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

Submission Title: [OFDM Refinements to accommodate limited channel coherence time]
Date Submitted: [November 11, 2009]
Source: [Steve Shearer] Company [Independent]
Address [Pleasanton, CA]
Voice:[(925) 997 0576], FAX: [], E-Mail:[Shearer_inc @ yahoo.com]

Re: [IEEE P802.15.4e]

Abstract: [Refinements to the existing OFDM proposal to allow mixed-mode differential and Coherent demodulation as well as a suggestion for cycling the position of the pilot tones to help in channel estimation of non-stationary channels]

Purpose: [Document for discussion and amendment of the current OFDM proposal to include these new modes.]

OFDM Refinements to accommodate limited channel coherence time

Steve Shearer Nov 2009

Introduction

- Many OFDM systems use coherent demodulation of the phase encoded data carriers because coherent demodulation
  - Offers very good performance
  - Enables higher order phase modulation schemes to be utilized
- Coherent demodulation requires accurate estimation of phase references for each data tone to accomplish correct demodulation
- Many OFDM implementations are able to achieve these phase references using very simple, effective, methods
- Application of OFDM to SUN channels makes estimation of the phase references more complicated than many conventional OFDM systems

Initial Channel estimation

- Many OFDM systems use a training sequence as part of the synchronization procedure to estimate the reference phase and amplitude for each data tone at the start of the burst

- The assumption is that the channel is stationary for the entire length of the burst
  - This assumption is valid when data rates are high, or data packets are very short and the fading rate is low
  - Used with great success in many systems, WLAN, UWB, etc.

- But this may not be true when using OFDM in SUN channels
  - Data rates are low, time on the channel could extend out to 0.4s for long packets
  - Fading rates can be quite high, 80Hz in possible due to cars passing by at 70mph [1]

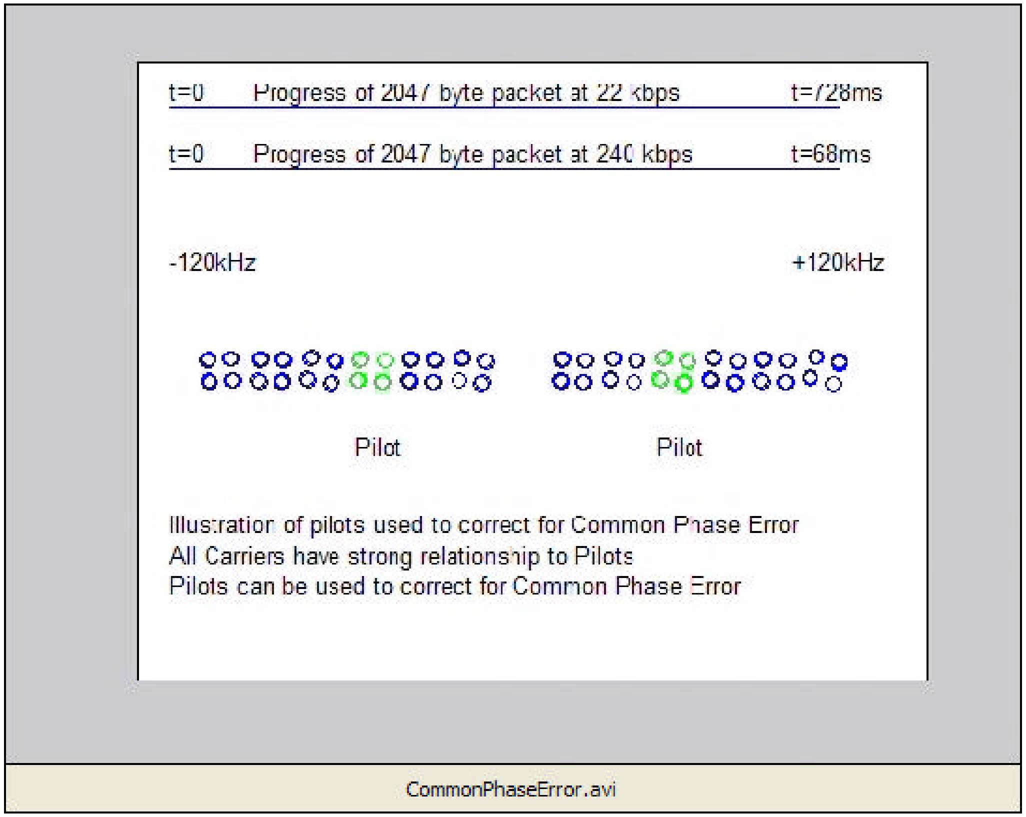
- [1] ‘https://mentor.ieee.org/802.15/dcn/09/15-09-0742-00-004g-fading-in-900mhz-smart-utility-radio-channels.pdf‘

