Texas Instruments Smart Grid Business Unit

www.ti.com/smartgrid

Agenda

- WW Smart Grid Activities

- TI Smart Grid Business Unit

-TI PLC Development & Roadmap

- HW Architecture

- plcSUITE

- TI PLC FlexOFDM

- TI PLC Standard Activities

- TI PLC field test overview

- TI PLC certification and lab test procedure

WW Smart Grid Activities

Overview about WW Smart Grid activities

North America

- Obama announced $3.5B USD government **stimulus funding** for Smart Grid

- US is one of the leading countries in moving to a smart grid

- Main communication technologies used:

  a) meter to grid RF mesh <1GHz

  b) meter to home area network (HAN) RF 2.4GHz ZigBee

- Smart Grid applications move to all IPv6 which demands higher performance & high memory **application processors**

-Smart Energy Profiles at Home Area Network for smart appliances, energy monitor, etc

- **OFDM based Power Line Communications** for Grid-2-home, solar panel/solar farms, smart building, street lighting applications

Overview about WW Smart Grid activities

Europe

- The European Technology Platform (ETP) estimates an investment of €390B USD until 2030

- Italian utility Enel became the first utility in the world to roll out smart meters (**40 million customers**. By 2006, Enel had **spent $3 billion** for smart grid infrastructure and was reaping $750 million in annual savings)

-Iberdrola, ERDF, Enel and E.ON are first rolling out smart meters with PLC

    - PLC PRIME standard for AMI/AMR deploying >500K units in Iberdrola Grid in 2011

    - PLC G3 standard by ERDF deploying >2K units in French Grid in 2011

    - 1Mu rural meters, 34Mu city meters of G1 by ERDF 2012-2013

- France, Spain are the most experienced in PLC implementation (FSK, PRIME)

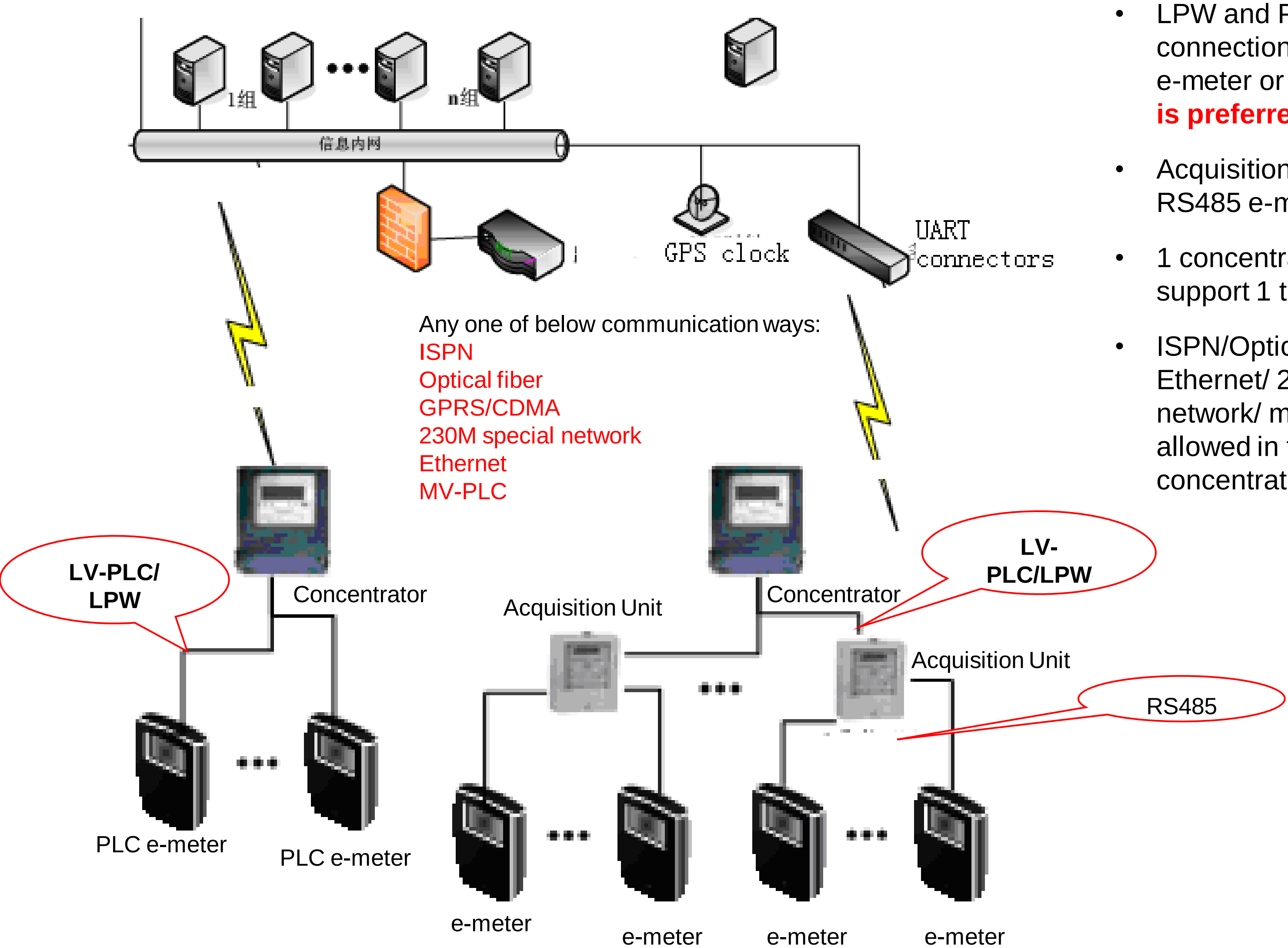
- W-Mbus for In-Home network connectivity

