problem of intolerance to phase-noise at microwave frequencies

Does 802.16 Need to Be Concerned with Big Echoes and Dynamic Multipath?

- Model is for line-of-site operation and line of site typically has low delay dispersion
- Requirements document also calls for multipath tolerance as well as interference from adjacent cells

Look Over Your Shoulder

- Sub - 11 GHz effort will be a high-volume (low cost) application
- What keeps a Sub-11 modem from operating in 10-60 GHz band?
  - Data Rates?
  - Applications or MAC?
  - Non-constant envelope or phase noise?
- Equipment designed for non-line of site can be just as efficient when operating line-of-site
- How are we going to distinguish ourselves?
- Will their success == our failure?

Multipath Distortion

- Also known as echoes or ghosts
- A linear distortion
- Copies of the same signal with different delays and attenuations - also diffuse echoes
- A weak echo increases BER in the presence of noise. A strong echo makes the data useless.
- A traditional solution is an adaptive equalizer, but adaptive equalizer’s coefficients must be programmed to match the echoes
- Adaptive equalizer may use a training signal or blind equalization

Characteristics of Echoes at 10-60 GHz.

- Because distances between the transmitter and receiver are short, echo delay will also be short, therefore response ripple will change slowly vs. frequency
- Because the wavelength is short, if motion causes the echo to be dynamic, the phase of echo will change rapidly vs. time

Dynamic Multipath Distortion

- Caused by echoes or ghosts that change e.g. wind-blown foliage, tower sway, pedestrian traffic, birds, and repeaters
- Transmitter, receiver, or reflector may move
- The programming of the adaptive equalizer must change to match the moving echo
- At microwave frequencies change is very quick
- Rapid accurate reprogramming is difficult
- Noise increases the programming time
- Rapid signal fades also occur
- Sometimes no direct signal path is available

Echo Characterization

- Costs bandwidth
- Frequently required bandwidth is low
- Rate of change of echoes with time
- Rate of change of echoes with frequency
- Noise in the channel characterization increases intersymbol interference
- BER curves typically assume echo is gone

FDRM - Theory of Operation

Let S(f)= normal transmitted signal in frequency domain and H(f)= channel's frequency response. Therefore a normal received signal is:

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

If a reciprocal signal block is created:

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

A received reciprocal signal will be:

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

Theory of Operation cont.

So the originally sent unimpaired signal can be found:

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

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

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

so the channel's frequency response is:

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

Theory of Operation - cont.

- Approximately the same linear distortion must be applied to both blocks
- If any frequencies have low magnitude components computing the frequency domain reciprocal results in large (impractical) values
- OFDM fits the bill as a modulation with controlled energy at all frequencies (no low energy frequencies)
- Another method is single block FDRM. Normal carriers and reciprocal carriers are interleaved in the same block
- Assumption is that approximately the same echo afflicts adjacent carriers

Theory of Operation - cont.

- Noise affecting each block adds on a 10 log basis, but normal and reciprocal HCs are correlated and add on a 20 log basis
- Signal to noise ratio improved by 3 dB
- Noise in channel's frequency response is also reduced by 3dB
- Coherent interference from repeaters or other sectors is automatically canceled if delay is less than guard interval
- Square root has two solutions

Microwave Transmission

- Line of site is primary method for 10-60 GHz
- Wide-beam antenna at central site
- Narrow-beam antenna at remote site
- Impairments
  - Rain fade
  - dynamic multipath
  - co-channel interference
  - intermod products
  - random noise

Holtzman’s Proposal

- FDRM/OFDM adapted to microwave with out-of-block pilots to tolerate phase noise and reciprocal transmissions for moving echoes
- Pilot assisted demodulation for both upstream and downstream
- Reciprocal transmission starts each upstream burst
- Reciprocal transmissions as-needed on downstream
- Stored coefficients will deghost harmonic carriers without accompanying reciprocals
- Transmissions are adapted to subscriber's path

