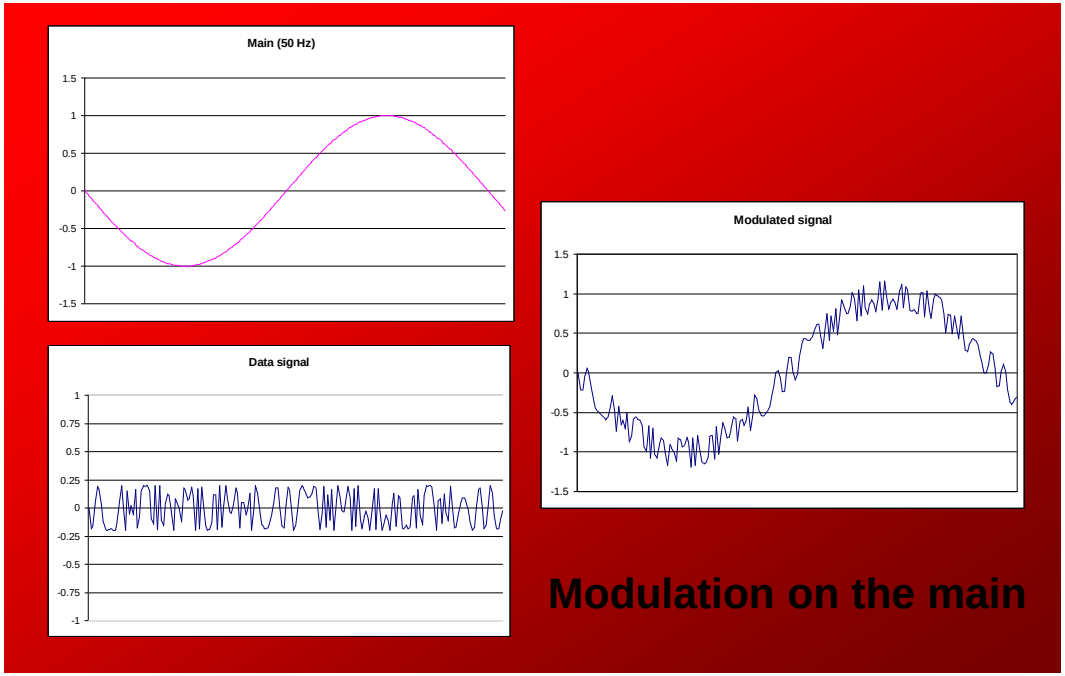
TI Innovation Day France 2010

Power Line communication (PLC)

PLC definition

- Power line communication
  - Wired technology
  - Use of the electricity networks for data transmission
  - No expensive deployment

