PLC Standardization Progress and Some PHY Considerations

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Outline

PLC Standards

- **IEEE**
- **ITU-T**

Overview of Baselines

Some Considerations on the PHY Choices

- **Wavelet and OFDM**
- **Turbo Codes and LDPC**

Conclusions

An Old Joke

"The nice thing about standards is that there are so many to choose from!"

Unfortunately, this does not apply to PLCs yet!!!

But maybe it will apply next year….

IEEE P1675

- P1675 is focused on equipment testing and installation
- Standards approved and published

IEEE P1775

- The P1775 effort focuses on specific measurement issues associated with BPL emissions
- Chair: Aron Viner, Ambient Corporation
- Standard ballot vote ongoing, deadline for voting is April 16, 2009

IEEE/ITU Standardization

IEEE P1901

- Focuses on MAC/PHY, started in June 2005
- Scope: broadband over PLC for in-home and access
- Baseline document for the IEEE 1901 standard was approved in December 2008.

ITU-T G.9960 (G.hn)

- Focuses on MAC/PHY, started in May 2006
- Scope: broadband over all in-home wires (phone, PLC, coax)
- Foundation document (PHY, part of MAC) consented in December 2008

IEEE P2030

- Focuses on “Guidelines for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System, and End-Use Applications and Loads,” started in March 2009
- Scope: functional performance and evaluation criteria, and the application of engineering principles for smart grid interoperability of the electric power system with end use applications and loads

IEEE P1901 Status (1/2)

- **Feb. 2007 (Tokyo):** All FTR have been finalized for the three clusters (in-home, access, co-existence). Call for submission of technical proposals was issued with a deadline of June 4
- The following proposals were submitted:

- In-Home
  - HiSilicon
  - HomePlug
  - Panasonic
  - UPA
- Access
  - HomePlug
  - Mitsubishi
  - Panasonic
  - UPA-OPERA
- Co-Existence
  - HomePlug
  - Si-Connect
  - Telcordia
  - UPA-CEPCA

- **July 2007 (Edinburgh):**
  - Presentation of technical proposals, followed by first low hurdle vote

- **October 2007 (Boston):**
  - Mergers occurred: Panasonic/HPA (IH and AC), CEPCA/HPA (CX)
  - Proposal became a dual-PHY proposal: OFDM and Wavelet-OFDM

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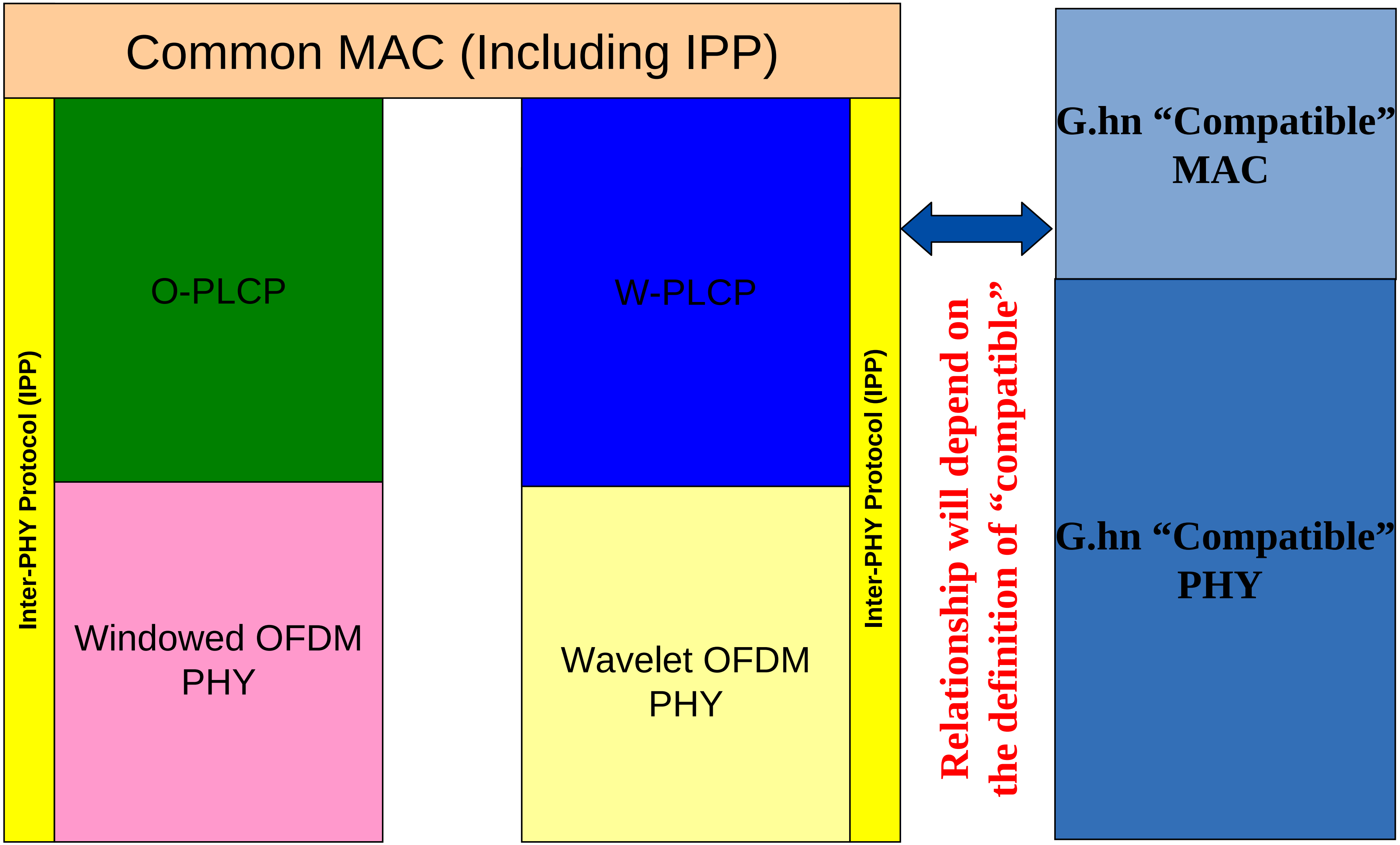
IEEE P1901 Status (2/2)

- **During 2008**: series of postponed or failed confirmation votes, until a further compromise was reached in adding a G.hn "compatible" mode
- **Dec 2008 (Kyoto):** Baseline document was approved by the WG for Access (97%), In-Home (85%), and Co-Existence (100%).
- **Next steps**
  - WG is now working on merging the three baseline documents (IH, AC, CX) in a single baseline document. If the final single baseline document receives 75% approval from the WG, it will become the IEEE P1901 Draft Standard
  - WG is now working on defining in more detail what "G.hn compatible" actually means – could mean anything between co-existence and interoperability
  - Co-existence mechanisms such as IPP and ISP have to be merged and integrated into the IH and AC specifications