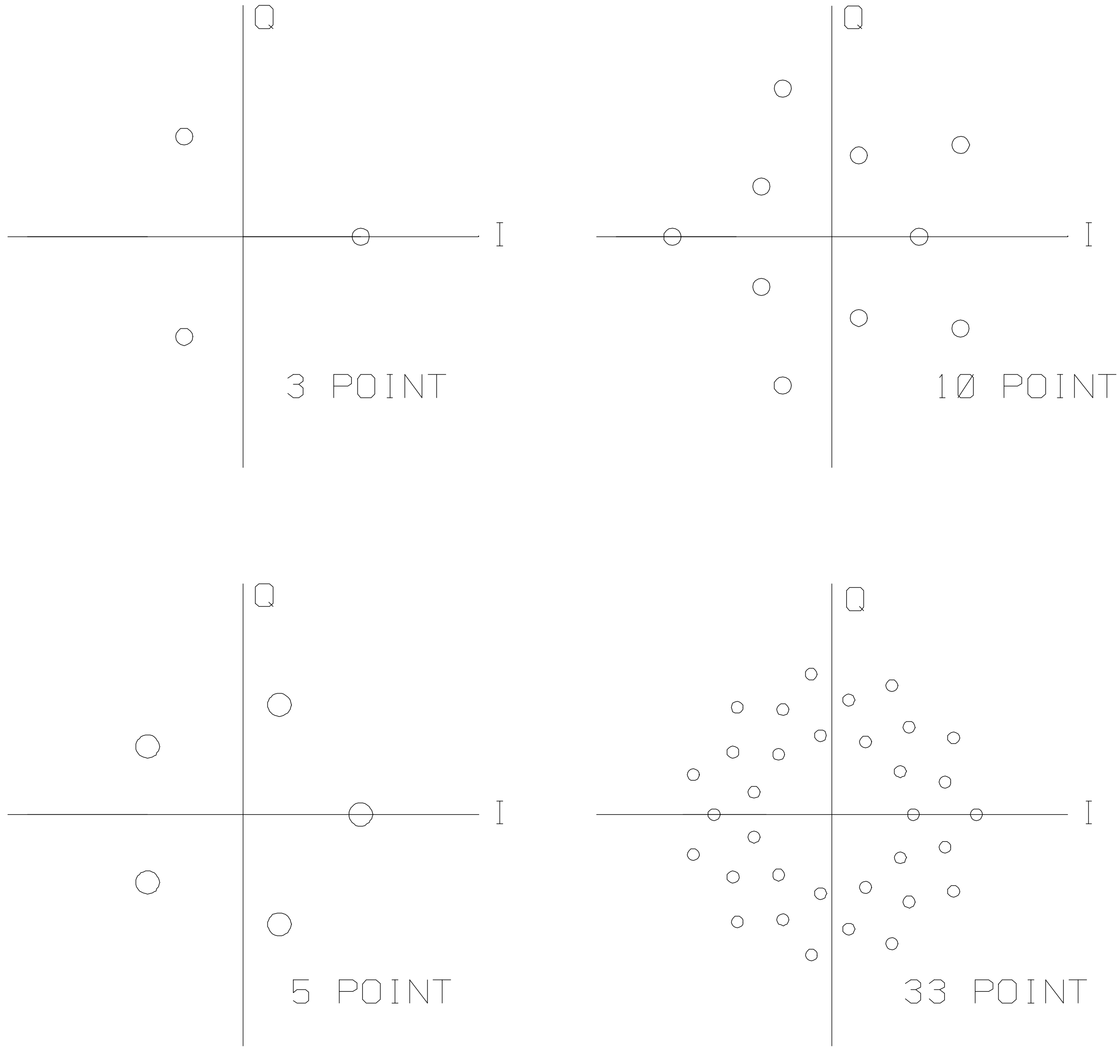
Out-of-Block Pilot Signal

- Ka band phase noise from low cost transmitters is way too great for OFDM or FDRM
- Pilot is separated by vacant spectrum
- Another hot harmonic carrier
- Located at both upper band edge and at lower edge
- Used to demodulated the block transmission
  - Remove phase noise by mixing
  - Cancels the frequency offset
  - Vacant spectrum contains the frequency error and phase noise modulation