Pilot Tones

- The channel is often assumed to be stationary
  - But phase changes from the initial starting point are introduced by the “random phase walk” of the TX and RX local oscillators

- Pilot tones are often used to compensate this effect
  - the phase movement is the same for all tones so interpolation can also be used

- Why not use pilot tones to compensate for channel phase changes?



t=0 Progress of 2047 byte packet at 22 kbps t=728ms

t=0 Progress of 2047 byte packet at 240 kbps t=68ms

Illustration of pilots used to correct for Common Phase Error
All Carriers have strong relationship to Pilots
Pilots can be used to correct for Common Phase Error

Channel Coherence Bandwidth

- Studies [1] have shown that phase changes caused by the channel are not correlated between tones
  - 50% of locations have a correlation b/w of less than 70kHz i.e. ~8 tones [2]
  - 10% of locations have a correlation b/w of less than 25kHz i.e. 3 tones

- Therefore the use of pilot tones to compensate for channel phase perturbations is not effective

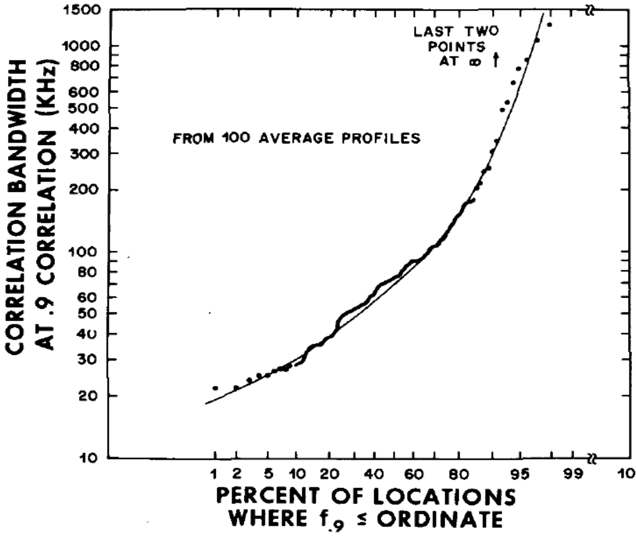


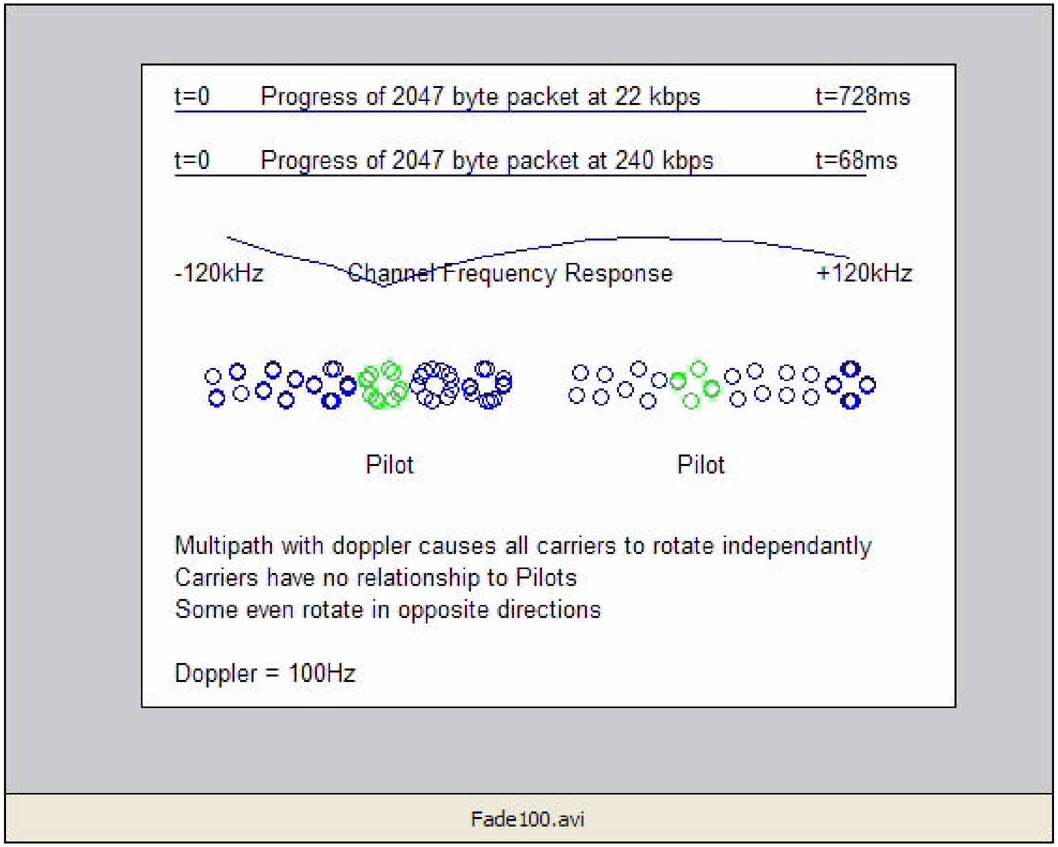
Fig. 14. Cumulative distribution of correlation bandwidth at 0.9 correlation.

- [1] IEEE TRANSACTIONSON COMMUNICATIONS, VOL. COM-23, NO. 11, NOVEMBER 1975 "Correlation Bandwidth and Delay Spread Multipath Propagation Statistics for 910-MHz Urban Mobile Radio Channels" Donald C. Cox, Robert P. Leck
- [2] Tone spacing in the 802.15.4g OFDM PHY is approx 8kHz

Animation

- This animation using Multipath with Doppler shows that carriers rotate independently [1]
  - Carriers have no relationship with pilots
  - Some even rotate in opposite directions

- Pilots alone cannot be used to correct for channel changes



Multipath with doppler causes all carriers to rotate independantly
Carriers have no relationship to Pilots
Some even rotate in opposite directions

Doppler = 100Hz

- [1] Fade rate is chosen at 100Hz for visual effect, but similar effects take place with lower dopplers

Potential solutions

- This problem can be overcome in several different ways
- Using Viterbi assisted decision feedback equalizers on each data tone
  - Very effective, but quite complex, 96 DFE’s in mode 1
  - Possibly not that well suited to small FFT sizes like Mode 5 due to Viterbi latency
- Using Differential demodulation
- Introducing training symbols into the symbol stream
- And possibly some others too…

