Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Future Proof Platform for SUN – Technical Overview
Date Submitted: July 6, 2009
Source: Steve Shearer, Independent
Address: Pleasanton, CA, USA
Voice: (408) 417 1137 , FAX: [], E-Mail: Shearer_inc @ yahoo.com

Re: [802.15.4g] TG4g Call for Proposals, 2 February, 2009

Abstract: Technical Overview of the merged OFDM proposals of Steve Shearer, Landis&Gyr, Maxim and ETRI. This document highlights key signal processing areas of the proposal that make this a good choice for the new SUN PHY.

Purpose: Technical Proposal to be discussed by IEEE 802.15 TG4g

A Future Proof Platform for Smart Utility Networks

Top Level Technical Overview

Steve Shearer

July 2009

Supporters: Roberto Aiello [Independent], Sangsung Choi [ETRI], Bob Fishette [Trilliant], Michel Veillette [Trilliant], David Howard [On-Ramp], Rishi Mohindra [MAXIM], Emmanuel Monnerie [Landis & Gyr], Partha Murali [Redpine Signal], Shusaku Shimada [Yokogawa Electric Co.], Kendall Smith [Aclara], Mark Wilbur [Aclara], Mark Thomson [Aclara] , John Buffington [Itron], Rodney Hemminger [Elster], Elad Gottlib [Silver Springs Networks], Jay Ramasastry [Silver Springs Networks], Xing Tao [Chinese Academy of Science], Betty Zhao [Huawei]

Introduction

- The purpose of this presentation is to introduce key technical aspects of the Future Proof Platform merged OFDM proposal
  - Demonstrates that an OFDM system, properly configured to the application at hand, can lead to a highly efficient, low complexity PHY
- This presentation shows how the combination of several simple signal processing methods have been used to create the SUN OFDM PHY proposal
  - And shows how this proposal is compatible with the existing standard and some new proposals
- We believe that this proposal is worthy of consideration as a candidate for new Smart Utility Networks PHY standard.

Contents

- Proposal meets the requirements of the PAR
- Some common concerns about OFDM
- Key aspects of this proposal
  - Data rates / Bandwidth
  - Compatibility with existing MAC
  - Modulation
  - Soft decisions
  - Convolutional coding
  - Time and Frequency Spreading
  - Data structure
  - Reference Transmitter Diagram
- How Multicarrier systems maximize the use of the radio channel
  - Inter Symbol Interference
  - Frequency selective fading
  - Spatial/Geographic nulls
  - Rayleigh fading
  - Performance Advantage Snapshot
- Conclusions

Requirements of the PAR

- Operation in any of the regionally available license exempt frequency bands, such as 700MHz to 1GHz, and the 2.4 GHz band.
- Data rate of at least 40 kbits per second but not more than 1000 kbits per second
- Carrier Grade Reliability
- Achieve the optimal energy efficient link margin given the environmental conditions encountered in Smart Metering deployments.
- Principally outdoor communications
  - **“highly obstructed, high multipath locations with inflexible antenna orientation”**
  - **“Applications for Wireless Smart Metering Utility Network further intensify the need for maximum range”**
  - **“Wireless Smart Metering Utility Network requirement of 100% coverage”**
  - **“ability to provide long-range point-to-point circuits available for meshing”**
- PHY frame sizes up to a minimum of 1500 octets
- Simultaneous operation for at least 3 co-located orthogonal networks
- Connectivity to at least one thousand direct neighbors characteristic of dense urban deployment

This Proposal meets the PAR

- It is applicable to the 700, 800, 900 MHz and 2.4Ghz bands
- Scalable data rates from 780 kbps down to 46 kbps
  - Enables accessing "difficult-to-get-to" nodes
- Achieves excellent energy efficient link margin (E_b/N_0) to achieve Carrier Grade reliability without wasting power
- Designed for outdoor environments because it addresses:-
  - Multipath by using long symbol times and a cyclic prefix
  - Spatial nulls by using slow frequency hopping or Frequency Diversity
  - Fading by employing channel coding and Time Diversity for improved packet error performance
  - Provides long range where necessary
- Supports packet sizes up to 2047 octets with low PER in outdoor environments
- Is adjacent channel friendly to allow co-located orthogonal networks
- Supports connectivity to multiple neighbors
- In addition, battery consumption can be shown to be as low, or lower, than single carrier systems

Common concerns about OFDM

- More complicated MAC?
  - Intended to re-use current 802.15.4e MAC
- High SNR?
  - This proposal shows reliable operation in negative SNR conditions
- High PAPR?
  - Low order modulation allows PA back-off to be 3dB or less
- High TX Power?
  - 15 to 30dB link margin advantage allows lower TX power (same data rate on the same link)
- Complexity?
  - Orders of magnitude lower than popular WLAN systems
- Cost?
  - System cost can be as low as single carrier systems
- Accurate Xtal oscillators?
  - 20 ppm is sufficient, 40 ppm can be tolerated
- High Power consumption?
  - Analysis shows superior performance for battery operated devices
- 'Brick wall' analog filters?
  - Not necessary