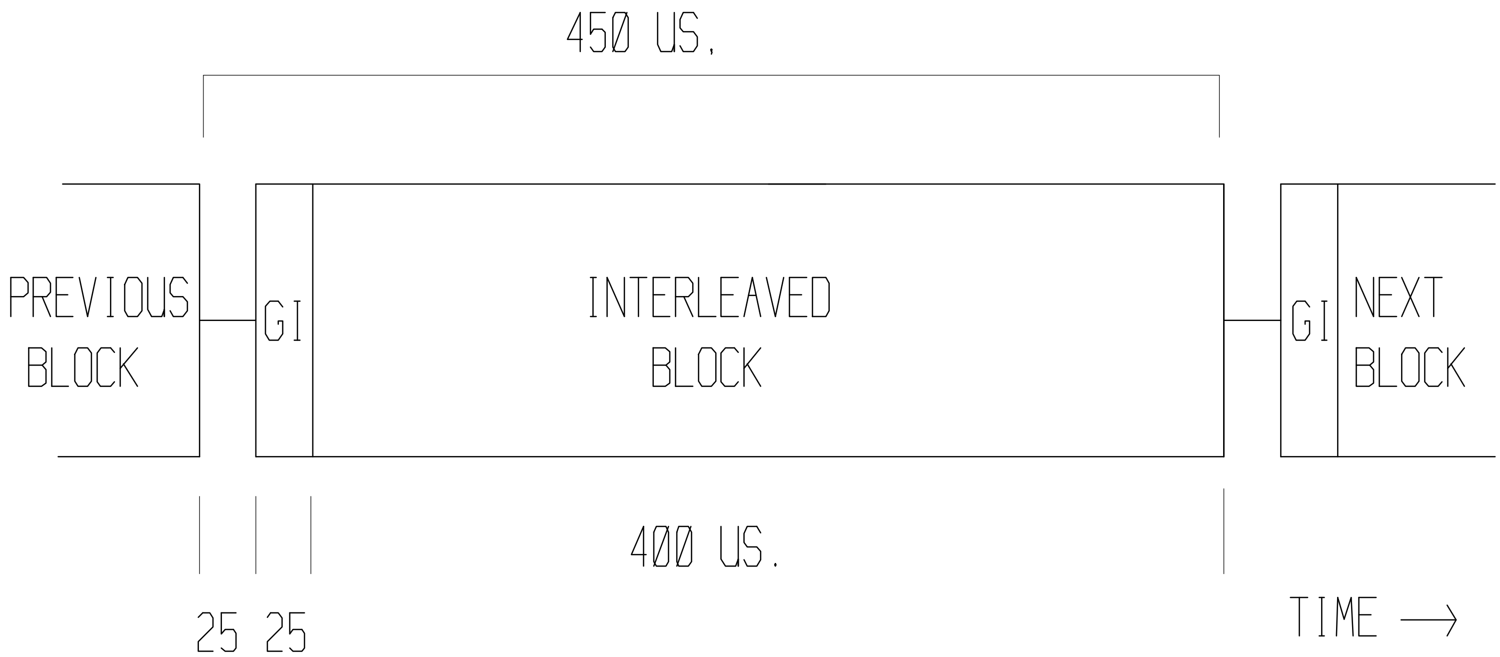
Antenna Diversity

- A second receive antenna is located a half wavelength further from the transmitter
- Deep fades are very unlikely to occur at the same frequencies on both antennas
- With OFDM or FDRM receiver can pick best antenna to use on a harmonic carrier by harmonic carrier basis
- With FDRM channel information, H(f), makes antenna choice easy for each HC
- Signals from 2 antennas can be added using H(f) data to align phases
- Coding overhead on OFDM or FDRM block can be lower