Differential Demodulation

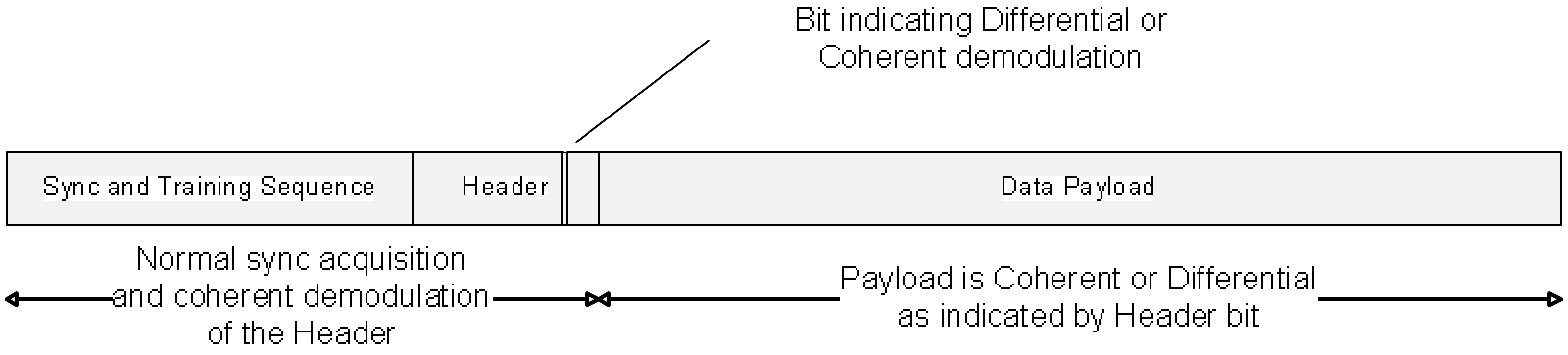
- Does not require pilot tones
  - Extra tones can be used to convey data
- Inherently corrects for Common Phase error **and** channel phase changes
- Allows efficient soft decisions because the previous symbol can be considered as a channel estimate
- Very low complexity
  - Suitable for implementation on a microcontroller for fast time-to-market
- Differential demodulation incurs only a small performance penalty
  - 0.3dB for DBPSK
  - 2dB for DQPSK

Previous Merging Difficulties

- Differential demodulation requires a differentially encoded transmission
- Coherent demodulation of a differentially encoded transmission is possible
  - But noise smearing between symbols adversely impacts soft decision quality
- These constraints previously made the two methods incompatible unless a new set of modes, headers and sync sequences was defined
  - Just too many options
  - No clear way was understood at the time to combine the two
- Previously it was not clear how much the channel would change during the length of the burst
  - Simulations for coherent demodulation were only performed in a Pseudo Static or AWGN channel
- We agreed to postpone the decision on differential until more information was available

Proposed Solution – Mixed Mode

- Accept that the channel is static for at least the length of the header
  - Use the same sync and training sequences and perform coherent demod of the header
  - Add one bit to the Header to signal coherent or differential demod of the payload
- The receiver acquires synchronization, decodes the training sequence and then decodes the header using coherent demodulation
- If the differential bit is set, then the Payload is demodulated using differential demodulation
  - Otherwise data demodulation proceeds using coherent demodulation



- This approach preserves the requirements for coherent, and allows differential as an option without conflict or complication

MCS Table

- Minimal changes to the MCS levels
  - Parameters are implicit by selection of diff/coherent bit
  - Addition of 8 DPSK for use where channel is not noise limited

- Suggest keeping the lower data rates for robustness

	OFDM Option 1		OFDM Option 2		OFDM Option 3		OFDM Option 4		OFDM Option 5		Unit
Modulation	Coh	Diff	Coh	Diff	Coh	Diff	Coh	Diff	Coh	Diff	
FFT Size	128		64		32		16		8		
Active Tones	104		52		26		14		6		
# Pilots tones	8	0	4	0	2	0	2	0	2	0	
# Data Tones	96	104	48	52	24	26	12	14	4	6	
# DC null tones	1		1		1		1		1		
Approximate Signal BW	11		518		264		146		68		kHz
MCS 0 - BPSK 1/2 rate coded and 4xFDS	93.75	101.56	46.88	50.78	23.44	25.39	11.72	13.67	3.91	5.86	kbps
MCS 1 - BPSK 1/2 rate coded and 2xFDS	187.50	203.13	93.75	101.56	46.88	50.78	23.44	27.34	7.81	11.72	kbps
MCS 2 - QPSK 1/2 rate coded and 2xFDS	375.00	406.25	187.50	203.13	93.75	101.56	46.88	54.69	15.63	23.44	kbps
MCS 3 - DCM QPSK 1/2 rate coded	750.00	812.50	375.00	406.25	187.50	203.13	93.75	109.38	31.25	46.88	kbps
MCS 4 - DCM-QPSK 3/4 rate coded			562.50	609.38	281.25	304.69	140.63	164.06	46.88	70.31	kbps
MCS 5 8 PSK 3/4 rate coded						457.03		246.09		105.47	kbps
MCS 6 - 16QAM 1/2 rate coded			750.00		375.00		187.50		62.50		kbps
MCS 7 - 16QAM 3/4 rate coded					562.50		281.25		93.75		kbps