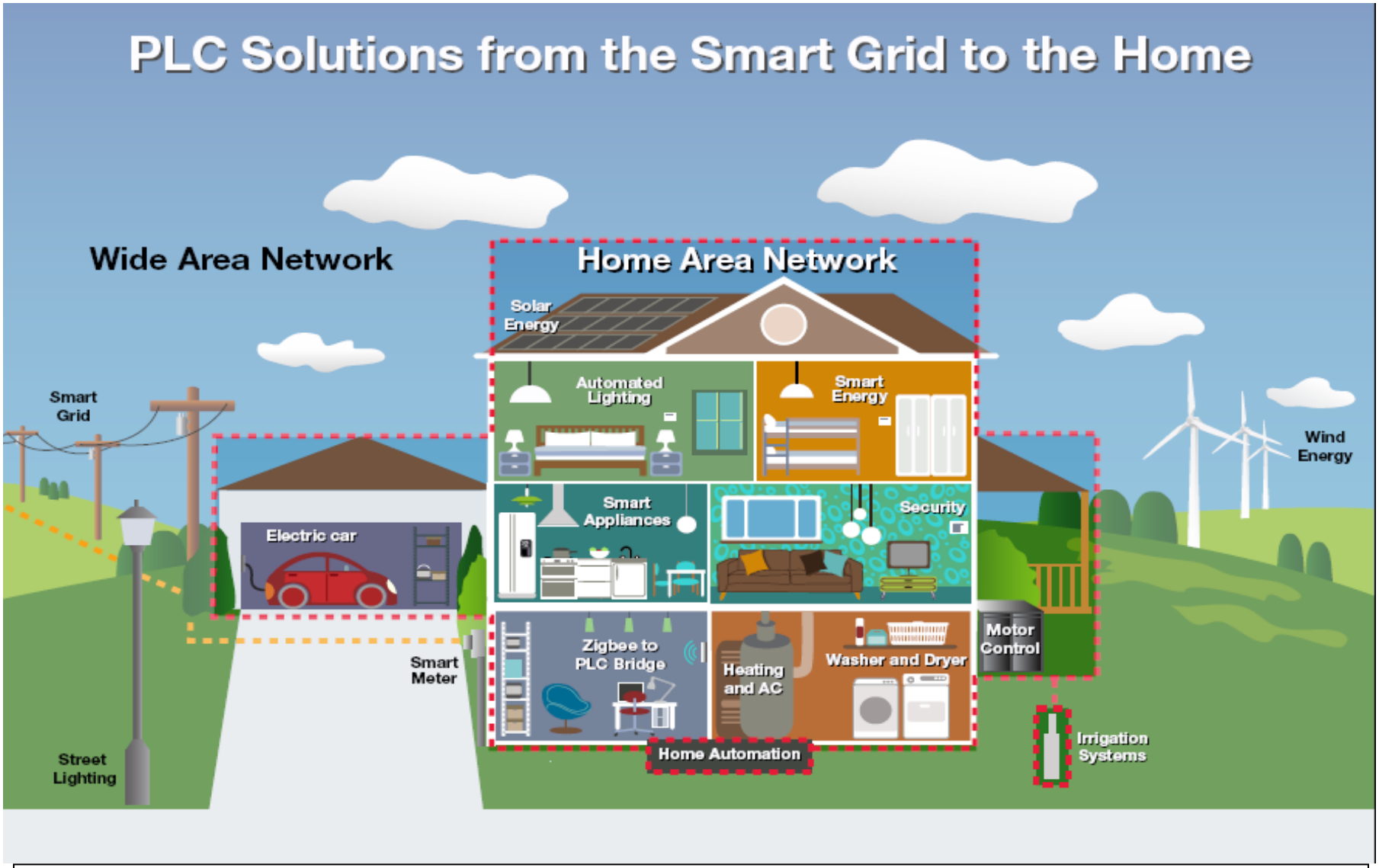


PLC Communication depends on

- The modulation
- The frequency band
- The protocol

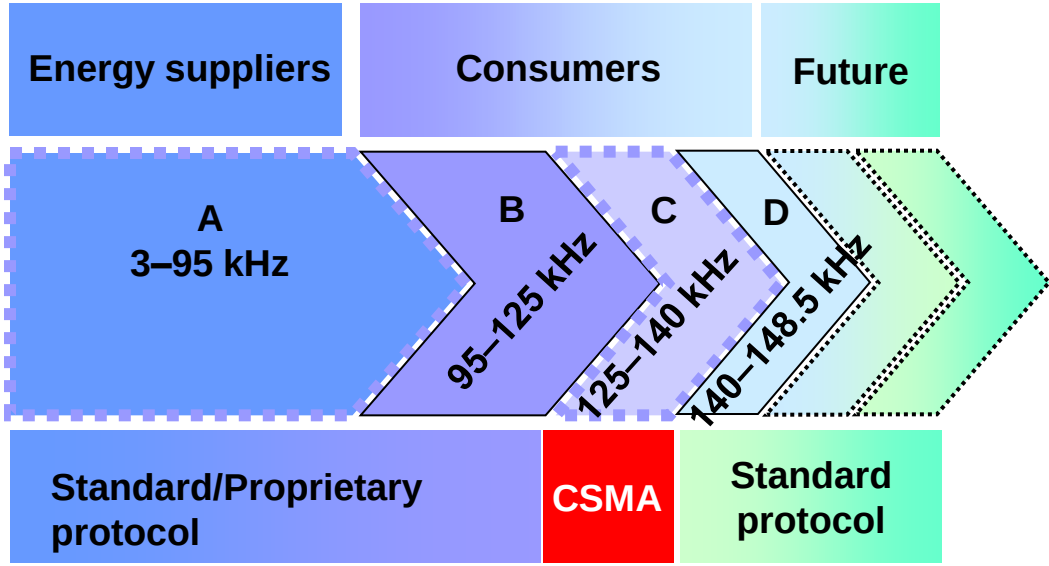
TI PLC solution application spectrum

Low Frequency Narrowband (up to 500kHz)



PLC Frequency Bands

- **PLC frequency bands in Europe**
  - Defined by the CENELEC:
    - CENELEC-A (3 kHz – 95 kHz) are exclusively for energy providers
    - CENELEC-B, C, D bands are open for end-user applications
  - Bands A, B and D protocol layer is defined by standards or proprietarily defined
  - Band C is regulated – CSMA access



- **PLC frequency bands in USA**
  - Single wide band – from 150 to 450 kHz
  - FCC band 10 kHz – 490 kHz
  - Access protocol defined by standard
  - HomePlug broadband: 2–30 MHz

- **PLC frequency bands in Japan**
  - ARIB band 10 kHz – 450 kHz

- **PLC frequency bands in China**
  - 3–90 kHz preferred by EPRI
  - 3–500 kHz single-band not regulated

TI is Very Active in Power-Line Communication

- **PRIME principal member**
  - TI is a principal member of PRIME consortium (TWG and MWG)

    www.prime-alliance.org

    Solution available and delivered to customers worldwide
  - Successful MAC/PHY on field trials in Madrid

- **Narrowband supporter**
  - **S-FSK** IEC61334-4-32 LLC
  - **OFDM PRIME** and **G3 support**

- **Contributing member**
  - IEEE 1901.2: Narrow band PLC
  - ITU – G.hnem: board of director
  - Electrical car charging (SAE/IEC/JARIB)
  - Committees: TEVHYB6 (PHEV), TEVEES17/17B (EMI)
  - J551-5 analysis on conducted emissions in PHEV
  - Worked with J1772™ to clarify EMI requirements

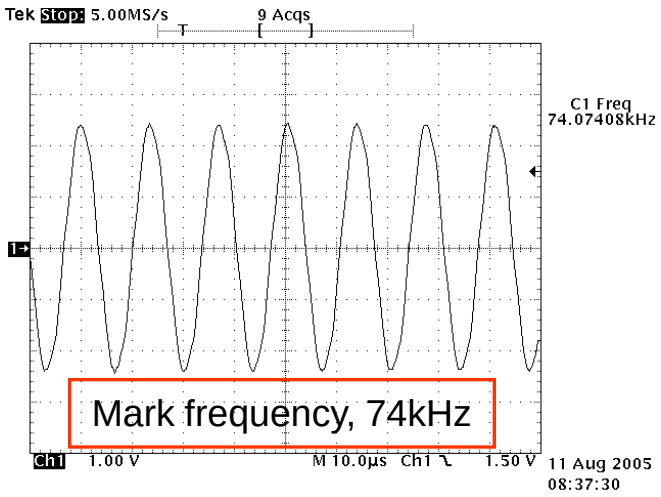
TI supports also other EE

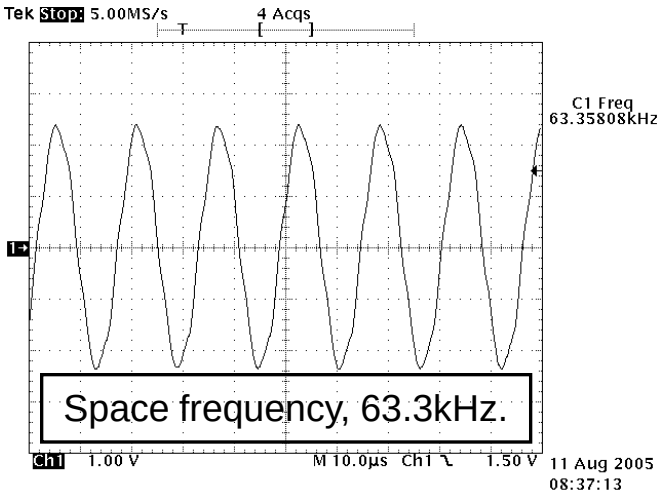
- Lighting
  - First tests in in Dallas where parking lot light lamps were controlled using PLC
- Solar
  - Demonstrated 30kbps in Cenelec B using a system with 6 solar panels, 3 DC/DC micro-converters, 1 DC/AC inverter
- …and many more