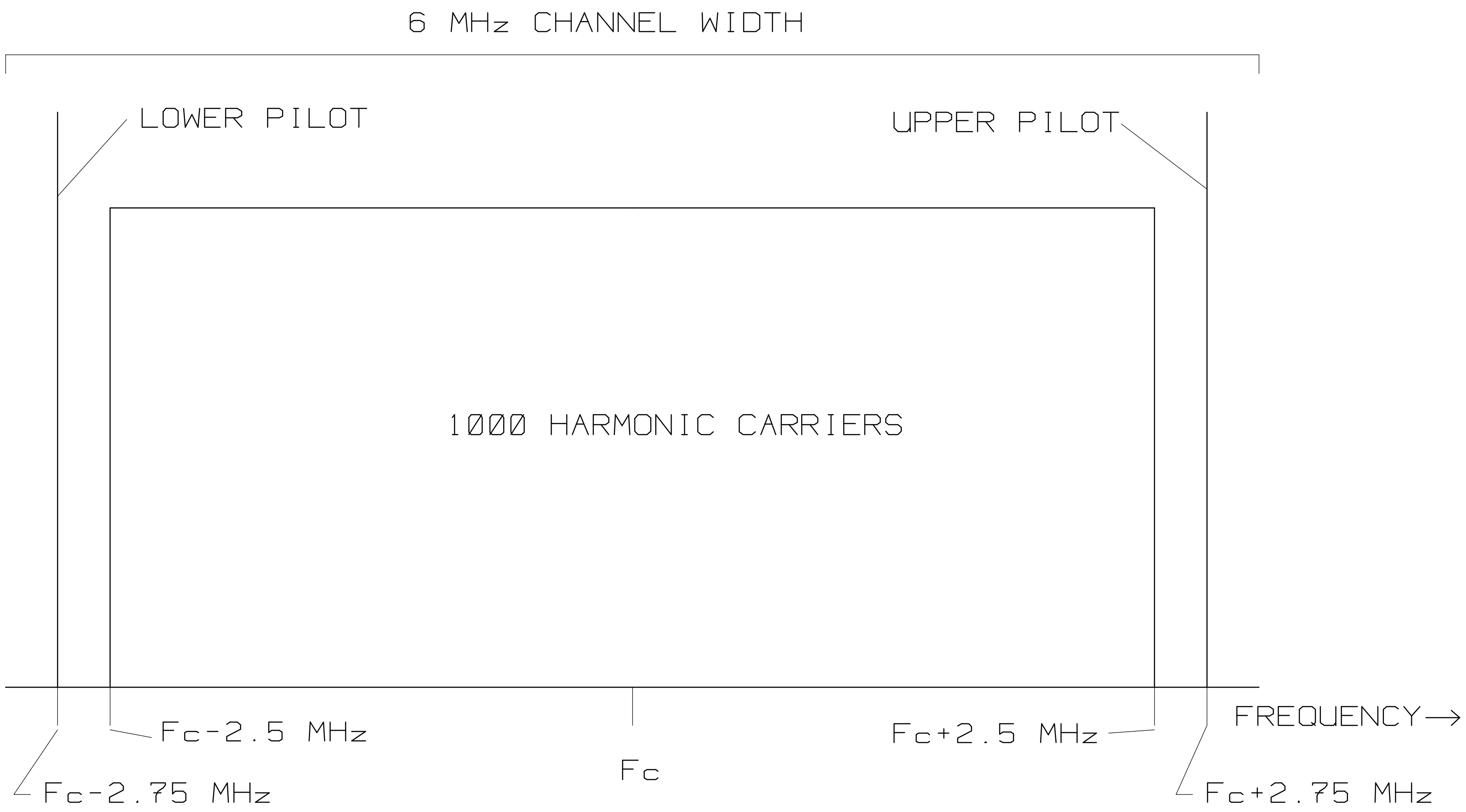
Proposed Constellations



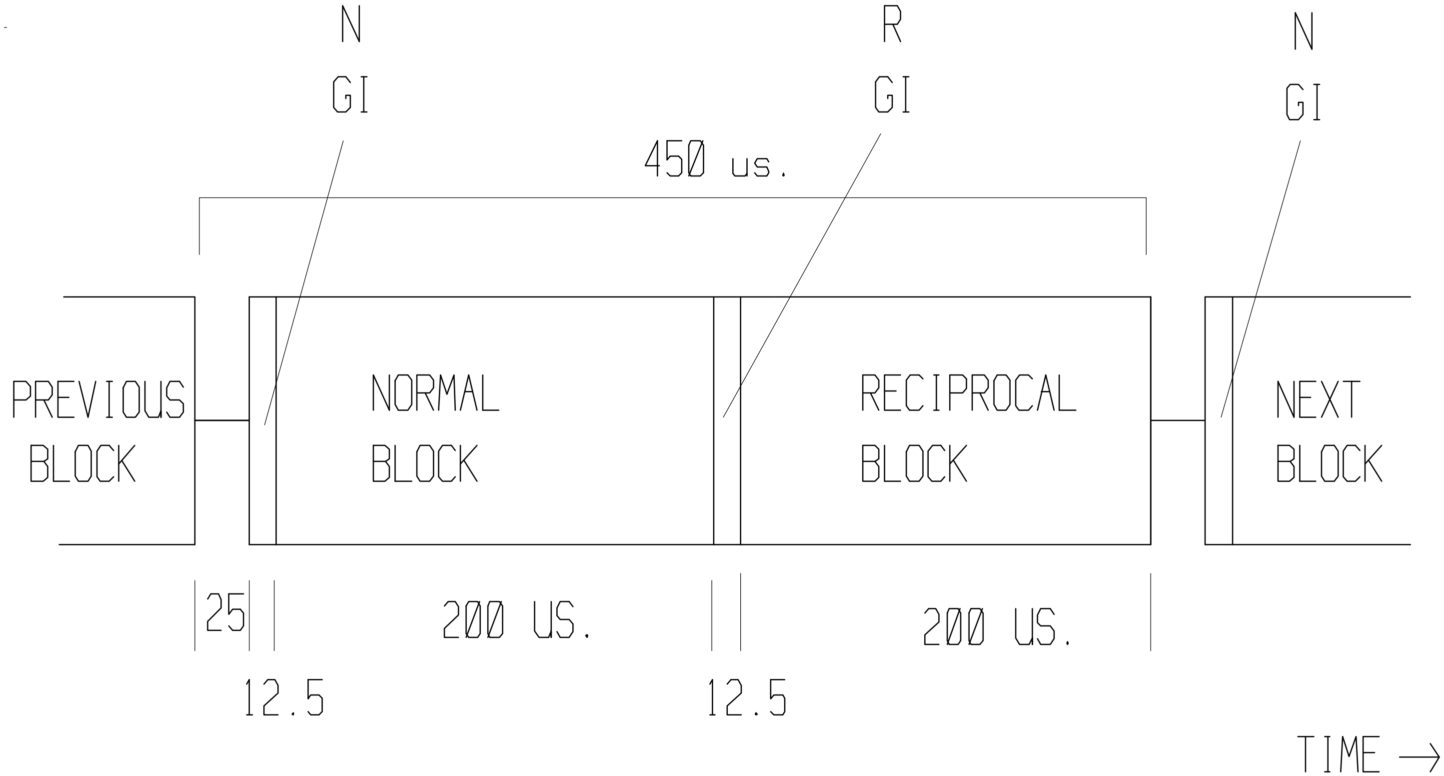
Proposed Time Plot of an Interleaved Burst