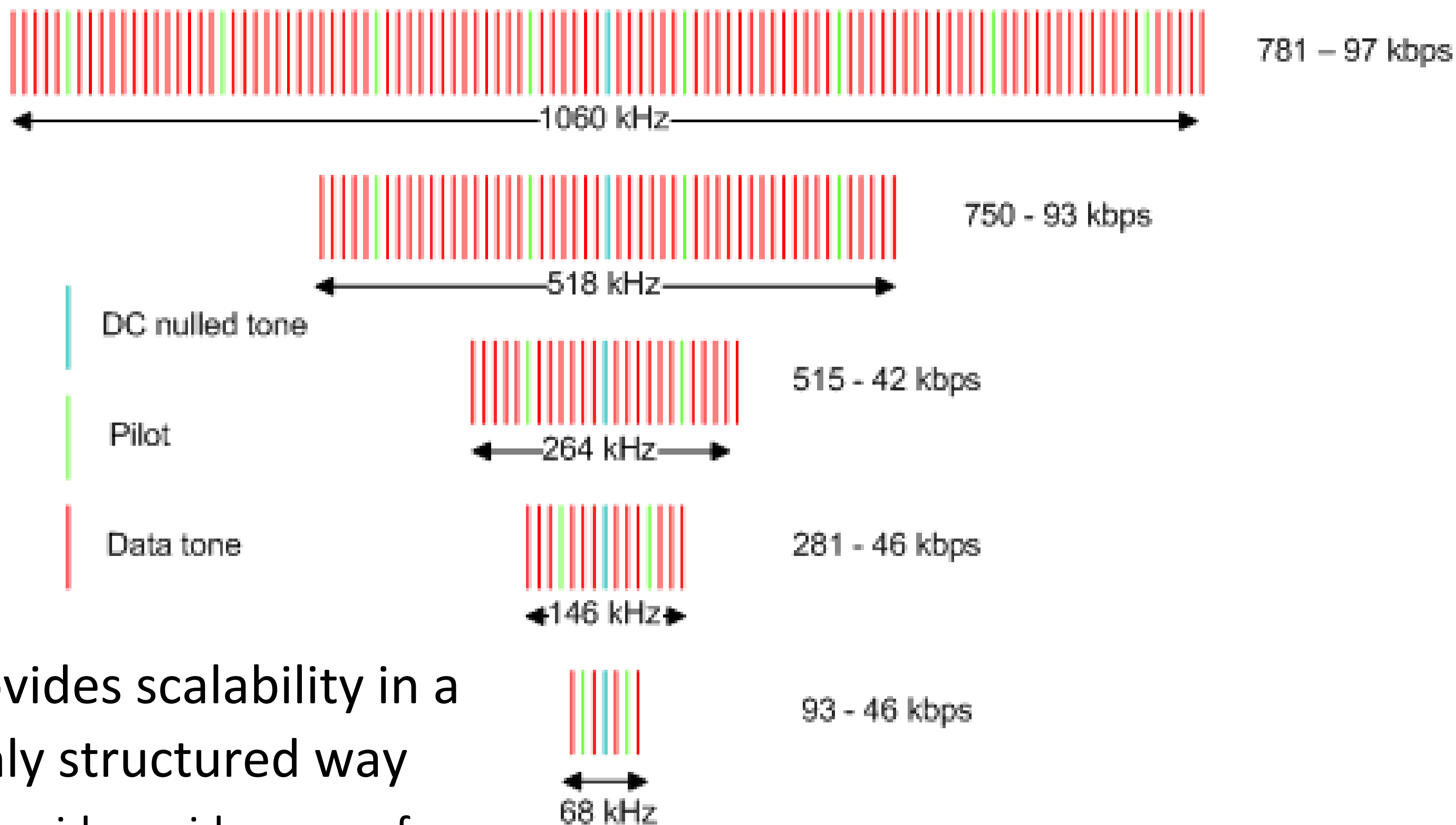
Key Parameters

- Several configurations to suit different Regulatory b/w requirements
  - Option 1 1060 kHz 128 pt FFT
  - Option 2 518 kHz 64 pt FFT
  - Option 3 264 kHz 32 pt FFT
  - Option 4 146 kHz 16 pt FFT
  - Option 5 68 kHz 8 pt FFT
- Common parameters for all options
  - Symbol time 128us
  - Cyclic prefix 25.6us
  - Tone spacing 9.7kHz
  - Multipath tolerance > 25us at all data rates
  - Low order modulation BPSK, QPSK, 16QAM
- Supports low packet-by-packet frequency hopping to mitigate spatial nulls
- Non hopping mode to ease concerns on battery consumption
- Complexity is orders of magnitude lower than WLAN

- Channel Coding derived from ½ rate convolutional mother code
- Coding rates from 3/4 through to 1/8 using
  - Puncturing
  - Frequency Repetition
  - Time Repetition
- Soft decision decoding for higher performance

	OFDM Option 1	OFDM Option 2	OFDM Option 3	OFDM Option 4	OFDM Option 5	Unit
FFT size	**128**	**64**	**32**	**16**	**8**	
Active Tones	108	52	26	14	6	
# Pilots tones	8	4	4	2	2	
# Data Tones	100	48	22	12	4	
Approximate Signal BW	**1064.45**	**517.58**	**263.67**	**146.48**	**68.36**	kHz
BPSK 1/2 rate coded and 4x repetition	97.66	46.88	21.48	11.72	3.91	kbps
BPSK 1/2 rate coded and 2x repetition	195.31	93.75	42.97	23.44	7.81	kbps
BPSK 1/2 rate coded	390.63	187.50	85.94	46.88	15.63	kbps
BPSK 3/4 rate coded	585.94	281.25	128.91	70.31	23.44	kbps
QPSK 1/2 rate coded	781.25	375.00	171.88	93.75	31.25	kbps
QPSK 3/4 rate coded	1171.88	562.50	257.81	140.63	46.88	kbps
16-QAM 1/2 rate coded	1562.50	750.00	343.75	187.50	62.50	kbps
16-QAM 3/4 rate coded	2343.75	1125.00	515.63	281.25	93.75	kbps

Scalable Data Rates / Bandwidth



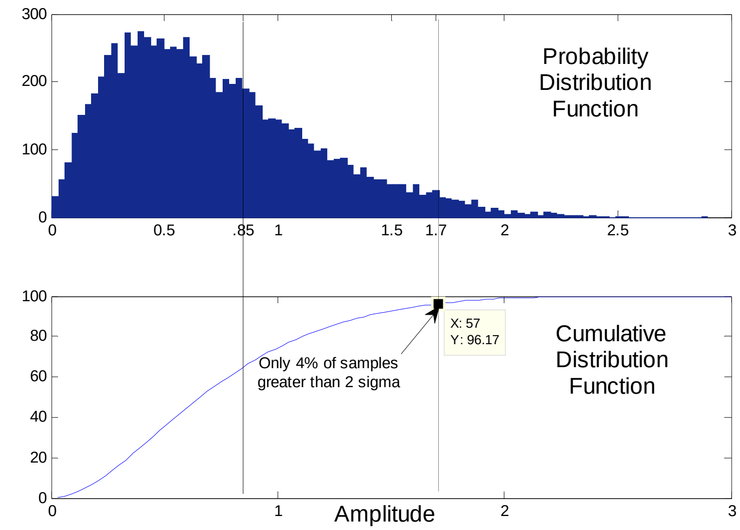
- Provides scalability in a highly structured way
  - Avoids a wide array of independent parameters