Modulation

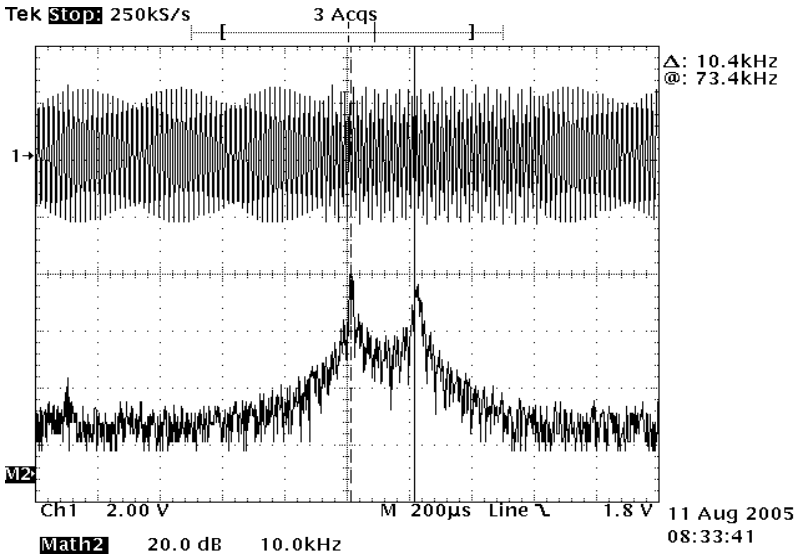
S-FSK

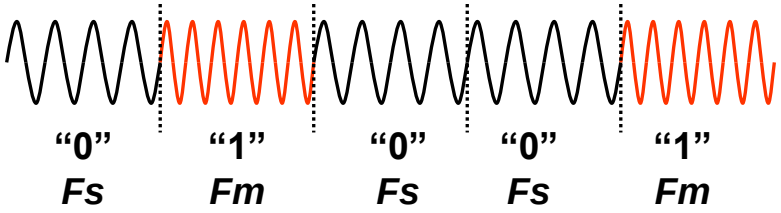
(S)FSK Waveform





Frequency Spectrum





S-FSK

- "0" is transmitted using Fs = 63.3kHz
- "1" is transmitted using Fm = 74kHz

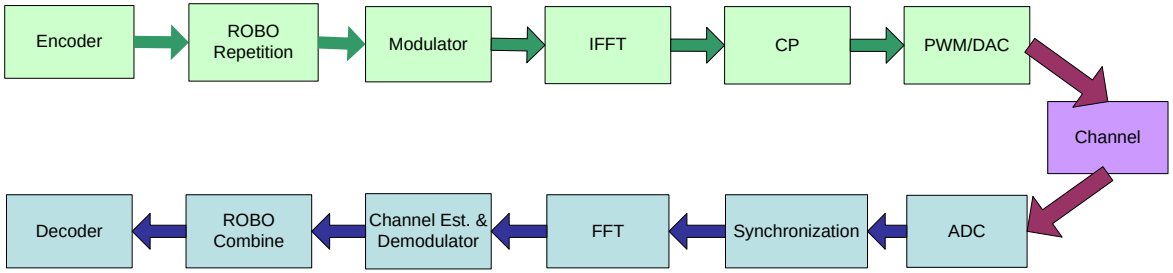
SFSK implementation on ‘F28x

- Modem:
  - SFSK Modulation with dual carrier: 74kHz and 63.3kHz
  - Bi-directional and half-duplex
  - Transfer rate 2400 bps
  - Zero cross detection used for sync
- All signal processing for communication done by a low-cost Piccolo device.
- Evolution
  - Scalability is key for future evolution.
  - Other functions/tasks can be integrated, too (PFC,…).

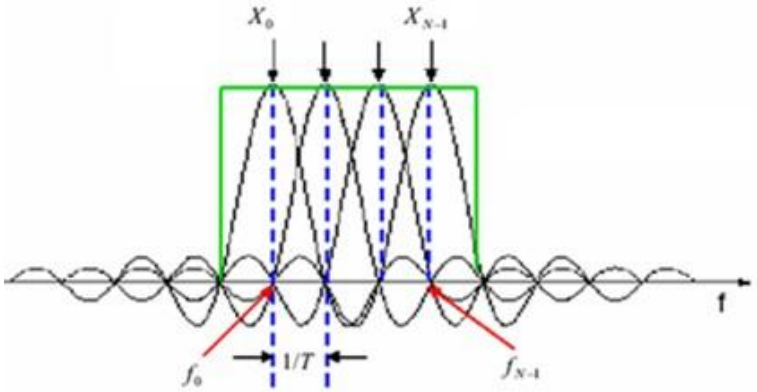
Modulation

OFDM

System Overview



- OFDM PHY
  - Higher data rate
  - Simpler equalizer
  - Less dependent on channel characteristics
  - DBPSK, DQPSK, D8PSK
  - ROBO (DBPSK+1/4 or 1/8 Repetition)
  - 97 sub-carriers, 488.28125Hz spacing
  - *Higher peak-to-average power ratio*



OFDM - Strengths and drawbacks

- Strengths
  - Higher data rate than other systems
  - Less dependency of channel characteristics
  - Simple equalizer for receiver

- Weaknesses
  - Sensitive to Timing errors
  - Sensitive to Phase noise
  - Large Peak-To-Average Power Ratio

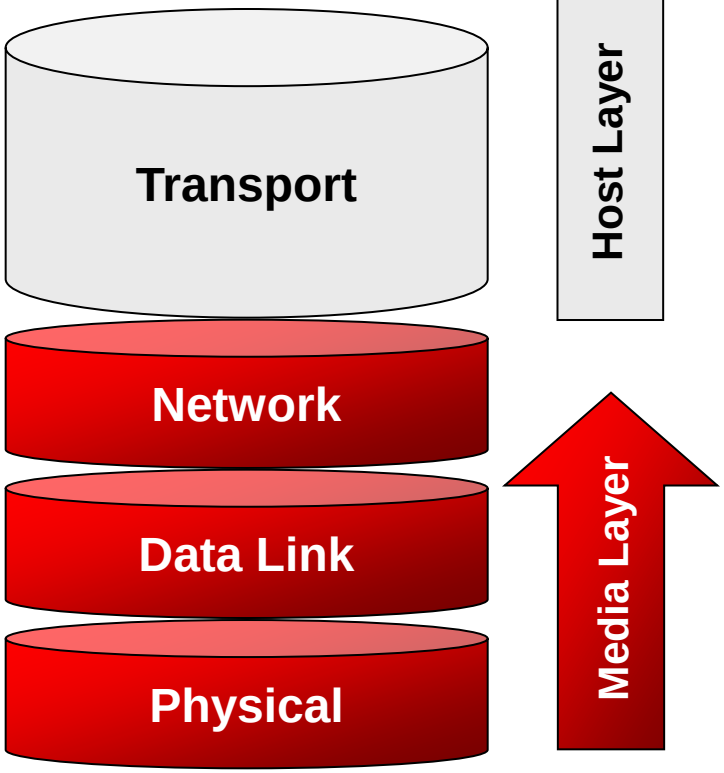
Software

TI PLC Solution Standards Compliance

Standard	Techno-logy	Band occupied	Data rate range	Target TI processor	TI status / availability
IEC 61334	SFSK	60–76 KHz	1.2–2.4 kbps	Piccolo™ F28335 (now) F28xPLC (future)	**Now**
PRIME	OFDM	42–90 kHz	21–128 kbps	F28335 (now) F28xPLC (future)	**Now** Multiple customers Field trials Interoperates
ERDF G3	OFDM	35–90 kHz	2.4–34 kbps	F28335 (now) F28xPLC (future)	**Now**

- PRIME designed for low-voltage lines with low noise → targets higher data rates
- G3 designed for medium voltage lines → lower data rates, 802.15.4 like MAC
- SFSK easy to implement, estimating 10–15 MIPS

PLC node architecture



	Data unit	Layer	Function
Host Layer			
Media layer	Packets	Network	Path determination and logical addressing (IP CL)
	Frames	Data link	Physical addressing (MAC & LLC)
	Bits	Physical	Media, signal and binary transmission

