Broadband Power Line Communications for Smart Grid

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Contents

History

- In June 1956, an AIEE Report titled "*Guide to Application and Treatment of Channels for Power Line Carrier*" introduced first a real PLC system
- Initially, low voltage (LV) PLC applications were mostly introduced
  - Load management
  - Distance metering: electricity, water, gas and temperature
  - Average rate 1 bps!
- Late 1990s, some medium or high voltage (MV or HV) PLC applications were introduced
  - Carrier Frequency System (CFS)[Dost97]
  - But limited narrowband services (<1MHz)
- In 2010, international broadband PLC standard (IEEE 1901) has been adopted
- Currently, there has been a lot of LV & MV BPLC research activities including Home Networks and Smart Grid
- *Once, one PLC Pioneer, Media Fusion, gives a promise of the max data rates above 2.5Gbps through power cables (Are you sure??!!!)*

Advantages of PLC via electrical power grid

- PLC is a low-cost, easy-to-access, and ubiquotous transmission medium
  - No infrastructure cost
  - Easily accessible via any wall outlets: no extra cables
  - Available wherever power energy is provided
  - No concern about lack of frequency (like cellular)
  - *Alternative way of communication in case of emergency

Overview

- PLC Frequency spectrum depending on applications
  - Narrow band applications: less than 1 MHz
  - Broad band applications: 1MHz ~ 100MHz
- Since power supply networks are not mainly designed for communications, there are several issues in PLC:
  - Large frequency-dependent attenuation: relatively short distance communications
  - Various unavoidable noise sources from supply networks
  - Unshielded Cables (especilly, LV case) cause EMC problems
  - Some concern about power quality degradation & safety issues

Overview

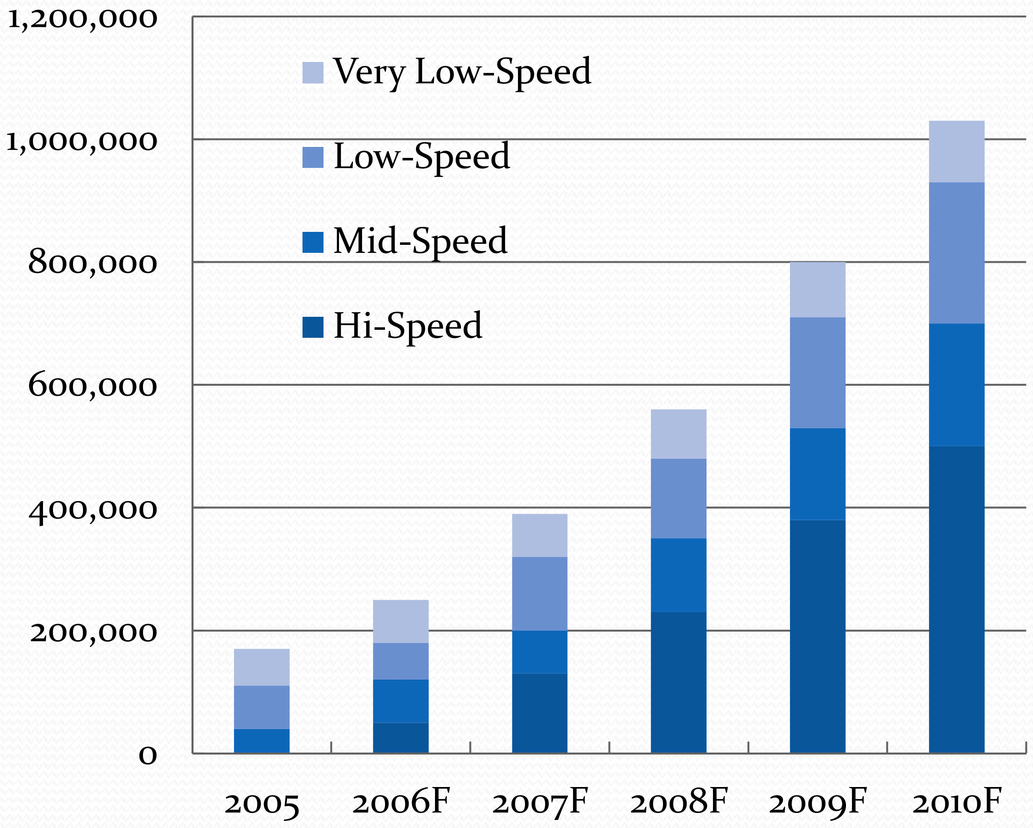
- Compared to cellular, PLC study is not so active until recently due to the delayed international standardization (IEEE1901 in 2010)
- PLC Standards
  - CENELEC EN50065: Narrowband (30 – 148.5 KHz, LV only, <100Kbps), limited applications
  - Several De Facto standards: HomePlug1.0, HomePlugAV, etc
  - IEEE1901: Broadband (2MHz ~ 100MHz, LV&MV, 100Mbps)

Overview

- Various PLC applications
  - Home networks
  - Smart Grid
  - Home automation and intelligent building systems: security, supervision of heating, light control
  - High-speed internet
  - Smart metering
  - Disaster recovery
  - Voice services to confined geographic areas (provide dual purpose, attractive to developing countries)

PLC Market Share

(Unit: 1,000 Dollars)

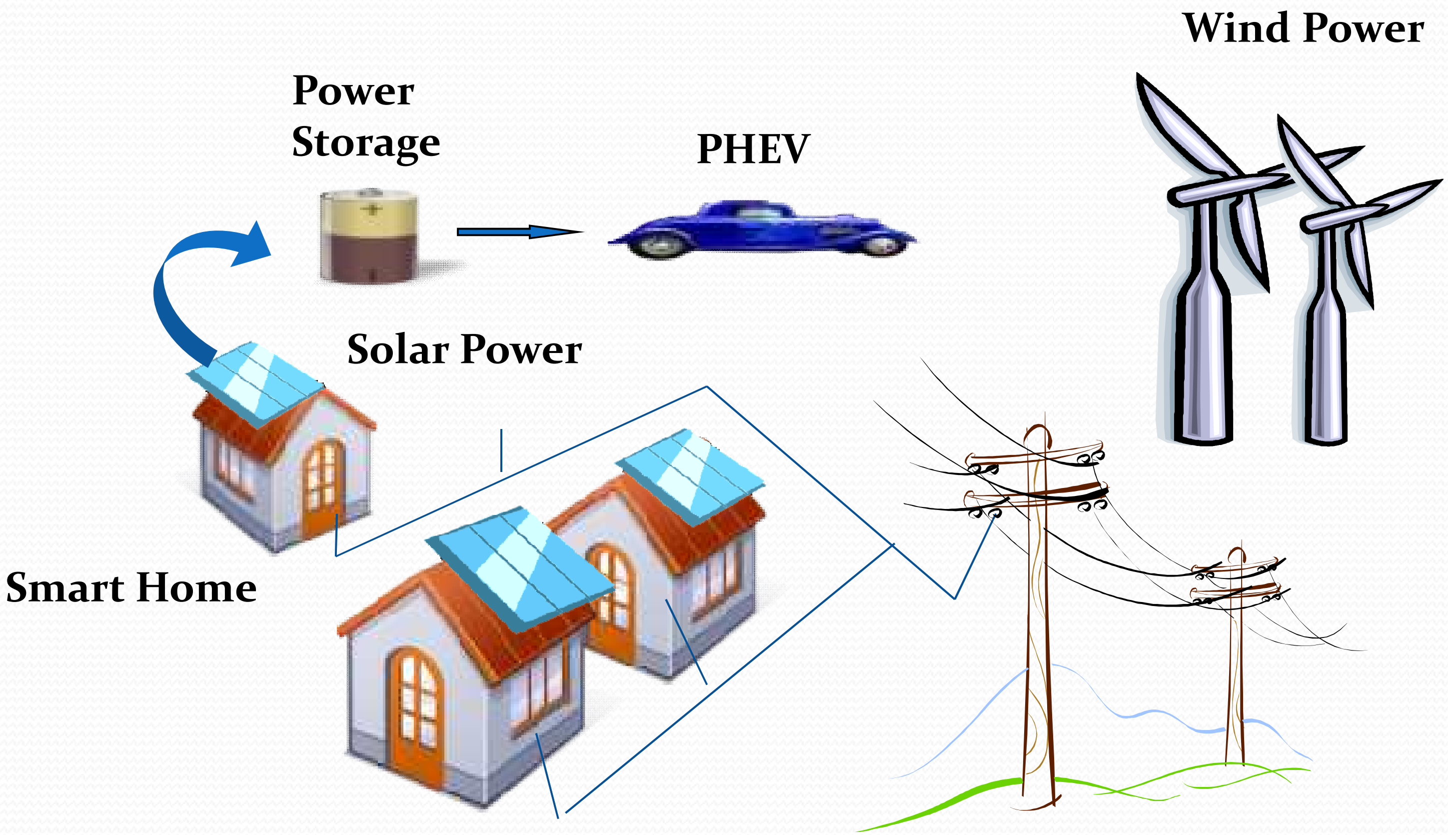


<자료>:"2006 Market Analysis of Power Line Communication", TSR, 2006.6

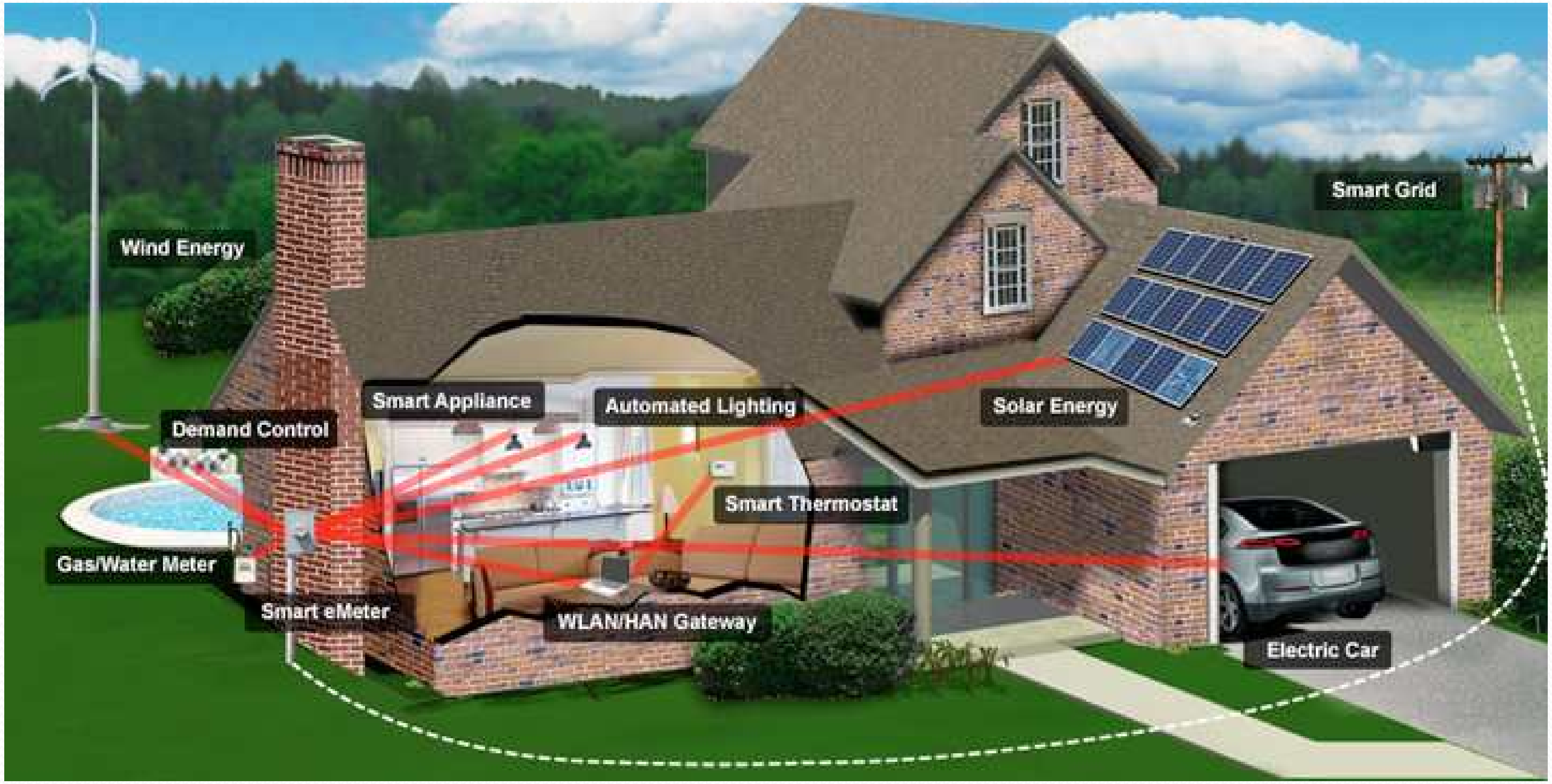
Smart Grid

- Backgrounds
  - Electricity consumption increases 1.4% annually
  - Kyoto protocol: Low CO2 becomes mandatory
  - Current power grid is very old, unreliable, almost full capacity reached
  - Various renewable energy services are coming
  - Electric Car (PHEV)

Smart Grid



Smart Home and Smart Grid



Smart Grid

- Greed Energy and Low CO_2 based Power Grid Networks (PGN)
  - Include renewable energy resources: Offshore wind power, Solar Energy, etc
  - Request Efficient PGN Operation, Maintenance, and Power Quality Monitoring
  - Preparing electric vehicles
- Interactive and customer-centric
  - Interactive services: single directional $\rightarrow$ bi-directional
  - Customer-centric: central grid $\rightarrow$ distributed grid
- <u>ICT Infrastructure</u>
  - Decentralized networks
  - Reliable, robust, flexible, simple, real-time communication
  - Secure information transfer
  - Communication infrastructure allowing millions parties interactions in a single market

SG Principal Characteristics

- Self-heals
  - **Real-time** contingency (fault or disruption) analysis, management, and maintenance
- Motivates and Includes the consumer
  - **Two way and real time** communications (R_b < 1Mbps)
- Provides power quality for 21st century needs
  - Communicating smart meters: voltage imbalance reports; **high quality** data
- Resists attack: **high security** guaranteed
- Accommodates all generation and storage options
- Enables markets
- Optimizes assets and operates efficiently

What would be Smart in the Grid

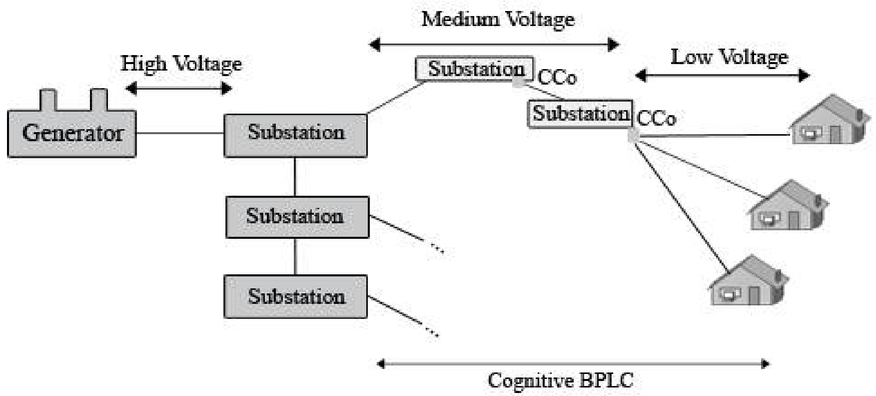
- Intelligent Devices
  - Electronic sensing and measuring
  - Digital intelligence to take certain decisions
  - Communications to share data and cooperate in decision making
- Bidirectional communications between operators and customers
- Advanced control systems
  - Distribution automation
  - Energy management system
  - Intelligent network agents
  - Demand/Asset side management systems
  - Geographic information systems
  - Grid modeling, simulation, and design systems

Telecommunication Networks for Smart Grid

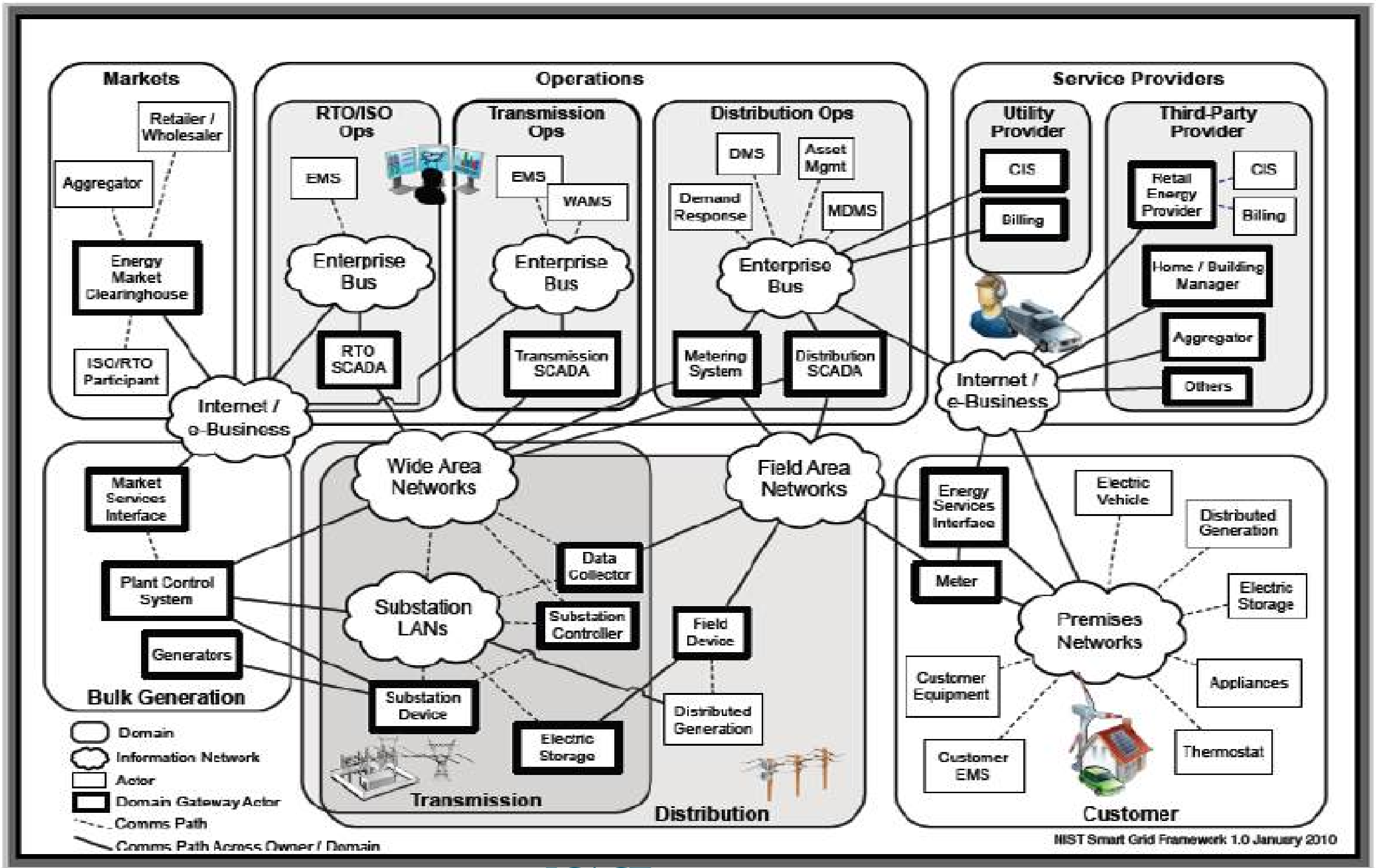
- Digital Radio Systems: WiMAX, WiFi
- Asynchronous Digital Subscriber Line (ADSL)
- General Packet Radio Service
- Optical Fiber Communication System
- PLC
  - MV PLC (point-to-point between transformer substations, Mbps)
  - LV PLC (point-to-multipoint between meters and transformer substations, Kbps)

PLC Merits in Smart Grid

- No Infra cost using existing PGN
- Guarantee reliable & ubiquitous communications
- Make use of power distribution lines as communication carriers using PLC
- Recent PLC standard efforts (IEEE 1901 and ITU-G.hnem) are dedicated to PLC technology for SG



(a) Hierarchical Structure for CBPLC



(b) Conceptual Reference Diagram for Smart Grid Information Networks [1]

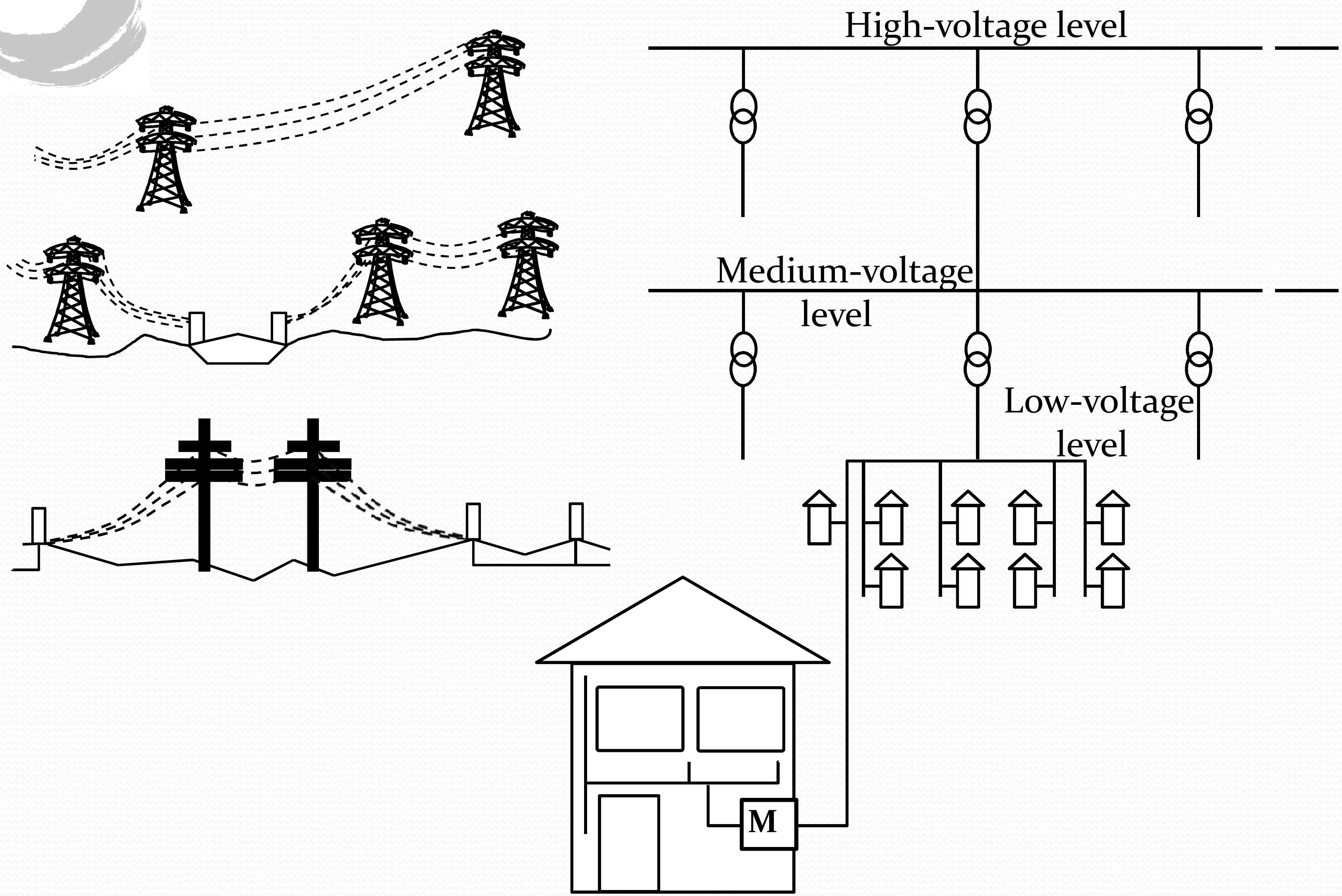
Current PLC System Candidates for Smart Grid