Multicarrier Modulation

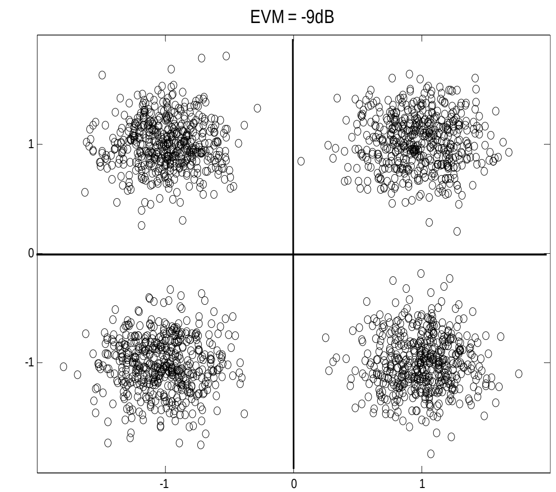
- This proposal modulates each carrier using BPSK, QPSK, or 16-QAM
- The PSK symbols are mapped onto individual tones in the frequency domain
- Several frequencies are nulled out
  - The nulled DC component helps in the implementation of cheap, zero-IF receivers (does not exclude passband receivers)
  - The nulled frequencies at the band edges significantly ease filtering complexity for adjacent channel performance
- An appropriate size Inverse FFT produces the time domain samples for transmission

Modulation and PAPR

- PA nonlinearity causes two issues
  - Spectral regrowth from compression of the peaks
  - High EVM from signal distortion



- The amplitude of an OFDM signal is approximately Rayleigh distributed
  - Fortunately the peaks don't happen very often thus minimizing average spectral regrowth



- This proposal uses only low order modulations which can withstand much higher EVM without loss of performance

- Therefore PA linearity requirements for this proposal are considerably reduced
  - See IEEE 802.15-15-09-0483-00-004g for details

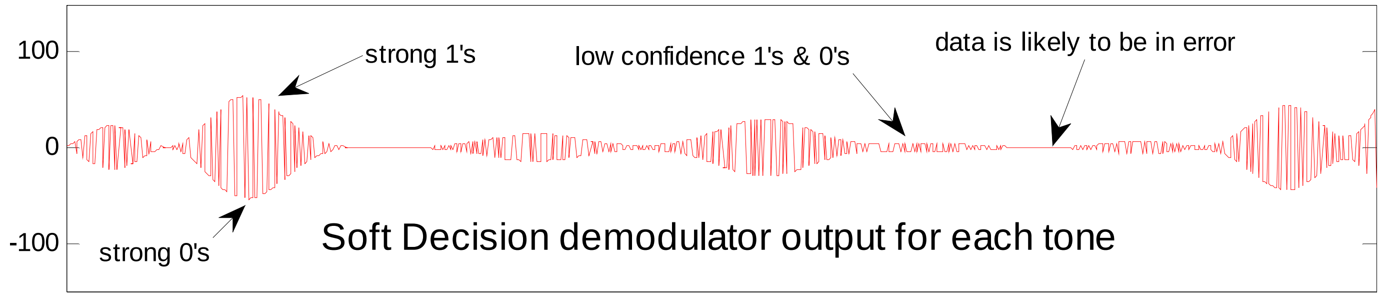
Compatibility

- The basic concept of this PHY is directly compatible with the current 802.15.4e work
  - It does not impose any further requirements on the MAC
  - Allows the entire upper s/w stack to be re-used
- All modes can use packet-by-packet frequency hopping
  - Although this is probably only necessary for narrowband modes
  - Wider band modes allow Battery efficient non-hopped operation in many popular bands (e.g. 900MHz)
- The time domain waveform leaving the antenna is different in nature to that of FSK or DSSS systems, but this is invisible to the upper layers

OFDM enables simple Soft decision generation

- The demodulator for each tone outputs the bits as ‘confidence levels’ based on an estimate of the channel quality
  - Bits demodulated during a fade will have small +/- confidence levels
  - Bits demodulated in a peak will have larger +/- confidence levels

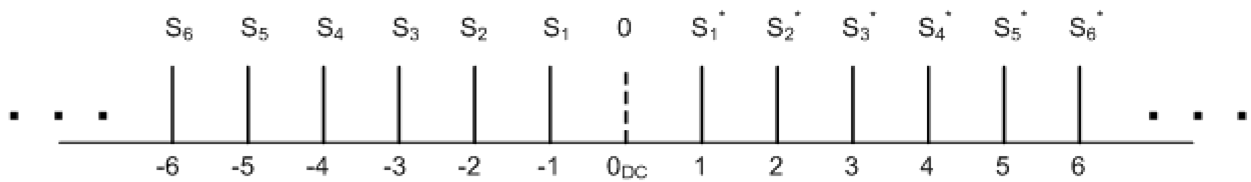
- Provides additional information about where errors may lie
  - Decoder can concentrate its error correction capabilities on the bits that are most likely in error



- Allows Maximal Ratio Combining for Frequency Spreading and Time Spreading modes

Frequency Spreading

- Frequency spreading is a method of replicating PSK symbols on different carriers
- The diagram indicates how the left half of the spectrum is replicated using conjugated versions of the PSK symbols



Mapping of data and guard subcarriers to logical frequencies for 2x frequency spreading

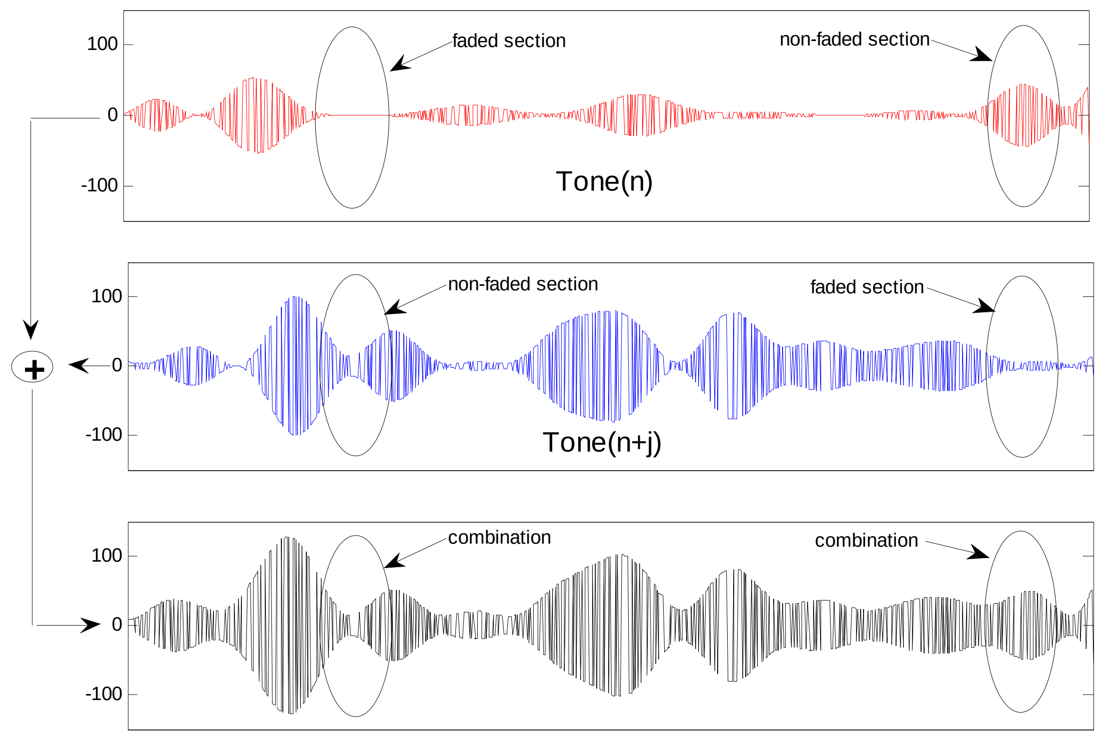
- Protects against frequency selective fading by providing **Frequency Diversity**
  - Enhances SNR performance