Proposed Enhancement to Coherent Demod – Pilot Cycling

- The current system uses pilot tones in fixed positions to compensate for CPE

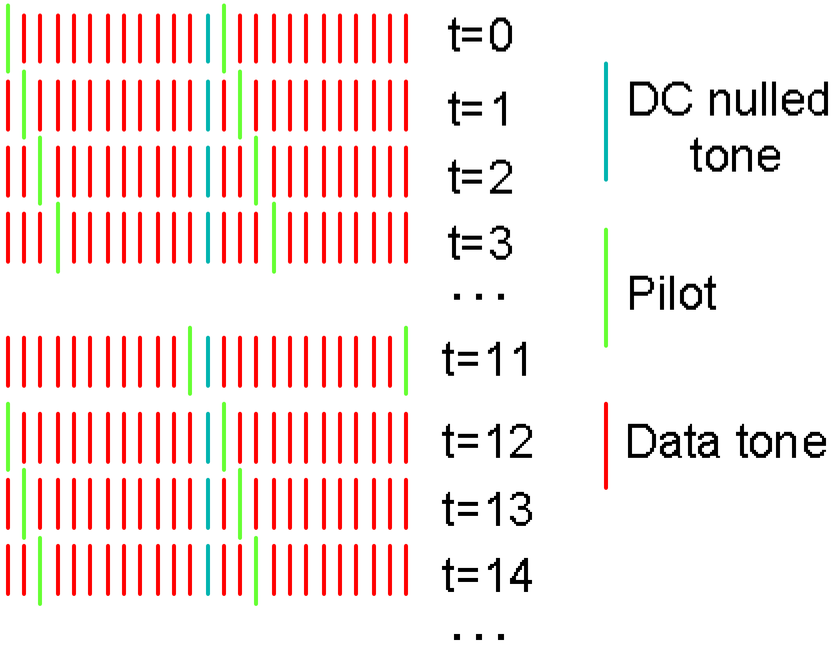
- We have seen that they are of limited effectiveness in a fading channel due to the lack of phase coherence across all the tones

- And we have also seen that, while the channel changes through a long burst, it can be considered static over the space of a few symbols
  - Say 12 symbols = 125us*12 = 1.5ms

Pilot Cycling

- The transmitter successively cycles the pilot tones through the OFDM data tones as shown in the diagram
  - Other PHY modes using more data tones will cycle the tones in the same way

- This allows the receiver to “see” a pilot tone at each data tone position on a regular basis.
  - Shorter than the coherence time
  - Can be thought of as a training symbols interleaved with the data on each tone



- Apriori knowledge of the pilot tone phase allows the receiver to compensate for both the Common Phase Error **and** channel phase change for each particular tone [1]

- [1] Pilot tones are usually transmitted using a randomising sequence know to both the transmitter and the receiver to provide a uniform transmit spectrum. This mechanism is expected to be used, but is not explained in this paper in the interests of clarity.

Conclusion

- Two refinements have been presented to accommodate reliable demodulation when the channel is changing during the burst
- Both address the problem directly by slightly reconfiguring the signaling format
  - No changes to the STF, LTF
  - One bit added to the Header
  - Minimal changes to the overall proposal
- Both methods have the potential to considerably reduce the complexity of the system and provide the best performance for the given conditions
- Request the groups consideration of both of these refinements as part of the final draft
  - Mixed-mode enables low cost differential implementations for modes 3,4,5
  - Pilot Cycling improves the robustness of all coherent modes and is compatible with DCM and 16QAM

Thank You