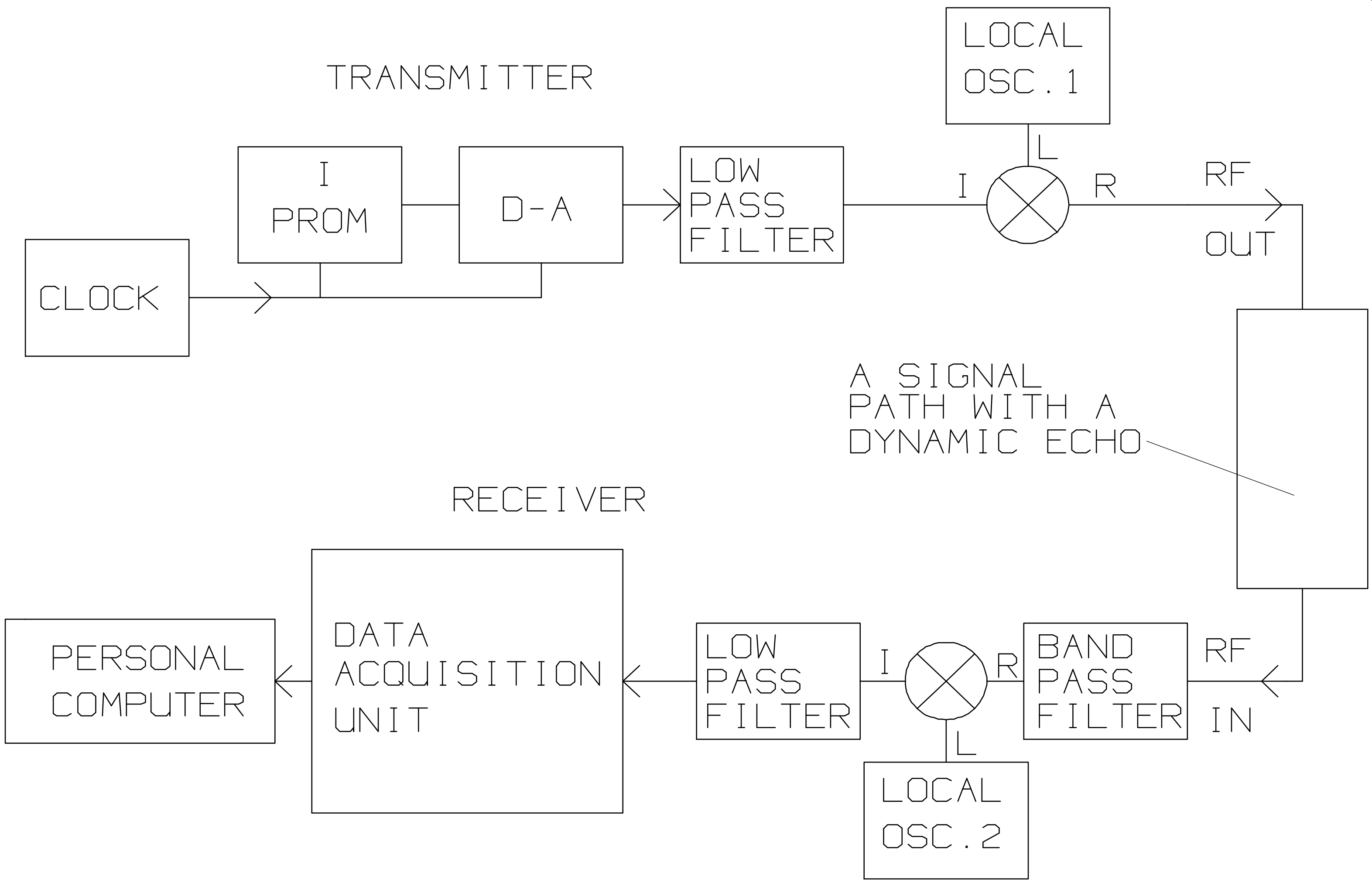
Proposed Spectral Plot