Frequency De-spreading

- Frequency diversity relies on the fact that fading on separate carriers is independent
  - While one is fading the other may be strong

- Soft decision PSK symbols can be optimally combined at the receiver with little computational overhead

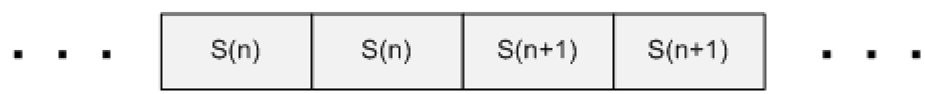
- Diversity gain offers significant improvement in performance as shown by the quality of the combined data
  - No 'dead ' spots



Time Spreading

- Time spreading is a method of replicating OFDM symbols at different times

- The diagram indicates how symbols are repeated



Replication of symbols in time to provide time diversity

- Protects against Rayleigh fading by providing **Time Diversity**
  – Enhances SNR performance

- Frequency Spreading and Time Spreading can be used together for additional robustness

Convolutional Code

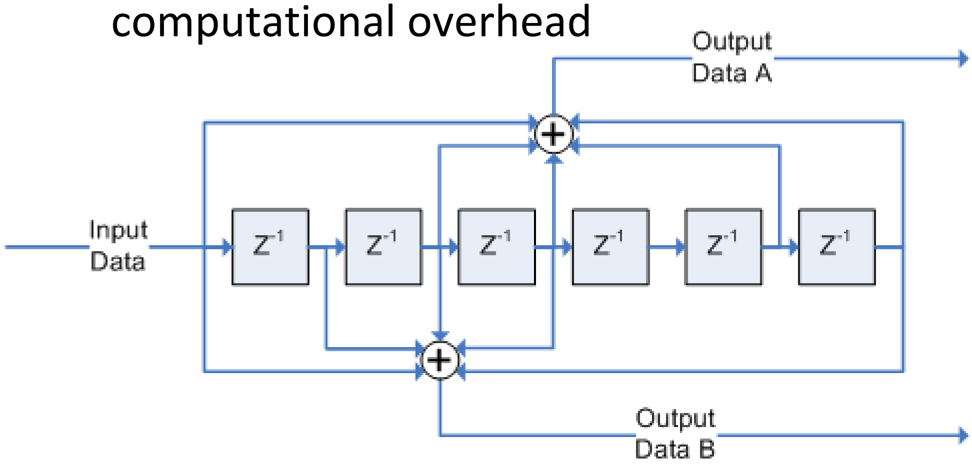
- Convolutional Codes are well know for their ability to effectively use soft decisions to correct errors
  - Coding gain is normally quoted as Eb/N0
  - SNR improvement at a **normalized** net information rate
  - And with modern hardware, they are easy to implement

- This proposal uses a constraint length 7, ½ rate code
  - Well known generator polynomials $G_{1,2}$ = [133, 171],

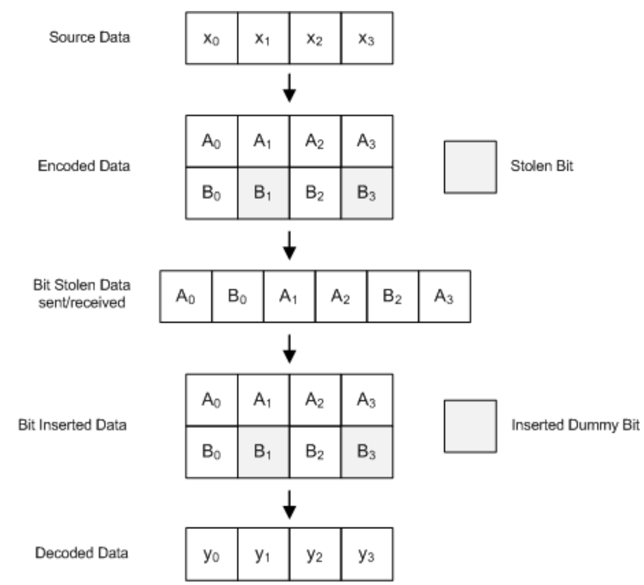
- Offers a coding gain of 6 dB for the same information rate
  - (9dB SNR)

Puncturing for Flexible data rates

- Puncturing is a process of removing redundancy to increase the coding rate
  - Bits are removed before transmission
  - And replaced with dummy bits on reception
- This is a well researched area (Hagenauer et al.)
  - Used in many systems
- Easy to implement using array indexing operations
- Provides very flexible data rates with no computational overhead



Convolutional Encoder: Rate ½, constraint length K=7
Generator polynomials [133, 171]



Interleaving

- Interleaving is used to spread bits in frequency over one symbol
  - Still investigating if interleaving over more symbols gives a performance advantage
- Interleaving equation for 32-FFT shown below