IEEE P1901 Baseline Document: AC and IH



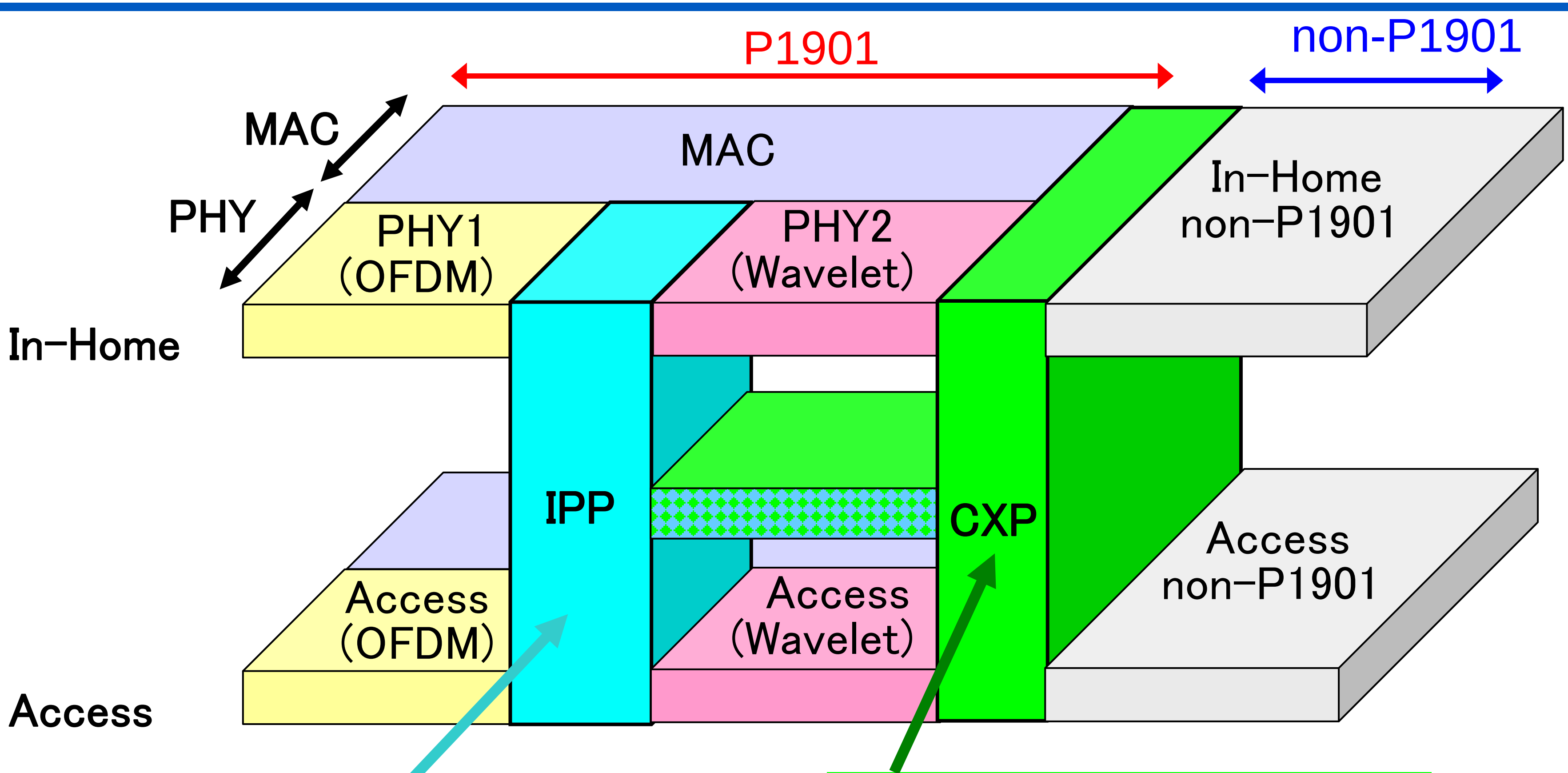
IEEE P1901 Baseline Document: AC and IH

Communication Method	Fast Fourier Transform (FFT) OFDM
FFT points	3072, 6144
Sampling Frequency [MHz] (respectively)	75, 150
Symbol Length [µsec]	40.96
Guard Interval [µsec]	Variable according to line conditions: 5.56 (12%), 7.56 (16%), 47.12 (53%)
Primary modulation (per sub-carrier)	2-, 4-, 8-, 16-, 64-, 256-, 1024-, 4096-QAM
Frequency Band [MHz]	2 - 30 [Optional Bands: 2-48 and 2-60]
Error Correction	Turbo Convolutional Coding
Maximum Transmission Speed [Mbps] (2-60 MHz band and FEC)	545 (8/9 CTC)
Diversity Modes	Normal ROBO, Mini ROBO, High Speed ROBO, and Frame Control

IEEE P1901 Baseline Document: AC and IH

Communication Method	Wavelet OFDM
Discrete Wavelet Transform points	512, 1024, 1536
Sampling Frequency [MHz]	62.5, 125, 187.5
Symbol Length [μsec]	8.192
Guard Interval	➔ Not necessary ➔
Primary Modulation (per sub-carrier)	BPSK, 4-, 8-, 16-, 32-PAM
Frequency Band [MHz]	2 - 28 [Optional Band: 2-60]
Error Correction	RS-CC; LDPC (optional)
Maximum Transmission Speed [Mbps] (2-60 MHz band and FEC)	544 (239/255 RS)
Diversity Modes	MAC header, TMI/FL, Payload

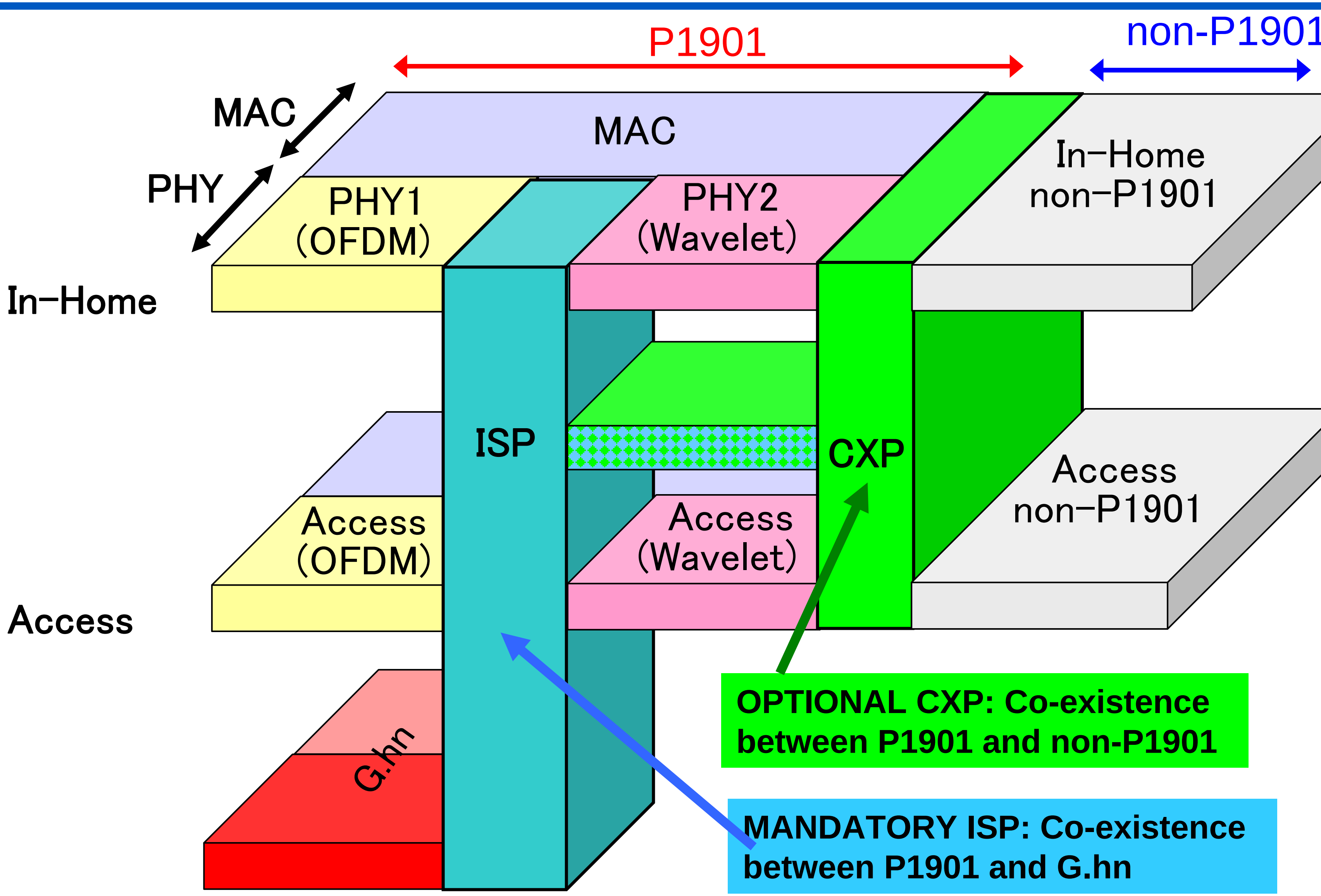
IEEE P1901 Baseline Document: Co-Existence



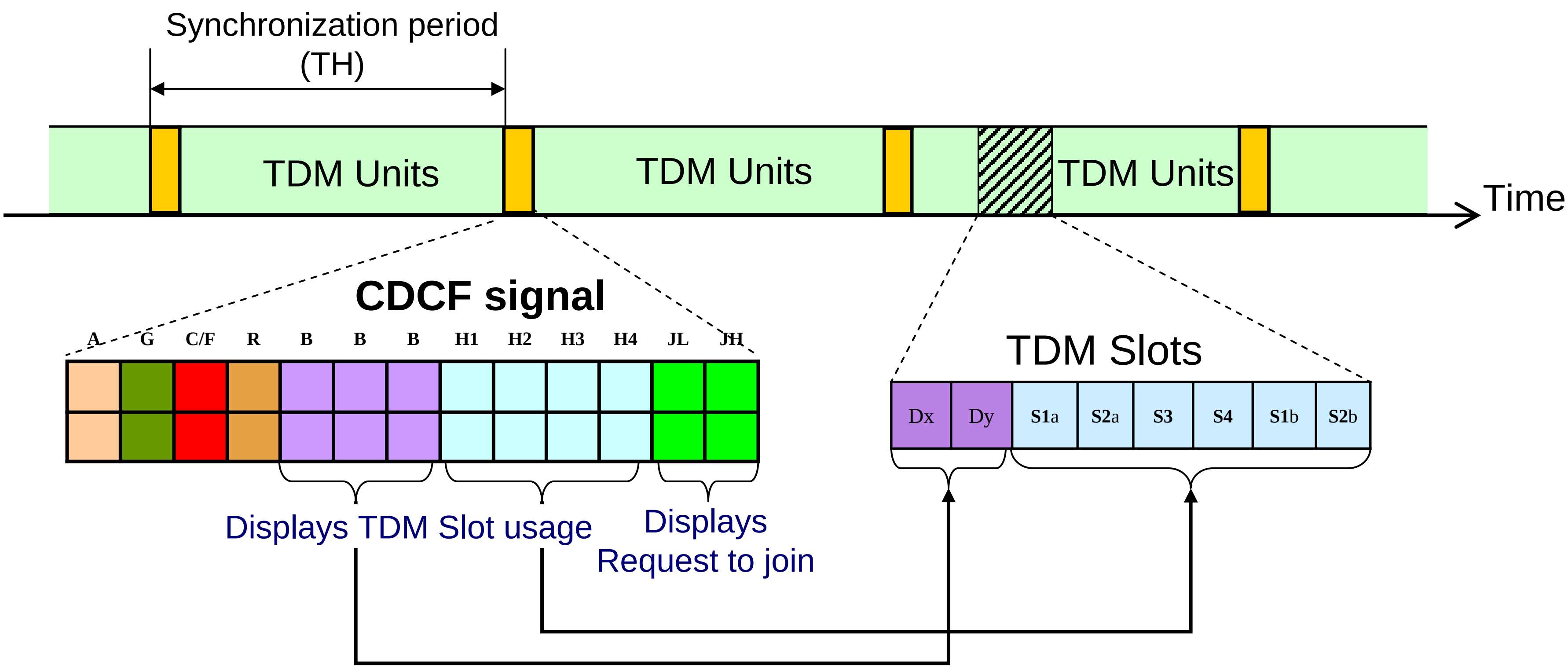
MANDATORY IPP: Co-existence between P1901 PHY1, P1901 PHY2, and P1901 Access