- PoweRline Intelligent Metering Evolution (PRIME)
  - Advanced Digital Design, CURRENT Croup, Iberdrola, etc
  - Narrowband LV PLC: CENELEC A Band (fc = 42~89KHz)
  - Data Rate: 21.4Kbps ~ 128.6Kbps
  - Adaptive OFDM
  - CSMA/CA MAC
- HomePlug Command and Control (C&C)
  - HomePlug Alliance
  - Spread Spectrum modulation
  - Max 7.5 kbps (fc = 100 KHz ~ 400 KHz)
  - CSMA/CA MAC
- Automatic Meter Management
  - MAXIM Integrated Products, Inc (USA)
  - Fc = 10 -490 KHz, less than 100 Kbps
- DLC-2000 PLC
  - iAd GmbH (Germany)
  - OFDM, fc=9 -500 KHz
  - TDMA MAC

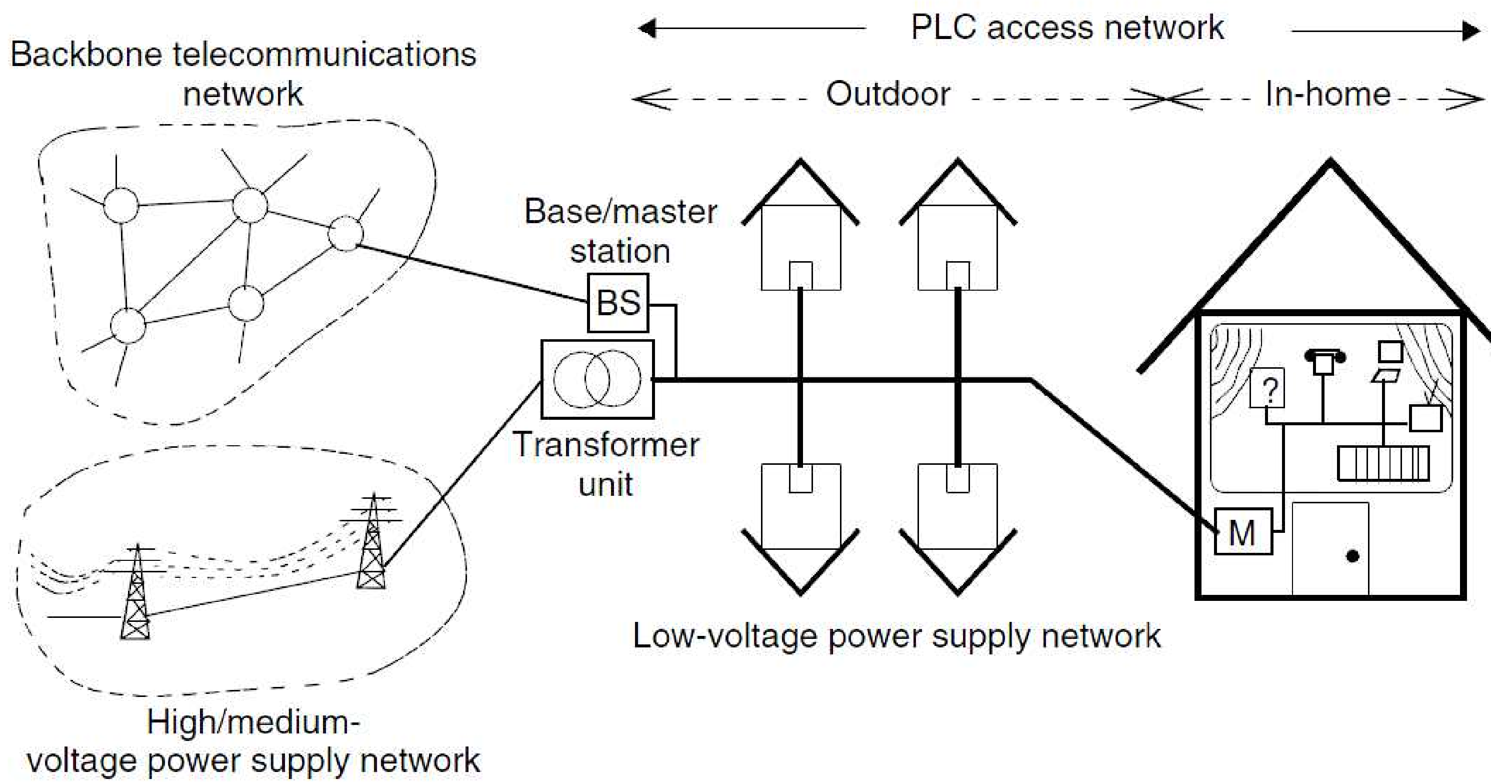
Power Supply Networks

- Low Voltage (LV): 100V ~ 500V
  - 1-phase 2-wires: Indoors / outdoors
  - Short distance: less than a few hunred meters
  - Most of end users (individual customers or a single big customer, etc)
  - LV PLC forms a PLC access network like LAN
- Medium Voltage (MV): 500V ~ 30 KV
  - 3-phase 4-wires: Mostly outdoors (Overhead / Underground type)
  - Long distance: above few hundred meters
  - MV PLC is used for interconnection of multiple PLC access networks
- High Voltage (HV): 100KV ~ 380 KV
  - Very Long distance, Just Overhead type, Outdoor
  - Just extention of MV PLC (but very limited applications & safety issues)

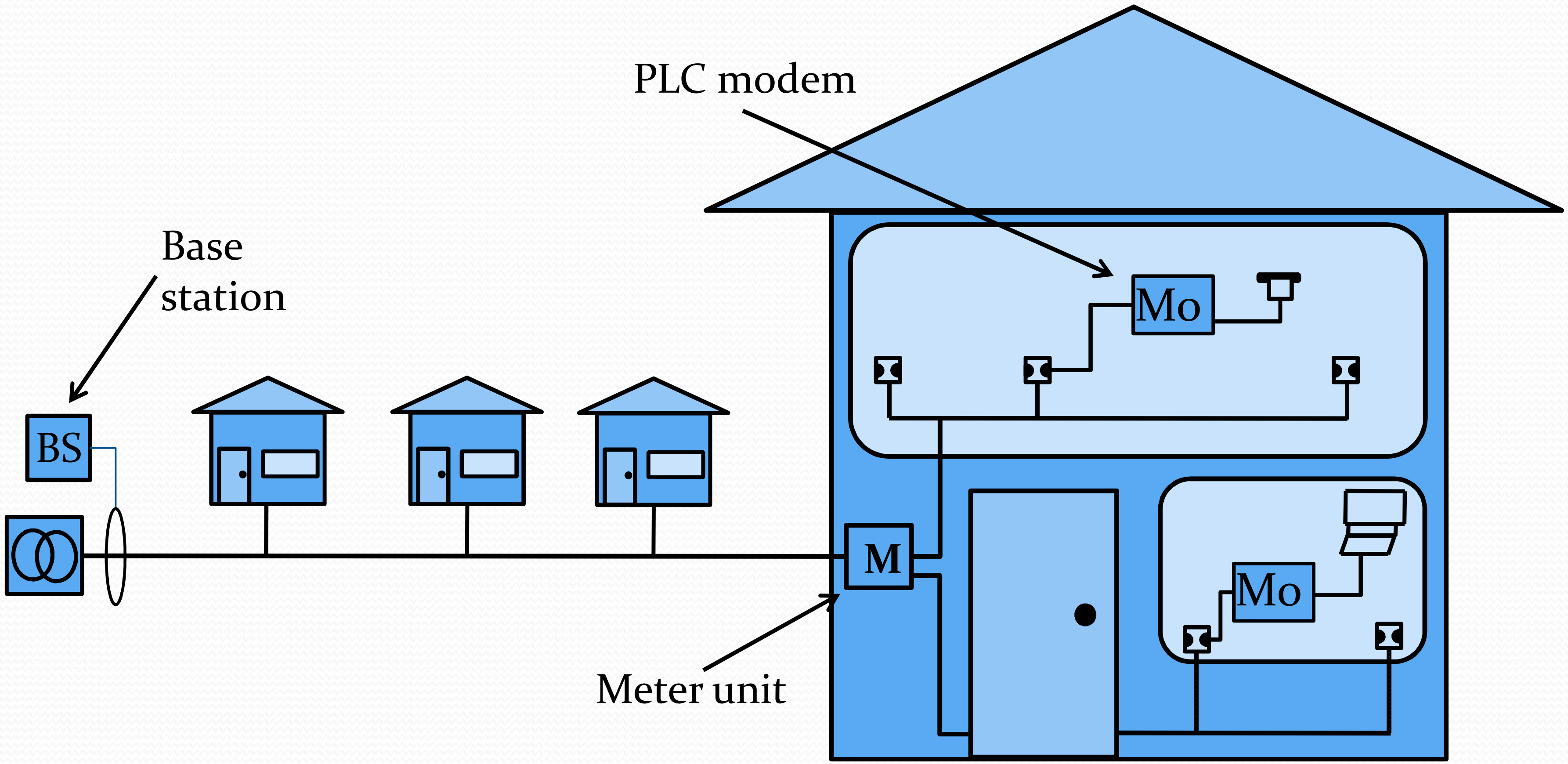
Electrical Power Supply Networks

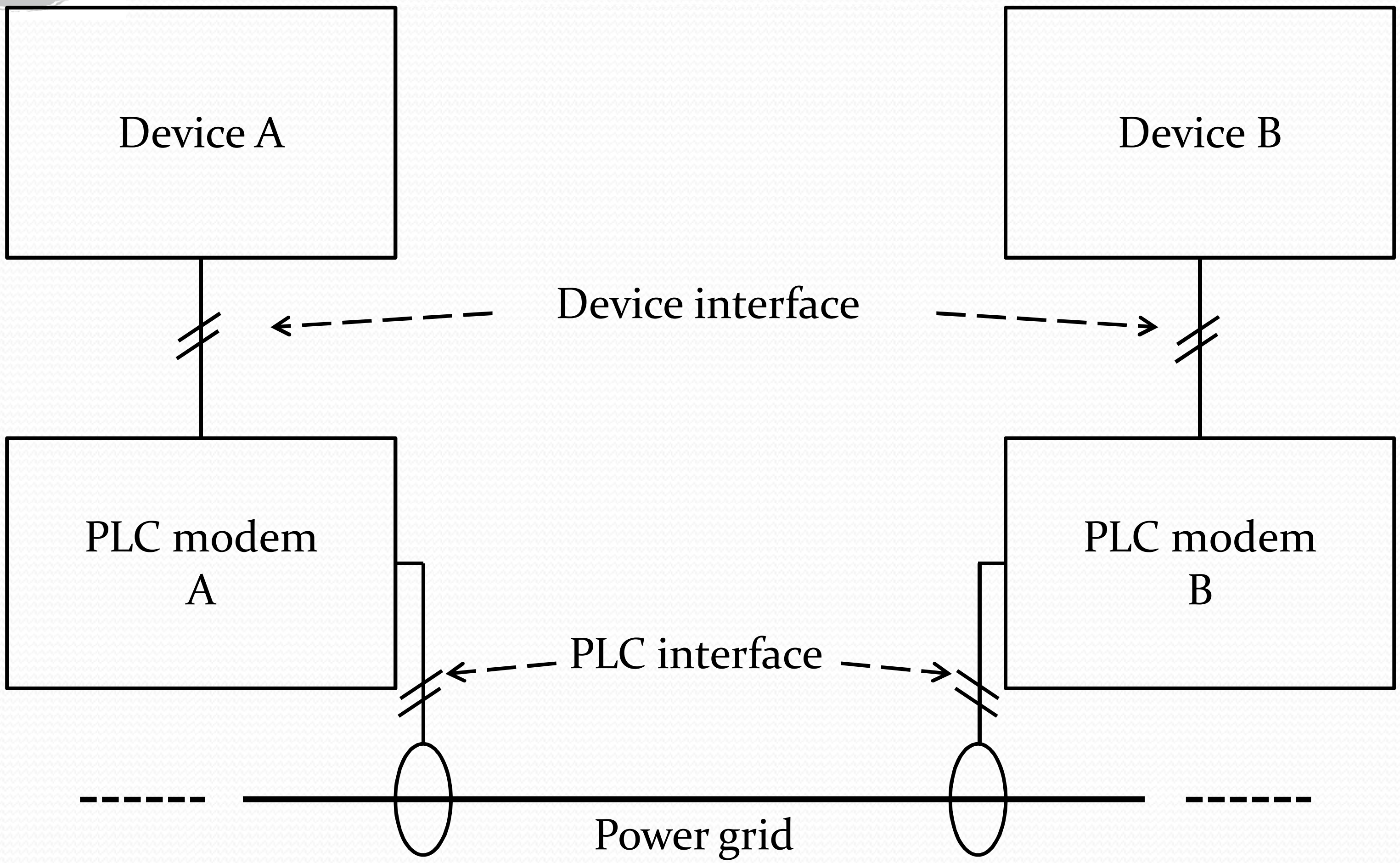


Structure of PLC Access Networks



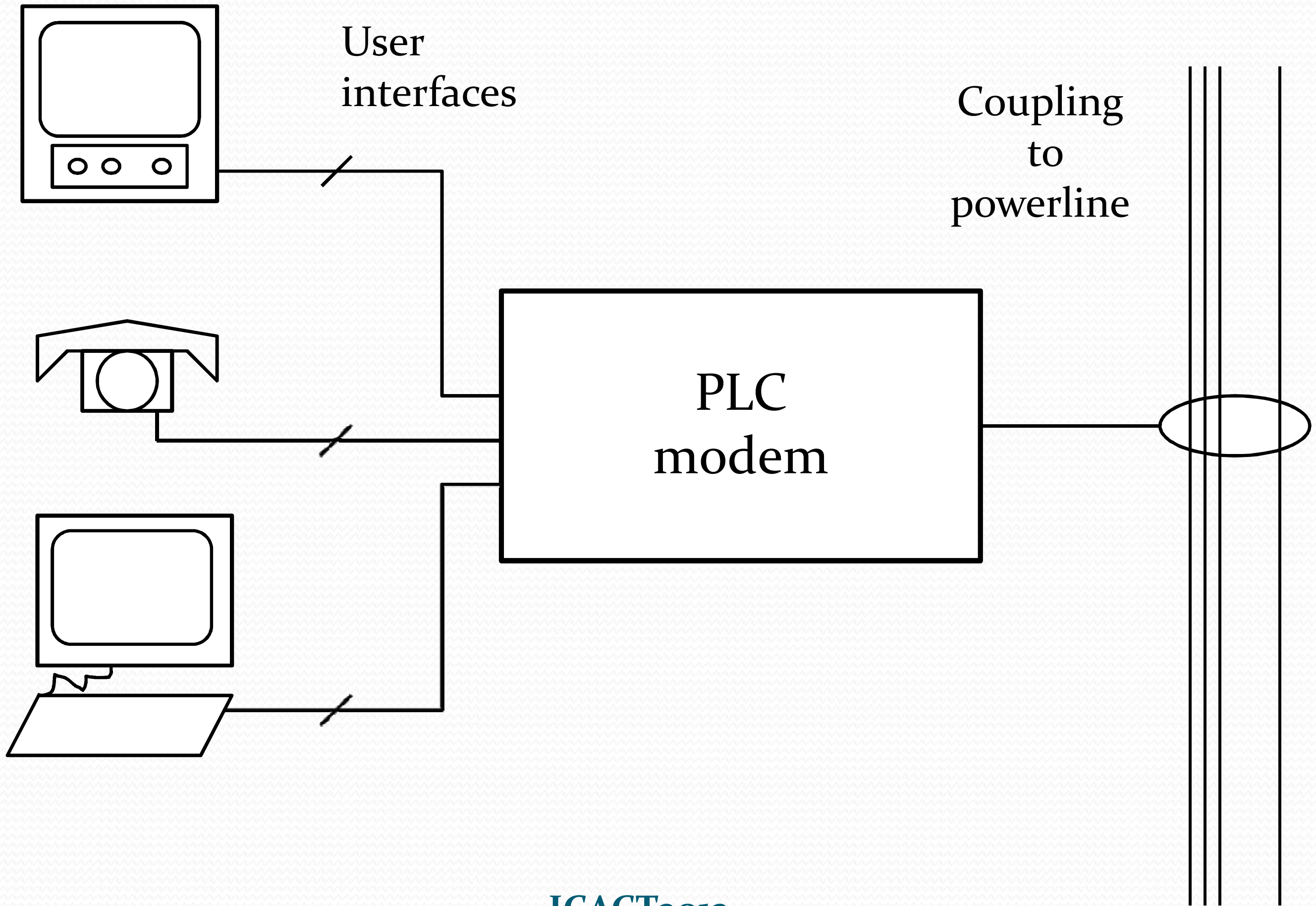
Connection of PLC subscribers



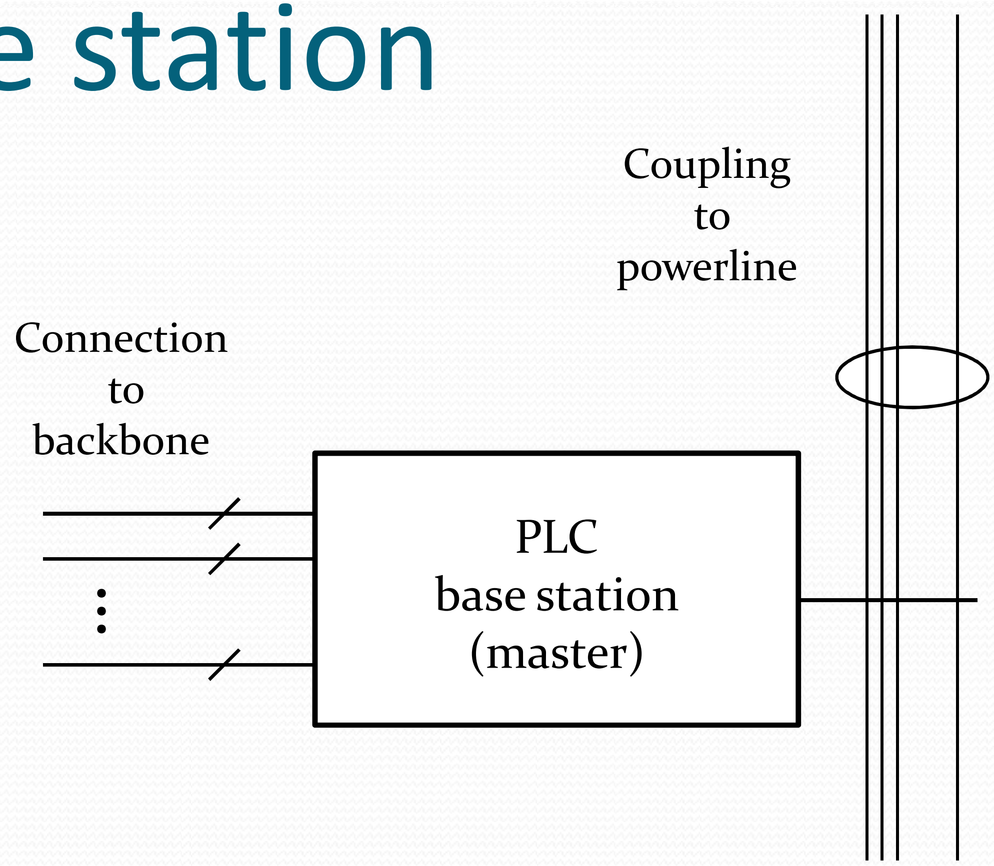

Device A
Device B
Device interface
PLC modem A
PLC modem B
PLC interface
Power grid

PLC Modem

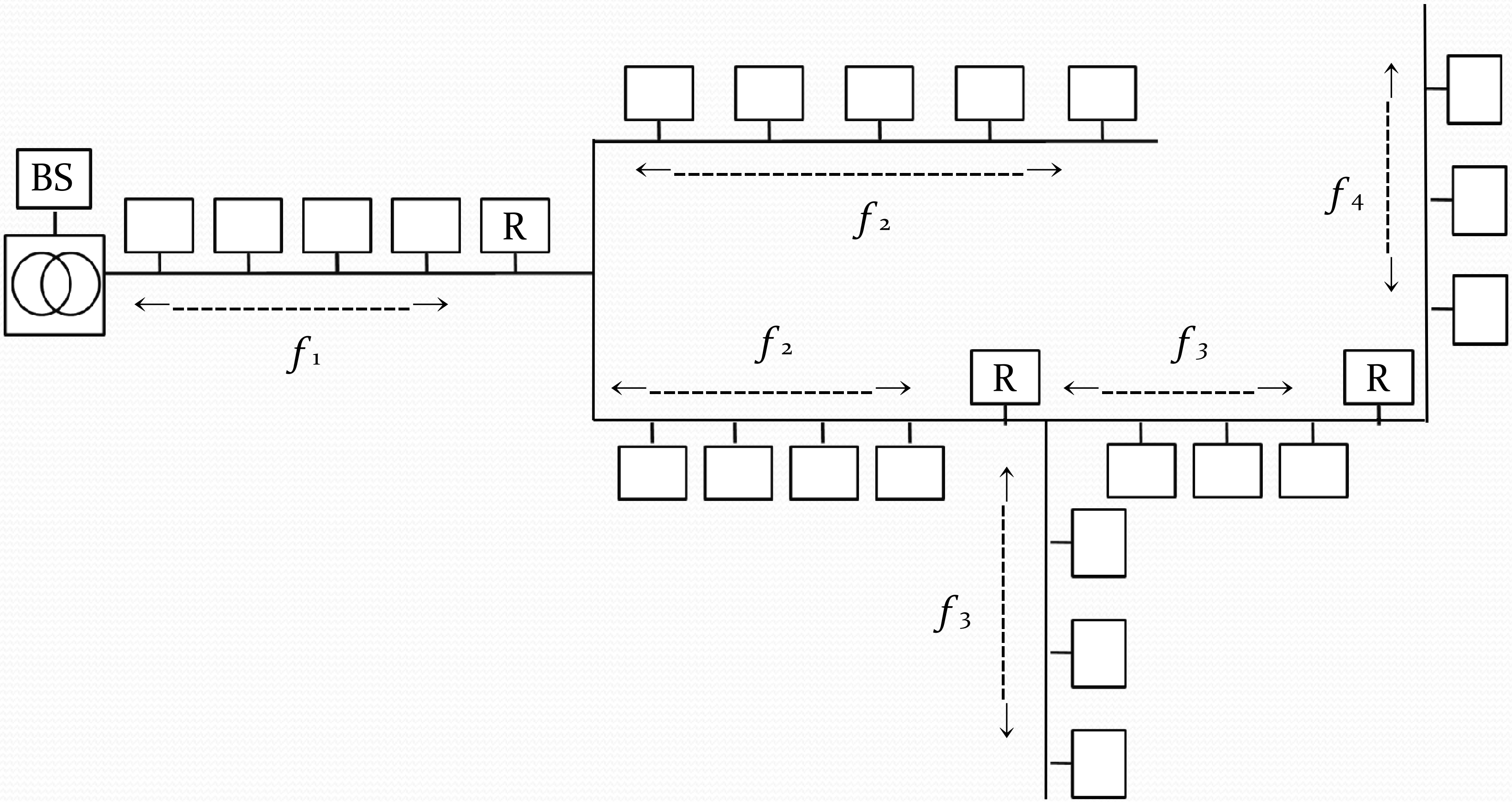
Powerline Coupling
- inductive coupling
- capacitive coupling