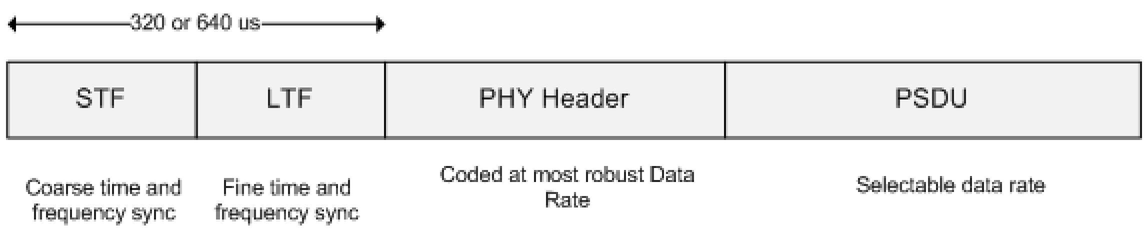
$$i = \frac{N_{cbps}}{12}(k \bmod 12) + floor\left(\frac{k}{12}\right)$$

$$\forall\, k = 0,1,2,\ldots N_{cbps} \quad and \quad N_{cbps} = 22 \times \{1,2,4\}$$

- Details for other n-FFT's given in detailed document IEEE 802.15-15-09-0489-00-004g

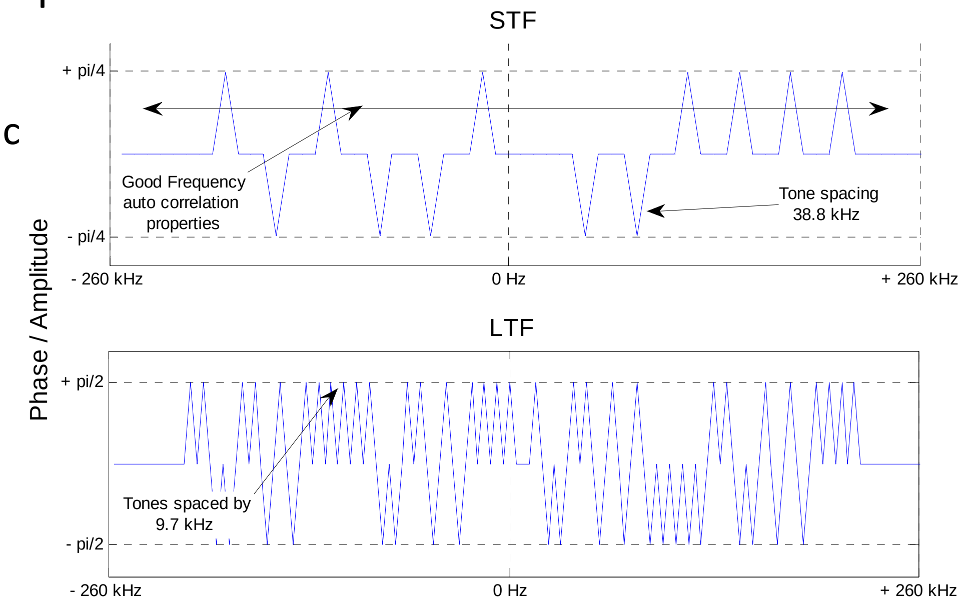
Data Structure

- Packets are made up of:-
  - Synchronization sequence
  - PHY header coded for maximum robustness
  - Variable length data payload coded according to data rate



Synchronization Sequence

- RF carrier reference and signal processing clock are derived from the same source
  - Frequency correction also corrects the symbol timing
- Synchronization sequence is made up of two sections
  - Set of tones spaced by 38.8 kHz for coarse frequency and time sync
  - Set of closely spaced tones for channel estimation and fine frequency/time sync



- This scheme allows simultaneous correction of timebase and frequency error for very loose tolerance Xtals.

PHY Header

- The PHY header contains 5 fields
  - Rate field specifies the data rate of the payload frame
  - Length specifies the length of the payload
  - Scrambling seed for the PSDU
    - helps with Regulatory compliance
  - Header Check sequence
    - 8 bit CRC taken over the data fields only
    - Avoids erroneous decoding of payloads and saves power consumption
  - Tail bits for Viterbi decoder flushing

Rate 6 bits	Length 11 bits	Scram 4 bits	Header Check Sequence 8	Tail 6 bits

PHY Header

- Encoded at the lowest data rate for robustness

Data Unit (PSDU)

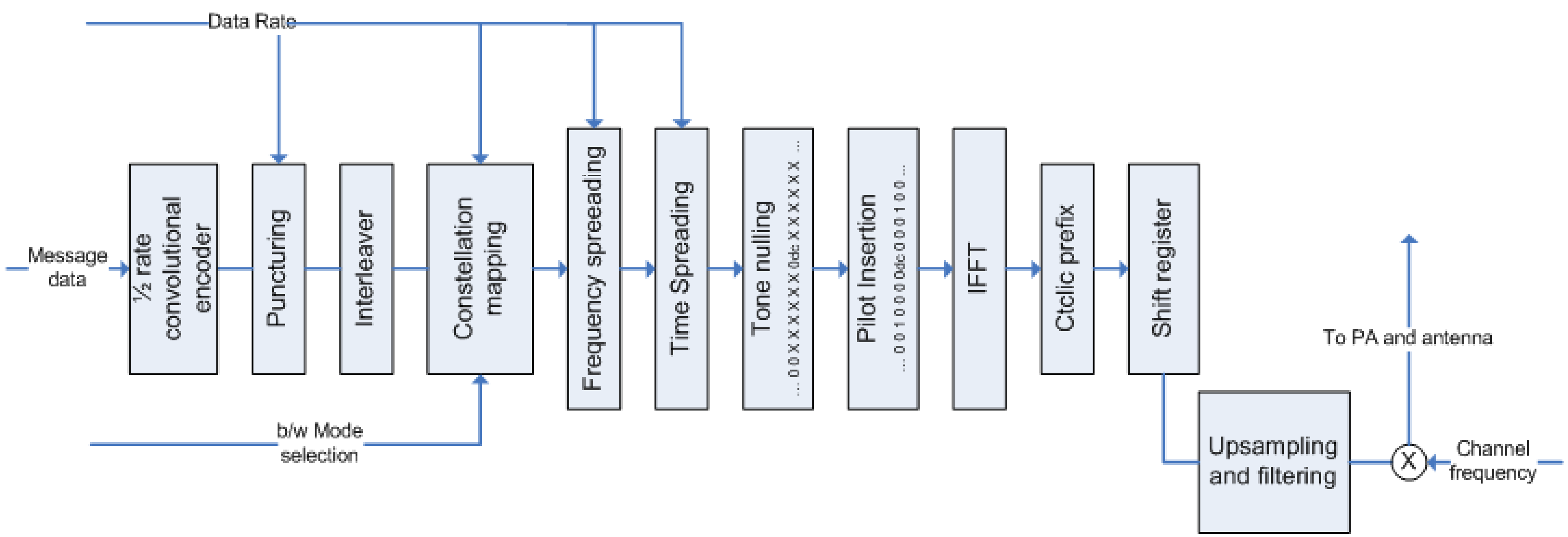
- Frame Payload
  - 8 to 2047 octets
- CRC
  - 32 bit IEEE CRC for error detection
- Tail and Pad bits
  - Used to clear encoder memory