OPTIONAL CXP: Co-existence between P1901 and non-P1901

IEEE P1901 Baseline Document: Co-Existence



- Co-existence protocol does not depend on a specific PHY
- Hybrid, static and dynamic allocation (fully centralized scheduling)
- Uses resources in time and frequency



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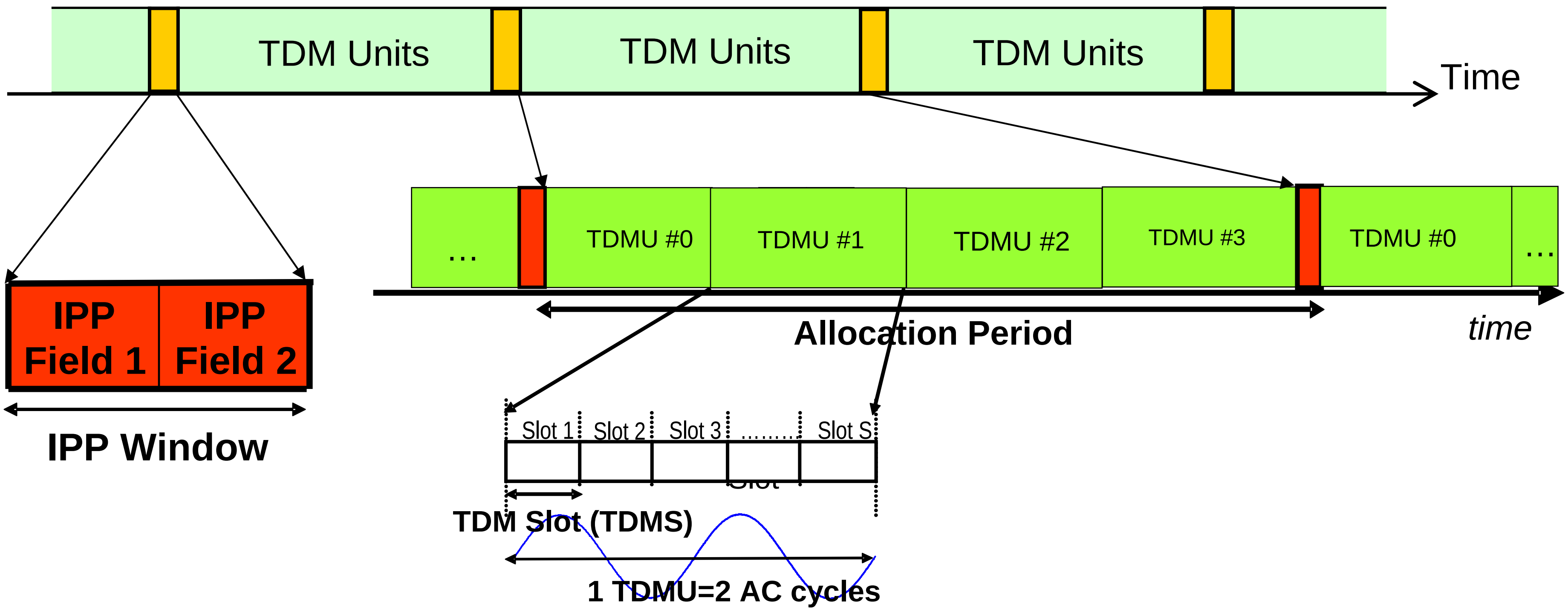
IEEE P1901 Baseline Document: IPP and ISP

- Co-existence protocol simpler than full CXP
- Dynamic allocation, with centralized *and* distributed features
- Time-reuse algorithm for increasing network throughput



For more details: Galli, Kurobe, Ohura, "The Inter-PHY Protocol (IPP): A Simple Co-Existence Protocol," IEEE Int. Symp. on Power Line Comms., March 2009.

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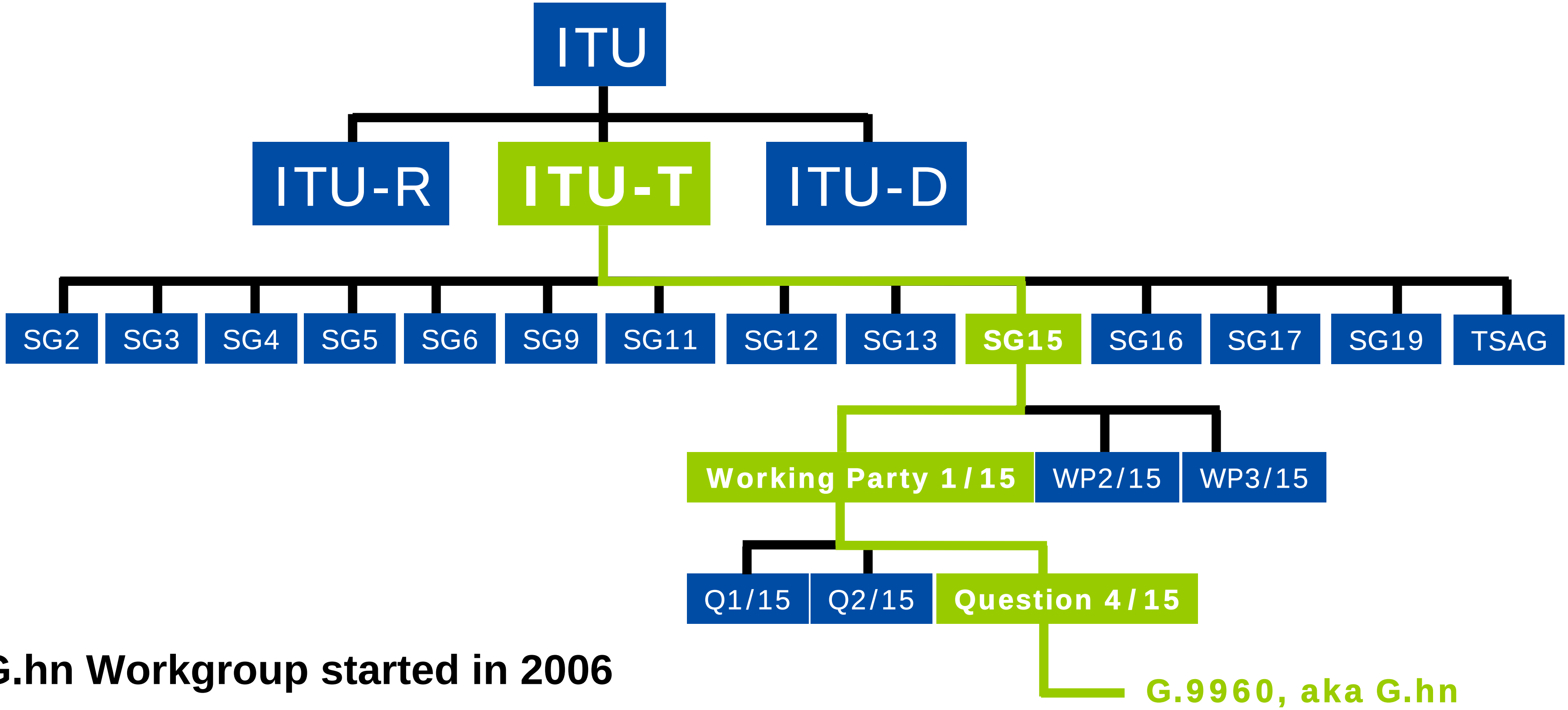
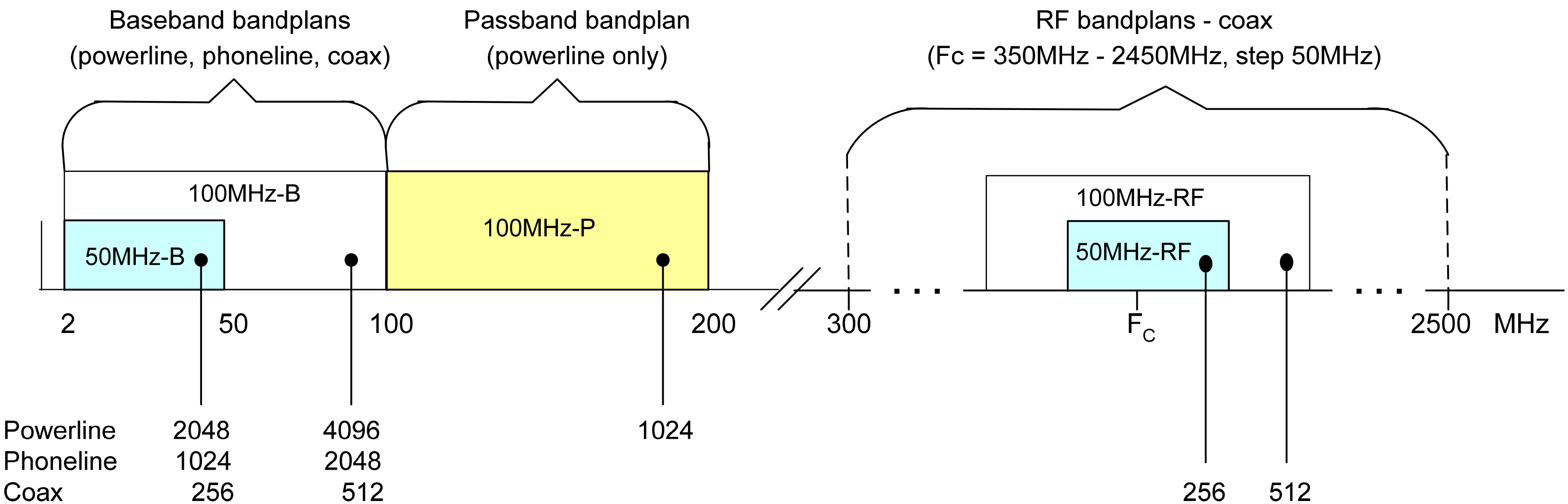
The ITU-T G.hn Standard