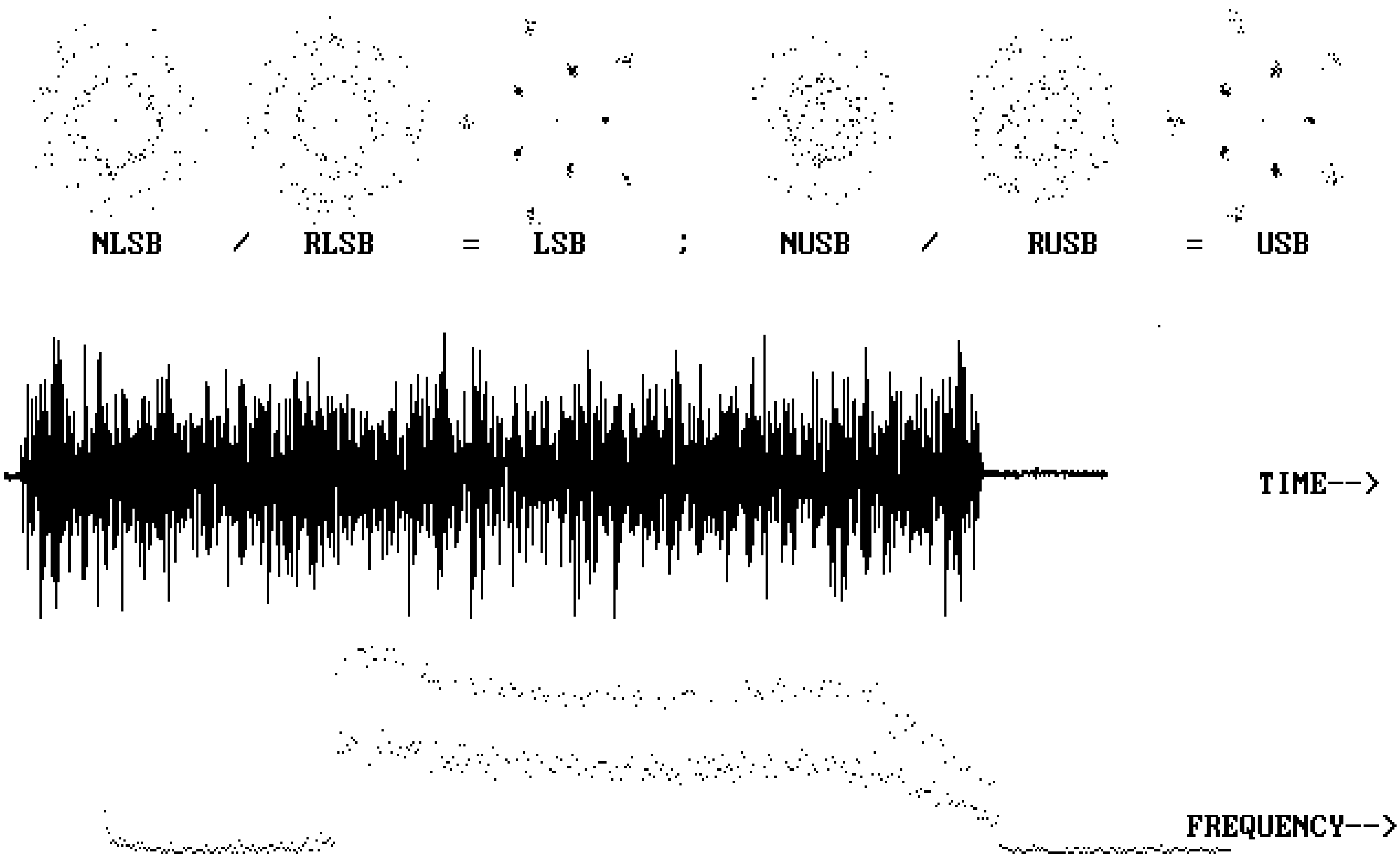
Alternate of a Sequential Burst Time Plot