Frame Payload 8 – 2047 octets	IEEE CRC 32	Tail 6 bits	Pad 4 bits

PSDU

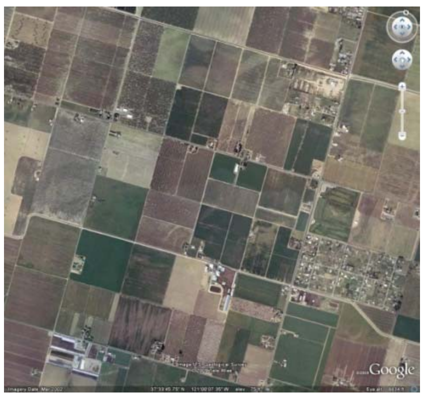
Reference Transmitter Diagram

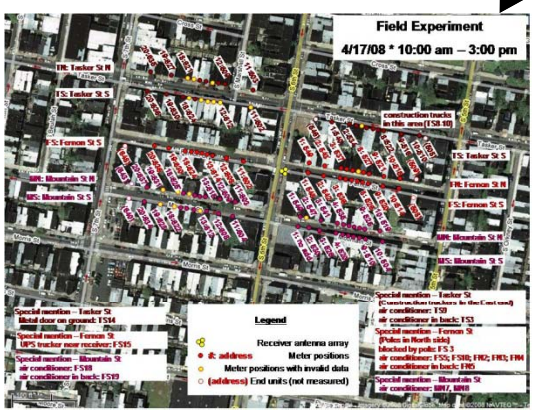
- Summary of transmitter signal processing
- Constellation Mapping block determines mapping of symbols and number of tones



Representative SUN Channels

- Simple two tap channel models used for performance evaluation
  - ETSI ETSI EN 300 392-2 V3.2.1 (2007-09)
- Performance simulations currently use only Pseudo Static methodology
  - Realistic fading rates still need to be defined for this application





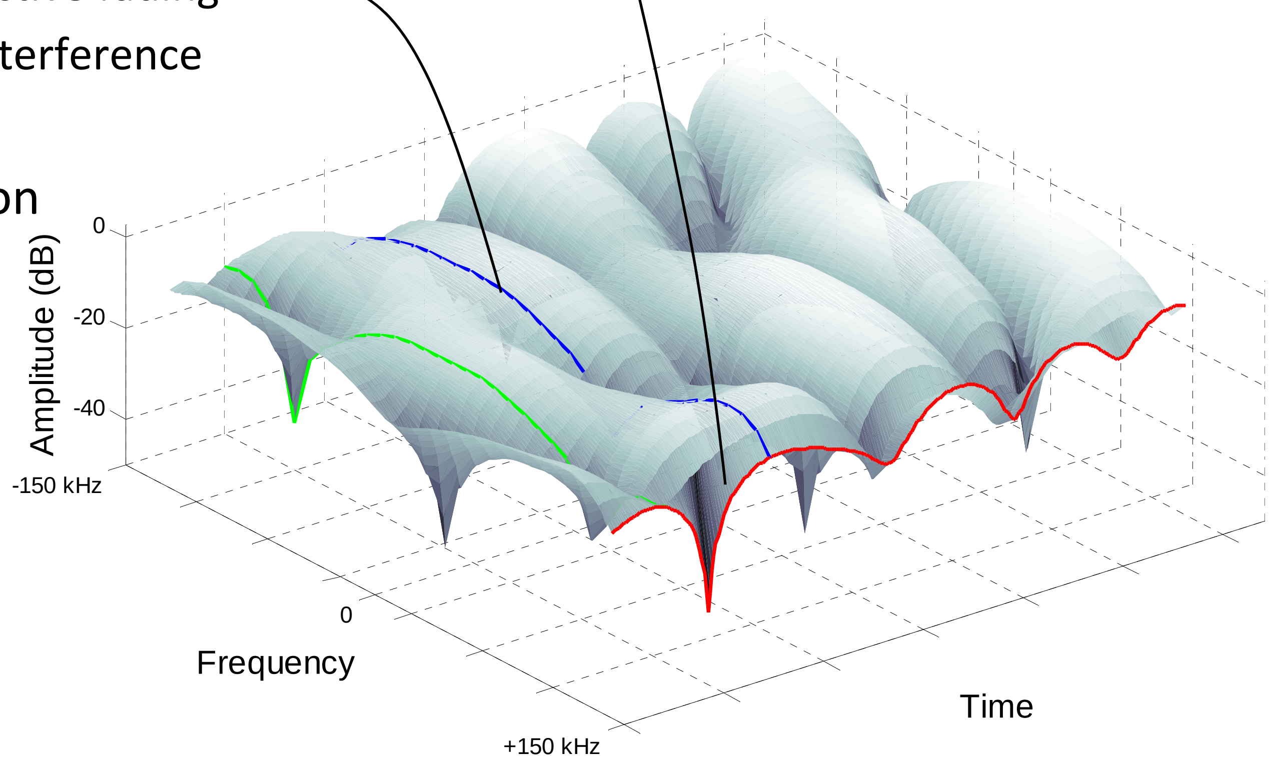
Channel Models taken from ETSI ETSI EN 300 392-2 V3.2.1 (2007-09)

Propagation Model	Tap Number	Relative delay (us)	Average relative power (dB)
Rural Area (Rax)	1	0	0
Typical Urban (Tux)	1	0	0
	2	5	-22.3
Bad Urban (Bux)	1	0	0
	2	5	-3
Hilly Terrain (HTx)	1	0	0
	2	15	-8.6

Key Channel Impairments

- Amplitude fading due to non LOS path
- Multipath due to reflections
  - Frequency selective fading
  - Inter Symbol Interference
- Spatial propagation nulls (not shown)
- How does OFDM overcome these problems?