- **G.hn Workgroup started in 2006**
- **Objective: Create a Single Next Gen PHY/MAC for all IH wiring (Coax, Phoneline, Powerline)**
- **G.hn supported by The HomeGrid Forum**
- **Foundation document consented in Dec. 2008 (PHY, part of MAC, most of architecture)**

The ITU-T G.hn Standard: PHY



- Windowed OFDM with scalable FFT size and all power-of-2 sizes
- Several bandplans: baseband, passband, and RF bandplans
- Uses external mixer for up-shifting to RF
- FEC: QC-LDPC-BC, based on the IEEE 802.16e standard
  - Two block sizes: 960 and 4320 bits (120 and 540 bytes)
  - Five Code rates: ½, 2/3, 5/6; 16/18 and 20/21 by puncturing 5/6

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The ITU-T G.hn Standard: PHY

- Is a power-of-2 scalable OFDM optimal for all media?
- How different is the RMS Delay Spread of the three media?
- For a reliable and high coverage OFDM system design, the OFDM parameters should be chosen based on the 99% worst case delay spread

RMS-DS	Power Line (μs)	Phone Line (μs)	Coax (ns)
99% worst case	1.75	0.39	46

- The ratios of the 99% worst-case RMS-DSs are:
  - PLC/Phone: 1.75/0.390 ~ 4.5 ~2^2
  - PLC/Coax: 1.75/0.046 ~ 38 ~2^5

- The ratios of RMS-DSs becomes the ratios of Guard Intervals, the choice of the number of carriers is made to ensure a certain overhead….

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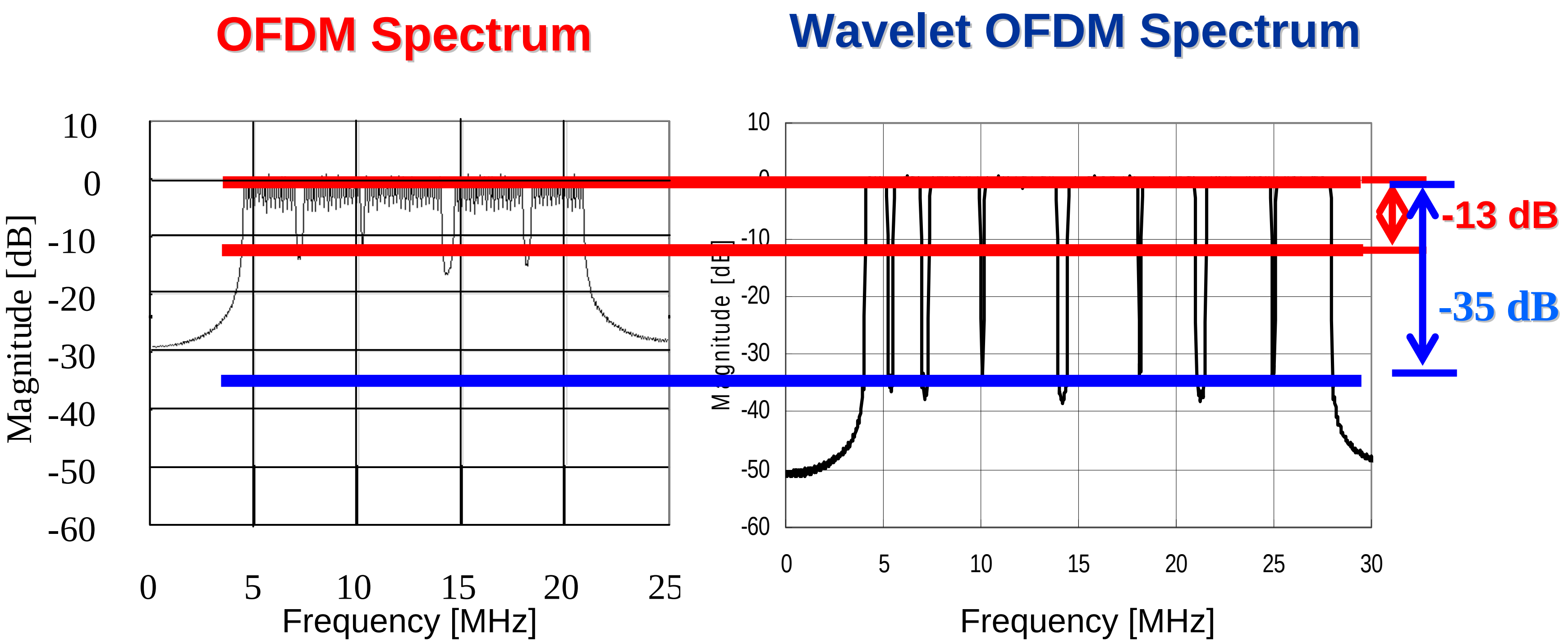
Why Certain Choices at the PHY?

- **Standards are not optimal, they are the result of compromises**
- **Some choices that seem contradictory have been made:**
  - ➢ IEEE P1901
    - o Based on OFDM, Turbo Codes
    - o Based on Wavelets, RS-CC and LDPC
  - ➢ ITU-T G.hn
    - o Based on scalable OFDM and LDPC
- **Two obvious questions arise:**
  - ➢ Why certain choices?
  - ➢ Is this diversity justified?
- **We'll focus on two issues**
  - ➢ Do Wavelets (DWMT, OQAM, …) offer any advantage over OFDM?
    - ❑ The purpose is not to compare G.hn and P1901 technologies, but to merely point out some known and lesser known features of Wavelets
  - ➢ Are LDPC better than Turbo Codes on PLCs and other wired media?

Wavelet Feature #1: Low Spectral Leakage (1/3)



Wavelet OFDM stopband is 22 dB higher, providing superior adjacent band rejection compared to conventional OFDM

But comparing with conventional OFDM is not fair so let's see what happens if we do transmitter windowing in OFDM…