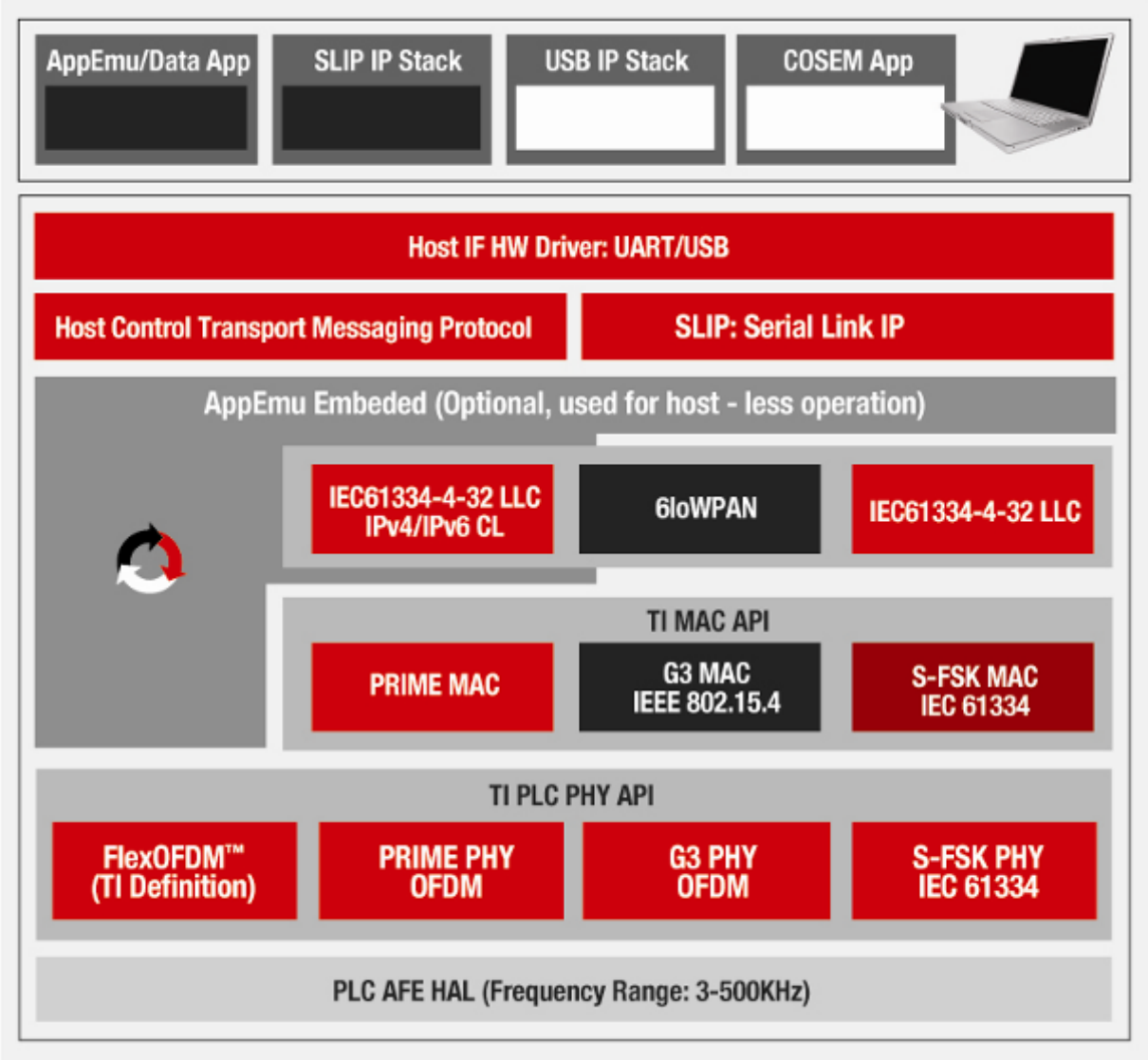
FlexOFDM– TI Proprietary Solution (I)

- **Why** did we do this?
  - To address customers not doing Metrology
  - Non-Metrology End Equipments (EE) not allowed to run in Cenelec A, however PRIME/G3 are made for this band
  - No standards available yet for EE, such as Lighting, Electrical Car Charging, Solar, Smart Appliances
- **How** did we do this?
  - FlexOFDM PHY adapted from PRIME

FlexOFDM– TI Proprietary Solution (II)

- Features
  - Supporting Sub-10kHz, Cenelec A/B/C/D band and FCC band with flexible frequency band and fixed bandwidth of 3kHz, 12kHz or 24kHz
  - Data rates up to 64kbps @ 24 data carriers used (fixed)
  - FlexOFDM PHY, PRIME MAC, IEC61334-4-32 LLC
- Uses TI PLC reference hardware with filter adaption in analog front-end to follow the desired frequency band and width

plcSUITE™ Software Framework



Host App SW reference

plcSUITE:

- Open source
- Layered API
- Component-wise Certifiable
- Scalable
- Lego architecture
- Custom build
- Documentation

PRIME vs. G3 Major Differences: PHY

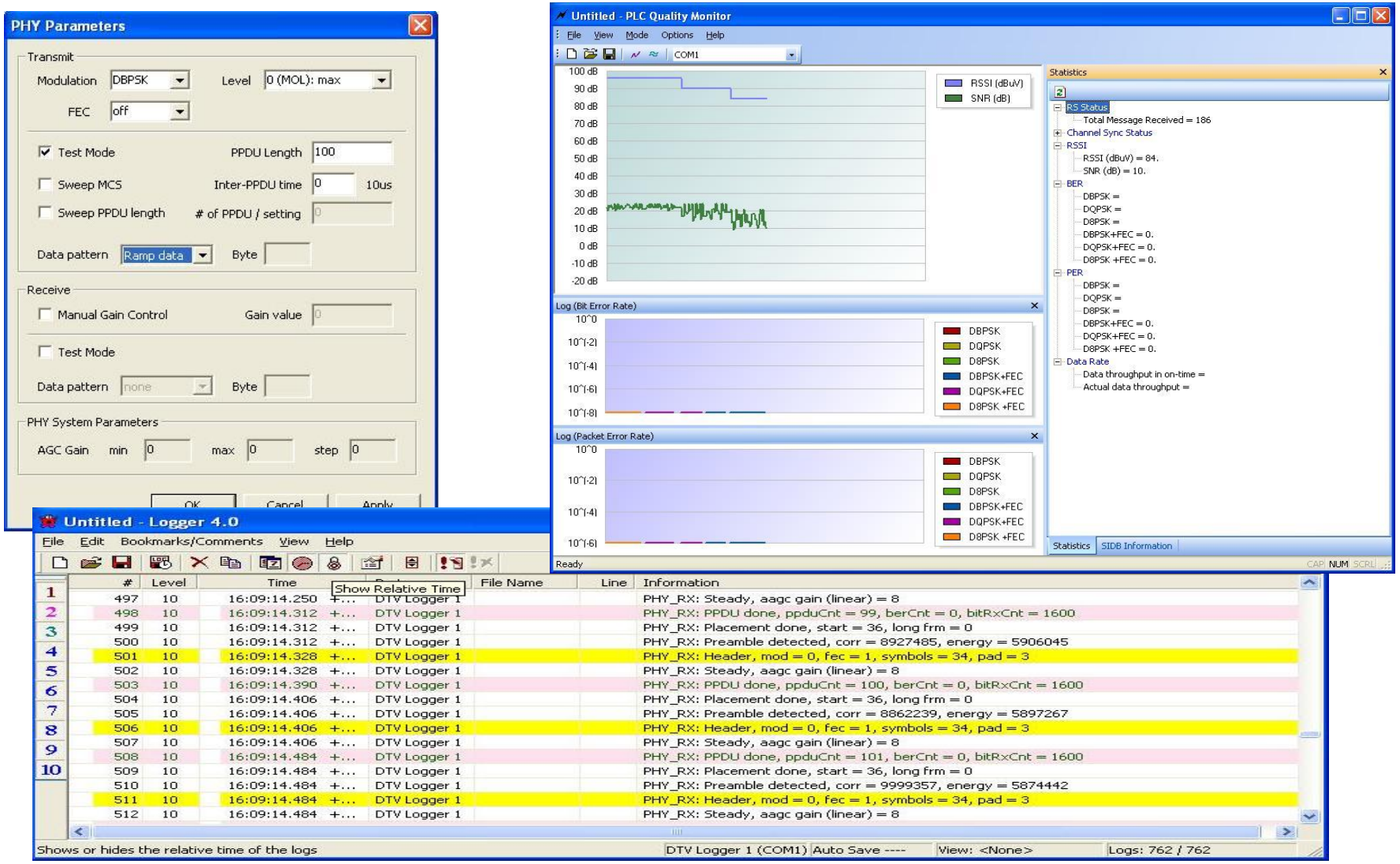
Parameter	PRIME	G3	Comments
Modulation Size	DQPSK / DBPSK/ **D-8PSK**	DQPSK / DBPSK	G3 has lower peak data rate, lower data rates robust due to concatenated and repetition coding
Forward Error Correction	Rate ½ conv. Code	**Outer RS** + inner rate ½ conv code	
Band plan	Continuous 42-90 kHz	35-90 kHz with gaps for SFSK	G3 aims to avoid interference with SFSK
Link adaptation	Only data rate	Data rate + Band plan	G3 has more complex / advanced link adaptation
Preamble + control overhead for median packet length	10%	29%	**G3 focuses on Robustness versus speed**