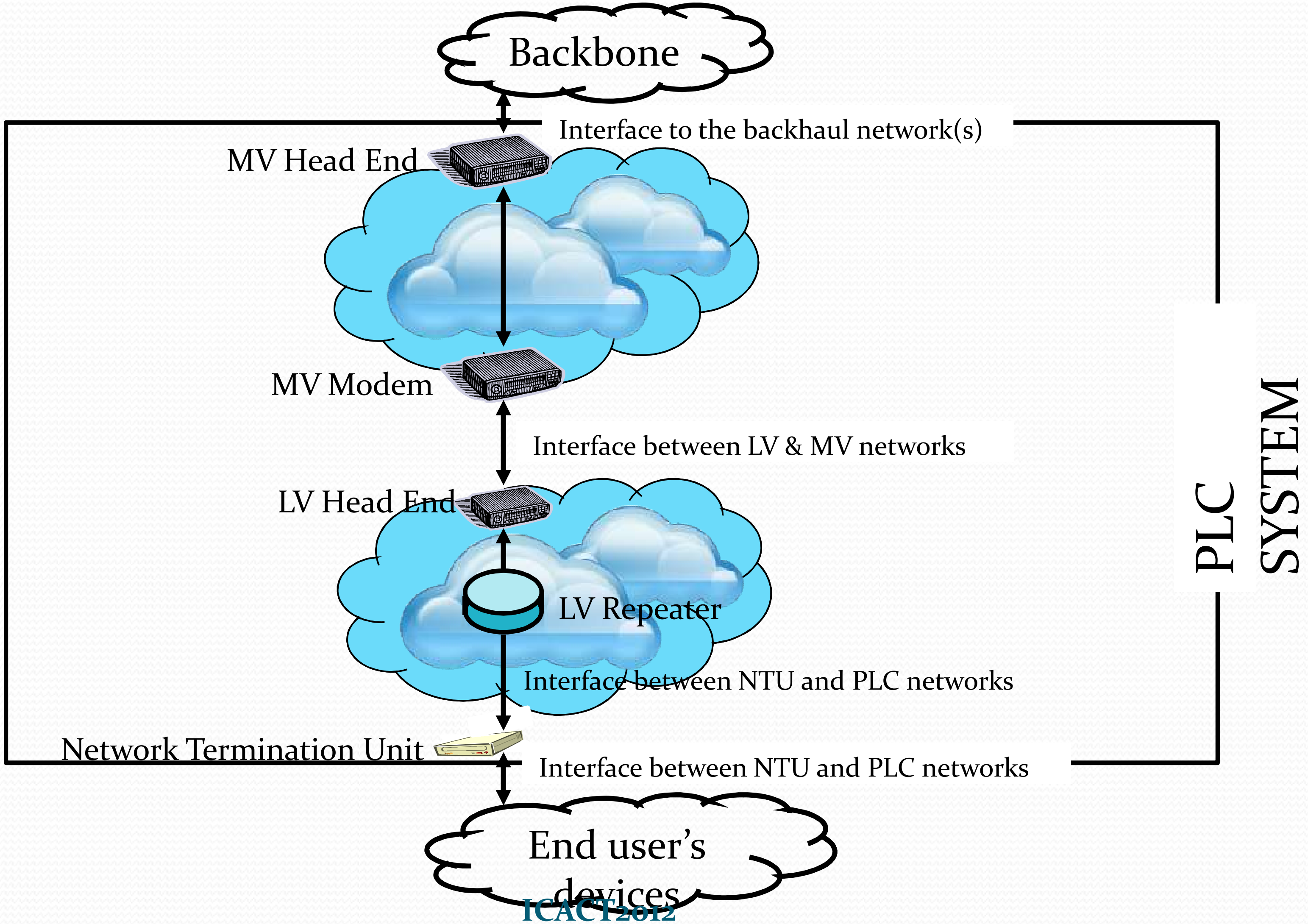
PLC base station



PLC Access Networks with repeaters



PLC Network Hierarchical Structure

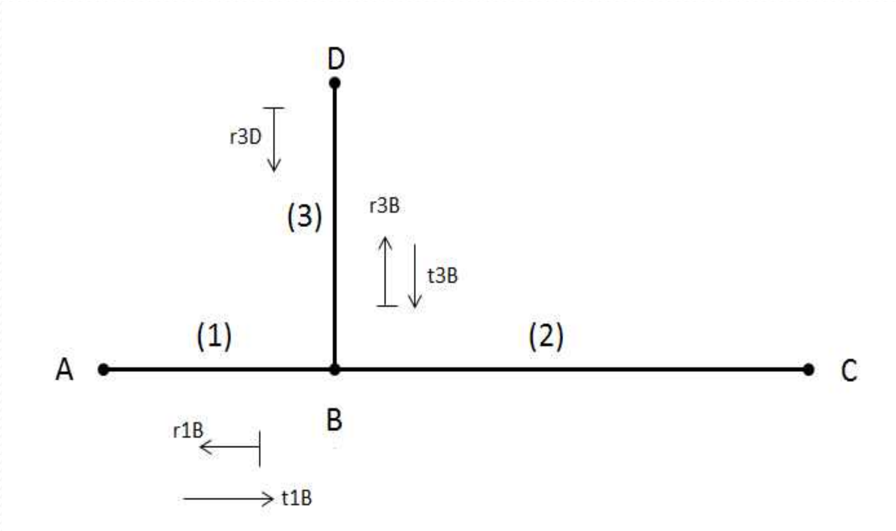


PLC Channels

- PLC is **cost-effective but not originally designed for data transfer**
- Signal reflections due to mismatched cable connections which result in **multipath fading** (like wireless channel!)
- Limited range (200m – 300m) due to large attenuation so repeaters may be needed for long distance communication
- Disturbances by various noise sources including switching power supplies, power converters, electric motors, TVs, computer monitors, etc : severe **impulse noise** channel
- **EMC problems due to unshielded cables** (mostly LV PLC): HF radio, HAM, different public or military services, etc

PLC Multipath Fading Channel

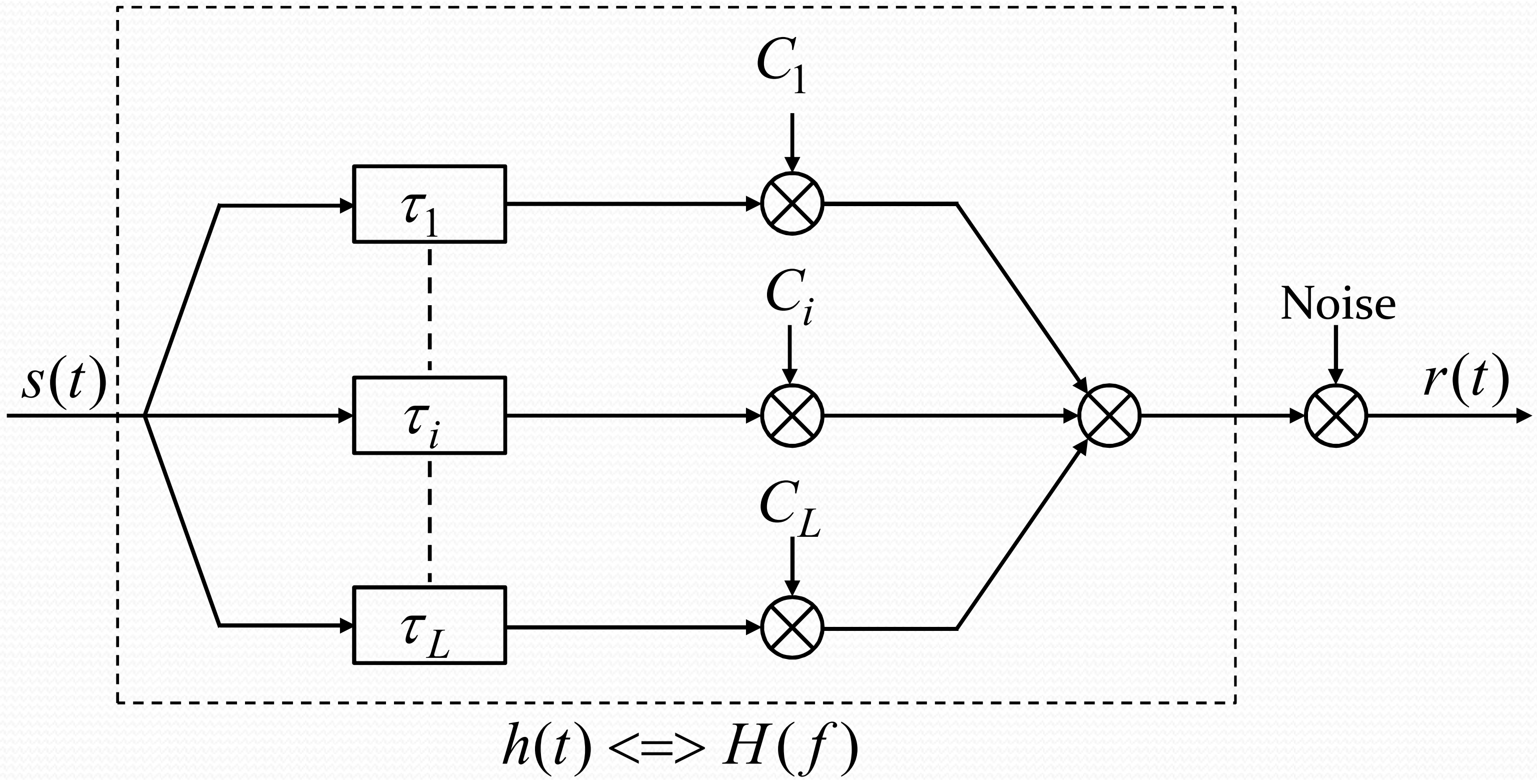
- Signal reflection due to impedance mismatch results in **multipath fading channel**



Path No.	Way of the signal path	Length of path, d_p
1	A → B → C	$l_1 + l_2$
2	A → B → D → B → C	$l_1 + 2l_3 + l_2$
⋮	⋮	⋮
N	A → B (→ D → B)$^{Np-1}$ → C	$l_1 + 2(Np-1)l_3 + l2$

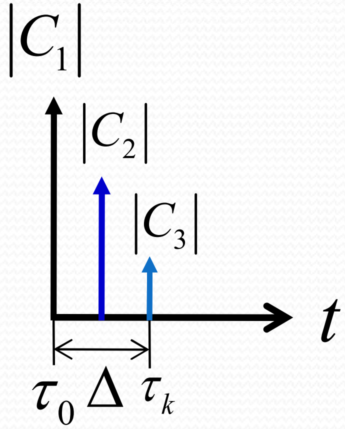
PLC Multipath Fading Channel

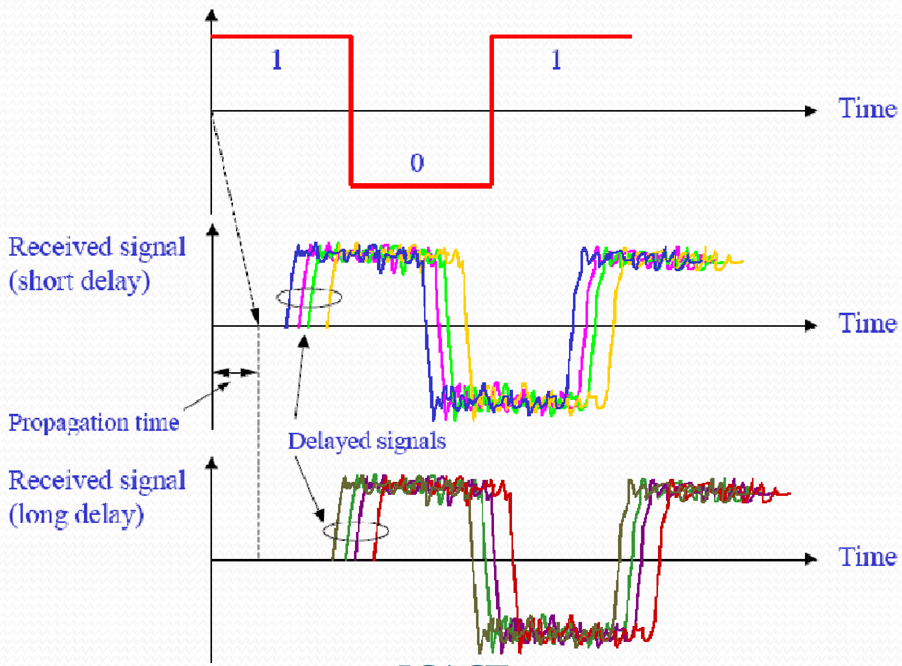
- PLC Multipath Fading Channel Model



ISI becomes severe as delay spread Δ increases

Delay Spread: $\Delta = \tau_k - \tau_0$

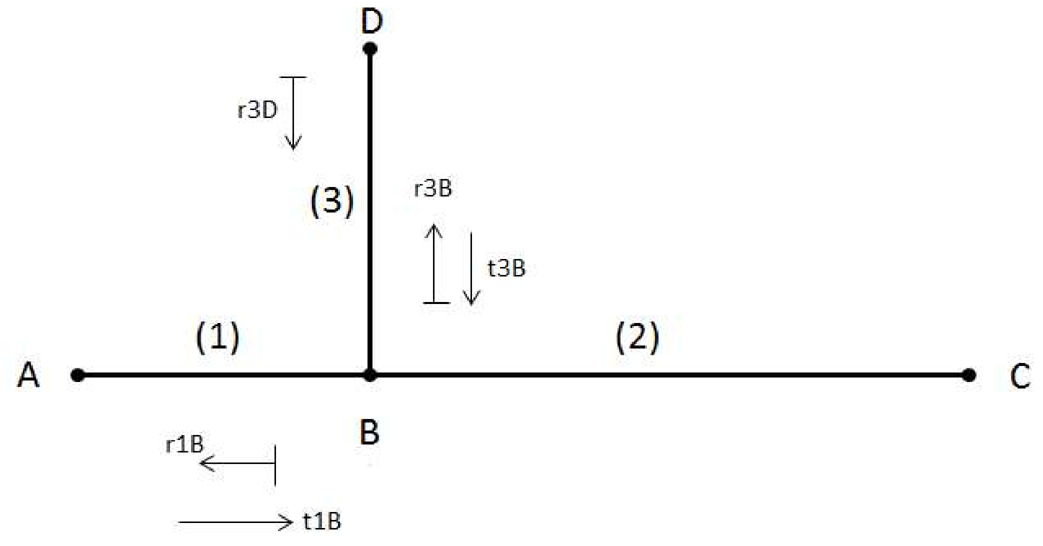


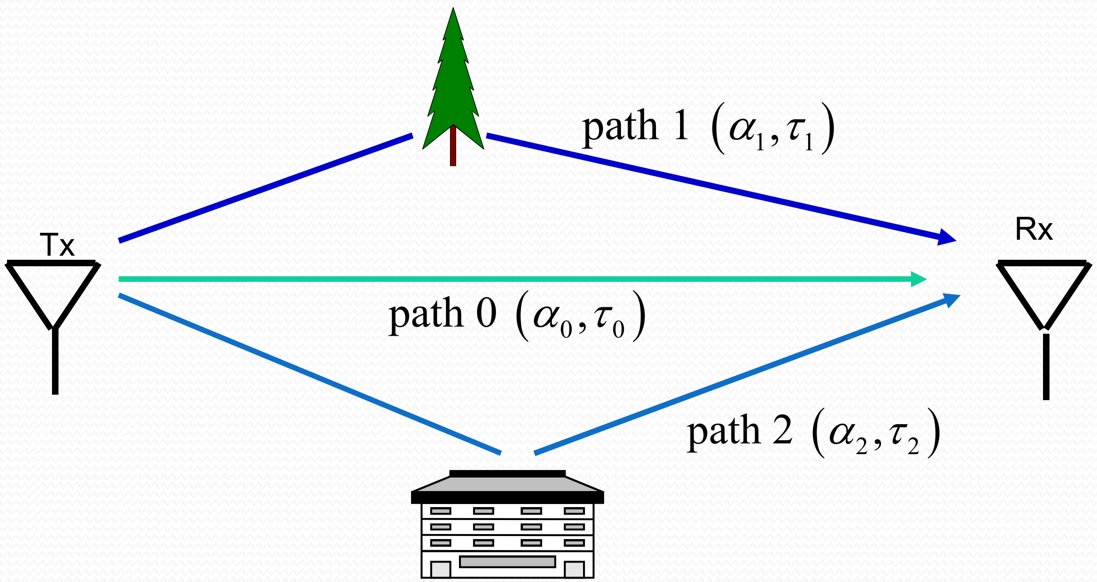


PLC Multipath fading

$$h(t) = \sum_{k=0}^{L-1} \alpha_k \delta(t - \tau_k)$$

$$\Delta = \tau_k - \tau_0$$





Multipath Fading Channel Models

- Multipath Fading Channel
  - Zimmermann's Model
  - Galli's Model
- Impulse Noise Channel
  - Middleton Class A Model

Multipath Fading Channel Models

- Zimmermann's Model [Zim02]
  - Frequency channel transfer function H(f) with L multi-paths

$$H(f) = \sum_{l=1}^{L} \underbrace{g_l}_{\substack{\text{weighting}\\ \text{factor}}} \cdot \underbrace{e^{-(\alpha_0 + \alpha_1 \cdot f^u) d_l}}_{\text{attnuation portion}} \cdot \underbrace{e^{-j 2\pi f (d_l / v_p)}}_{\text{delay portion}}$$

where d_l / v_p is equivalent to the corresponding path delay τ_l (where d_l represents lth path distance), ε_r is the non-insulation dielectric constant of the cable, and c_o is the speed of light

$$\tau_l = \frac{d_l \cdot \sqrt{\varepsilon_r}}{c_0} = \frac{d_l}{v_p}$$

PLC Multipath Fading Channel

- Galli's Model [Gal09]
  - Average channel gain E{G} = E{|H(f)|²} is log-normally distributed
  - RMS delay spread (energy spread) σ_τ is also log-normally distributed

$$\bar{G} = 10^{\bar{G}_{dB}/10} = h_1^2 + h_2^2, \ \ \sigma_\tau = \frac{|h_1 \cdot h_2|}{h_1^2 + h_2^2}\tau; \text{assuming two paths}$$

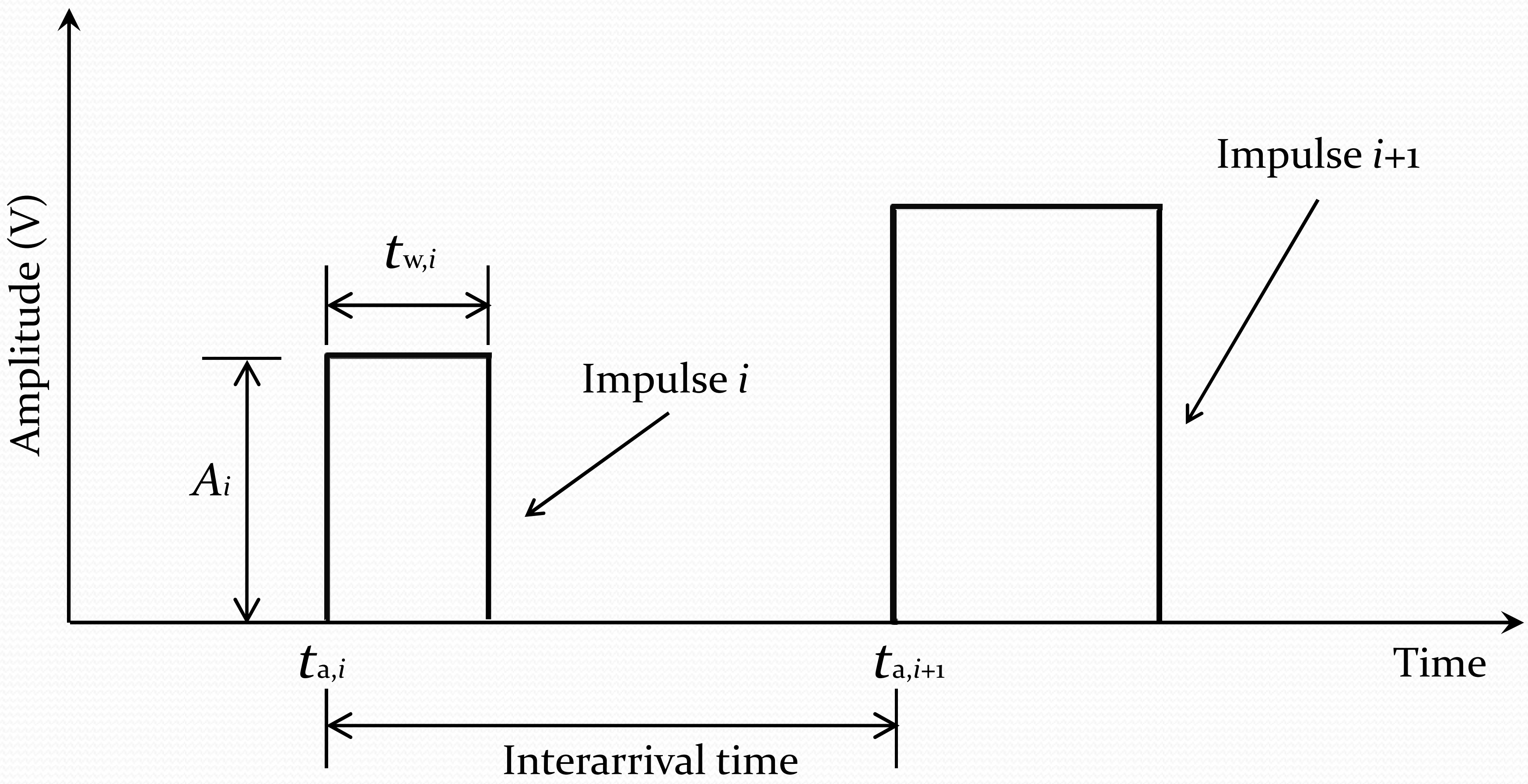
  - Modify Zimmermann's model H(f) considering statistical channel parameters

Impulse Noise Channel

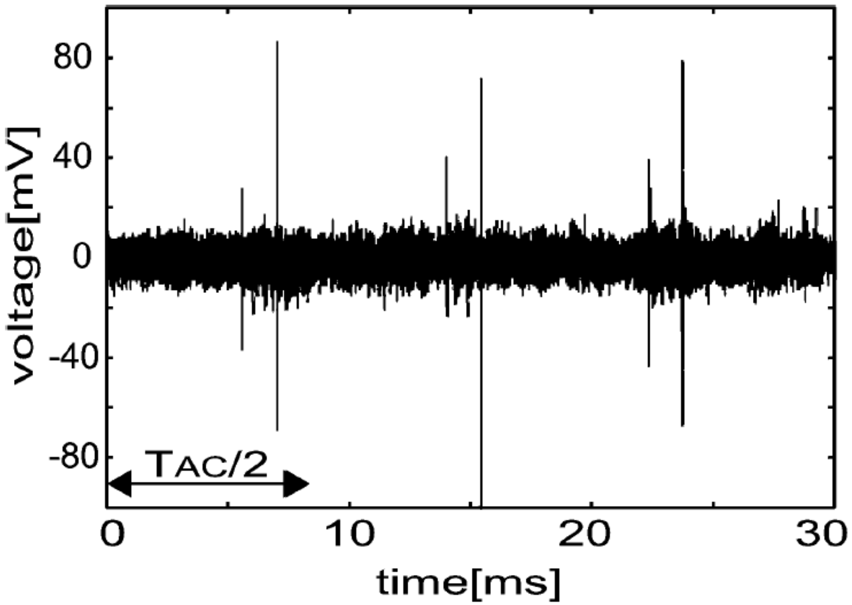
- Impulse noise sources
  - Periodic type: switching power supplies, power converters
  - Non-periodic type: switching transients in networks
- Middleton Class A Model [Har01]
  - Probability density function

$$p_X(x) = \sum_{m=0}^{\infty} e^{-A} \frac{A^m}{m!} \frac{1}{\sqrt{2\pi\sigma_m^2}} e^{-\frac{x^2}{2\sigma_m^2}} \qquad \sigma_m^2 = \sigma^2 \frac{m/A+\tau}{1+\tau}$$

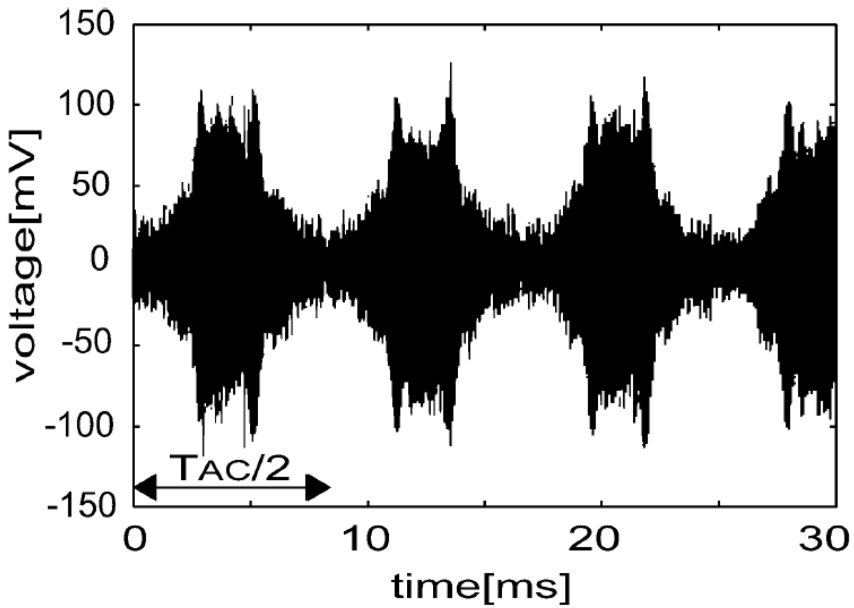
where $\sigma^2=\sigma_G^2+\sigma_I^2$ (σ_G^2 is the Gaussian noise variance and σ_I^2 is the pure impulse noise variance) and A is the impulse index.