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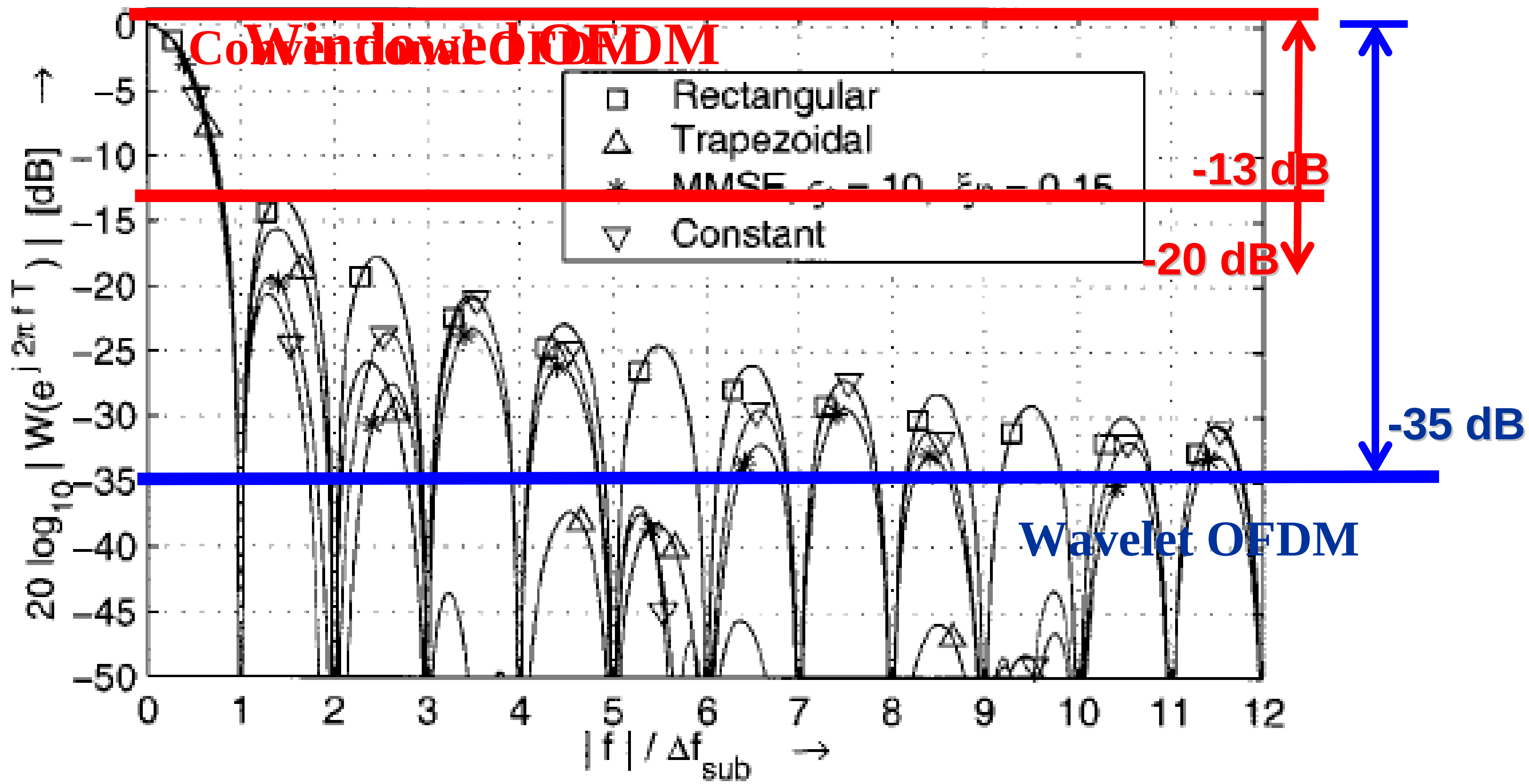


Stefan H. Müller-Weinfurtner, "Optimum Nyquist Windowing in OFDM Receivers," *IEEE Transactions on Communications*, Vol. 49, No. 3, Mar. 2001.

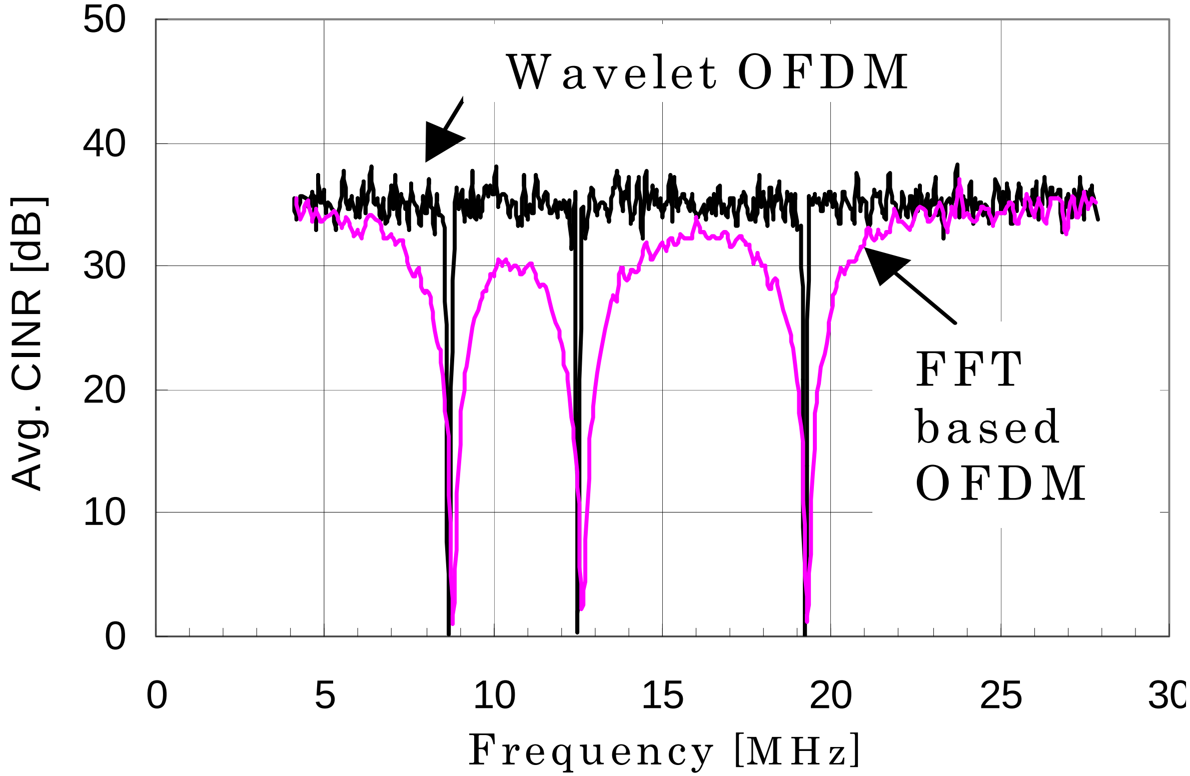
Even with transmitter windowing, the first few sidelobes of the windowed OFDM spectrum are still higher than the first sidelobe of Wavelet OFDM

Wavelet Feature #1: Low Spectral Leakage (3/3)

Wavelet OFDM is robust to narrowband interferers (NBIs)

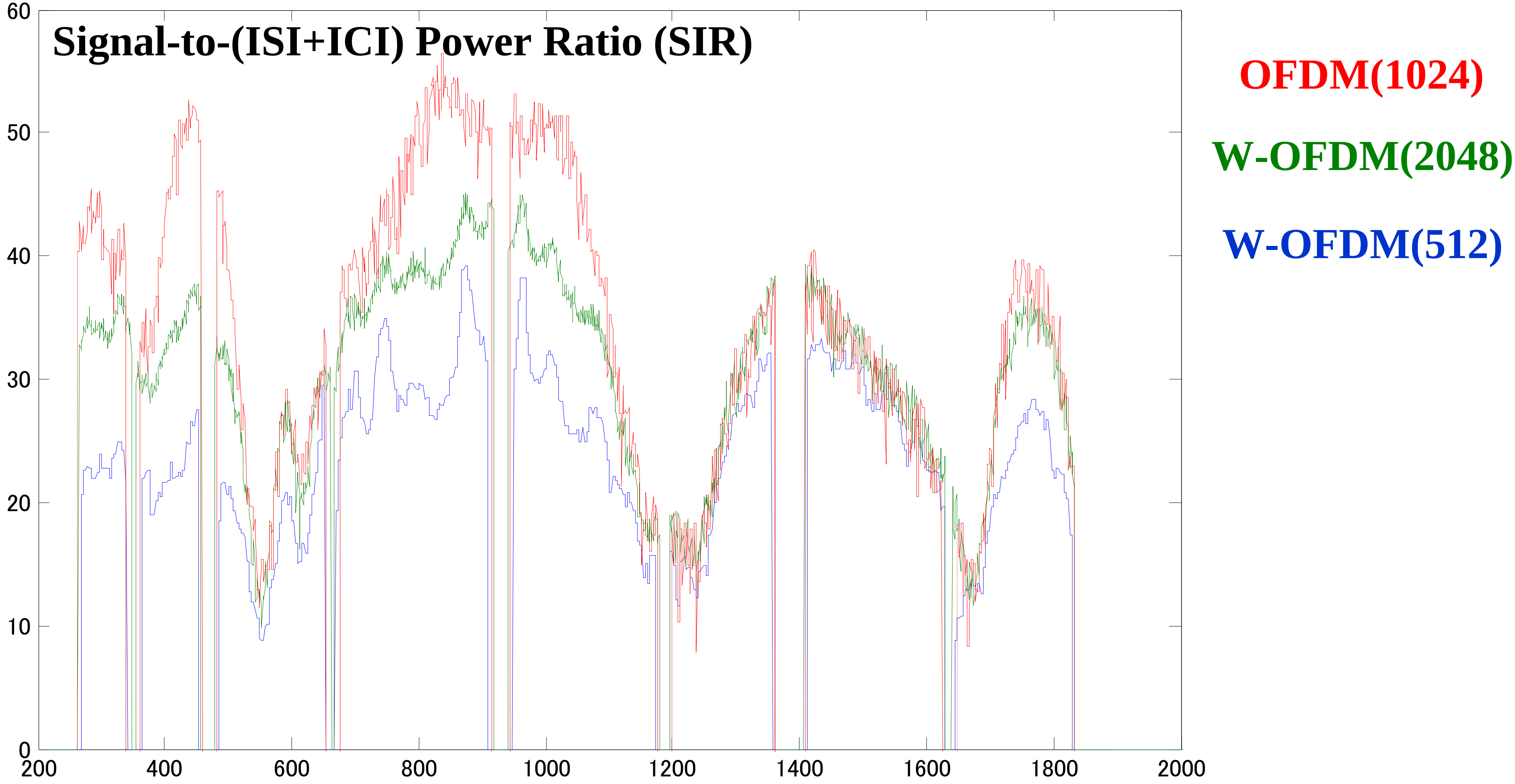
FFT-based OFDM less robust, PSD of interferer convolved with FT window