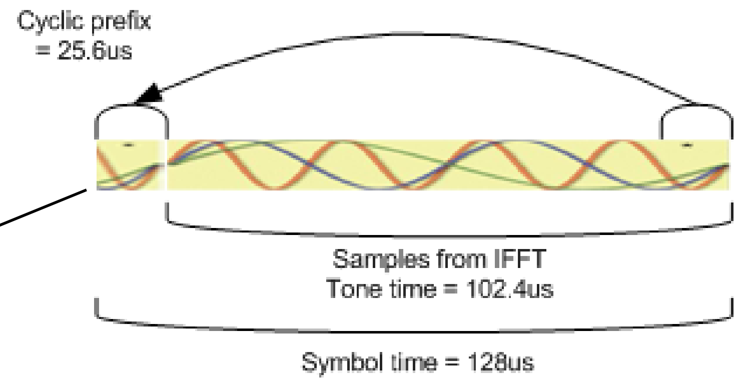
Spectral analysis of 300 kHz channel.
Two ray channel, 5us multipath



Multipath - ISI

- Multipath introduces Inter Symbol Interference
  - Every previous bit degrades every current bit
- OFDM overcomes ISI by
  - making the symbol much longer than the multipath
  - And using a cyclic prefix to contain the ISI
- OFDM retains the data rate by adding more carriers in the same proportion as the lengthening of the symbol
- Frequency hopping is very useful to mitigate spatial nulls but doesn't help with ISI

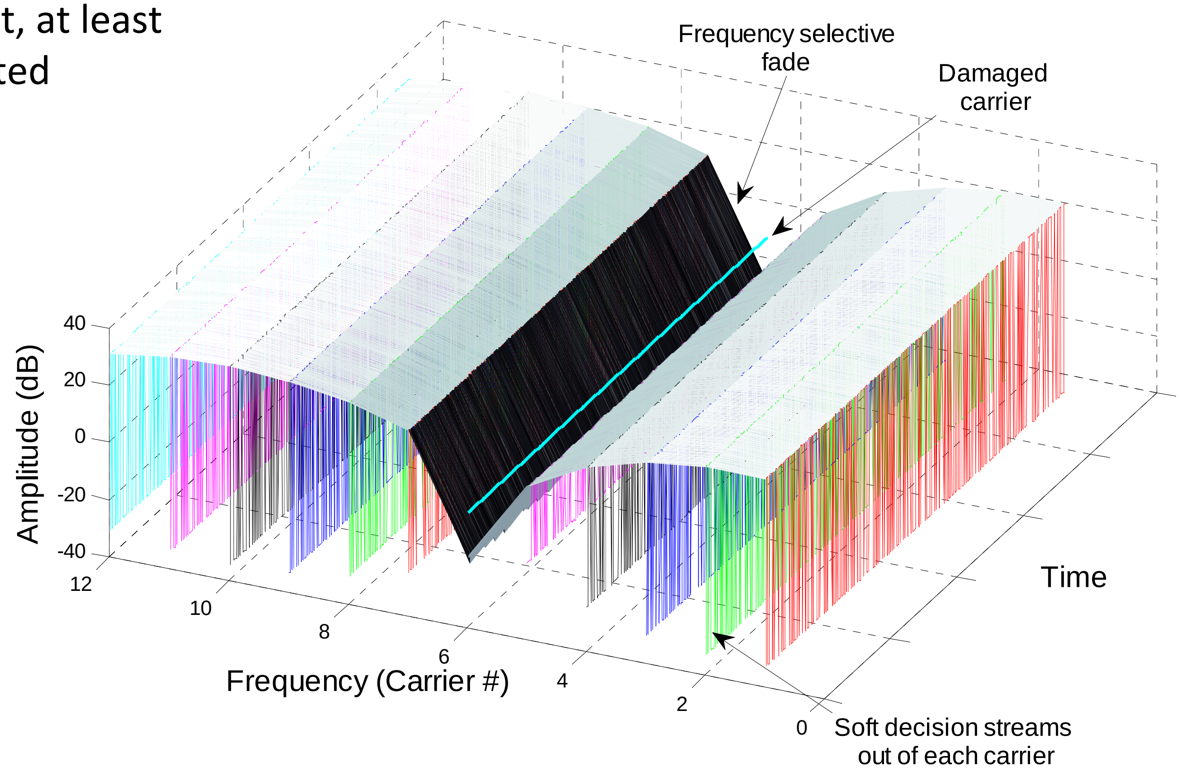
The delayed multipath components are contained in this prefix at the receiver and do not contaminate the demodulation process.