Amplitude (V)
Impulse i+1
tw,i
Impulse i
Ai
ta,i
ta,i+1
Time
Interarrival time

Impulse Noise Channel [Har01]



Color TV impulse noise



Fluorescent Lamp impulse noise

PLC Electromagnetic Radiation

- PLC system has to operate without disturbing other existing systems
- Power cables like antennas may cause electromagnetic radiation
  - Less than 100MHz, signal propagation characteristics are similar other cables used for communication
  - LV cables (sector shaped or round type) are unshielded so have severe radiation
  - MV cables are typically shielded like coaxial cables
  - Electric (E) field emission limits

$$E = 20\left(\frac{\text{dB}\mu\text{V}}{\text{m}}\right) - 7.7\log\left(\frac{f}{\text{MHz}}\right)$$

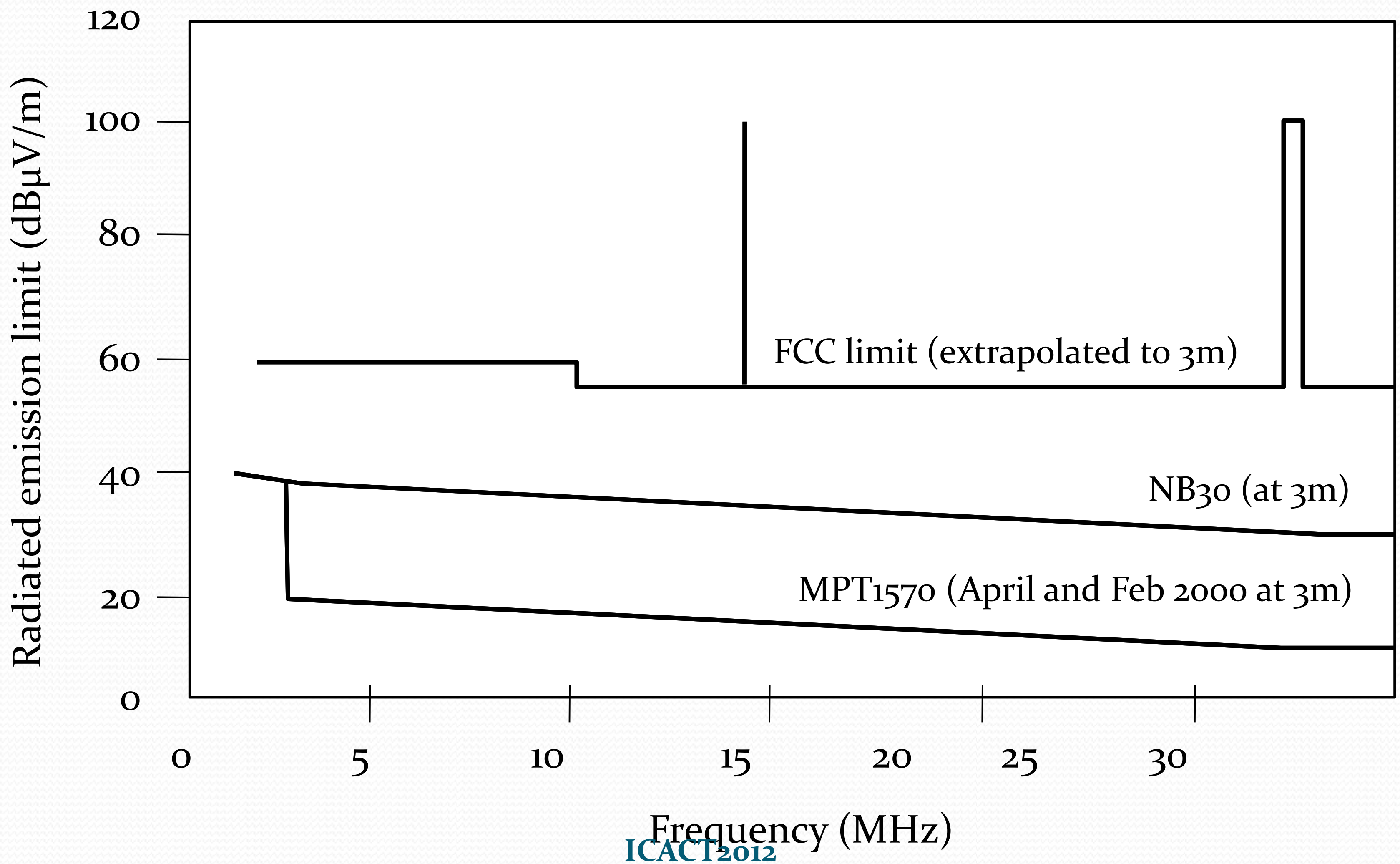
PLC Electromagnetic Susceptibility

- PLC system might be disturbed due to the following electromagnetic phenomena
  - Electrostatic charge
  - Fast transients (bursts) by switching activities
  - Surge due to lighting, etc
  - Radio frequency electromagnetic fields by mobile radios
- Special EMC protection circuit on the PLC system design might be needed

PLC Electromagnetic Compatibility

- EMC
  - Electromagnetic emission (EME)
    - Conducted emission (CE)
    - Radiated emission (RE)
  - Electromagnetic susceptibility (EMS)
    - Conducted susceptibility (CS)
    - Radiated susceptibility (RS)

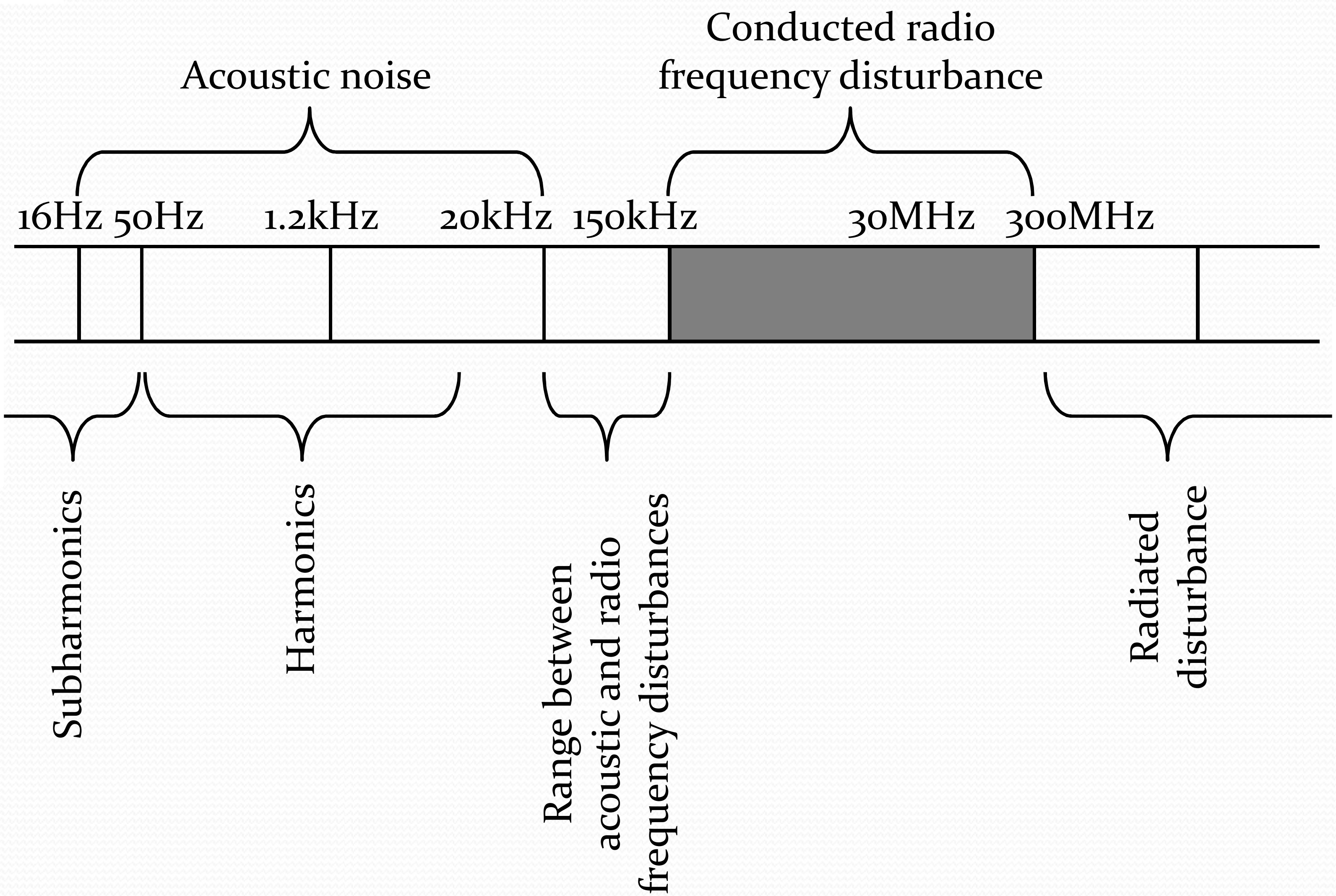
PLC radiation emission limits



Recommended E field strength for PLC according to FCC part15

Frequency band (MHz)	Radiated emission limit (μV/m) (peak)	Measured at (m)
1 – 1.705	15	47,715/frequency (kHz)
1.705 – 10	100	30
10 – 13.553	30	30
13.553 – 13.567	10,000	30
13.567 – 26.96	30	30
26.96 – 27.28	10,000(average)	3
27.28	30	30

Classification of EMC disturbances



Broadband PLC (BPLC) System Design

- Wideband (broadband) transmission techniques: OFDM, spread spectrum
- Forward error correction (FEC) & Mapping techniques
- Diversity Techniques: MIMO, MRC
- Efficient MAC layer design: TDMA, CSMA, CSMA/CA
- Cognitive Radio techniques: sensing EMI, etc

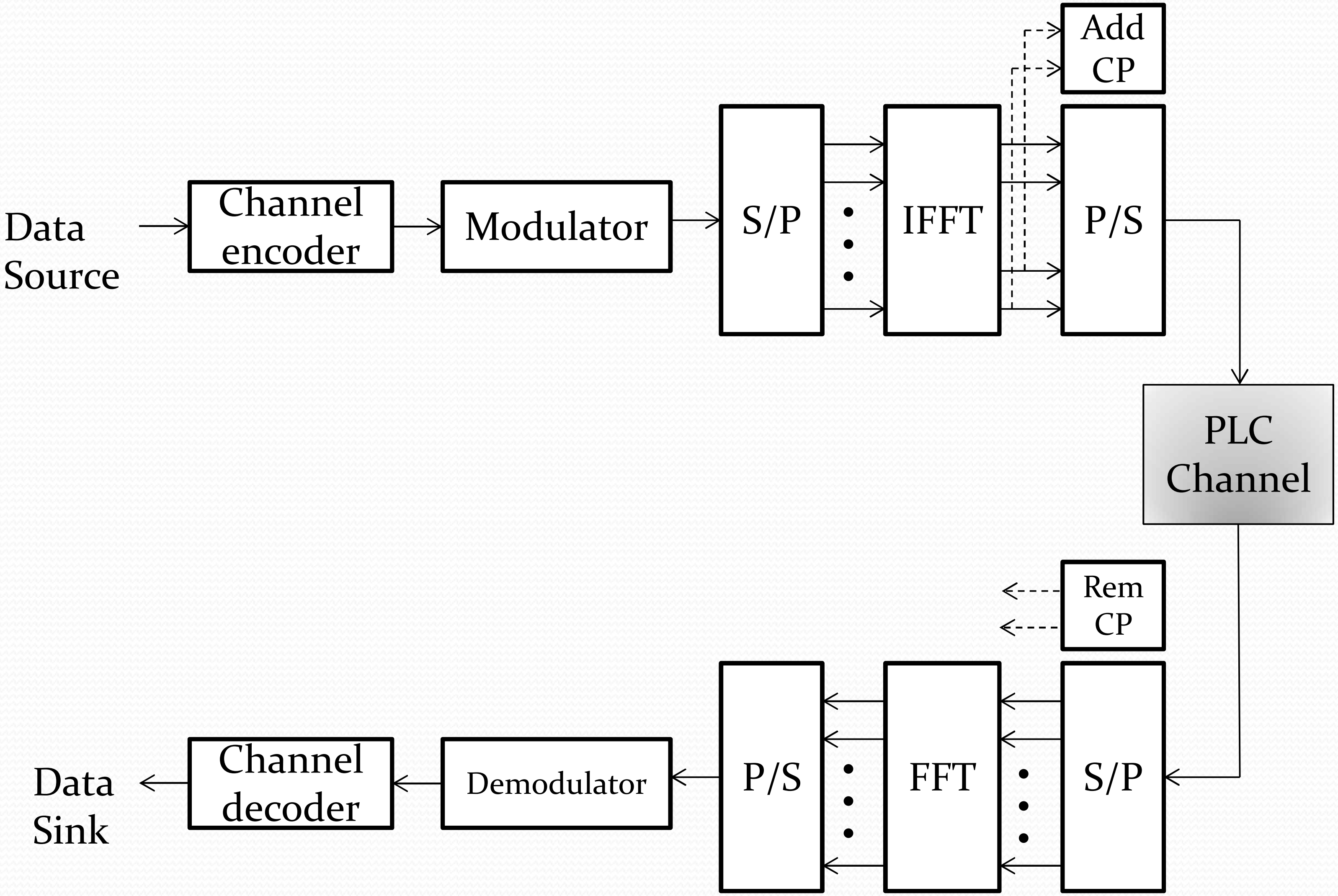
Wideband transmission schemes

- Wideband techniques to overcome nonlinear and time-varying fading channels
  - OFDM
    - Multicarrier techniques robust to ISI
    - High rate services via PLC channels
    - Optimum Bandwidth utilization
    - MIMO-OFDM further improves capacity & performance
  - Spread spectrum techniques
    - DSSS, FHSS
    - Low rate services via PLC channels
    - Low electromagnetic fields radiation: good for EMC

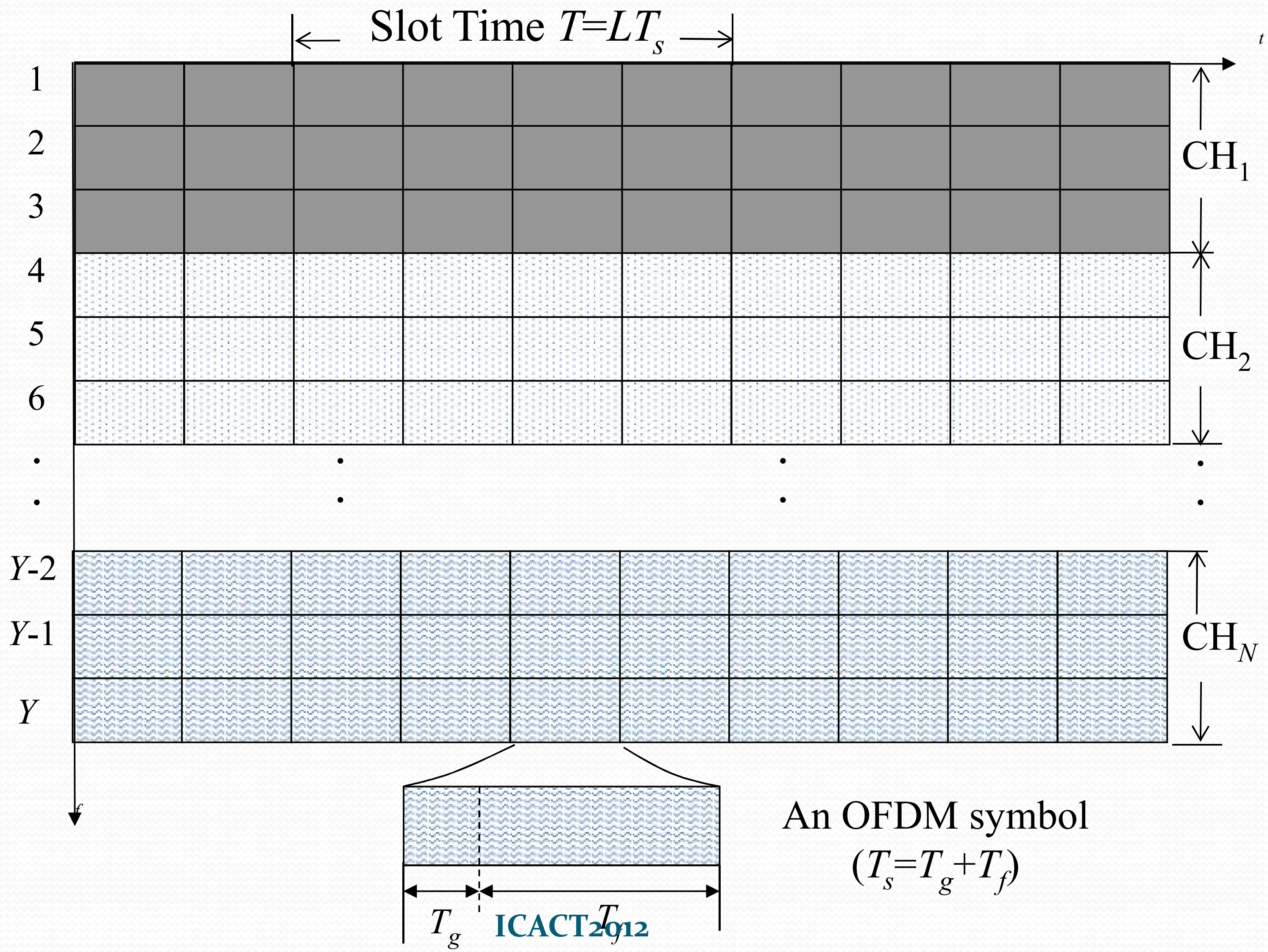
OFDM over PLC channel

- For a limited PLC channel spectrum, OFDM is a spectrally-efficient multicarrier modulation: Δf (subcarrier spacing) = 1/T(symbol time)
- Robust to PLC frequency selective fading (N: #subcarriers)
  - N times longer symbol period (by N parallel channels) releases ISI problem
  - Cyclic prefix (CP) cancels out ISI and ICI as well
- Allows flexible frequency allocation considering EMC and fading notches occurred to PLC channels
- Therefore, OFDM is well fitted to PLC channel environments

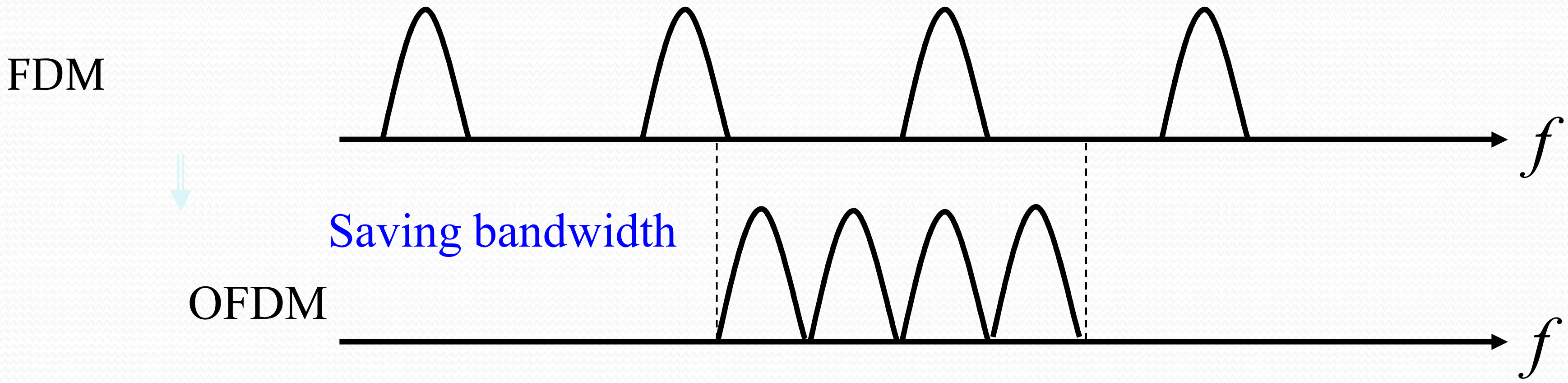
OFDM System Block Diagram



Cluster based Channel Allocation



Orthogonal Frequency Division Multiplexing (OFDM)

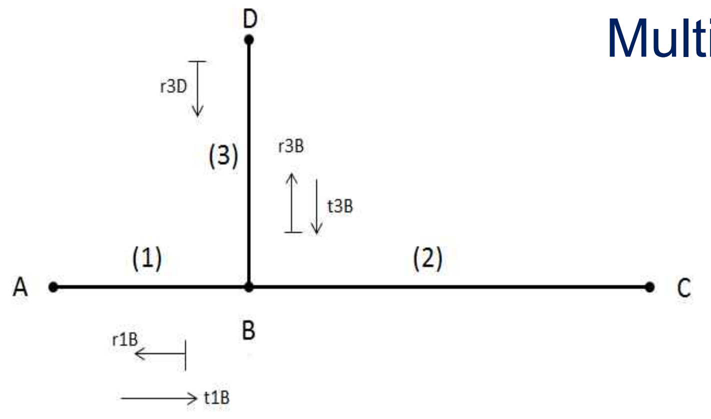


- Improved spectral efficiency using orthogonality condition

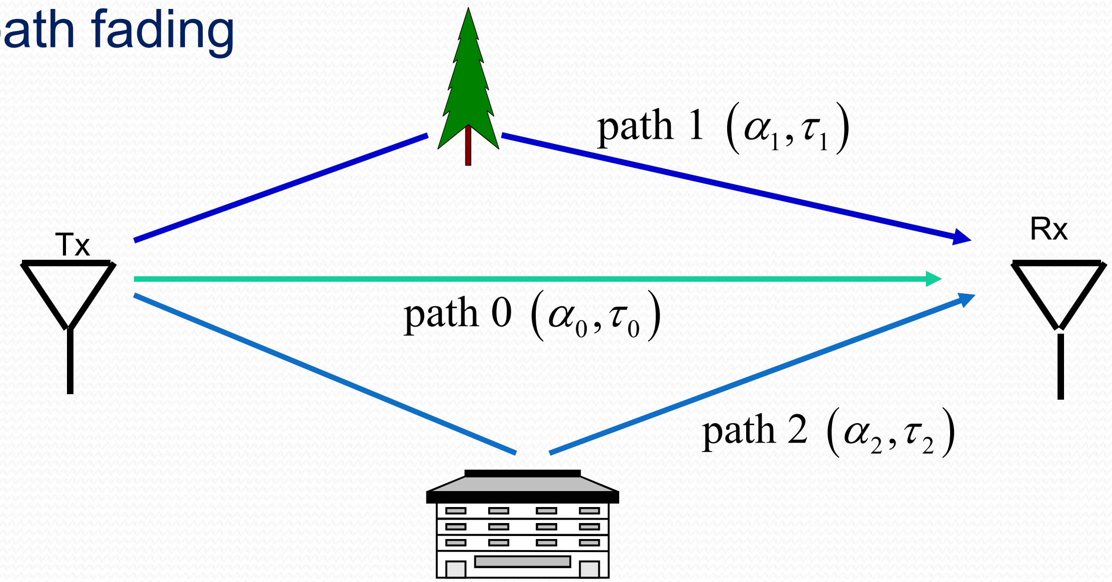
$$\Delta f = \frac{1}{T}$$

- OFDM Modem
  - Modulation IFFT $$s_n = \sum_{k=0}^{N-1} S_k e^{\frac{j2\pi kn}{N}} = \mathrm{IFFT}\{S_k\}$$
  - Demodulation FFT $$S_k = \sum_{k=0}^{N-1} s_n e^{-\frac{j2\pi kn}{N}} = \mathrm{FFT}\{s_n\}$$