Wavelet-OFDM has higher SNR when NBIs are present



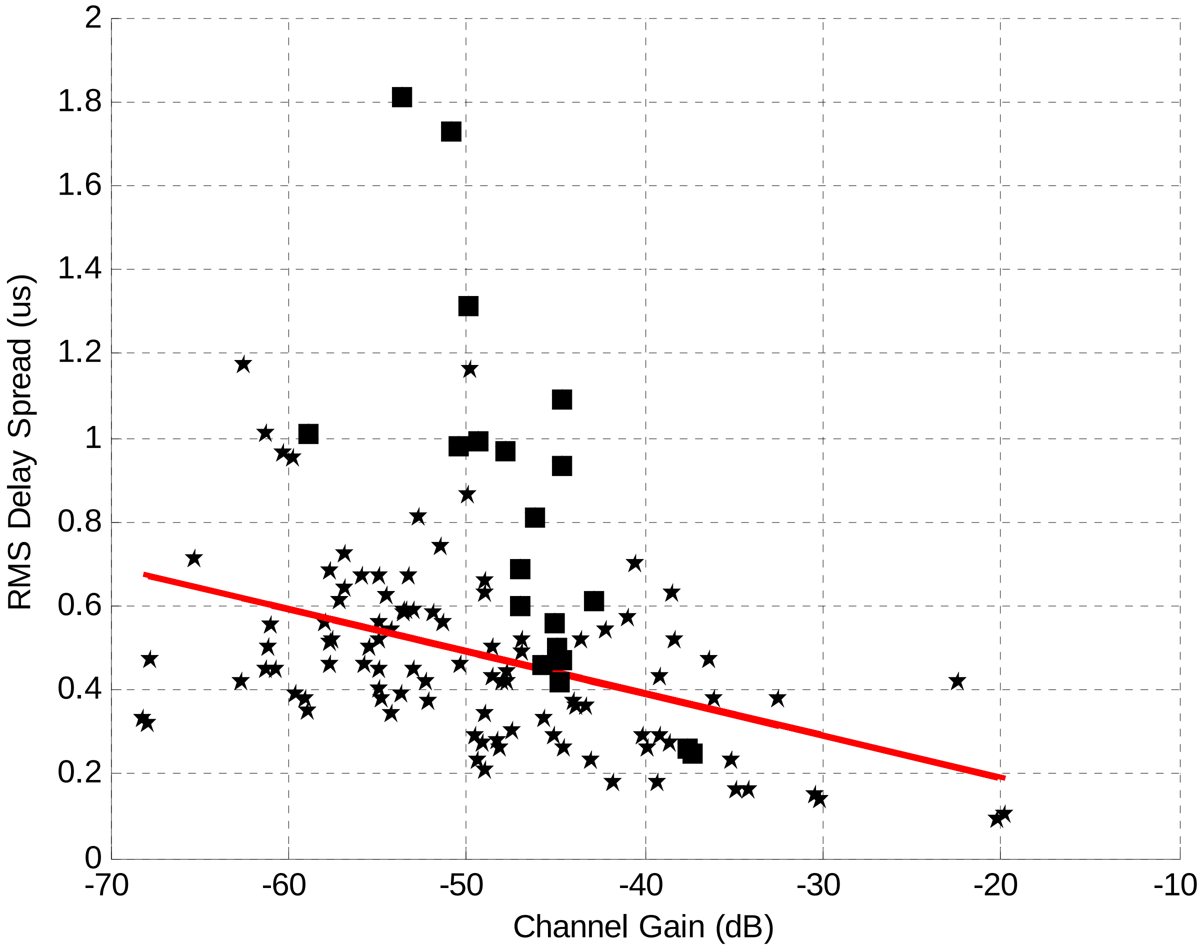
Measured CINR Characteristics with NBI (512 points)
(CNR = 35 dB, CIR = 0 dB, f_1 = 8.7 MHz, f_2 = 12.5 MHz, f_3 = 19.2 MHz)

Power Line Channel is not ISI Limited!!



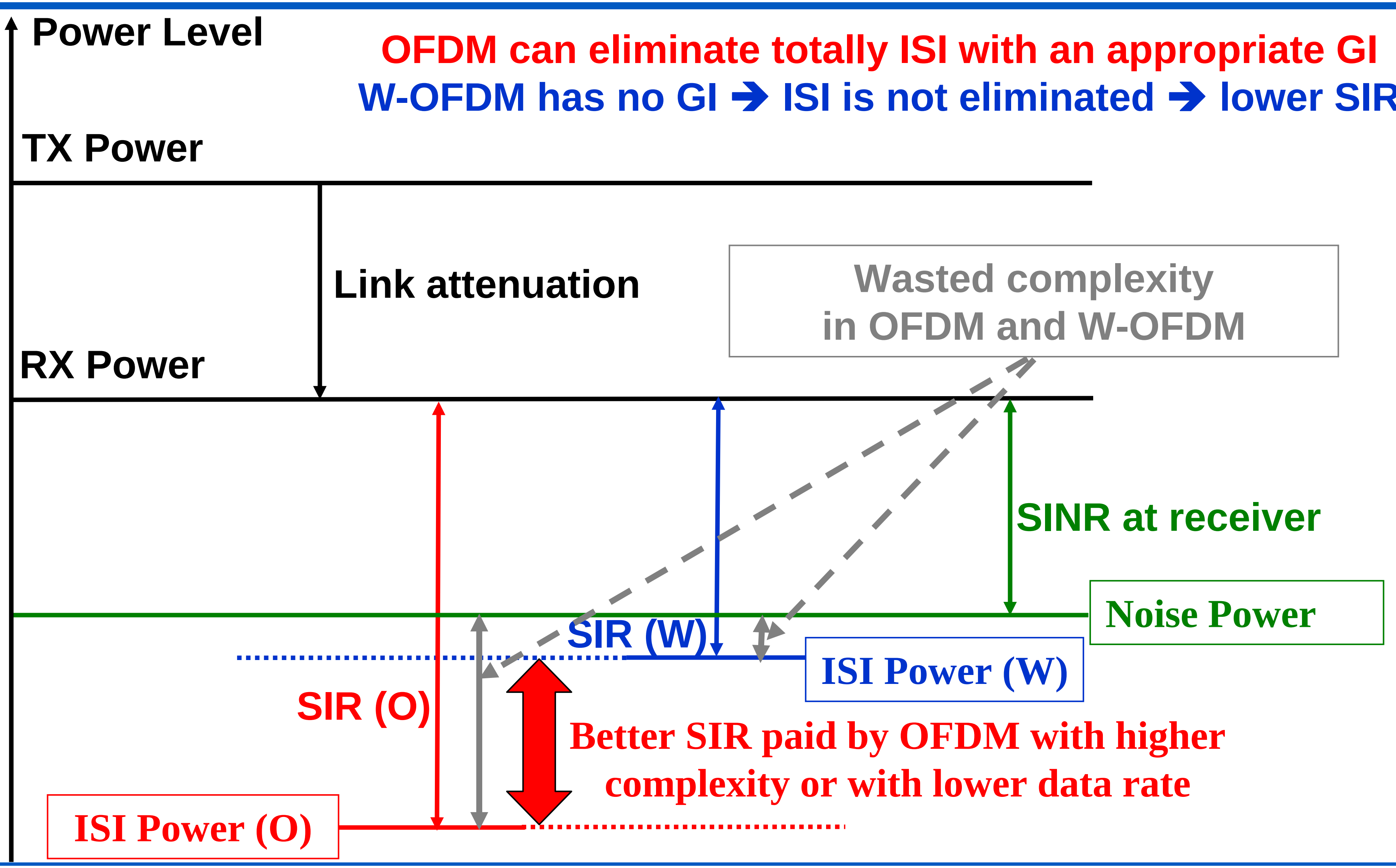
Wavelet Feature #2: Throughput and Chip Size (2/5)

When a channel is bad… it is really bad: high attenuation & large RMS-DS



For more details: S. Galli, "A Simplified Model for the Indoor Power Line Channel," IEEE Int. Symp. on Power Line Comms., March 2009.