- PRIME designed for low voltage lines
  - LV lines have lower noise, better coupling → PRIME targets higher data rates with relatively weak coding
- G3 designed for medium voltage lines → lower data rates → additional robustness due to concatenated and repetition coding
- G3 MIPS comparable to PRIME

PRIME vs. G3 Major Differences: MAC

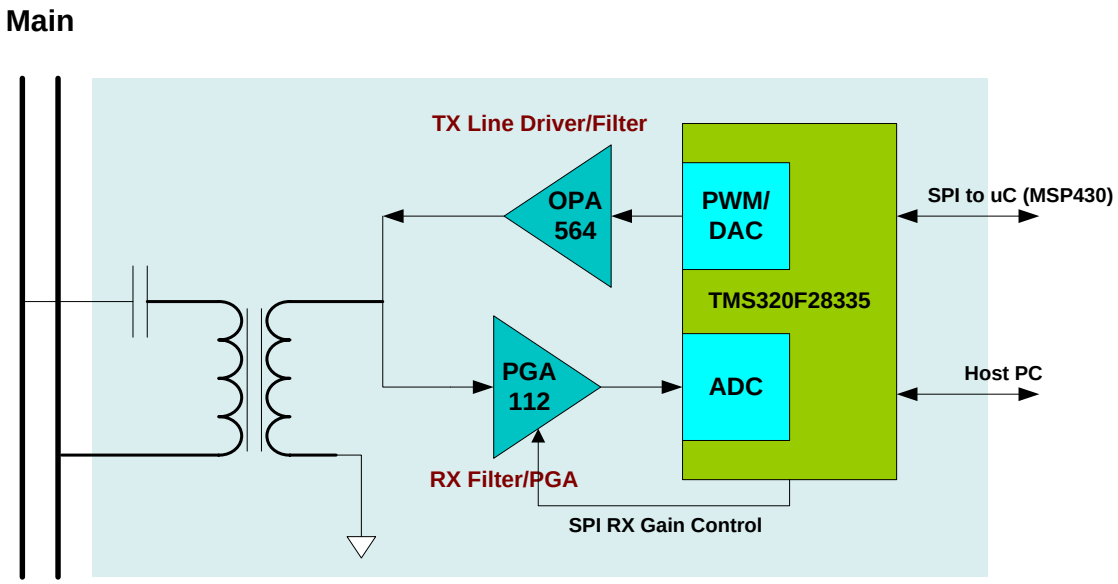
Parameter	PRIME	G3	Comments
Topology	Tree	P2p/star/cluster tree	Prime is more suitable for access network, G3 is better for HAN or PAN
Network Formation	Beacon discovery Automatic promotion	Beaconless Network	
Access Mechanism	CSMA/CA Optional CFP	CSMA/CA No GTS	G3 only supports contension based access
Packet Acknowledgement	ARQ for control and data (optional)	ACK/NACK at PHY	G3 has more robust link
Security	AES-CBS	AES-CCM	G3 also covers EPA-PSK
Power Management	No	Low Power Mode not used	G3 more suitable to low power device

TI PLC GUI Tool: Window to PLC System



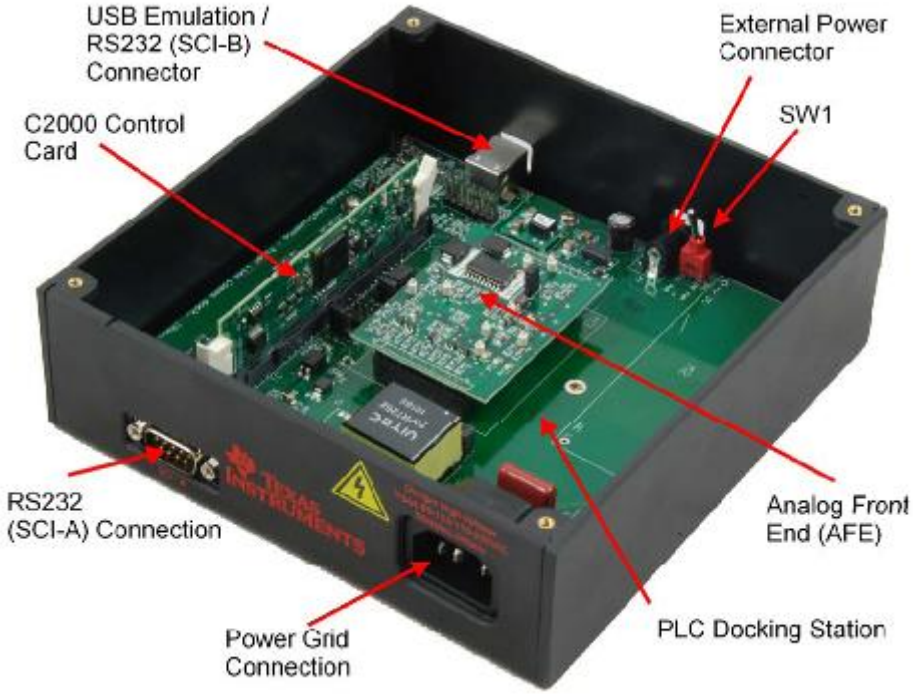
Hardware

System Overview



- Developed per PRIME
  - CENELEC compliant
  - OFDM (Orthogonal Frequency Division Multiplexing)
  - 42-89kHz (Band A: 5-95kHz)
  - Max. data rate 128kbps (uncoded D8PSK)
  - Max. output 1Vrms@2ohm load
  - Max. attenuation over 75dB
  - F28335 (PHY+MAC) & AFE
- Supports also G3/S-FSK

TI PLC Modem Development Kit (TI PLC DK)



TI PLC DK contains:

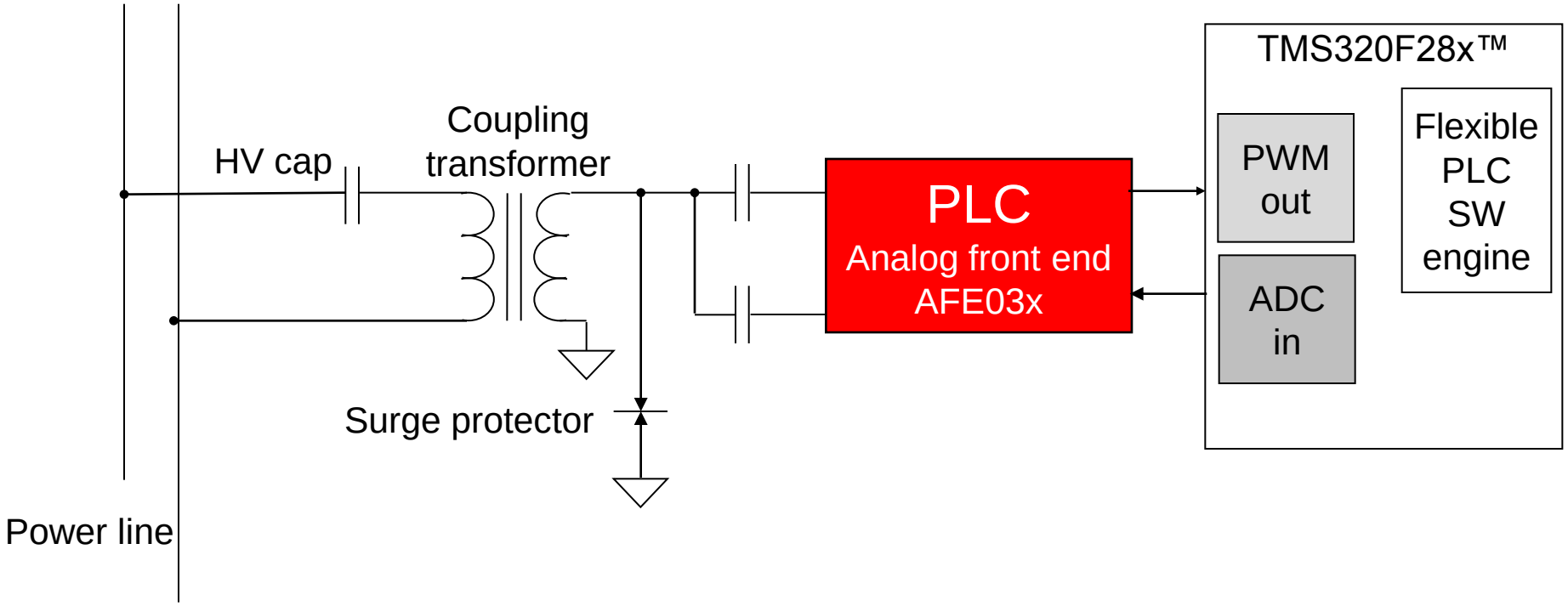
- 2 PLC modems
- Power supply and cables
- GUI and documentations
- Run any IP applications through PC host
- **Part#: TMDSPLCKIT-V2**
- **Price: $599 USD**
- **Distribution and TI eStore**
- **plcSUITE™ Software available via download**

- Robust narrowband PLC modem over low-voltage/medium-voltage power line
- PLC standards/modulation supported
  - PRIME
  - G3
  - FlexOFDM™
  - IEC61334 S-FSK
- Scalable data rates up to 128 kbps for single phase

- Software reference design package: **plcSUITE** APIs, Libs, source codes
- AFE operating frequency range 9–500 kHz (**usage of different filters**)
- Easy integration into end-point or network devices of AMR/AMI systems
- NRE and royalties FREE

New Optimized AFE in Development

AFE031 integrates and improves PLC system



AFE031 = PGA112 + OPA564 + filtering + zero crossing + (Euridis)

AFE031 (Samples 4Q10)

Integrated PLC analog front end

Features

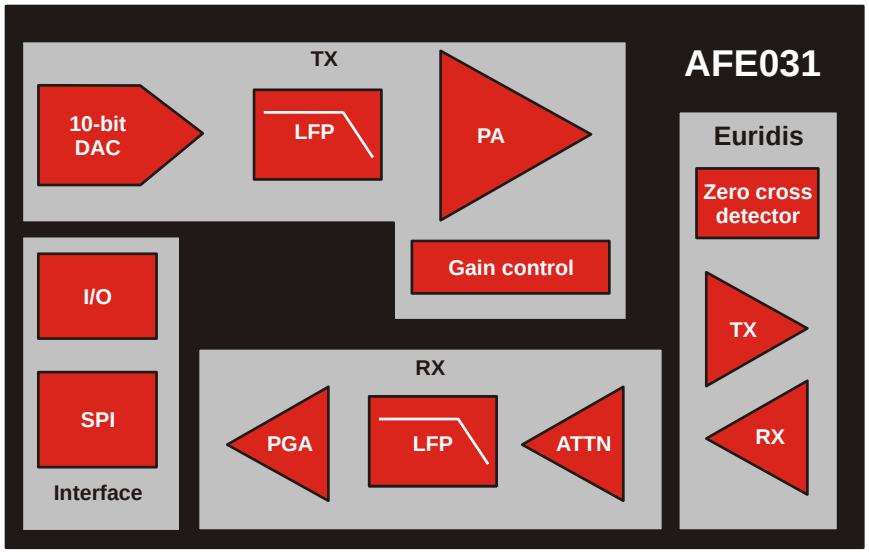
- Meets Cenelec A and B band requirements
- Output enable/disable control
- Integrated TX filters, power amp, RX filters & PGA
- Integrated zero-crossing detector
- Euridis 1&2 transmitter and receiver op amps
- Direct digital interface (glue less to TI PLC processor)
- Large output swing: 9Vpp @ 1.5A (12V supply)
- Thermal and over-current warning
- Internal thermal overload protection
- Resistor programmable current limit
- PA Supply: (12V), AV_{DD} supply (3.3V or 5V)
- Extended –40°C to +125°C temp range
- Package: 36-pin QFN with Power-Pad

Applications

- Power-line communications
- E-meters, solar power, HVAC
- Electric vehicles, street lighting
- Industrial applications

Benefits

- Fully integrated Tx and Rx PLC AFE, PLAN, PRIME, G3 compliant
- Fully controlled device
- Enables design flexibility
- Flexible, easy to use, low-cost solution
- Replaces RS-485 for low data rate applications



PHY

PRIME Modem: PHY Test and Validation

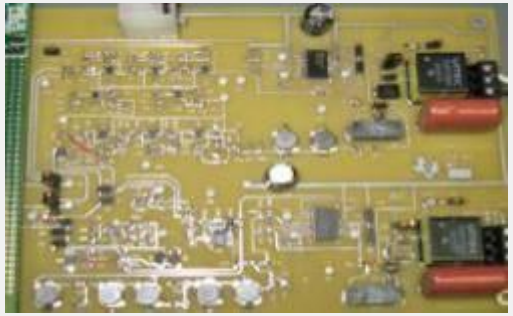
PC

PRIME Tx model in MATLAB®
Adds impulse noise, interference

Rohde & Schwarz AMU

Plays back MATLAB test vectors
Adds channel distortion, noise

Analog Front End Rx



Filtering + PGA112

TMS320F28335

Digital receive algorithms:
Synchronization, equalization,
FEC decoding…

PC

Display

PRIME PHY system layer development methodology

- Transmitter:
  - Digital side: Matlab → Assembly
  - Analog front end: Matlab (system analysis) → System specifications → Board level design
- Receiver:
  - Analog front end: Matlab (system analysis) → System specifications → Board level design
  - Digital side: Matlab → Assembly
- Integrated digital, AFE simulations for transmitter + channel + receiver
- Channel simulator: Matlab