OFDM is robust to multipath fading due to its longer symbol time T compared to delay spread Δ (when using CP, remove ISI completely)



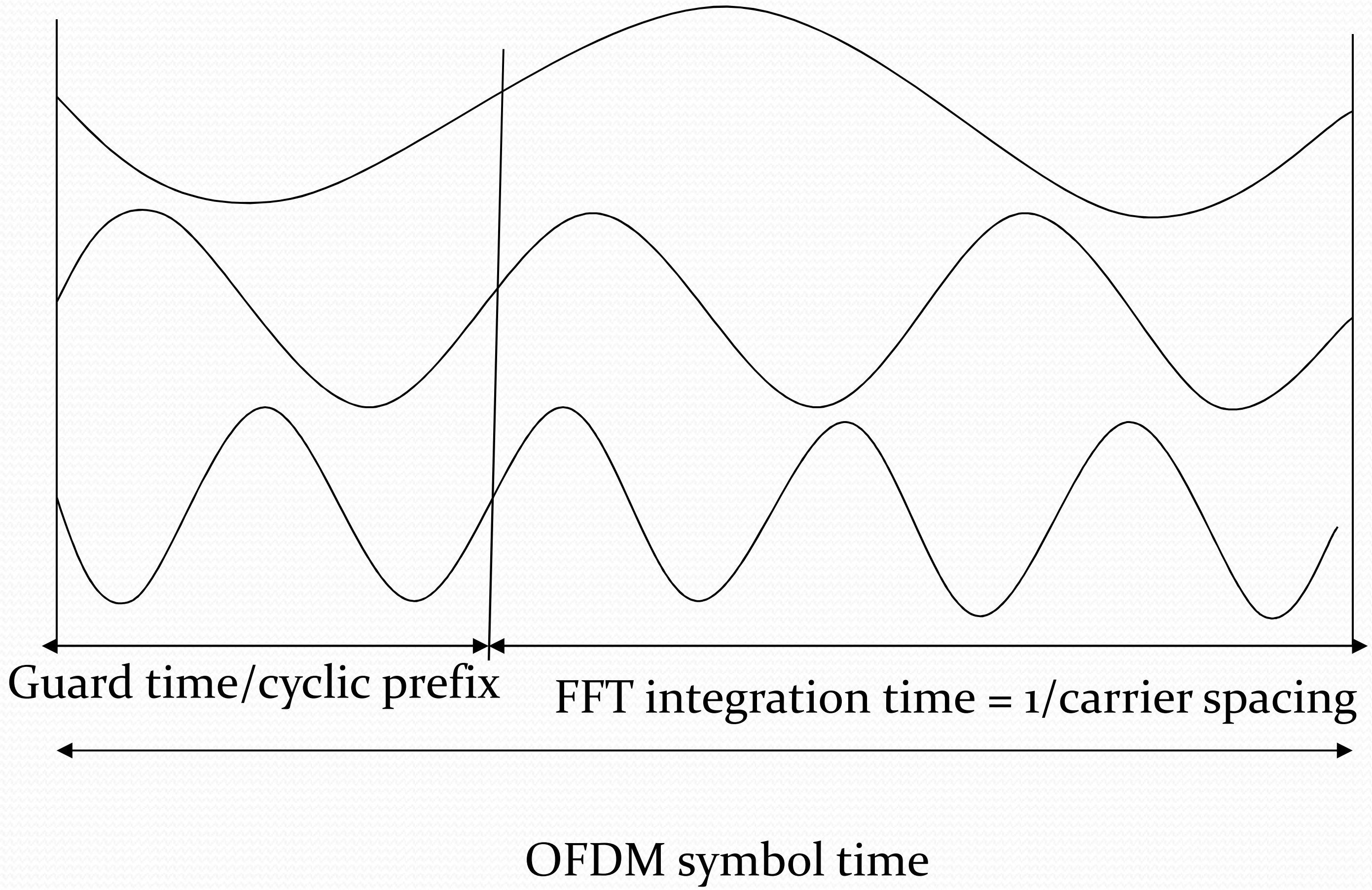
Multipath fading



$$h(t) = \sum_{k=0}^{L-1} \alpha_k \delta(t - \tau_k)$$

$$\Delta = \tau_k - \tau_0$$

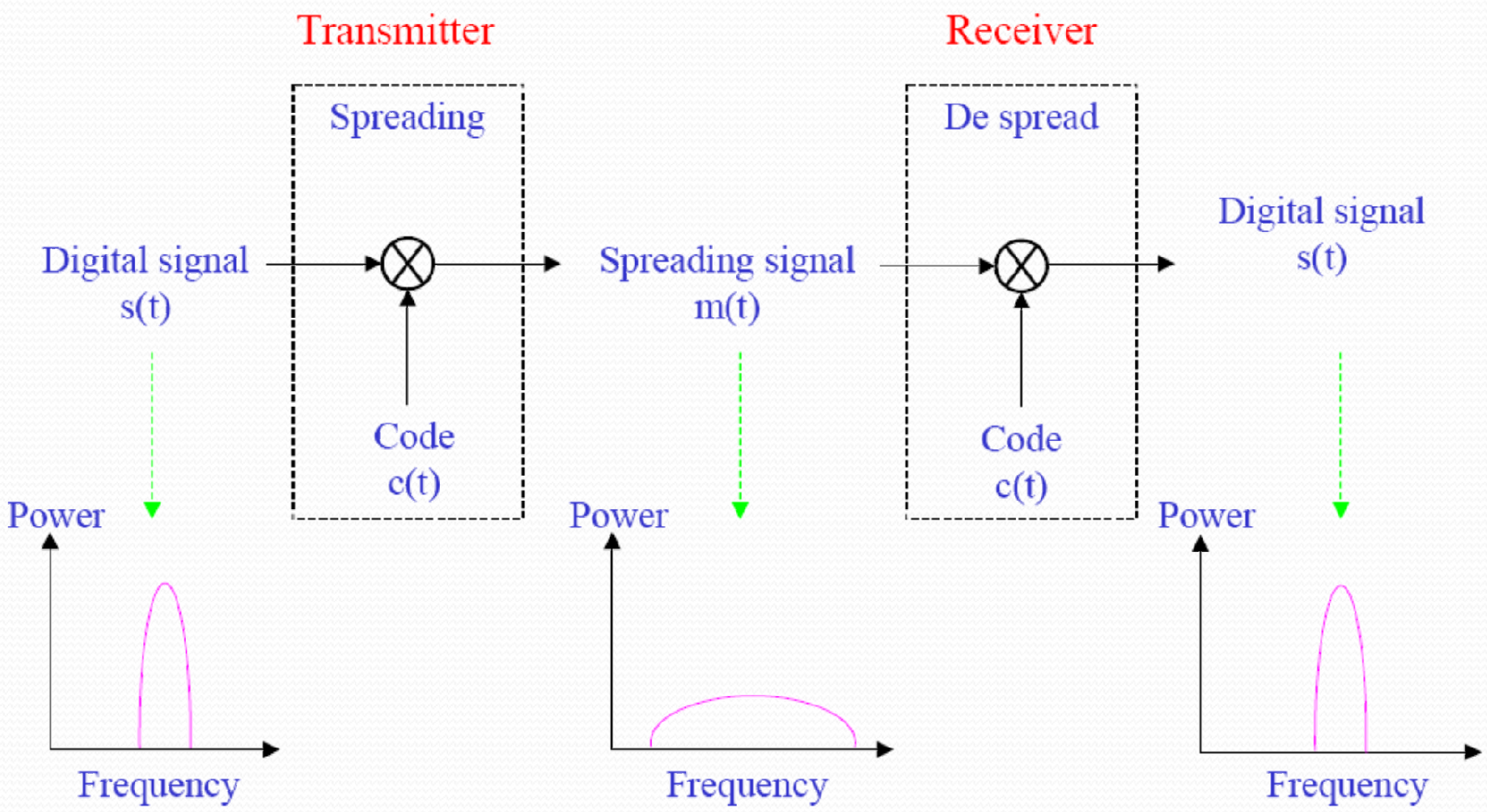
OFDM Symbol w/Cyclic Extension



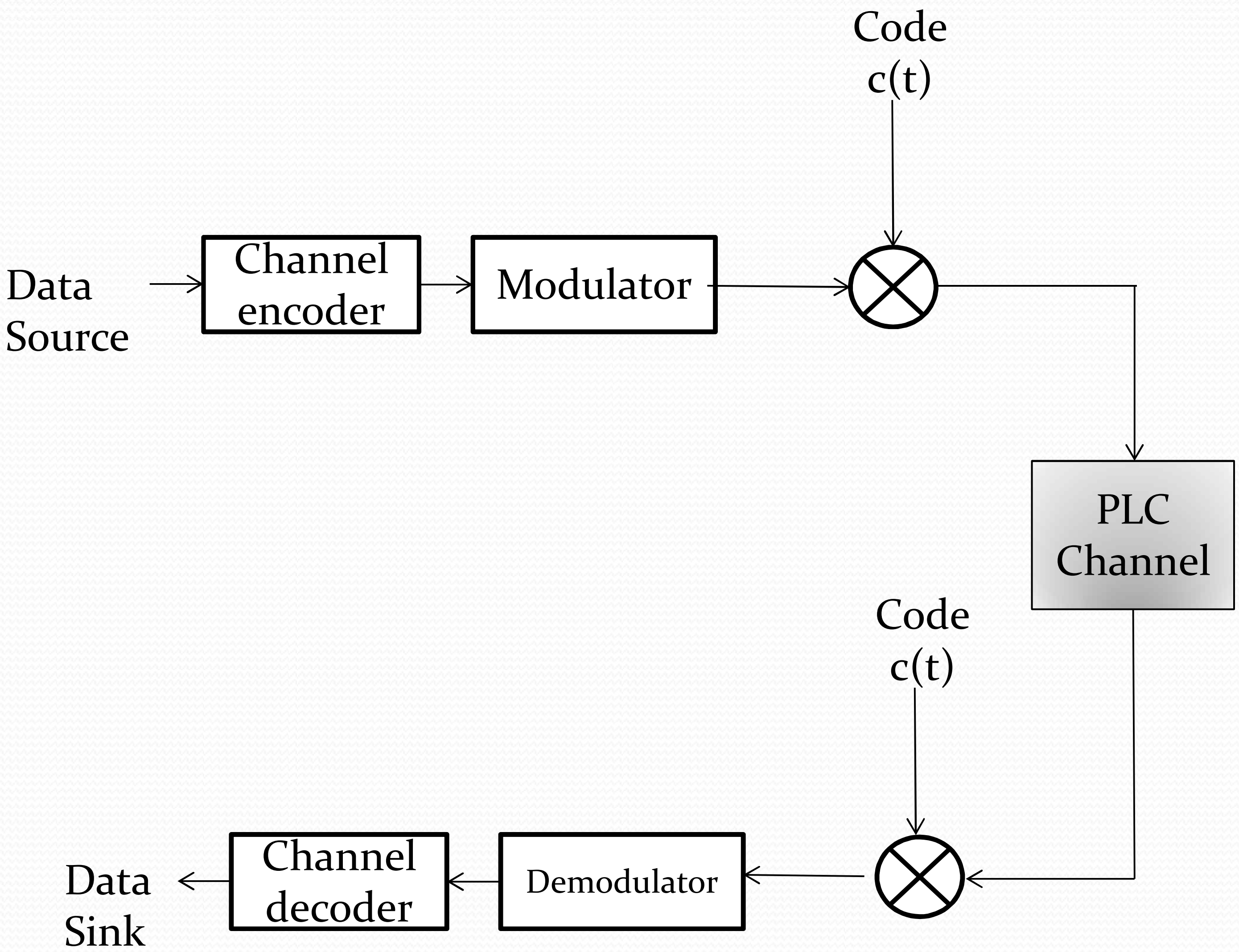
Spread spectrum systems

- Spread spectrum schemes
  - Direct-sequence spread spectrum (DSSS) systems
  - Frequency hopping spread spectrum (FHSS) systems
- Good for hostile channel environments like PLC
  - Processing Gain: G = W/B
  - Low spectral density (reduced EM radiation)
- Relatively lower data capacity compared to OFDM

DSSS systems



Spread Spectrum System Block Diagram



Channel Coding and Signal Mapping

- Channel Coding
  - Block Codes
  - Convolutional Codes
  - Turbo codes / LDPC codes [Ande10]
- Signal Mapping and Interleaving
  - Signal Mapping
    - QPSK/16QAM/64QAM
  - Interleaving: burst error due to deep fading to random error

PLC performance using LDPC Code [Ande10]

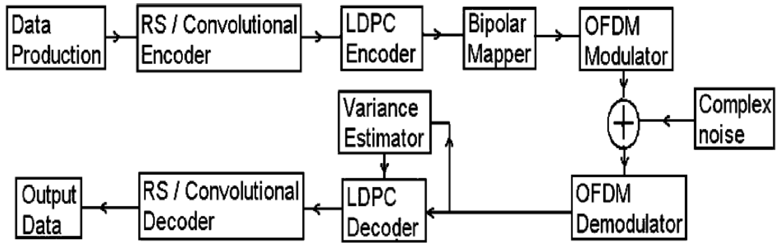


Fig. 9. System's block diagram with QC–LDPC codes as the inner coding scheme.

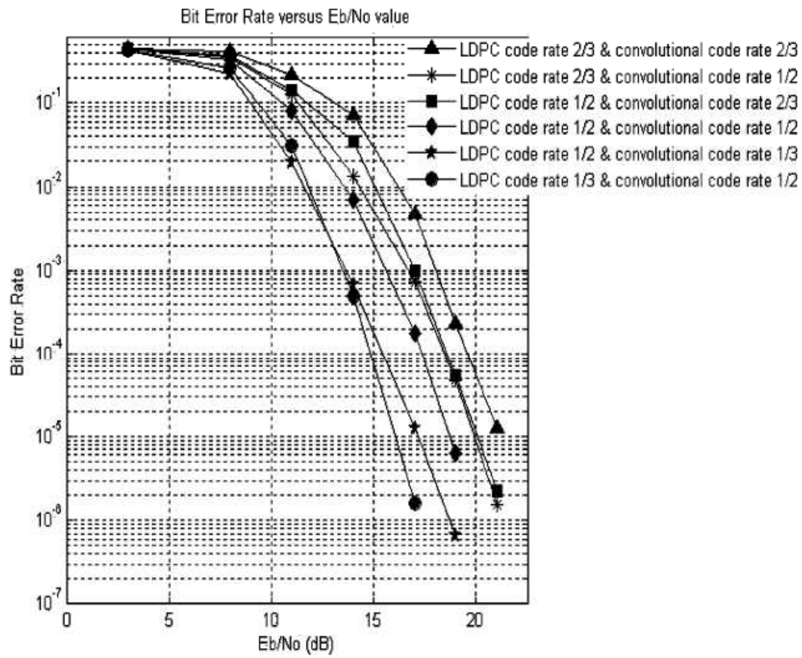


Fig. 8. BER versus E_b/N_0 for QC–LDPC and convolutional codes of various code rates, with LDPC as the outer decoding scheme.

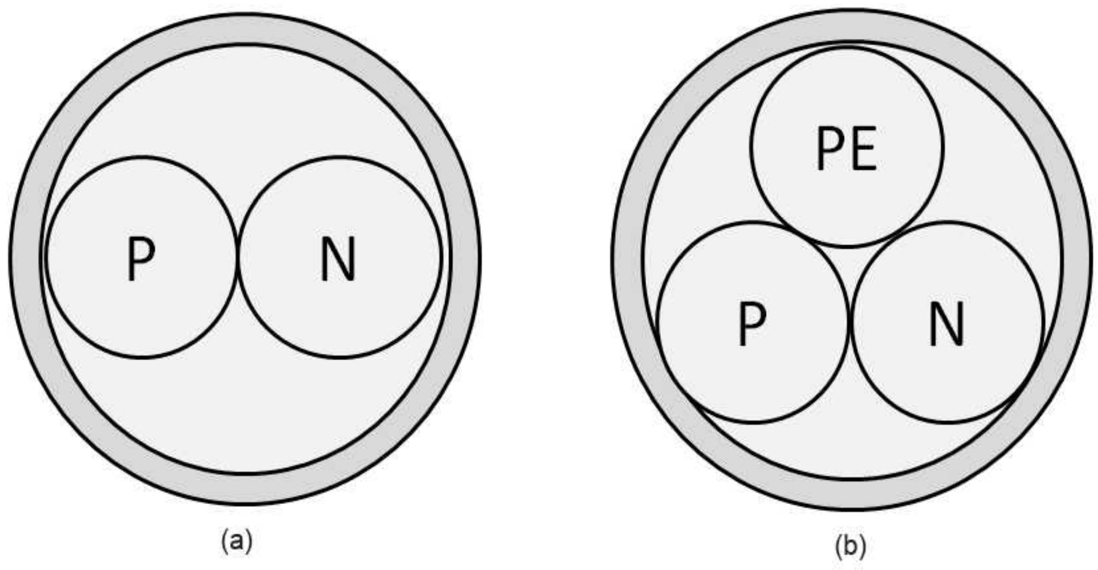
Spatial Diversity Techniques

- MIMO is a well-known spatial diversity technique using multiple transmit and receive antennas
- It is applicable to PLC by substituting transmit and receive antennas with signal feed and receive ports as well as the wireless channel with the existing electrical wiring
- By the spatial diversity gain, PLC system data capacity or performance is improved

MIMO PLC Techniques

- The number of transmit and receive antennas (I, J) are typically limited. It depends on the type of power line cables. Typically, I is equal to J.
- Generally, a power line cable with M wires (conductors) can form up to maximum (M-1) antenna paths
  - 1-phase 2-wires: SISO
  - 1-phase 3-wires: 2x2 MIMO
  - 3-phase 4-wires: 2x2 or 3x3 MIMO

- Indoor 1-phase power cables



Legend:
P: phase
N: Neutral
PE: Protective Earth

Cross section of typical household mains cable
(a) two conductors (b) three conductors

2X2 MIMO

$$H_{(MIMO)} = \begin{bmatrix} H_{1,1} & H_{1,2} \\ H_{2,1} & H_{2,2} \end{bmatrix}$$

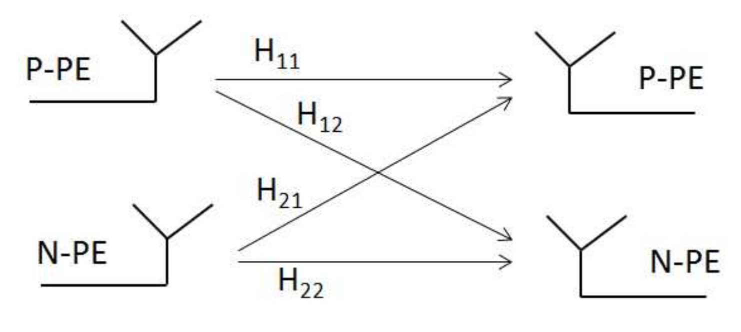


Figure : 2 x 2 MIMO Systems

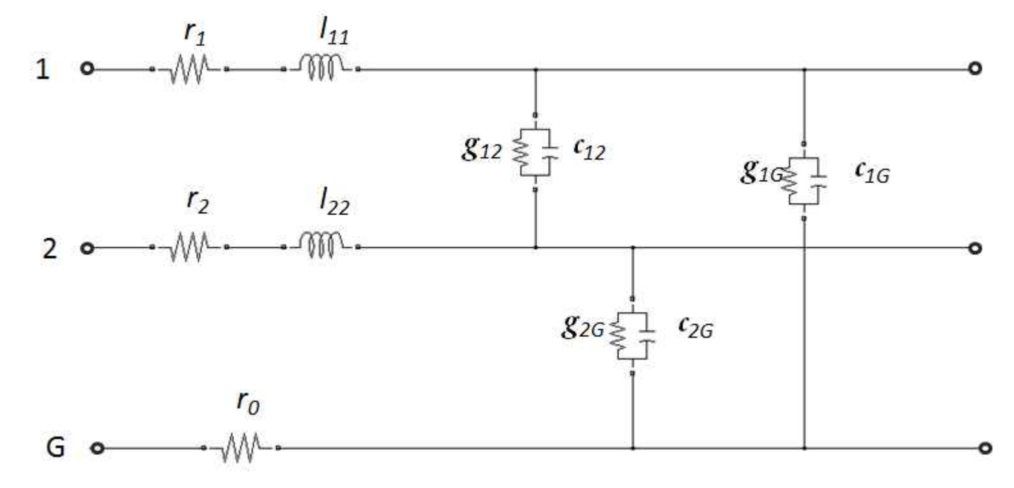


Figure : Equivalent per unit length representation of one-phase three-conductors line

- Outdoor 3-phase power cables

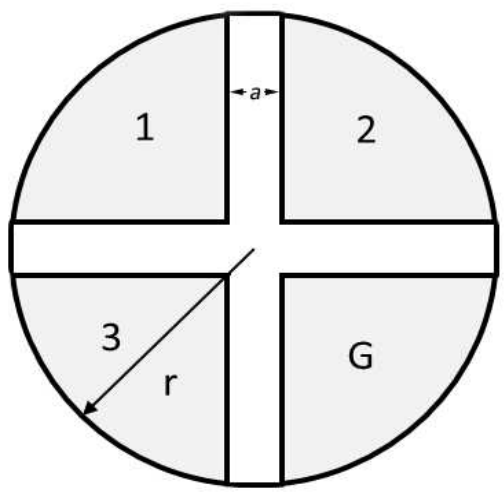


Figure : Cross section of a typical underground power-line cable

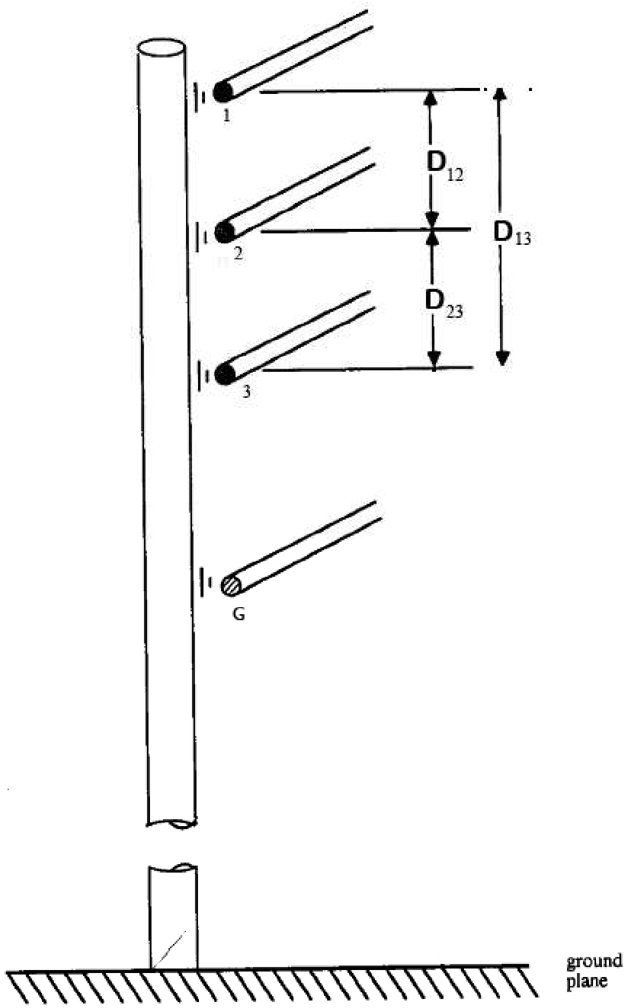


Figure: Spacing of Conductors on Overhead Power Lines

3x3 MIMO

$$H_{(MIMO)} = \begin{bmatrix} H_{1,1} & H_{1,2} & H_{1,3} \\ H_{2,1} & H_{2,2} & H_{2,3} \\ H_{3,1} & H_{3,2} & H_{3,3} \end{bmatrix}$$