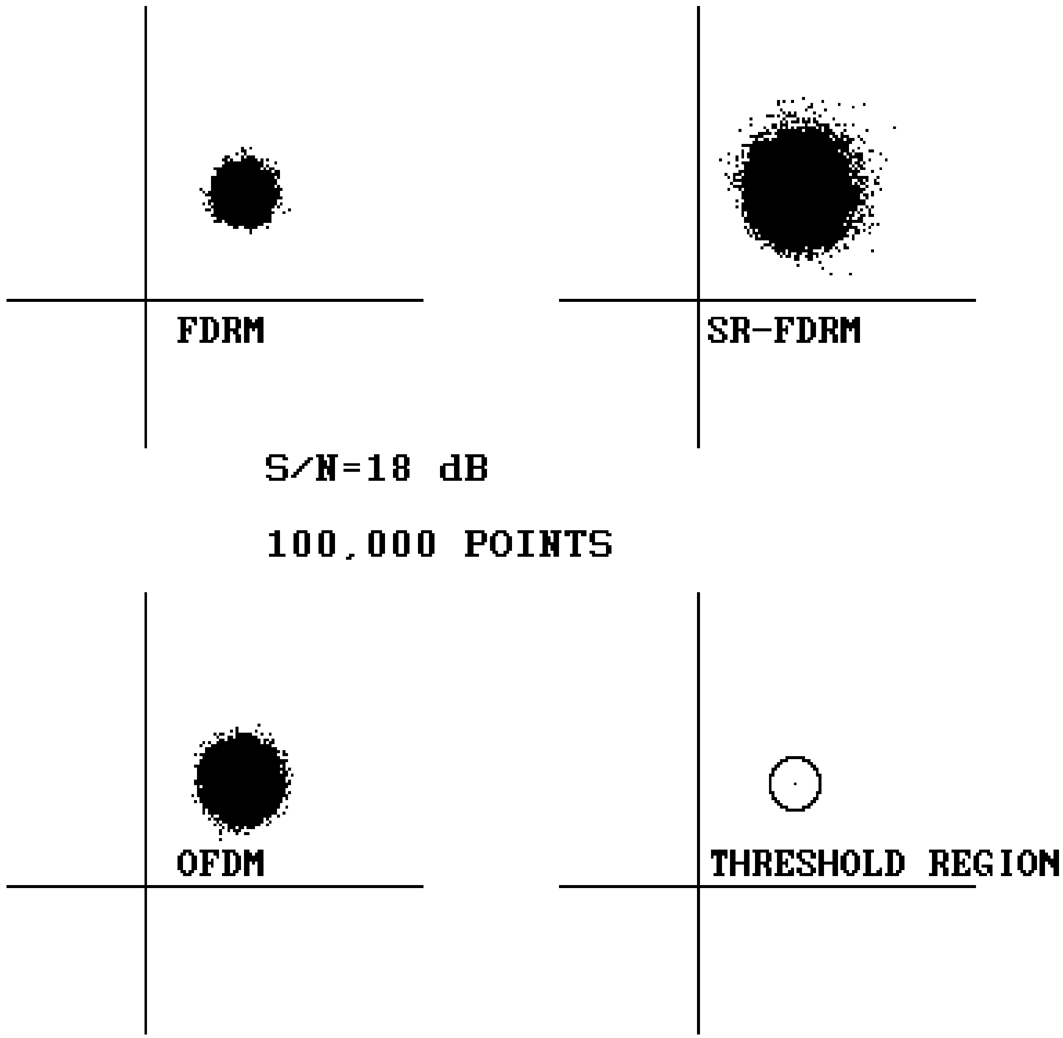
Block Diagram of Test Hardware



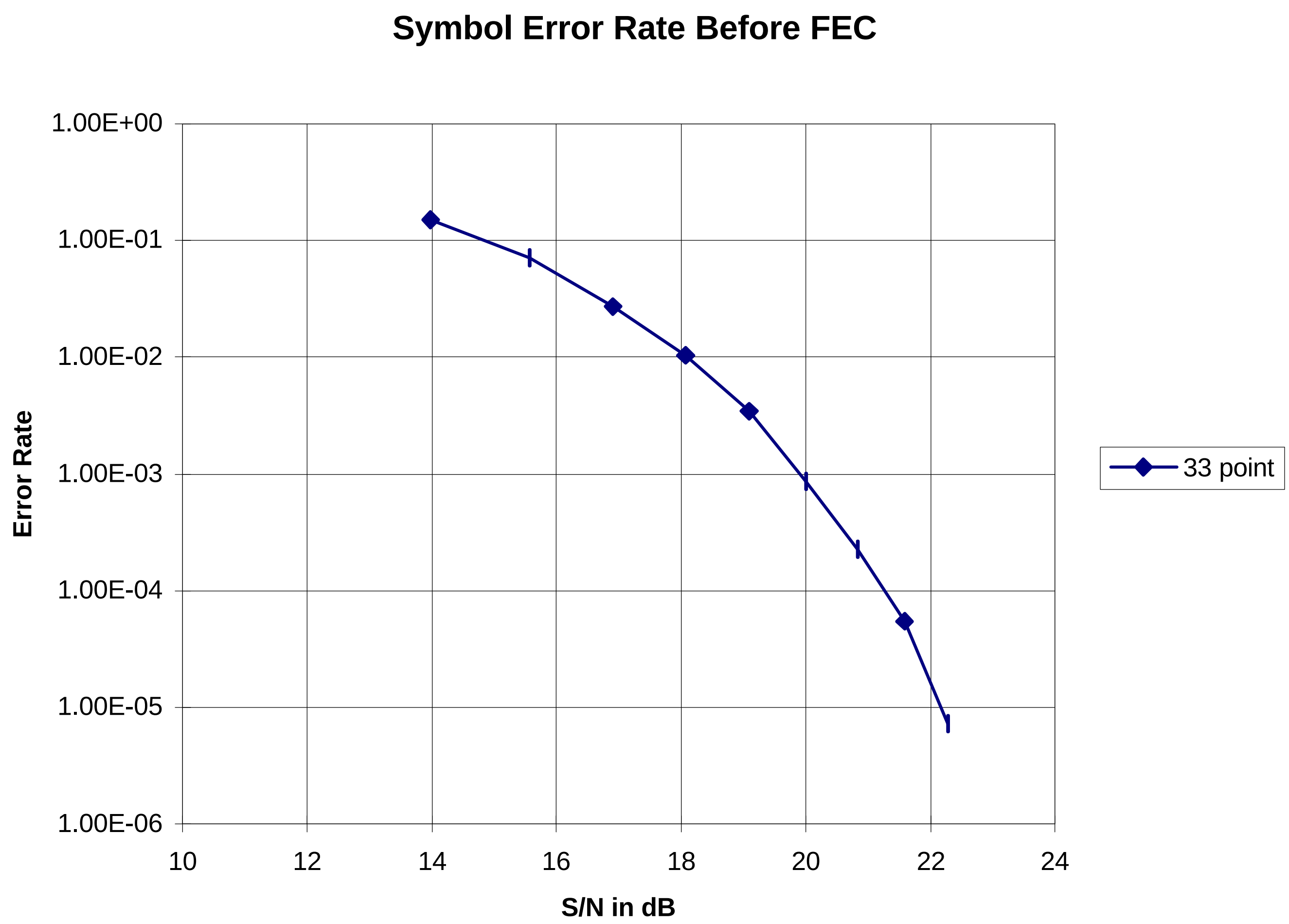
Test Results from Processing a Single Burst



Constellation Spread from Random Noise



Symbol Error Rate vs. Carrier to Noise



Observations from Test Data

- Technique works well
- Impairments from test setup corrected along with any echoes
- Easier to implement than OFDM
- Frequency differences between TX and RX LO's cause ISI (sequential blocks) or cause the processed constellation to be rotated (interleaved blocks)
- Forward error correction needed to recover symbols lost in deep fades.
- Signal adds on a 20 log basis while random noise adds on a 10 log basis. Result is a 3 dB better S/N ratio.

Conclusions

- FDRM = frequency domain reciprocal modulation
- Pilot assistance for phase noise
- Two blocks of data that are reciprocal to each other in the frequency domain are sent in an interleaved block
- The same echoes contaminate both blocks. The blocks are processed together at the receiver
- Linear distortion is automatically canceled as an intrinsic property of the modulation
- Reciprocal blocks sent as often a necessary

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Patents Pending