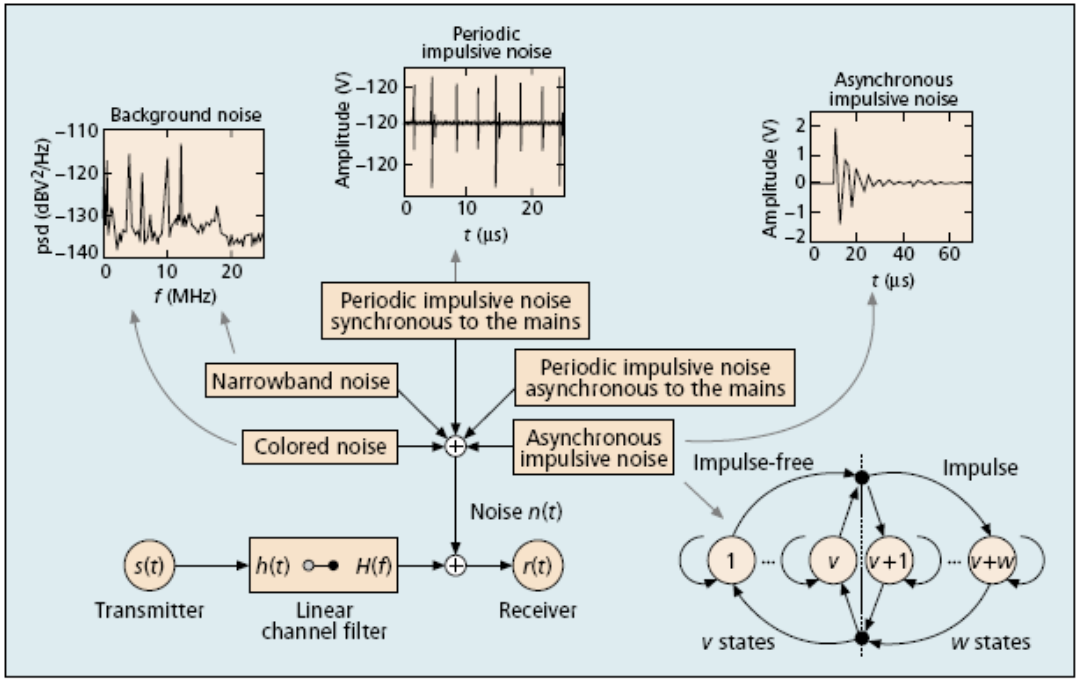
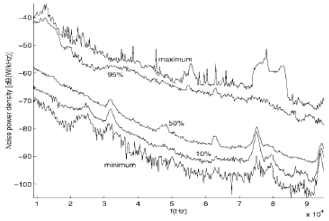


Figure 2. *Noise scenario on power lines.*

Power line channel impairments

- **Very low impedance on line (< 1 ohm) making line driver design very challenging**
- **Attenuation which can be possibly time varying**
- **Channel multi-path response due to reflections**
  - **Delay spread 10-20 micro seconds**
- **5 types of noise:**
  - Type a: Spectrally flat with spectral density decreasing with higher frequencies
  - Type b: Impulse noise due to different switching operations: Universal motors
  - Type c: Caused by silicon controlled rectifiers (SCR's) switching at every 50 Hz cycle
  - Type d: A periodic impulse noise due to surges, switching transients
  - Type e: Narrow band noise at frequencies unrelated to the power system frequency (TV disturbances etc.)

Type a



Type b

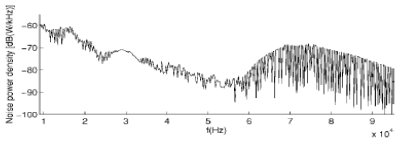


Fig. 4. Example of noise synchronous to the power system frequency as measured on a suburban location (Bijlmer, 26.07.1995, 6.00 h).

Type d

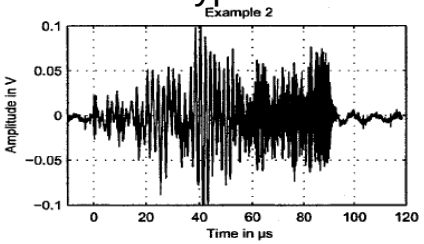


Figure 4: Time domain signal of two impulse events

Type e

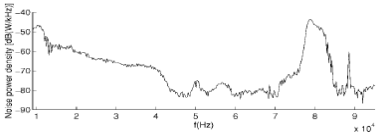


Fig. 5. Example of a narrow-band disturbance (around 80 kHz) as measured in the industrial site (Ypolder, 29.07.1995, 17.00 h).

Type c

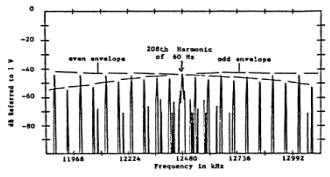


Fig. 6 Expanded plot of the voltage spectrum of the light dimmer about 12 480 Hz, showing both odd and even harmonics-from [1].

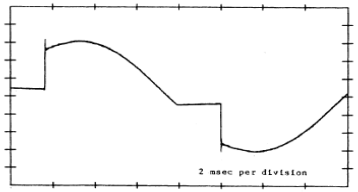
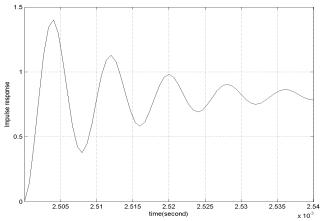


Fig. 13. Current through 100-W lamp with dimmer set for maximum brightness.



Performance Tests Available

Scenario 6: Line impedance channel+colored noise+NBI (coded perf.)