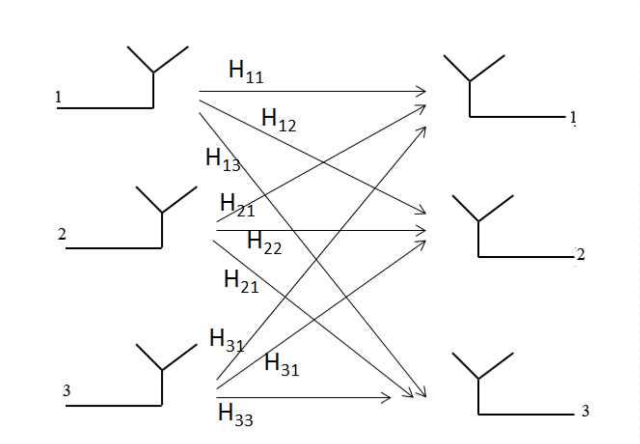


Figure : 3 x 3 MIMO Systems

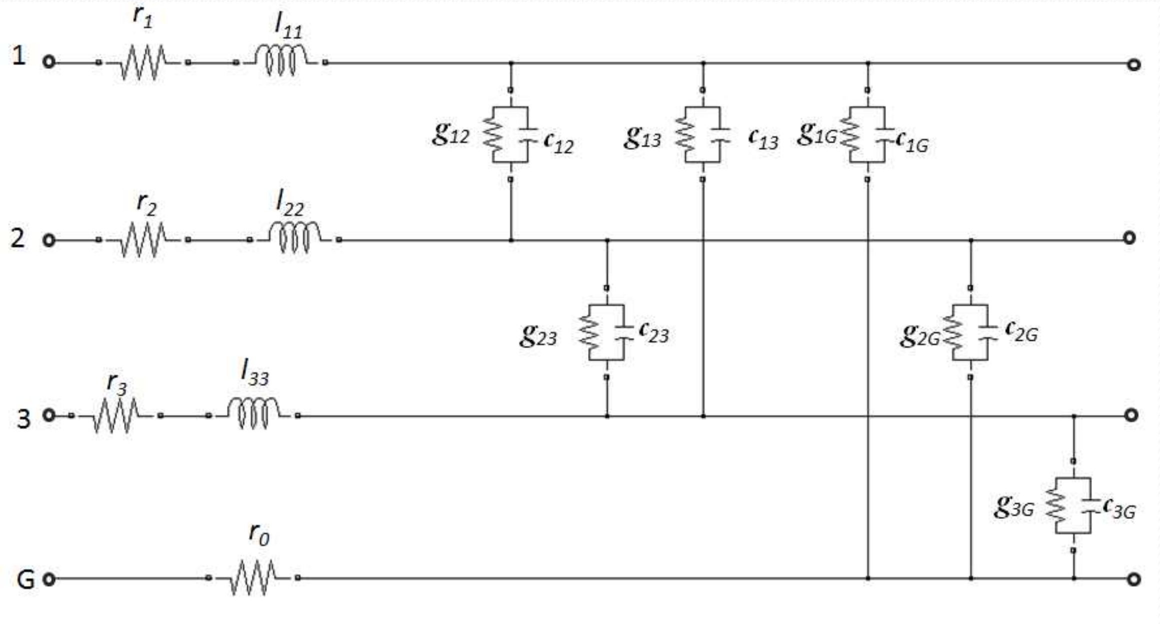


Figure : Equivalent per unit length representation of three-phase four-conductors line

MIMO PLC Techniques

- The number of transmit and receive antennas (I, J) are typically limited. It depends on the type of power line cables. Typically, I is equal to J.
- Generally, a power line cable with M wires (conductors) can form up to maximum (M-1) antenna paths
  - 1-phase 2-wires: SISO
  - 1-phase 3-wires: 2x2 MIMO
  - 3-phase 4-wires: 2x2 or 3x3 MIMO

Diversity Signal Combining Techniques

- Maximum Ratio Combing (Assuming *L* paths, PSK modulation, perfect channel estimation)

$$r_m = \alpha_m s + \eta_m$$

$$\hat{s} = \arg\min_s \sum_{m=1}^{L} \left| r_m - s\alpha_m \right|^2 = \arg\min_s \left| \sum_{m=1}^{L} r_m \alpha_m^* - s \right|^2$$

$$m\text{th SNR: } \gamma_m = \frac{\left|\alpha_m\right|^2 E_s}{N_0}, \text{output SNR: } \gamma = \sum_{m=1}^{L} \gamma_m; \text{avg output SNR: } \bar{\gamma} = LE[\gamma_m]$$

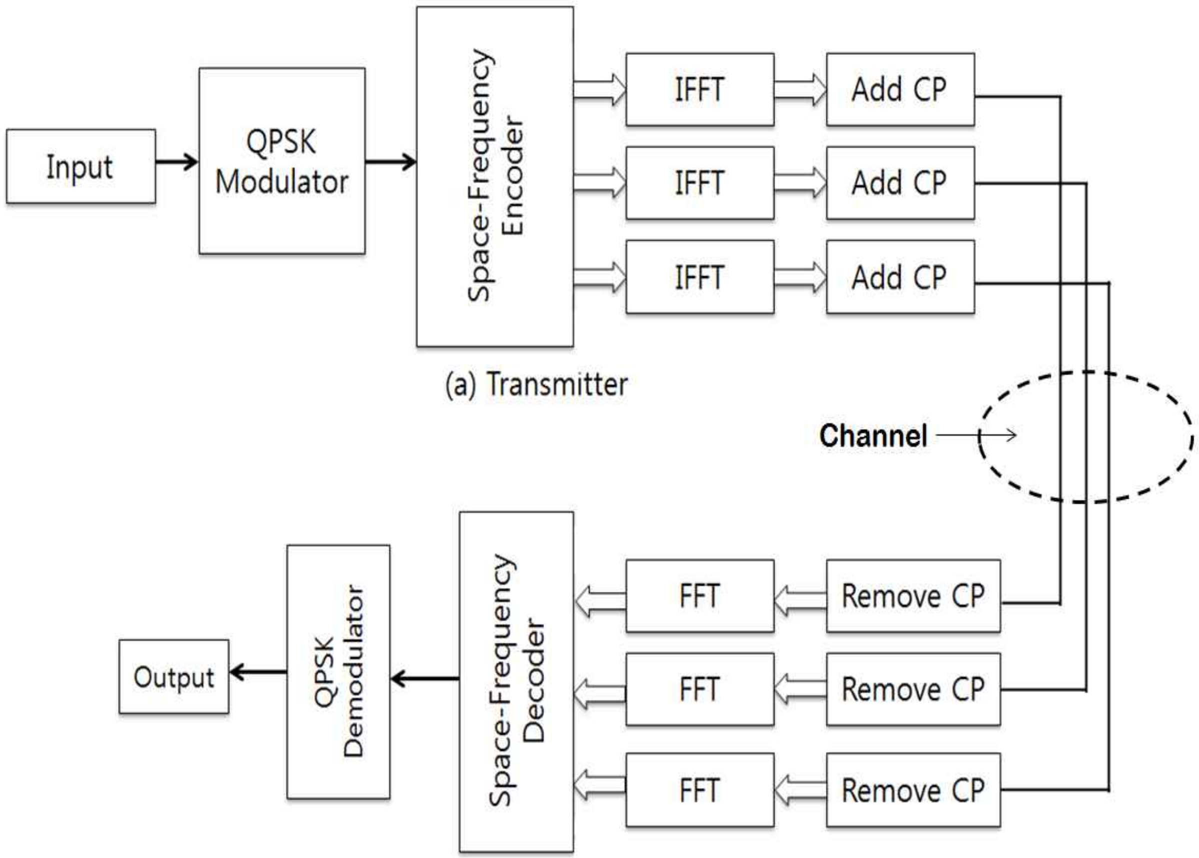
- Equal Gain Combing

$$\bar{\gamma} = \left[1 + \frac{\pi}{4}(L-1)\right] E[\gamma_m]$$

- Selection Combing

$$\bar{\gamma} = E[\gamma_m] \sum_{m=1}^{L} \frac{1}{m}$$

MIMO-OFDM BPLC



MIMO channel capacity

- Assuming nxn MIMO channels
  - $\mathbf{H}_n$ is the overall nxn channel transfer function
  - **U** is the nxn identity matrix (γ: signal-to-noise ratio)

$$C_{(MIMO)} = \log_2\left[\det\left(\mathbf{U} + \mathbf{H}_n\mathbf{H}_n^H \frac{\gamma}{n}\right)\right]$$

$$C_{(SISO)} = \log_2\left[1 + \gamma\,|\,\mathbf{H}\,|^2\right]$$

SISO/MIMO Capacity

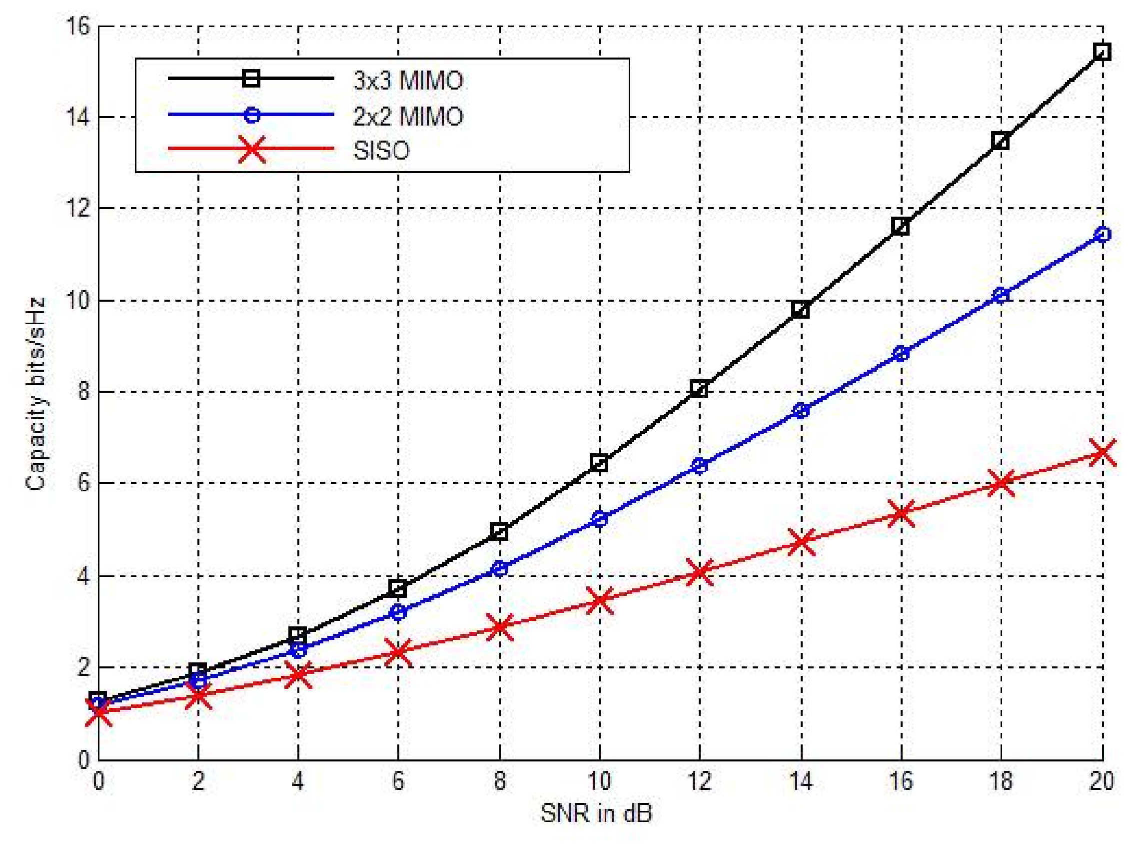


Figure : SISO and MIMO channel capacity

SISO/MIMO Capacity considering cross-talk

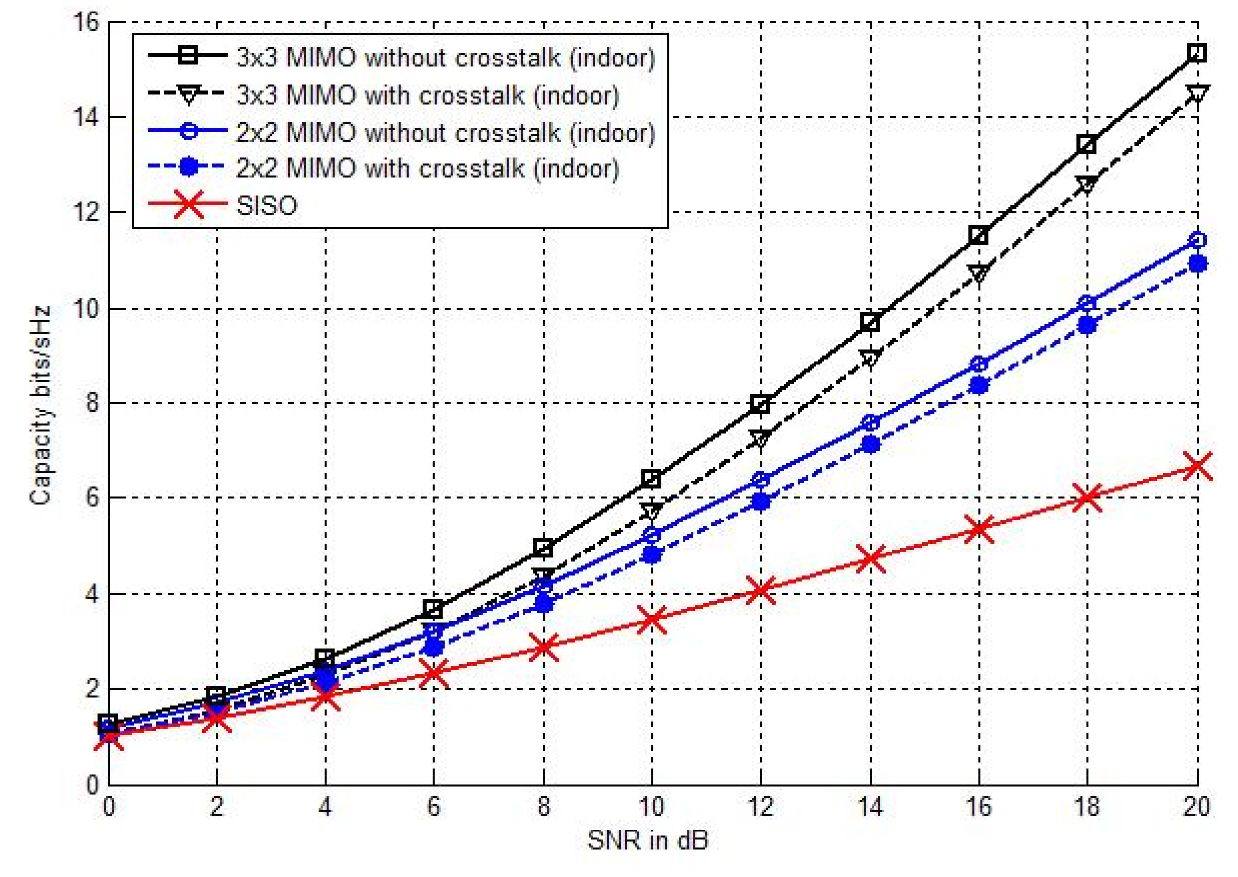


Figure : Channel capacity analysis for indoor cases which consider crosstalk

SISO-/MIMO-OFDM BER performance

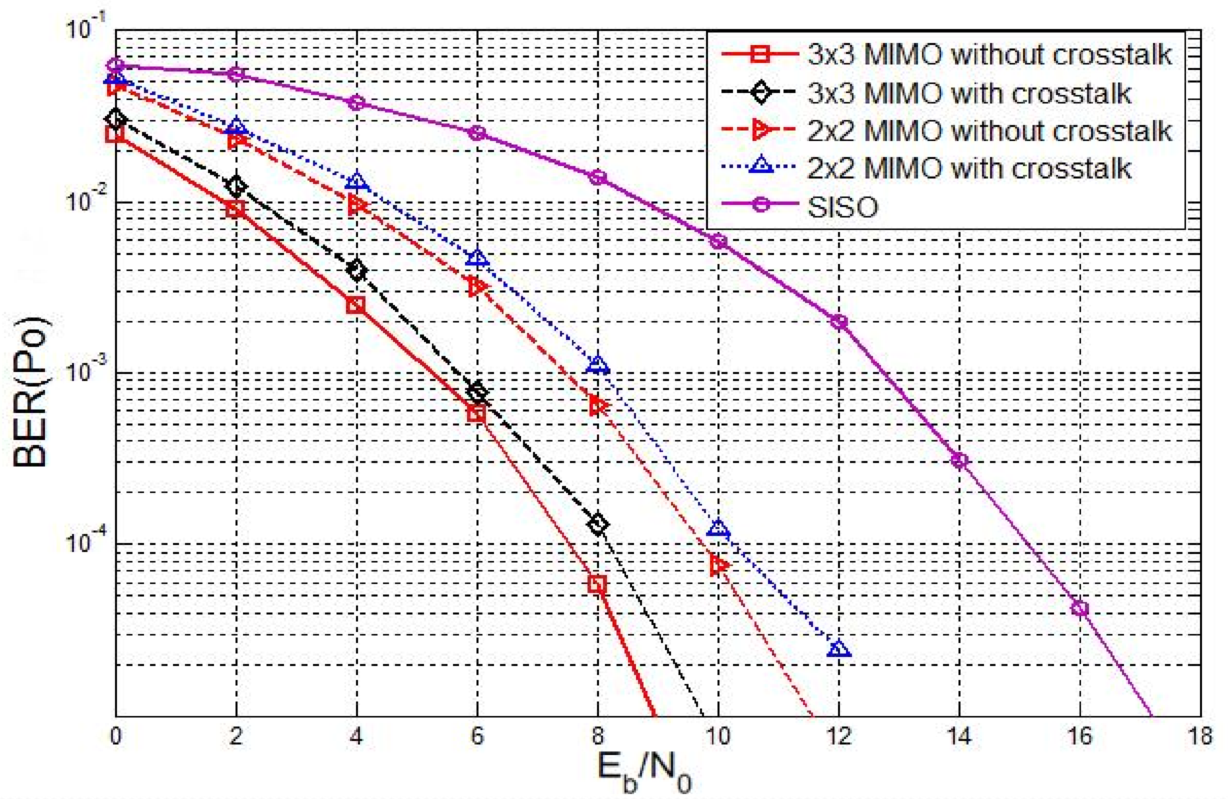
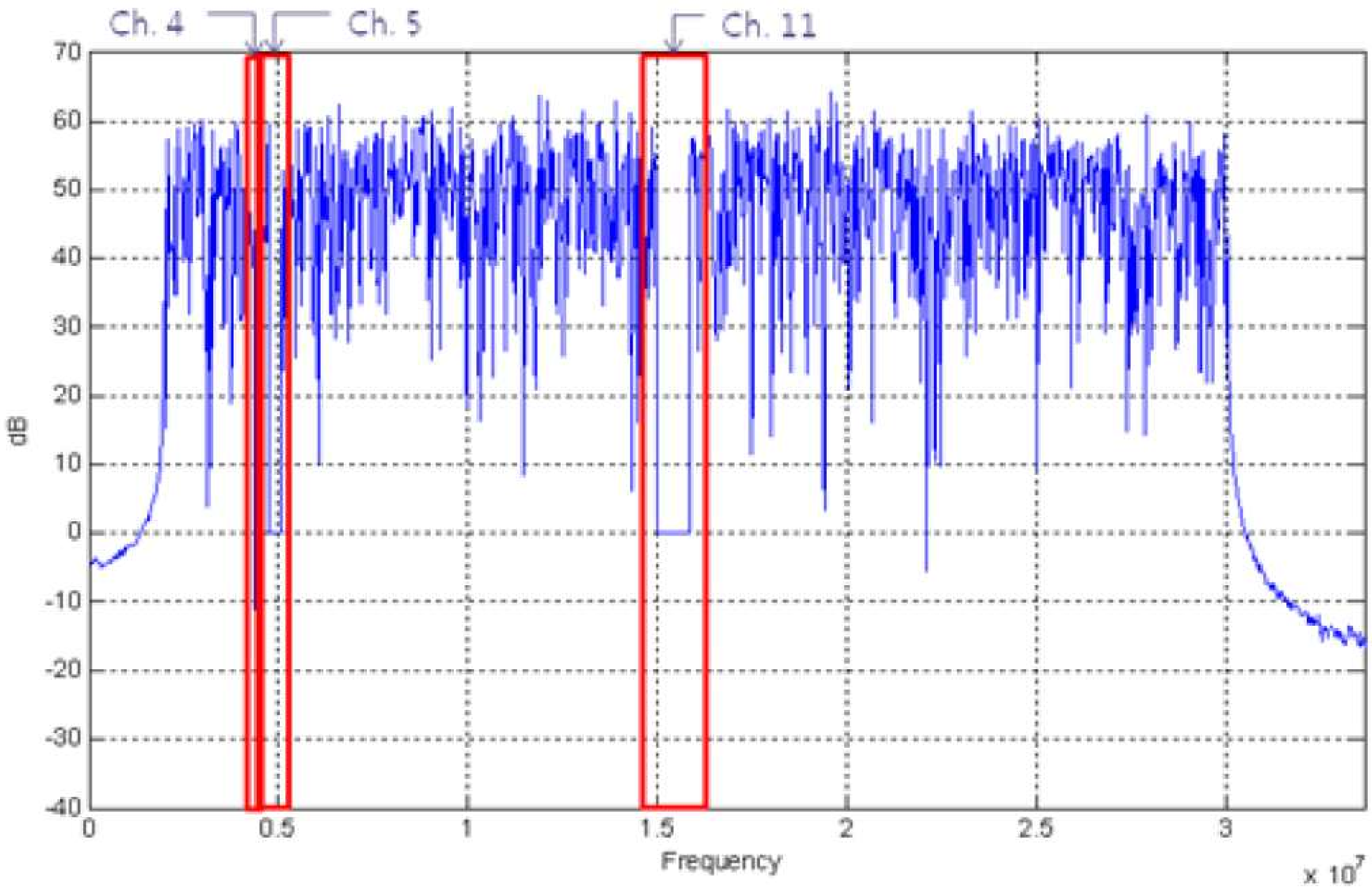


Figure : BER Performance comparison of SISO/MIMO with and without crosstalk

PLC channel spectrum and cognitive BPLC

- PLC channel spectrum is practically limited less than 100MHz.
- Within that channel, there exist several (or many) primary users (PUs: HF radio, HAM, etc). This PU spectrum should be protected — "EMC notches" are needed
- However, those PUs' are often inactive (spectrum utilization ratio is less than 10%, FCC report) and varied spatially and temporally
- Then what about applying cognitive radio (CR) concept to PLC to improve its spectrum efficieny?