Construction of the cyclic prefix

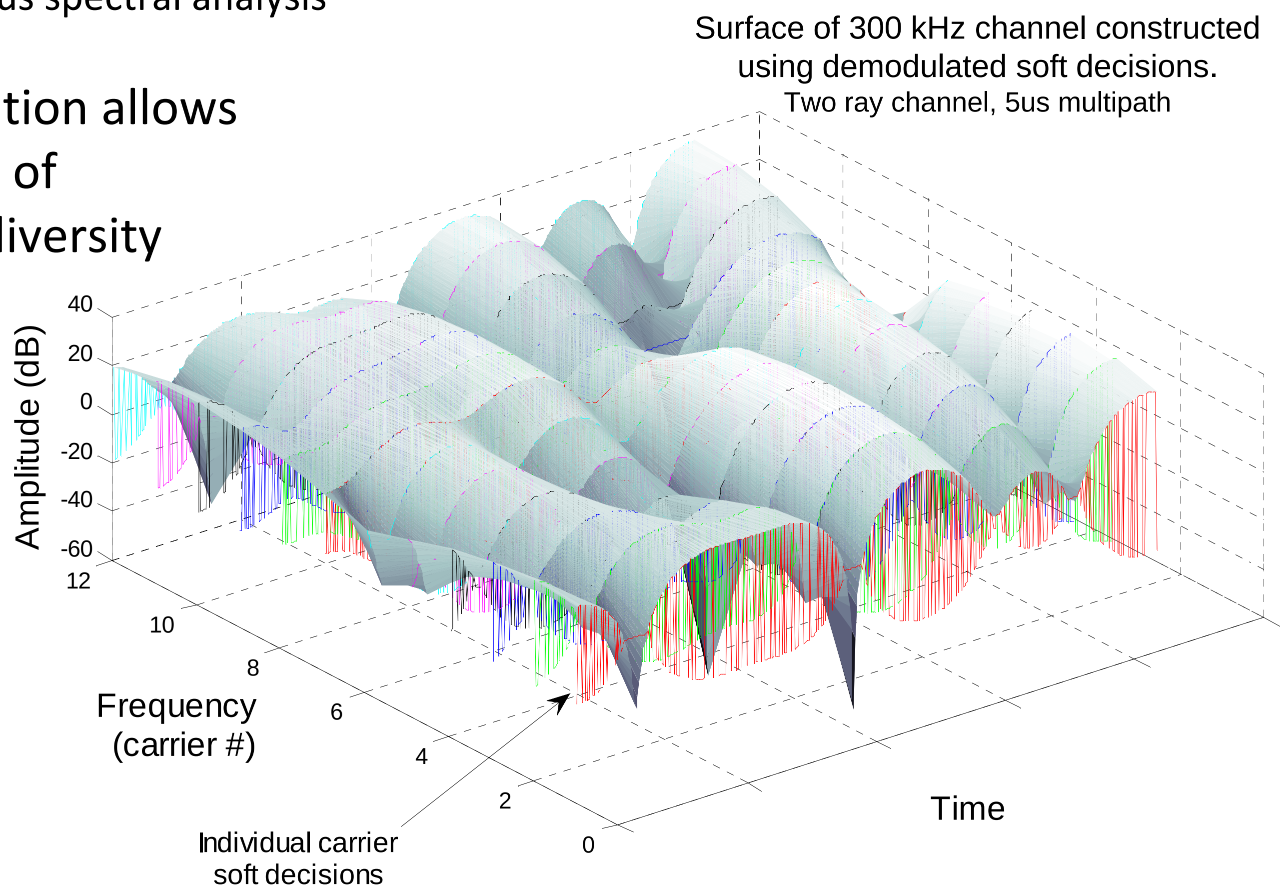
Multipath – Frequency selective fading

- Multipath also causes frequency nulls in the received spectrum
- OFDM overcomes frequency nulls by dividing up the channel into individual carriers
  - So if one is knocked out, at least the others aren't affected
- Frequency Diversity combining, or interleaving across frequency, together with FEC, help to 'fill in the gaps'



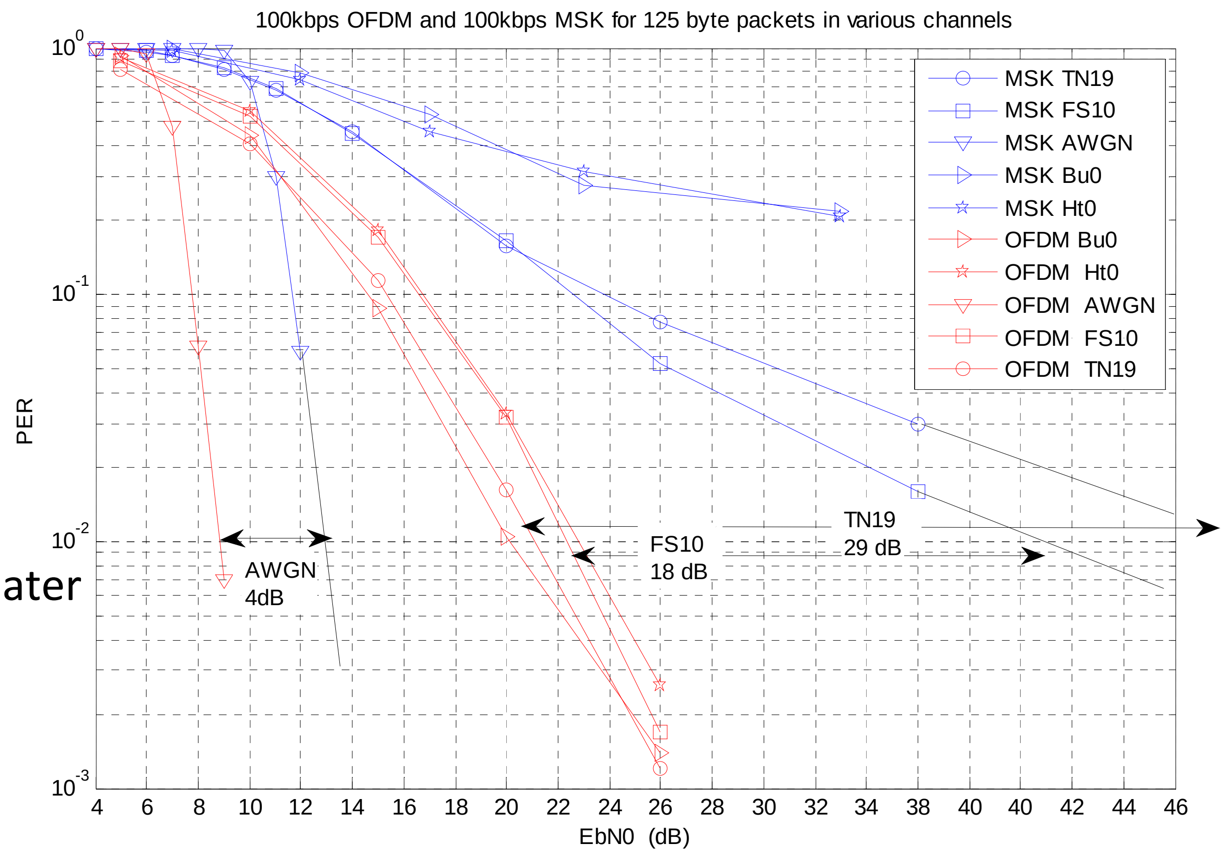
Visualization of OFDM's advantage

- Notice how the multiple carrier soft decision streams accurately convey channel quality information in both Time and Frequency
  - Re-creating the previous spectral analysis
- This valuable information allows effective combination of Time and Frequency diversity
- This is a key to why OFDM systems have such a performance advantage



Performance Advantage Snapshot

- FS10 and TN19 propagation channels as measured by L&G in low rise urban area
  - 1.6us multipath
- Bu0 and Ht0 channels as defined by ETSI for “Bad Urban” and “Hilly Terrain”
  - 5us and 15us multipath respectively
- OFDM shows 18 – 29 dB advantage even in **benign** 1.6us multipath channels with short 125 byte packets
- The advantage is even greater
  - for Bu0 and Ht0
  - Longer packets



Conclusions

- This Proposal adequately meets all the requirements of the PAR
  - Wide applicability in a range of Regulatory requirements
  - Wide range of data rates
  - Superior performance in the outdoor channels defined in the PAR
  - Carrier Grade Reliability
  - Wide range of packet lengths
  - Excellent link margin and efficiency
- Addressed some common concerns about OFDM
- Detailed the key Technical aspects that make up the proposal
- Showed how OFDM achieves its performance in the chosen channels
  - Hinted at some results
  - See later presentations for more details
- Provides flexibility is a consistent, highly structured way

Thank You for your attention

- What will you do with the dB’s you’ve saved?
- Questions