Wavelet Feature #2: Throughput and Chip Size (4/5)



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Wavelet Feature #2: Throughput and Chip Size (5/5)

- **The power line channel is noise limited not ISI limited so it is not necessary to achieve full equalization to cope with large RMS-DS**
- **Channels with large RMS-DS are characterized by small average channel gain (large link attenuation) ➔ SNR at receiver is low**
- **Design consequences on OFDM**
  - Partial equalization requires changing the GI on a per-channel basis ➔ scalable OFDM with adaptive GI
  - Shortening the GI duration increases transmission efficiency, but transmit windowing to improve OFDM sidelobes imposes lower bounds on GI reduction that limits beneficial effects on data rate
- **Design consequences on DWMT/OQAM**
  - ISI resiliency given by symbol duration (number of carriers)
  - Relaxing ISI resiliency means reducing symbol duration ➔ fewer carriers needed ➔ circuit size decreases with no data rate penalty
- **This feature gives DWMT and OQAM some advantages over OFDM**

We often forget that the PLC channel is a time-varying channel:

$\mathcal{L}[\delta(t-\tau)] = h(t, t-\tau)$, and $h(t,\xi)$ is the Input-Delay Spread function (Bello, '63)

We also forget that the PLC channel is an LPTV channel (Cañete et al., 2002), and thus can be decomposed in Fourier Series:

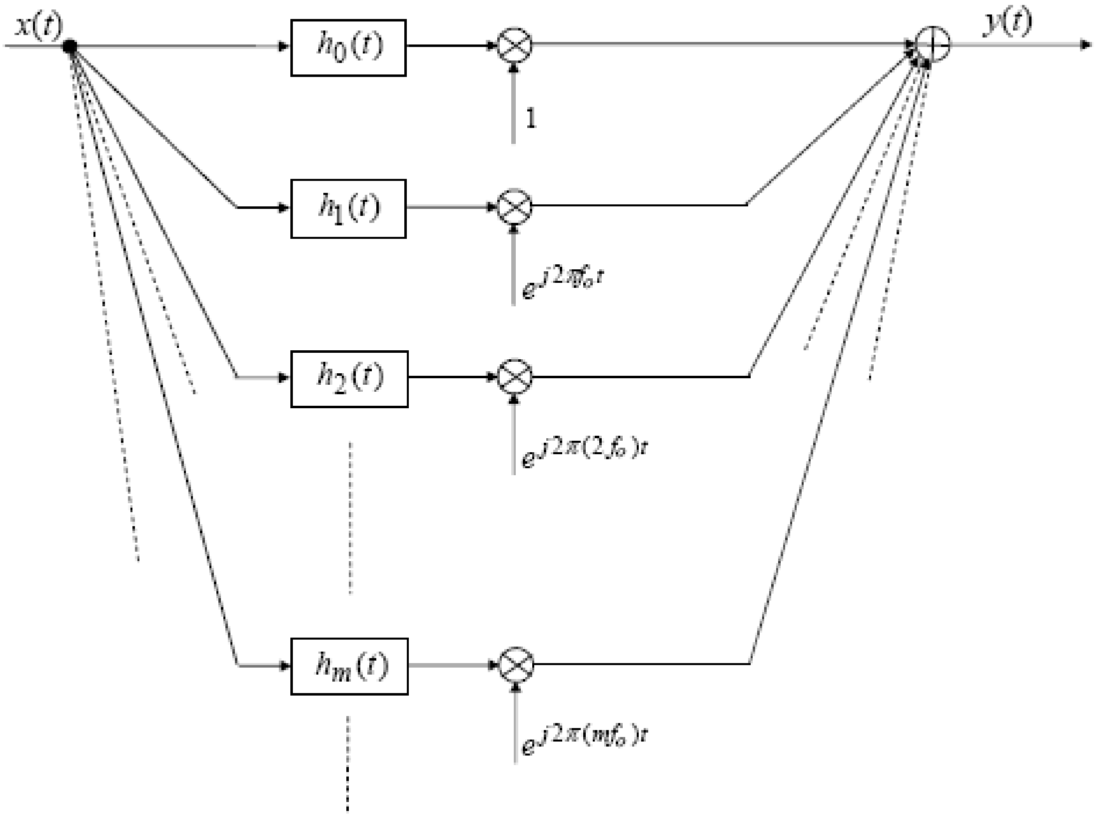
$$h(t,\tau) = \sum_{m=-\infty}^{+\infty} h_m(\tau) e^{j\frac{2\pi m}{T_0}t} \qquad h(t+kT_0,\xi) = h(t,\xi), \forall k \in \mathbb{Z}$$

$$y(t) = \sum_{m=-\infty}^{+\infty} e^{j\frac{2\pi m}{T_0}t} \int_{-\infty}^{\infty} h_m(\tau) x(t-\tau) d\tau = \sum_{m=-\infty}^{+\infty} e^{j\frac{2\pi m}{T_0}t} \{h_m(\tau) * x(t-\tau)\}$$

$$y[k] = \sum_{m=-\infty}^{+\infty} e^{j\frac{2\pi T_s}{T_0}mk} x[k] * h_m[k]$$

🡐 **MIMO model for LPTV channels!**

Wavelet Feature #3: Robustness to ICI (2/2)



MIMO model for LPTV channels is a "forgotten" result (Zadeh, 1950): the power line channel is a bank of static filters followed by a Doppler!

Doppler always causes ICI and robustness to ICI depends on windowing!!

W-OFDM more robust to ICI than OFDM!!!

Turbo Codes and LDPC (1/6)

- **We will look at a specific case, the comparison of:**
  - Duo Binary Convolutional Turbo Codes (DB-CTC)
  - Quasi-Cyclic Low Density Parity Check codes (QC-LDPC)
- **For AWGN, it is possible to give some general results for:**
  - Error floor
  - Performance sensitivity on block size/code rate
  - Decoder complexity
  - Class of applications best suited for DB-CTC or LDPC
- **Specific simulation results are given for the QC-LDPC FEC scheme chosen for G.hn and the alternative proposal based on DB-CTC**
  - AWGN only
  - Extrapolation to PLC is difficult because of impulsive noise and the lack of a statistical channel model

Turbo Codes and LDPC (2/6)

- **What about the error floor?**
  - Higher in DB-CTC than in QC-LDPC, one or two orders of magnitude
- **How much block size/code rate impacts performance?**
  - For small to medium block sizes DB-CTC outperform QC-LDPC, but for medium to large block sizes QC-LDPC outperform DB-CTC
  - Crossover threshold for block size changes with code rate and at target BLER of 0.01 we have (see European WINNER project report):
    - o R=1/2: ~2.2 kbits
    - o R=2/3: ~1.7 kbits
    - o R=3/4: ~1.1 kbits
- **What about decoder complexity?**
  - The DB-CTC decoder requires less memory than the LDPC decoder, but requires more basic operations (especially at high code rates)
  - Since logic complexity dominates at high data rates, LDPC offer better scalability than DB-CTC with respect to data rate
  - Shuffling/layered decoding (Fossorier ‘02) cuts in half convergence of BPA decoding allowing doubling of data rate at same performance

Turbo Codes and LDPC (3/6)

Comparing complexity is not easy, here is an example from the literature

Code	Parallelism level	Number of iterations	Bit rate (decoded Mbits/s)
DBTC	6	8	150
	12	8	300
	4	5	160
	8	5	320
BLDPCC	2	50 (flooding schedule)	192
	4	50	384
	1	20 (shuffled decoding)	240
	2	20	480

Table I: Achievable throughput for rate 0.5 DBTC and BLDPCC (200 MHz clock frequency)