EMC Notches

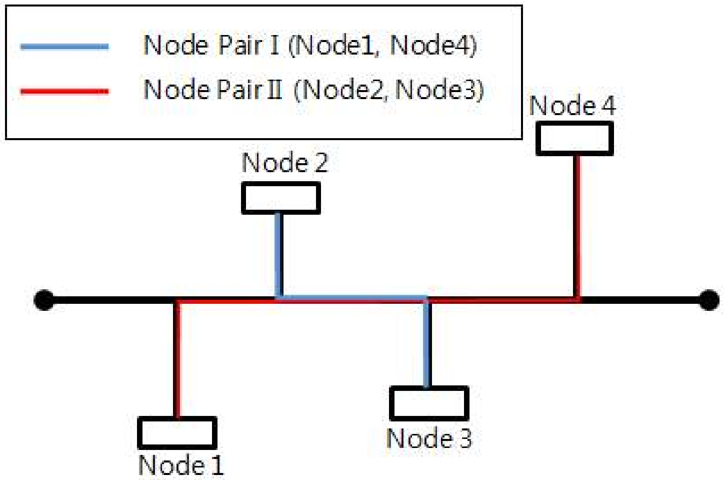


Ch. 4
Ch. 5
Ch. 11
70
60
50
40
30
20
10
0
-10
-20
-30
-40
dB
0
0.5
1
1.5
2
2.5
3
Frequency
x 10^7

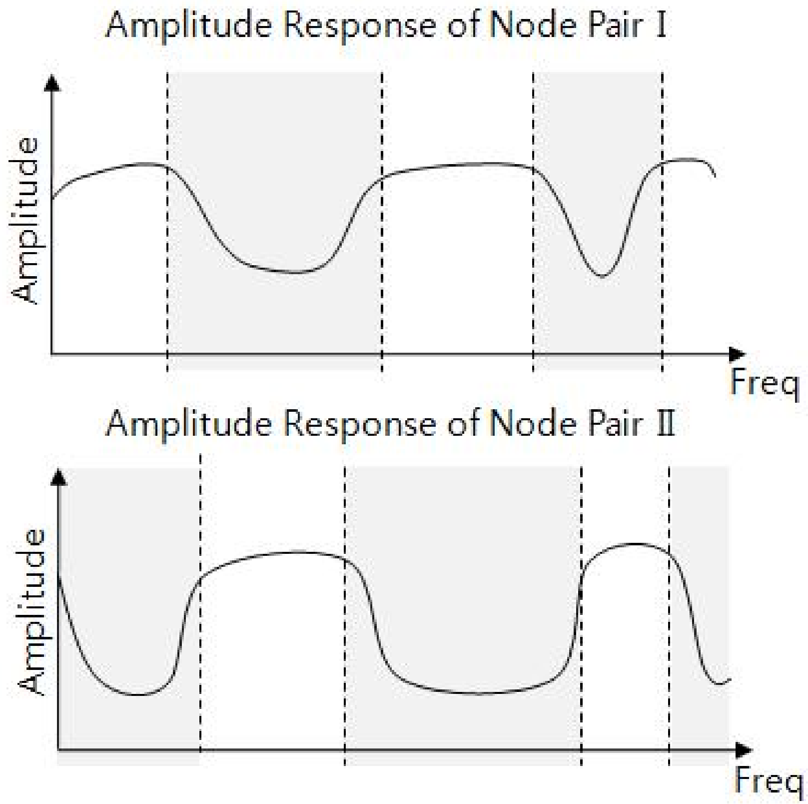
PLC channel spectrum

- Due to multipath fading, there exists several notches within the spectrum. Its characteristic is different depending on the link topology (i.e., node-to-node link configuration, see next slide figure)
- But the PLC multipath channel is (time-varying but) **quasi-stationary** since the link configuration (including taps along the cable) of each node with no mobility is seldom changed — Zimmermann's model
- Cognitive node can easily sense (estimate) (e.g., pilot symbol grids based channel estimator) its frequency channel notches as well—simply called "fading notches"

Cognitive BPLC

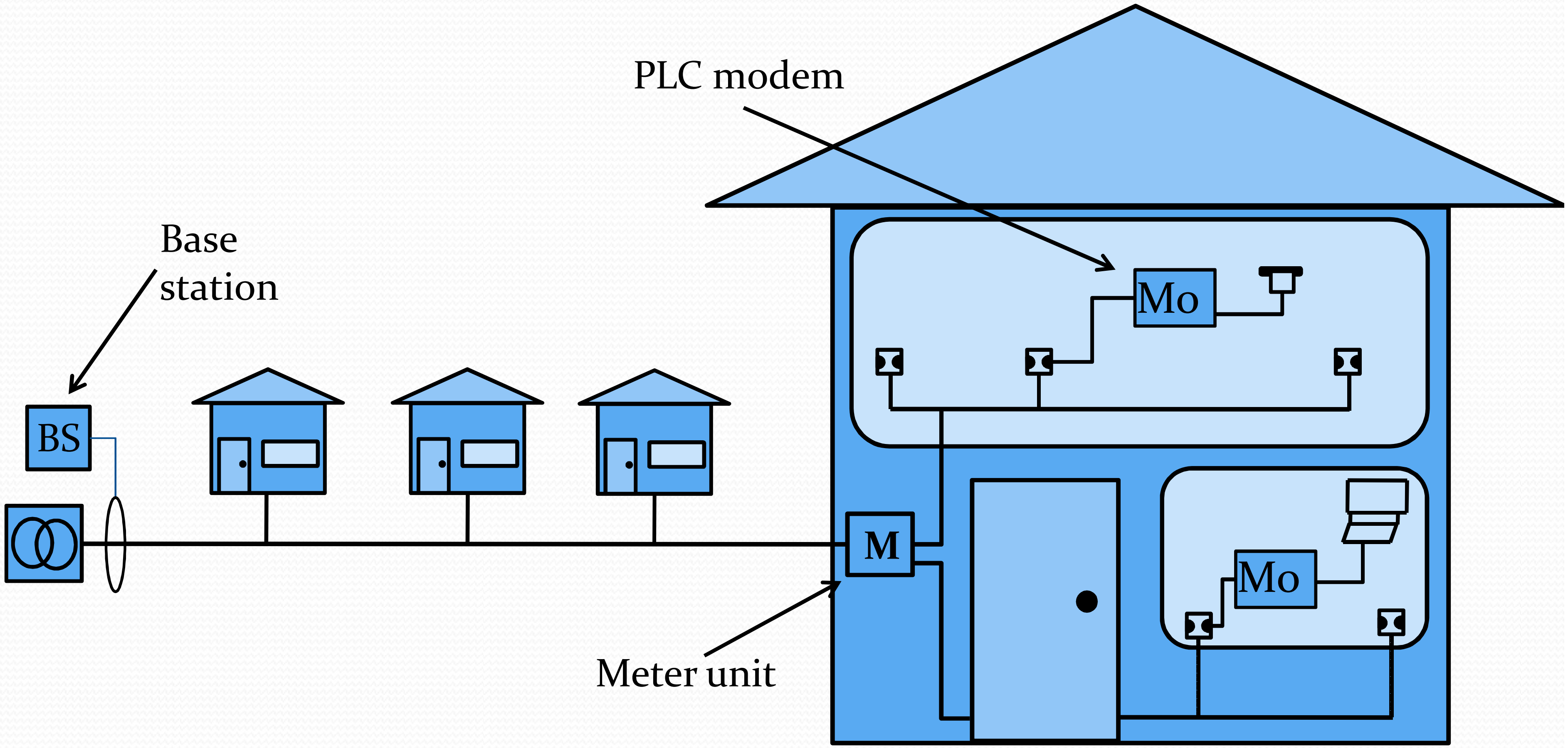


Power line network



Transfer function

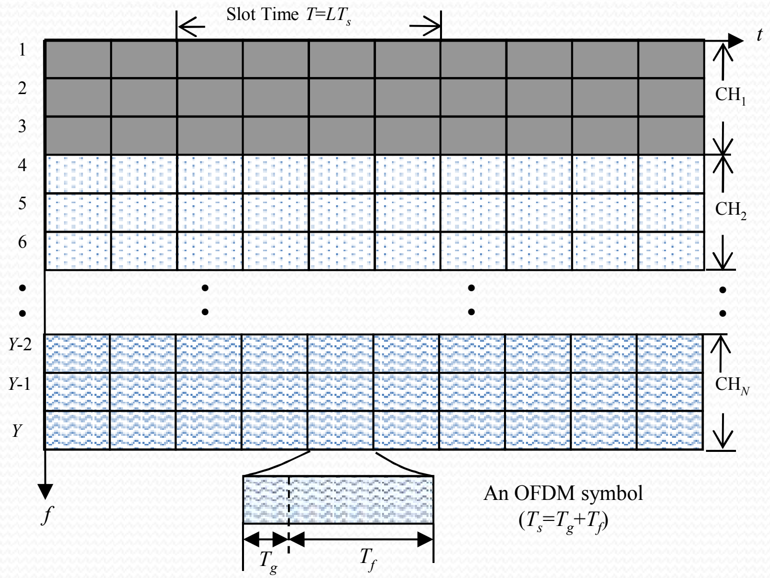
Cognitive BPLC LAN

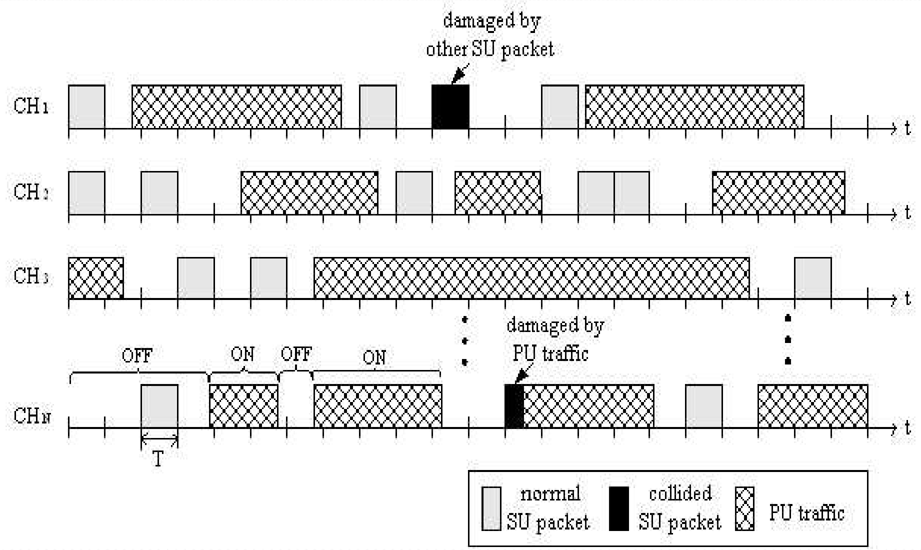


Cognitive BPLC LAN

- Cognitive BPLC node (SU) can sense PUs' activity to exploit their idle spectrum (white space)
- From its managing CB nodes, BS collects all the quasi-stationary channel state information (CSI) including the sensed EMC notches and fading notches
- Based on CSI, BS may allocate an optimum OFDM channel (one or several OFDM clusters) to each CB node depending on its link topology
- BS may do channel scheduling as well—Then what about PAPR?
- Prior to this channel allocation, using a proper PAPR reduction method (e.g., tone reservation method), BS can release the PAPR issue of each user to improve power amplifier efficiency.
- Opportunistic OFDM channel access is allowable

Opportunistic channel Access





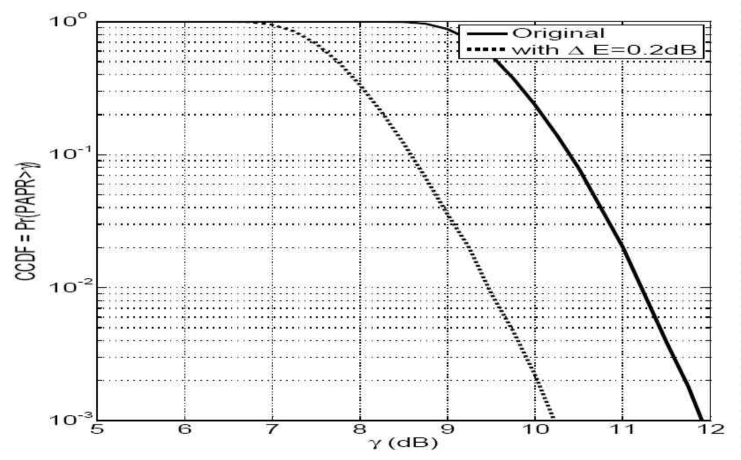
PAPR

- PAPR Reduction
  - Peak clipping
  - Tone Reservation method
  - Selective mapping
  - PTS
  - Algebraic Coding

$$\xi = \frac{\max_{t \in [0, T_s)} |s(t)|^2}{P_{av}}, P_{av} = E\left\{\overline{P}\right\} (= \sum_{n=0}^{N-1} |s_n|^2)$$

Multicarrier based CR system

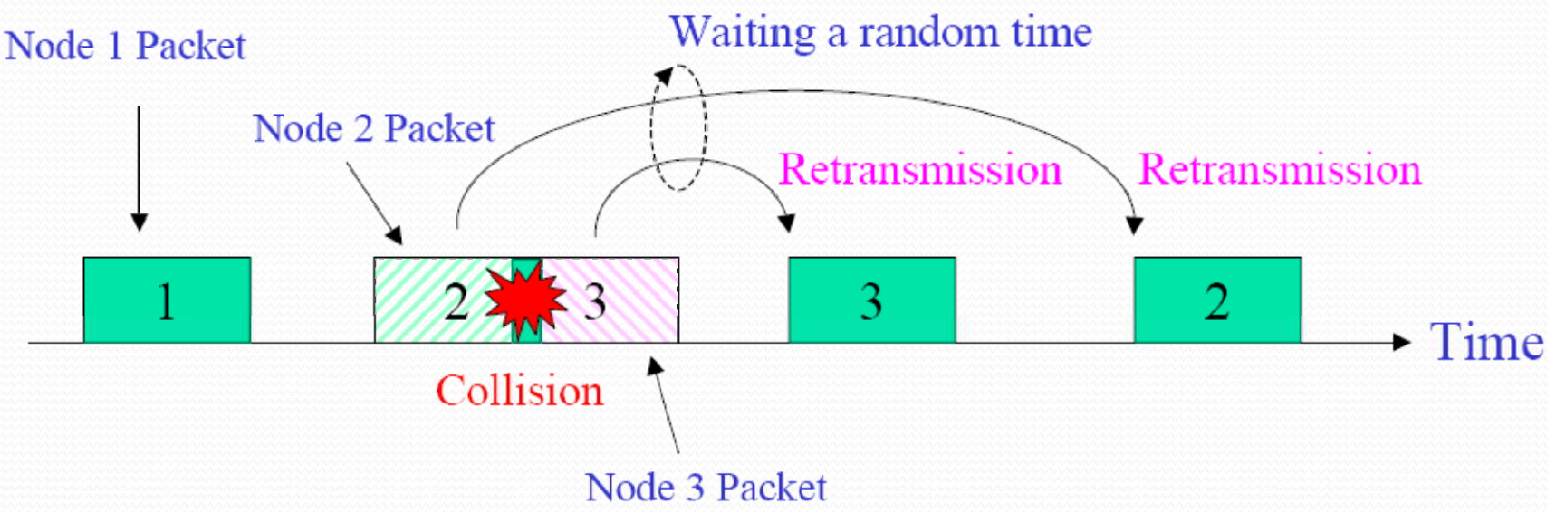
- Tone Reservation based PAPR reduction
  - Video broadcasting
  - Multicarrier based next generation CR system (below figure [Y. Louet]



Resource sharing strategies

- Access protocols (MAC protocols) of multiple subscribers using the same and shared network resources
  - ALOHA
  - Slotted ALOHA
  - CSMA
  - CSMA/CD
  - CSMA/CA

ALOHA



Collision mechanism in ALOHA

ALOHA

- Offered load (packets per packet time T) $G=gT$ where g is arrival rate
- Poisson Distribution w/mean a (= gt)

$$\Pr[k] = \frac{a^k e^{-a}}{k!}$$

- No Collision Probability for Guard Time 2T (=vulnerable period)

$$a = 2gT$$

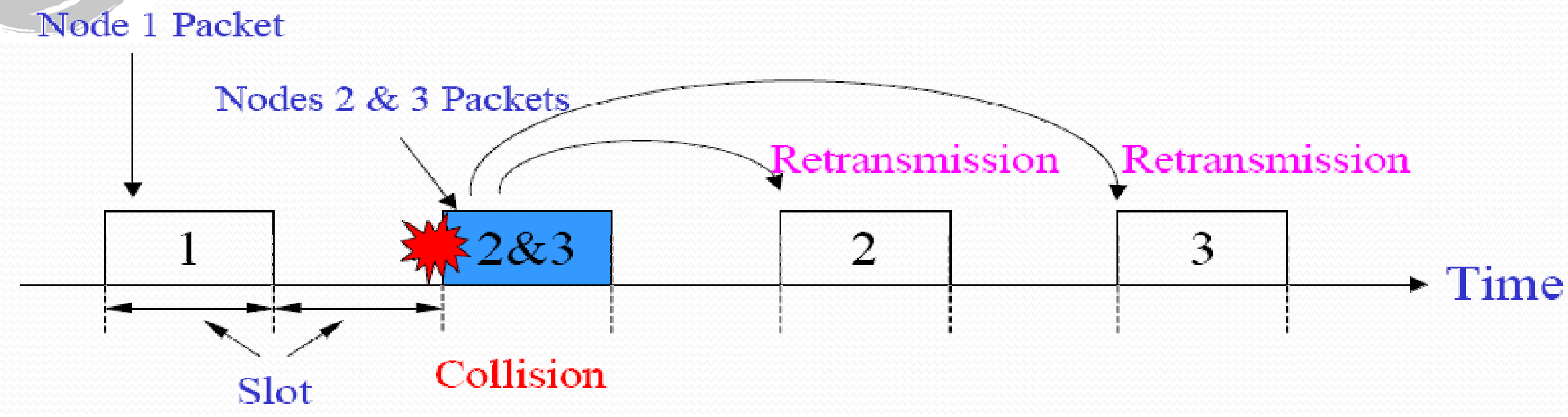
$$P_0 = \Pr[0] = e^{-2gT}$$

- Throughput and max throughput

$$S = GP_{0,} \therefore S = Ge^{-2G}$$

$$S_{\max} = S\big|_{G=1/2} = \frac{1}{2e} \approx 0.184$$

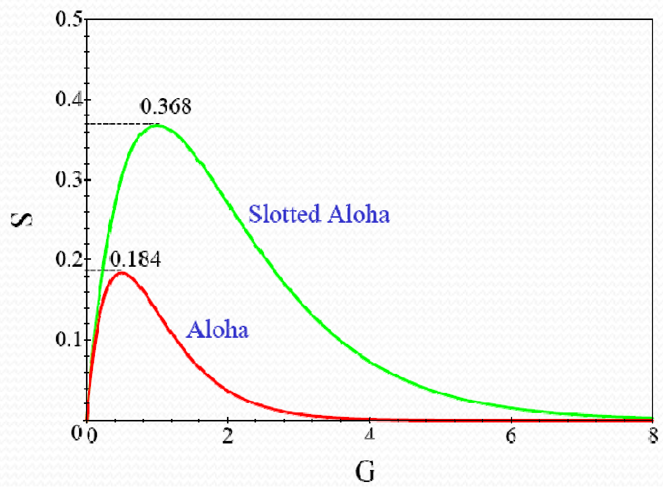
Slotted ALOHA



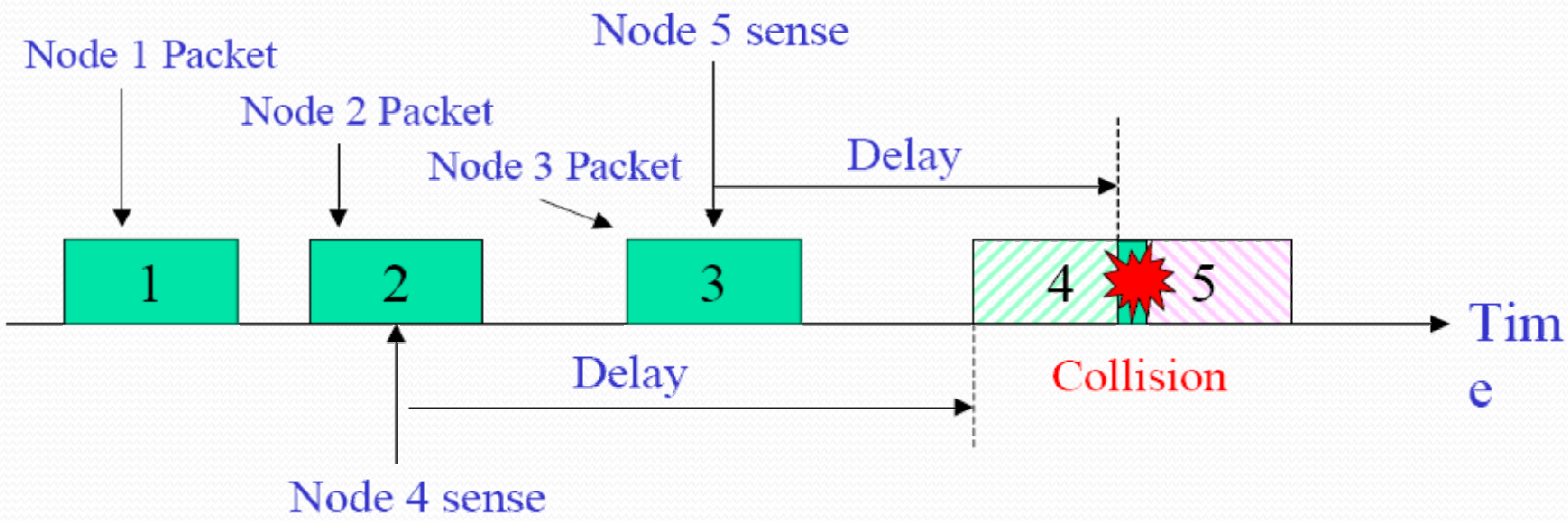
Collision mechanism in slotted ALOHA

- Reduced vulnerable period in half: $2T \Rightarrow T$

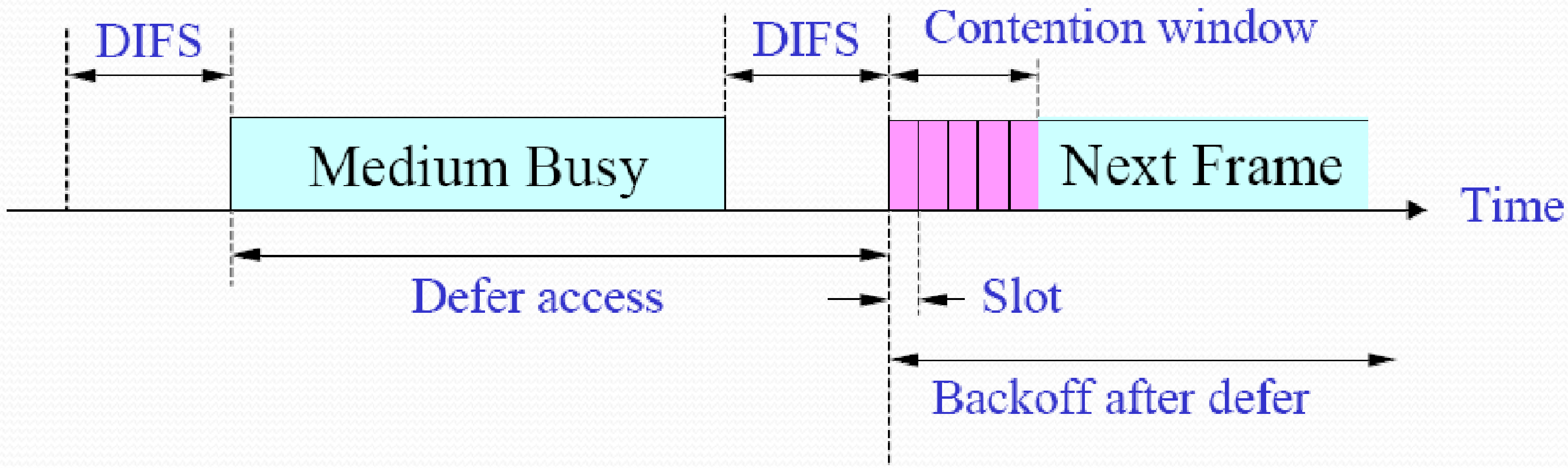
$$S = G \cdot e^{-G}$$



Collision Mechanism in CSMA



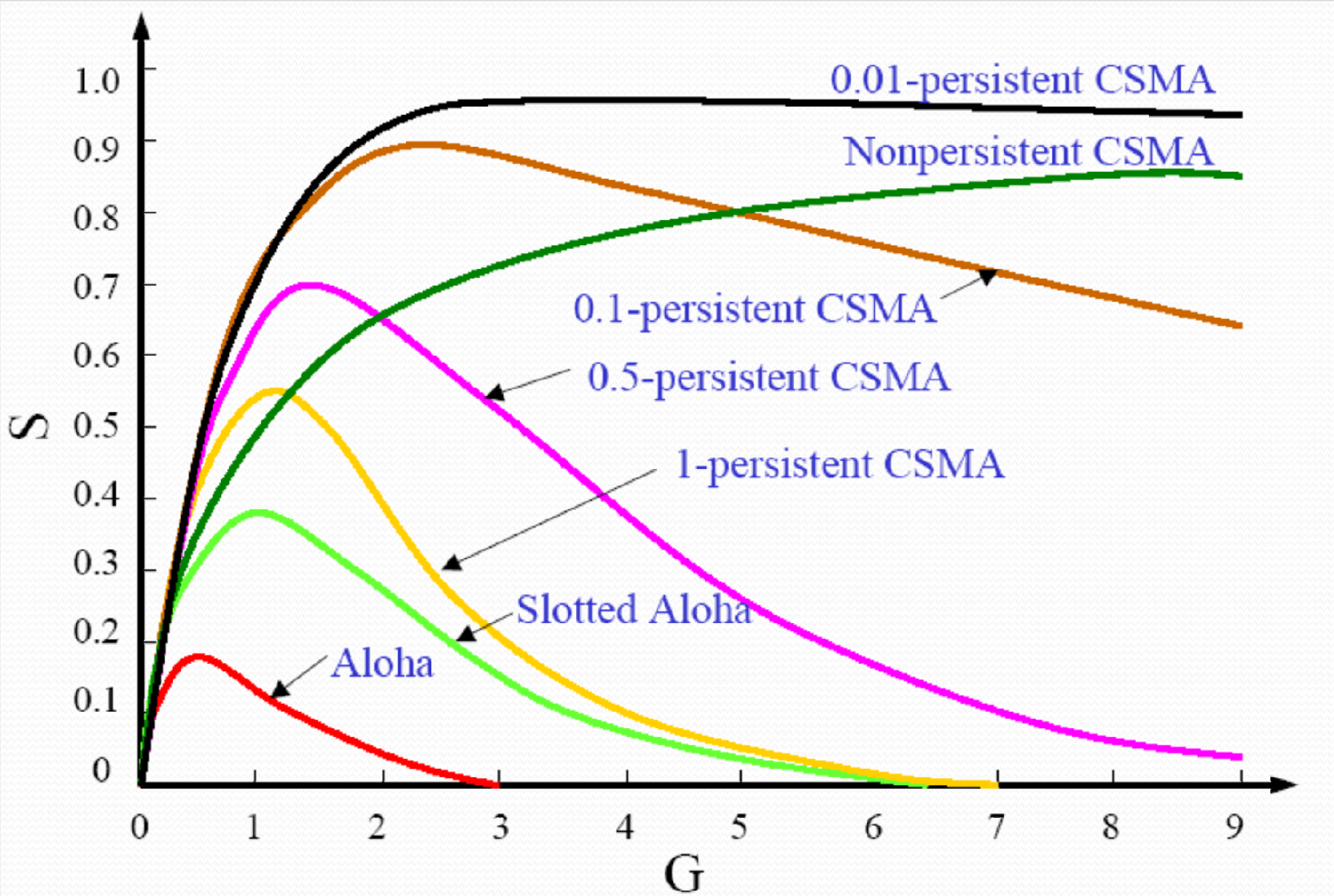
CSMA/CA Explained



DIFS – Distributed Inter Frame Spacing

<Note> Collision can occur when two or more terminals select the same time slot in which to transmit their frames