Severe NBI

MATLAB®-generated time domain Noisy test vector with line imp. channel

Test vector loading

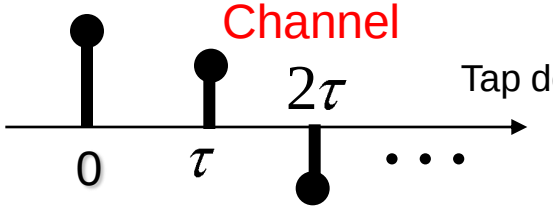
AMU operation

AFE board

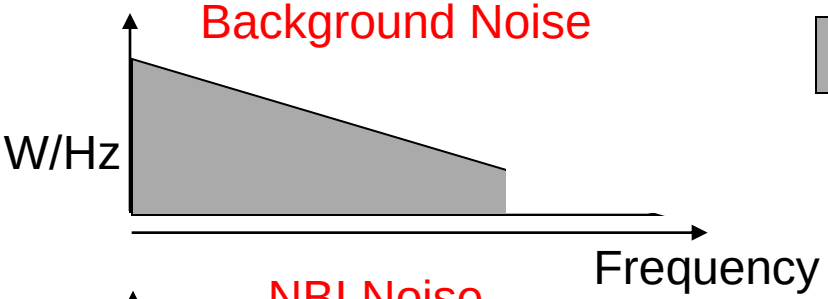
DSP board

BER meas

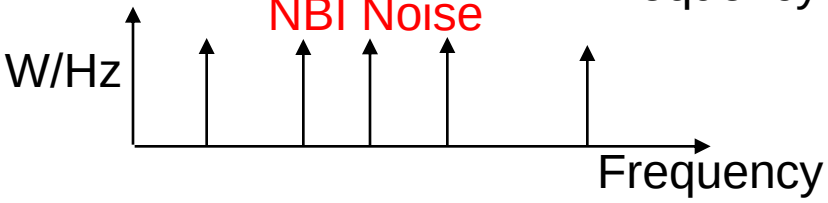
Channel

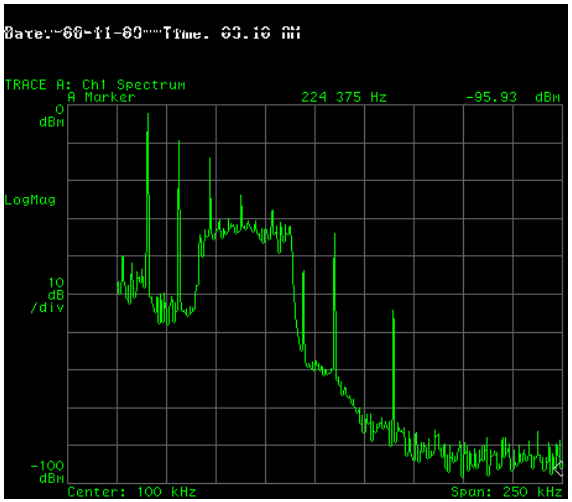


Background Noise

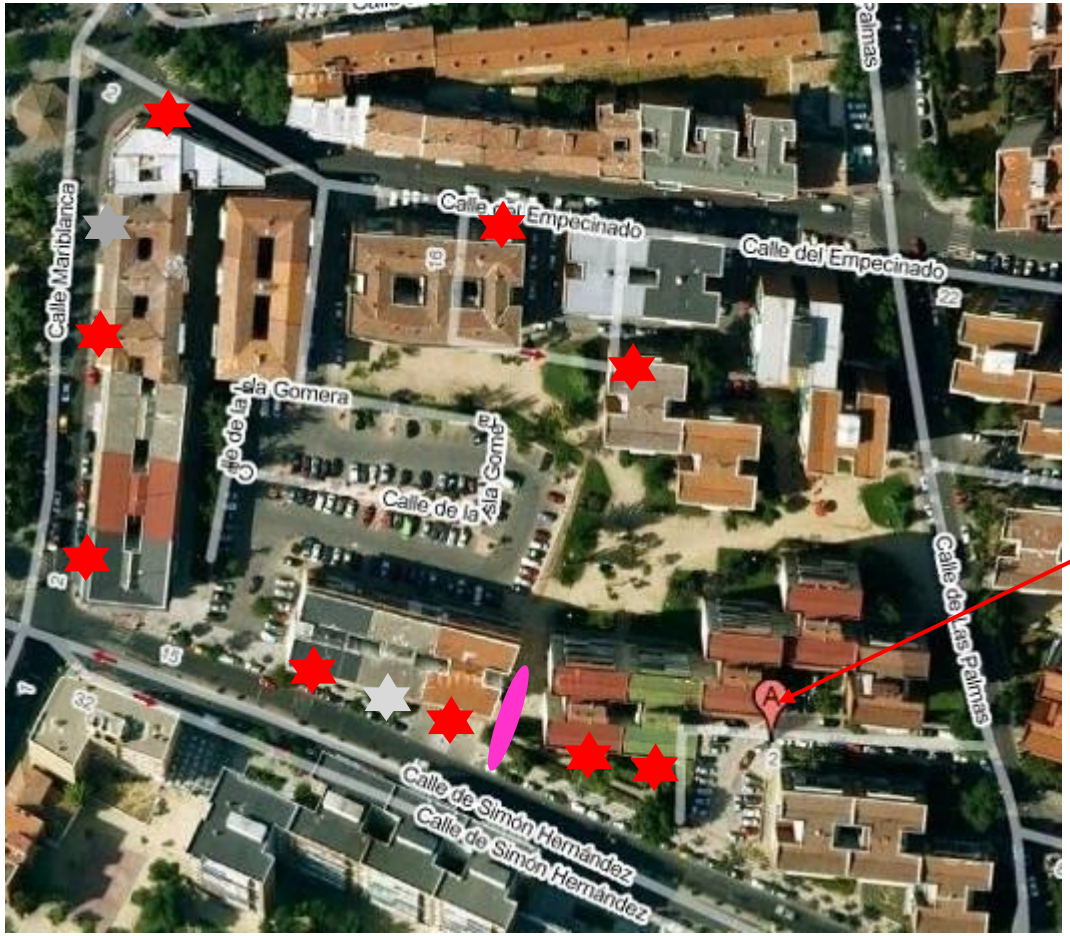


NBI Noise





Joint TI – Utility PLC Field test example



64 kbps

42 kbps

21 kbps

Service nodes in meter room

Transmitter In MV→ LV transformer room

TI PLC

Base Node in Substation

- 64 kbps with no packet errors seen in 8 out of 12 houses
- All but one house reached
- 42 kbps reception achieved at 263 m

PRIME Modem Test Summary

Internal Lab Tests

- PHY functionality and performance tests
  - Compare performance to Matlab end-to-end simulation under various channel impairments models
- PHY powerline tests : Tested on powerline to ensure electrical stability
- MAC functionality test
  - Point-to-point tests including packet fragmentation / aggregation, ARQ and AES
- Lab Network Tests (partnering with Current basenode implemented on Linux box)
  - Emulate real network including multi-level switching using attenuators

Field Tests On Iberdrola Grid in Spain

- TI PHY-only (point-to-point) tests in August 2009
  - Established stability of TI hardware, robustness of PHY algorithms
  - Data rate upto 63 kbps in 8 out 11 meter rooms, range up to 263m with 42kbps data rate
- Joint network level (PHY+MAC) tests with Current base node in Nov 2009
  - Established interop of TI service / switch nodes with Current basenode
  - Supported up to 24 modems concurrently, with both single-phase and three-phase coupling by the base node
  - Automatic network configuration, with up to two-level switches
  - Ran Iberdrola-specified AppEmu tests
- Mini-network with 12 modems (4 meter rooms) left running in Mostoles
  - Will be monitored for network stability, performance improvements

Selection Criteria?

Criteria	TI answer today
Bit rate	up to 128kbps
Modulation	S-FSK and LF NB OFDM
Robustness	Field experience
Standard	IEC61334, PRIME, G3
Proprietary	SW flexible approach
System Cost	MCU + AFE optimized
Application + PLC	SW Flexibility + MCU portfolio
Plug it-forget it	HW and SW references
Support	R&D Labs

TI is Very Active in Power-Line Communication

- **PRIME principal member**
  - TI is a principal member of PRIME consortium (TWG and MWG)

    www.prime-alliance.org

    Solution available and delivered to customers worldwide
  - Successful MAC/PHY on field trials in Madrid
  - Interoperability test with current technology – Press release link
- **Narrowband supporter**
  - **S-FSK** IEC61334-4-32 LLC
  - **OFDM PRIME** and **G3 support**
- **Contributing member**
  - IEEE 1901.2: Narrow band PLC
  - ITU – G.hnem: board of director
  - Electrical car charging (SAE/IEC/JARIB)
  - Committees: TEVHYB6 (PHEV), TEVEES17/17B (EMI)
  - J551-5 analysis on conducted emissions in PHEV
  - Worked with J1772™ to clarify EMI requirements