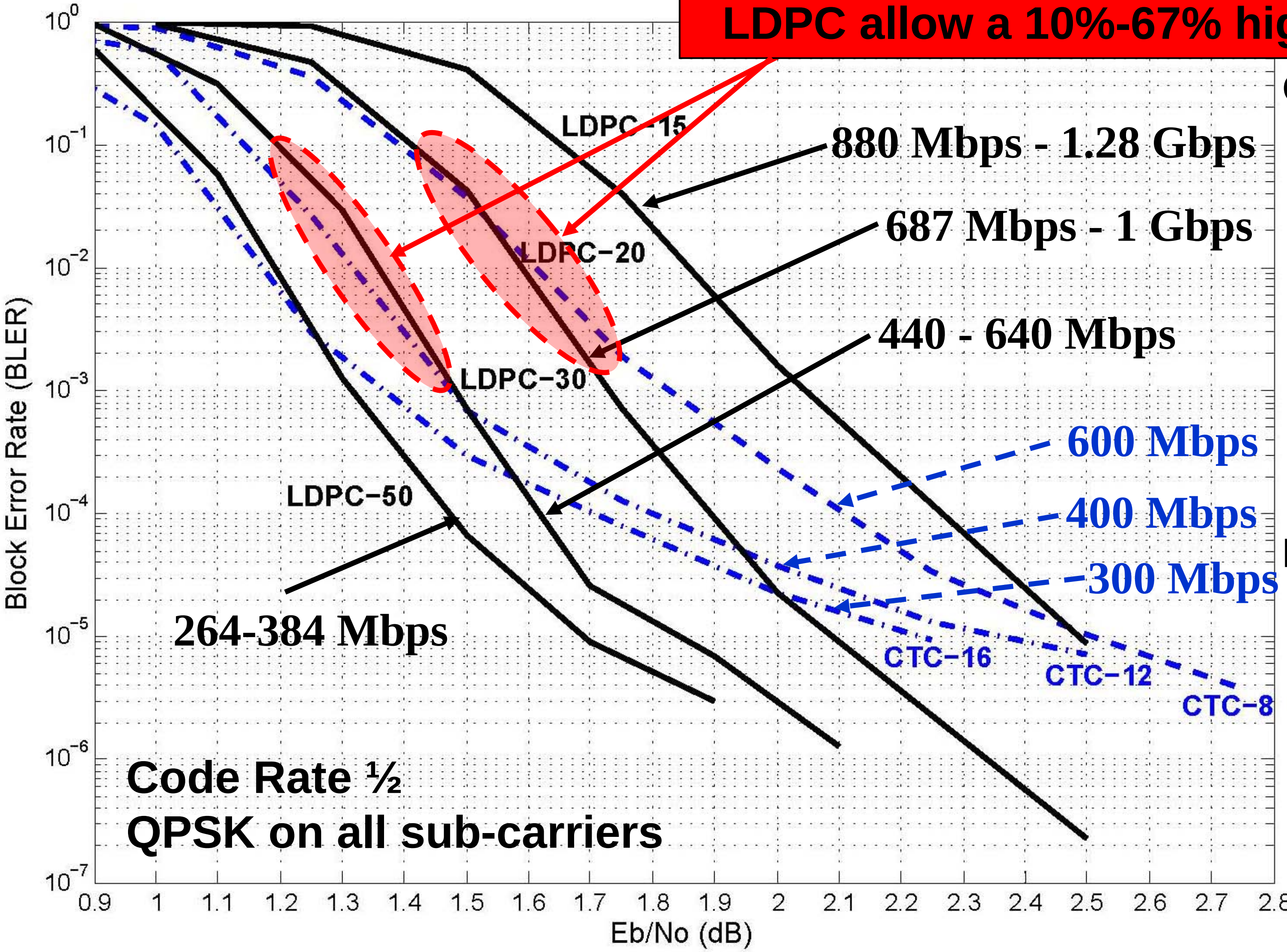
T. Lestable et al., "Block-LDPC Codes vs Duo-Binary Turbo-Codes for European Next Generation Wireless Systems," IEEE VTC 2006

Factor of 8 probably optimistic, others report factors between 5.5 and 8

- **Number of iterations (extrapolating best implementation from table):**
  - 300 Mbps: DB-CTC at 8 full its, QC-LDPC at 64 flooding its (32 shuffled)
  - 500 Mbps: DB-CTC at 5 full its, QC-LDPC at 39 flooding its (20 shuffled)
  - 1 Gbps: DB-CTC at 2.5 full its, QC-LDPC at 20 flooding its (10 shuffled)

Turbo Codes and LDPC (4/6)

Same coding gain on bad channels, but LDPC allow a 10%-67% higher data rate



QC-LDPC:
- 540 bytes
- Sum Product
- Flooding
- Data rate range calculated using previous table with two factors: 5.5 and 8

DB-CTC:
- 520 bytes
- Log MAP
- Sub-Iterations
- Data rate calculated using previous table

Simulation data from various ITU contributions and from A. Jimenez (DS2)

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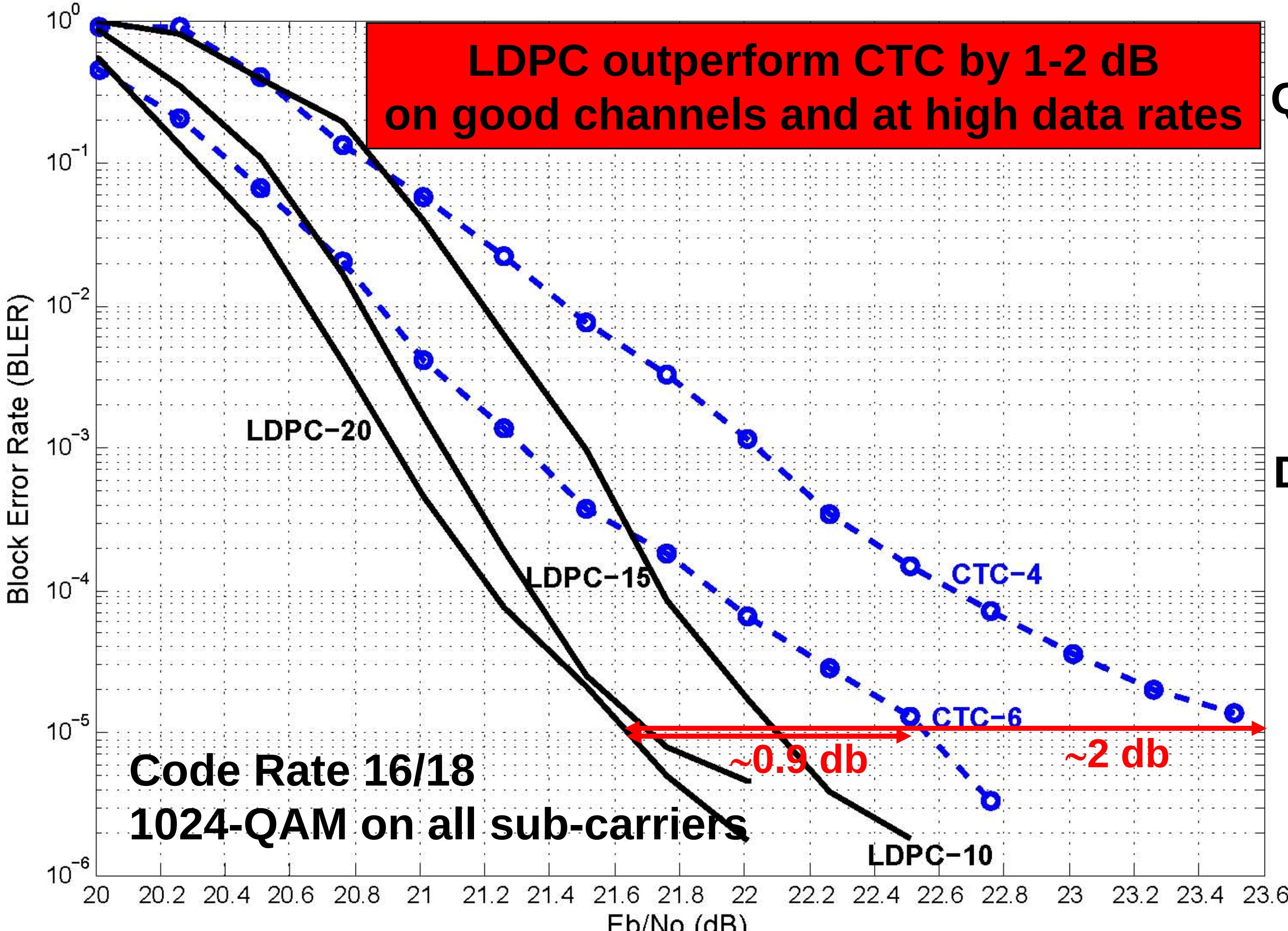
Turbo Codes and LDPC (5/6)



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- Sub-Iterations

Simulation data from various ITU contributions and from A. Jimenez (DS2)

Turbo Codes and LDPC (6/6): Summary of Comparison

- **Complexity**
  - Similar, when iterations are correctly equated:
    5 full DB-CTC ~ 15 QC-LDPC shuffled ~ 30 QC-LDPC flooding (R=1/2)
  - At higher code rates, factor goes up in favor of QC-LDPC
  - LDPC offer better scalability at high data rates
- **BLER Operating Point**
  - BLER>10^{-3}: DB-CTC and QC-LDPC have similar coding gains, but QC-LDPC allow higher throughputs at similar complexity
  - BLER<10^{-3}: QC-LDPC outperform DB-CTC in coding gain and throughput when operating at similar complexity
- **Codeword Size for Target of BLER=0.01**
  - QC-LDPC perform better than DB-CTC when codeword is above 2 kbits
- **Code Rate**
  - QC-LDPC behave increasingly better than DB-CTC at high code rates

Conclusions

- **The Good News**
  - ➢ Broadband PLC standards are finally coming out
  - ➢ They will co-exist with each other via ISP
  - ➢ They may also co-exist with installed base, with conditions
  - ➢ Data rates are going up
  - ➢ They offer a variety of solutions in the kind of multicarrier, FEC, MAC… the market will decide what is best on the basis of field performance
- **The Not-Too-Bad News**
  - ➢ They are not interoperable with each other ➔ co-existence is necessary and will help with technology migration
- **Important Open Research Problems**
  - ➢ Simple statistical PLC channel model, for static and time varying cases
  - ➢ Problem of scalability in dense networks, self-interference issue
  - ➢ Topologies of power grid have special “small world” properties
  - ➢ Overlay of communications network on power grid enabling distributed control under communication constraints ➔ the true Smart Grid enabler