Throughput comparisons



Resource sharing strategies

- Inherently centralized communication structure
  - Communication via a base station: two subscribers do not have to be able to reach each other directly
  - So there exists a hidden-terminal problem
  - Different network stations differently affected by disturbances (selective disturbances) hinders correct sensing of medium
- Hence, most of PLC standards favor CSMA/CD or CSMA/CA or their elaborated versions

Standard Activities

- De facto standards (Low Speed)
  - X-10: eletrical appliances control , less than 120bps, BPSK
  - CE Bus (also called ANSI/EIA-600): home automation
  - LonWorks (by Echelon Corp) : home automation, f_c=115-132KHz, R_b=3-6kbps
- De facto standards (High Speed)
  - HomePlug 1.0 (2000, by HomePlug Powerline Alliance)
    - In-home PLC networking
    - OFDM, f_c=4-28MHz, R_b=14Mbps/ 80Mbps (called HomePlug 1.0.1-Turbo), BPSK/QPSK
    - CSMA/CA type MAC

Standard Activities

- HomePlug AV (2005 , by HomePlug Powerline Alliance (HPPA))
  - In-home AV Services
  - OFDM, f_c= 2-30MHz, R_b=200Mbps, turbo coding, QPSK/16QAM/64QAM/256QAM/1024QAM
  - CSMA and TDMA hybrid type MAC
- Other De Facto Standards: DS2/UPA, HD-PLC

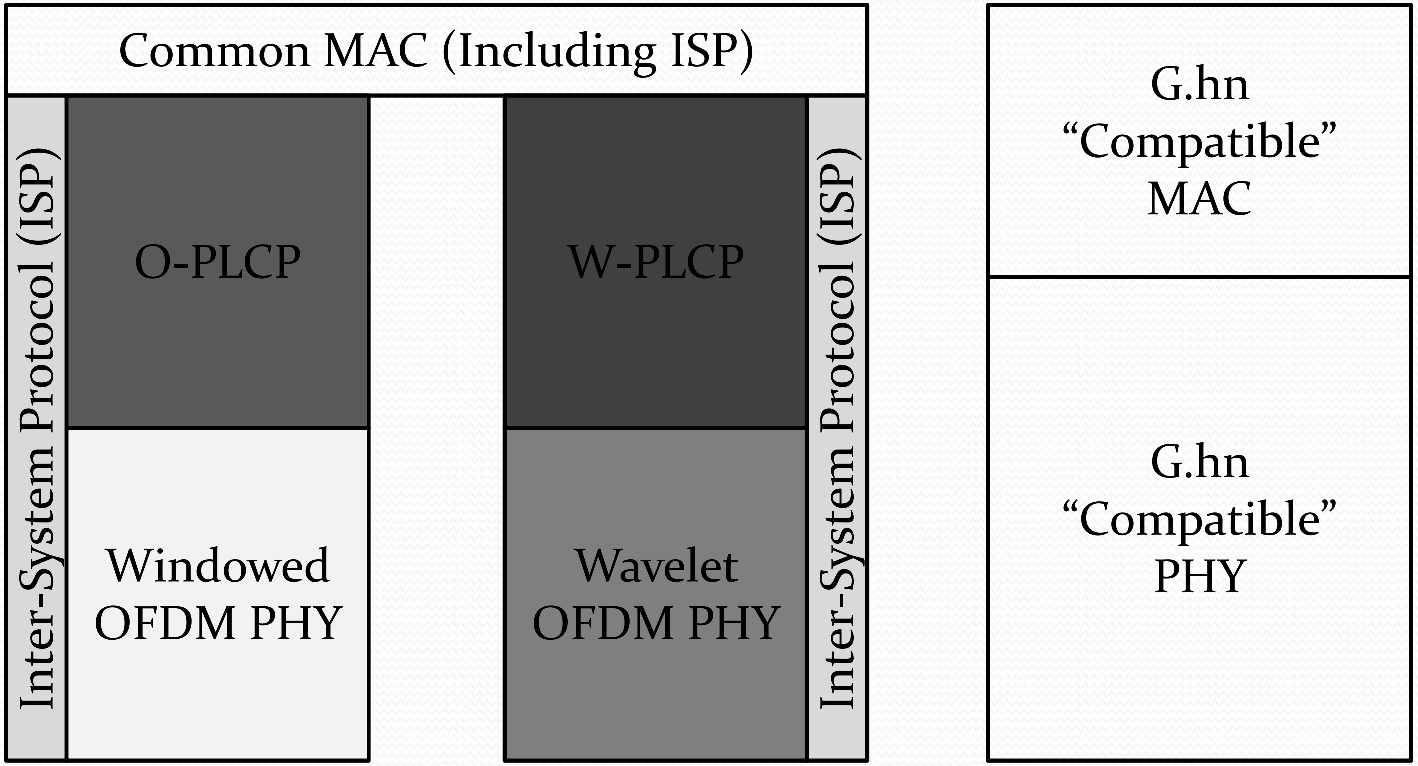
Standard Activities

- International standards
  - IEEE1901 (2010)
    - Home Networks and access applications
    - OFDM(512-point IFFT), R_b>100Mbps , fc <100MHz
    - Multiple PHYs: FFT-OFDM(by HomePlug Alliance) /Wavelet-OFDM (by High Definition-PLC alliance (HD-PLC))
    - ISP (intersystem protocol) to deal with the two IEEE 1901 PHYs/G.9960 PHY
    - TDMA and CSMA based MAC

Standard Activities

- International standards (Cont'd)
  - CENELEC EN 50065 (Low Rates, < 100Kbps)
    - 4 Bands
      - A(3-95KHz) : Utility usage
      - B (95-125KHz)/C (125-140KHz)/D(140-148.5KHz): Private usage
  - CENELEC EN 50412 (High Rates, but not well defined yet)
    - 1.6MHz~30MHz
    - Broadband PLC
  - ITU-T G.9960 (or G.hn, 2006)
    - Unified home network transceiver over all types of in-home wiring: phone-lines, power lines, coax, Cat5 cables, etc
    - Needs to design a single transceiver standard using multiple media
    - OFDM , QC-LDPC, 1 Gbps

IEEE 1901



Common MAC (Including ISP)
Inter-System Protocol (ISP)
O-PLCP
Windowed OFDM PHY
W-PLCP
Wavelet OFDM PHY
Inter-System Protocol (ISP)
G.hn “Compatible” MAC
G.hn “Compatible” PHY

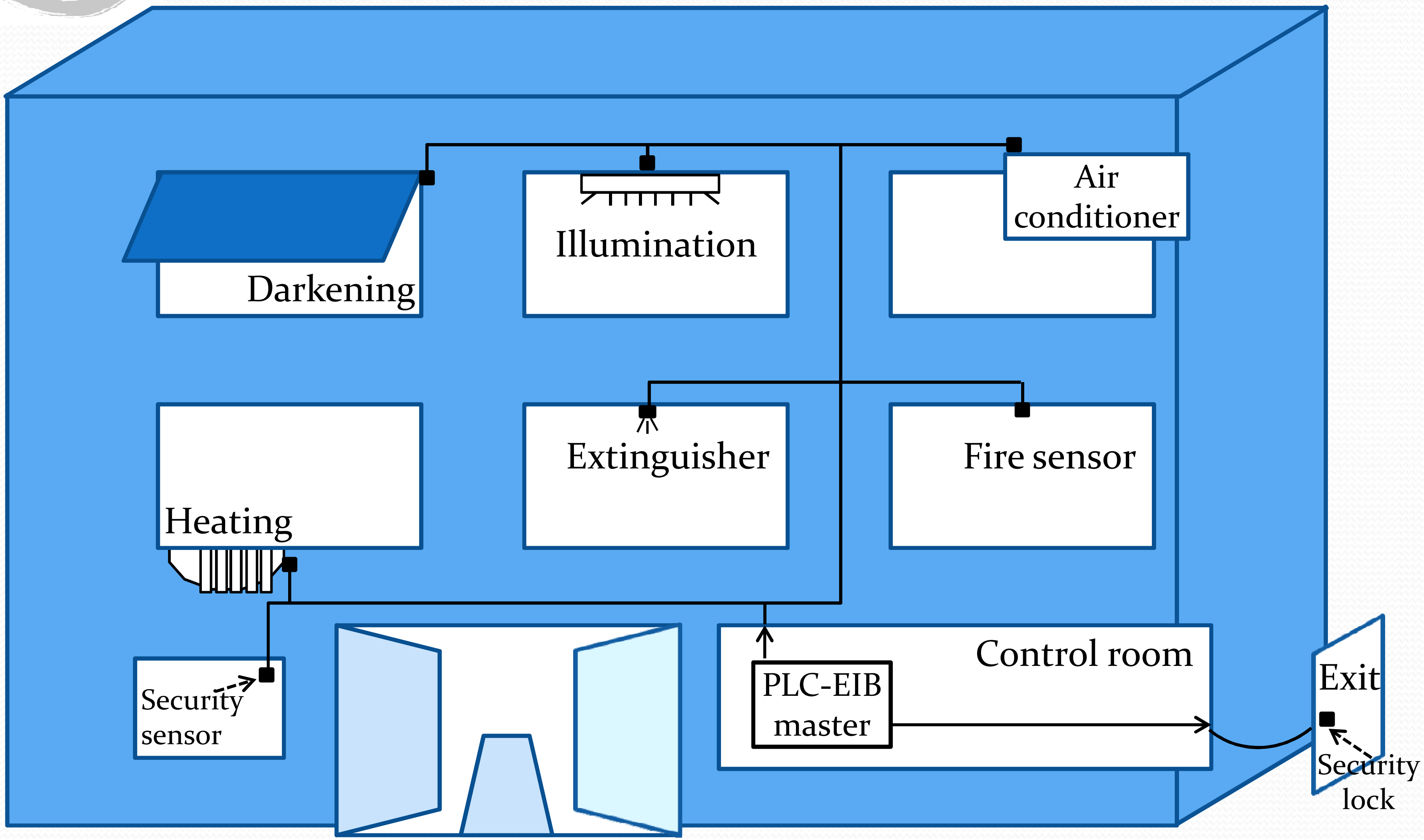
Multicarrier Modulation Comparison of different PLC alliances

	HD-PLC	HPPA	UPA
Modulation	Wavelet OFDM (DWMT)	Pulse-shaped/windowed OFDM	Pulse-shaped/windowed OFDM
Channel coding	Reed Solomon, convolutional, low density parity check codes	Parallel-concatenated turbo code, convolutional code	Reed Solomon concatenated with Trellis coded modulation
Constellation	Up to 16 PAM	Up to 1024 QAM	Up to 1024 DPSK
Max number of carriers	512 up to 2048	1536	1536
Sampling frequency (2*B*)*	62.5 MHz	75 MHz	>60 MHz
Effective band	4-28 MHz, 2-28 MHz optional	2-28 MHz	0-30 MHz, 0-20 MHz optional
Max PHY Rate	190Mbps	200 Mbps	200 Mbps

Other PLC Applications

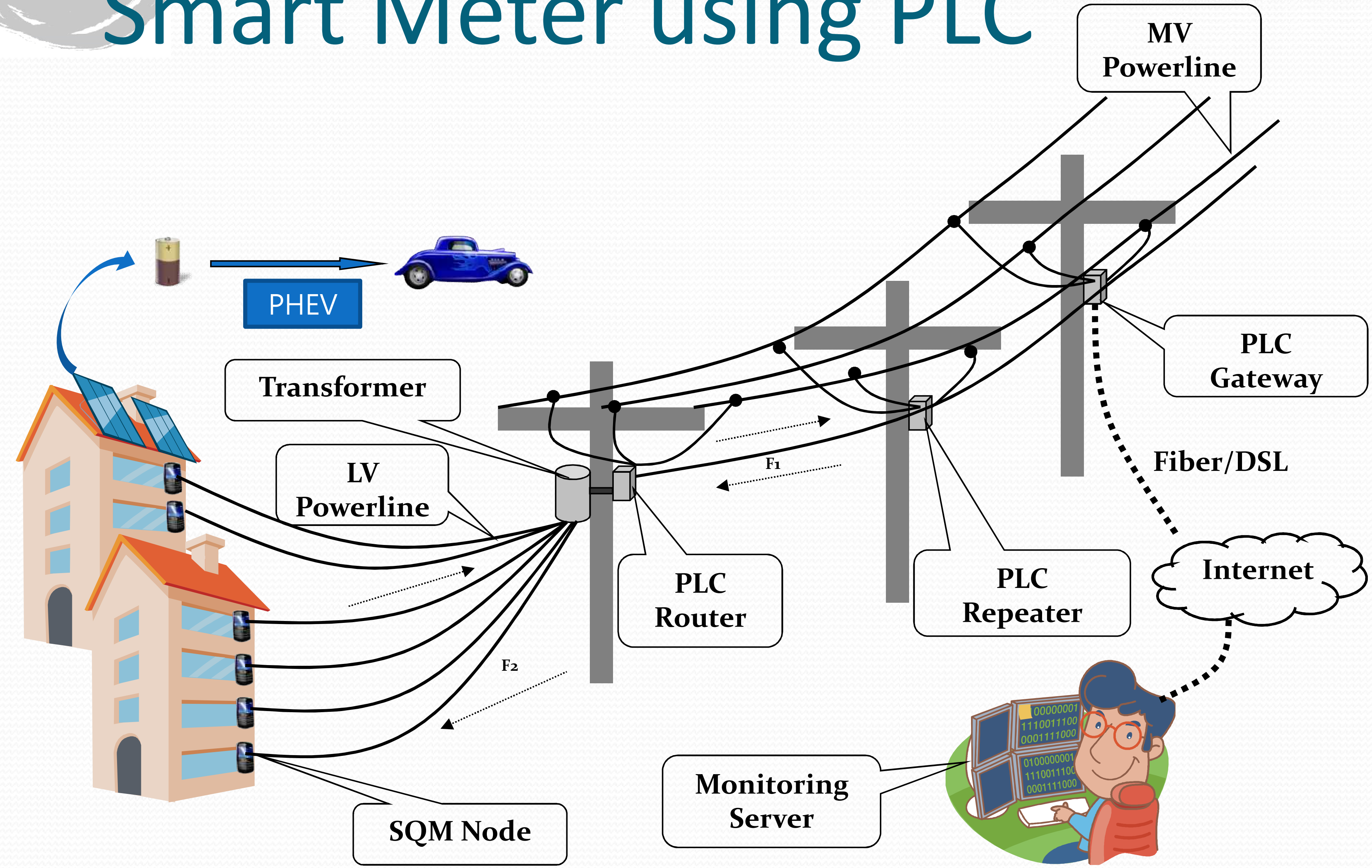
- Home Automation
- Home Networks
- Smart Meter
- Smart Grid
- PLC Broadband access networks
- DC-PLC systems: PLC Wearables, etc

Home Automation



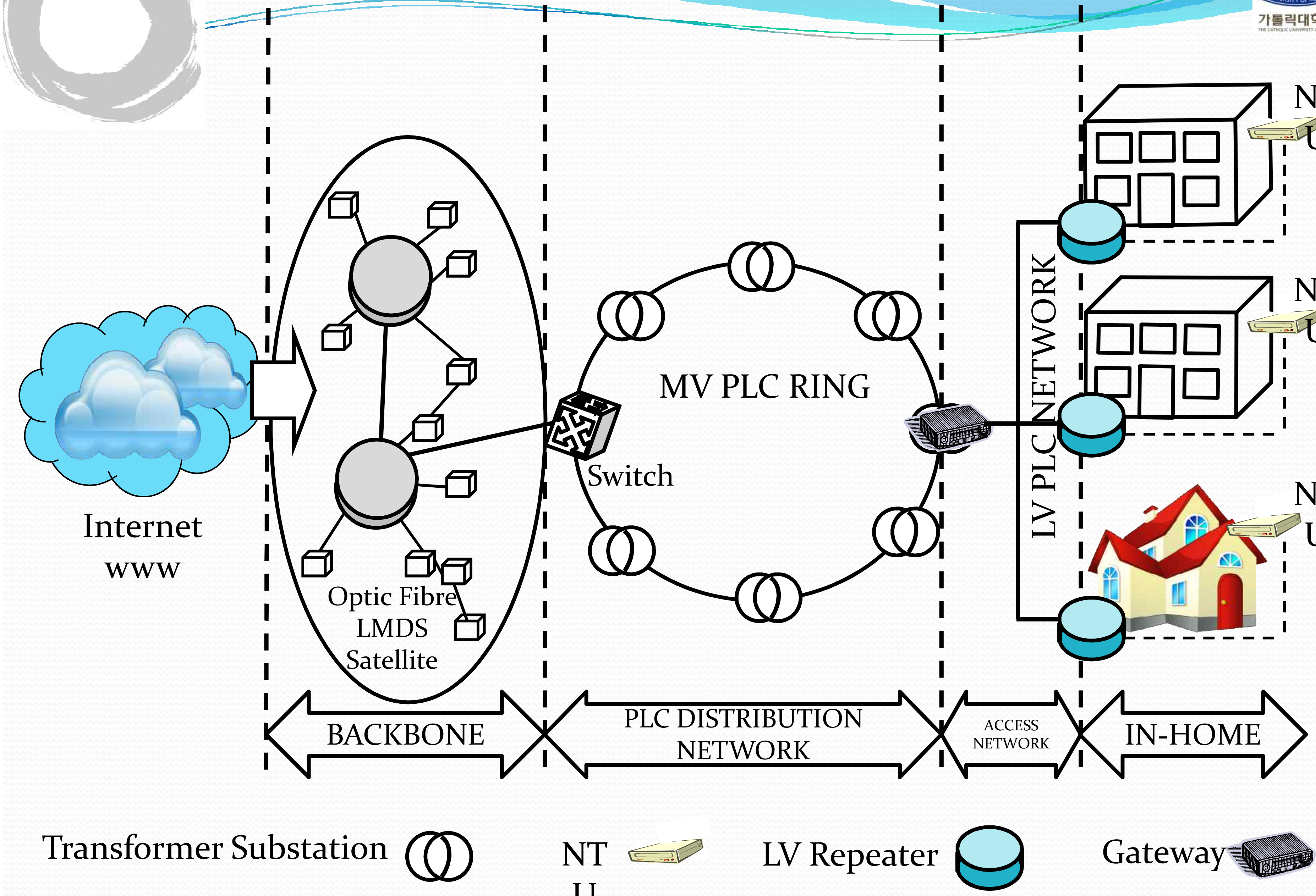
Indoor PLC Home Networks

Smart Meter using PLC



PLC Broadband Access Systems

- High data rates over MV or LV
- f_c = 2 – 80 MHz
- PLC Network Architecture (Fig 8.8 and Fig 8.9)
- ‘last mile’ end-user Services
  - Broadband internet
  - Voice over IP
  - Video Services
  - Multimedia PLC (over 200Mbps, HomePlug AV)



NT
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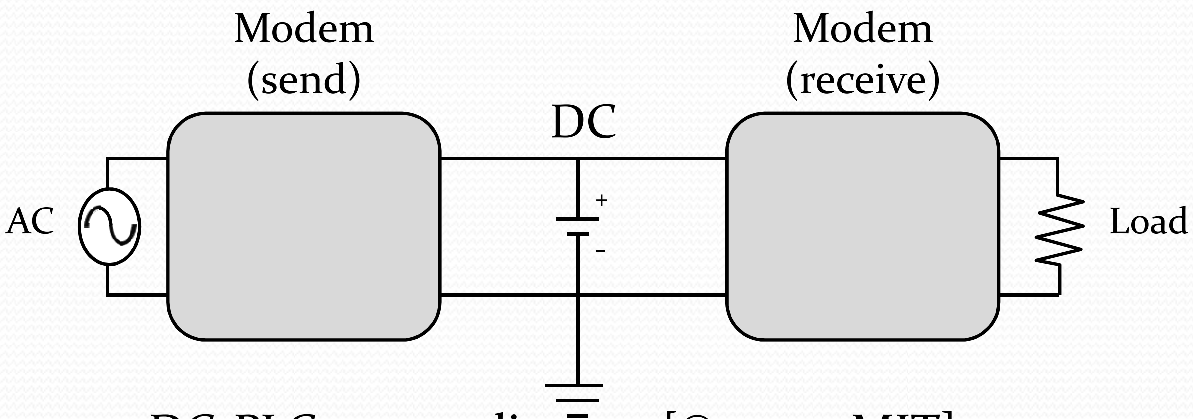
MV PLC RING
Switch
LV PLC NETWORK
Internet
www
Optic Fibre
LMDS
Satellite
BACKBONE
PLC DISTRIBUTION
NETWORK
ACCESS
NETWORK
IN-HOME
Transformer Substation
NT
U
LV Repeater
Gateway

PLC for wearables

- Use DC-PLC instead of AC-PLC
- Conductive fabrics
- Transmission Line Transformer Theory (Fig. 8.16 & 8.17)
- Simple installation (reduced components) and maintenance
- Great freedom of sensor locations (pervasive physical presence)
- Less interference compared to wireless systems
- Simple coordination (routing) and synchronization
- Use Rechargeable battery
- Applications
  - Wearable health monitoring
  - Wearable computing

- Comfort and soft
- Proxemics
- Light
- Easy placement of sensors
- Easy maintenance

Conductive fabric garment [© 2007, MIT]



DC-PLC system diagram [© 2007, MIT]

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Thank you for listening!