Overview about WW Smart Grid activities

China

- China government invests $$$ on all perspectives of smart grid application: smart metering (AMR/AMI), solar energy/solar farm, Electrical Vehicle
- China State Grid Corporation Company (SGCC) invests >$30B for 170M units smart e-meter project from 2010
    - 200M rural e-meters will be replaced by the standardized e-meter in 2010- 2011
- CEPRI is the technology arm of SGCC and plays an important role in China e-meter market
    - Standard drafts, lead the bidding, certificate the e-meter
    - TI formed strategic relationship with CEPRI for SoC for smart grid market
- China Grid Architecture:
    - Core Network ➔ Data Concentrator: Wireless (GPRS, etc)
    - Data Concentrator ➔ Acquisition Unit: LV PLC (main) and Low Power RF
    - Acquisition Unit → eMeter: RS485 (main) and LV PLC
- Key care-about: Robustness, Cost, Power

China State Grid E-meter Project AMR System

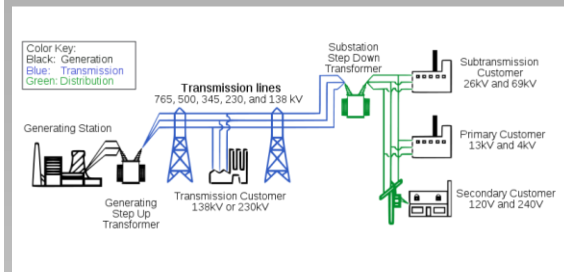


- LPW and PLC are allowed in the connection between concentrator and e-meter or acquisition unit, but **PLC is preferred by State grid now**
- Acquisition unit is used to connect the RS485 e-meter to PLC concentrator
- 1 concentrator or acquisition unit can support 1 to 32 meters
- ISPN/Optical fiber/ GPRS/CDMA/ Ethernet/ 230M special wireless network/ mid voltage PLC are allowed in the connection between concentrator and server center

TI Smart Grid Business Unit

Focus segments for a Smart Grid

Smart Grid infrastructure	Smart Meters	Smart homes and buildings



- Concentrators
- Power Monitoring & Protection
- Renewable Energy
- HV Circuit Breaker

- Electricity meter
- Gas meter
- Water meter

- In home display
- Thermostats
- Smart Appliances
- Circuit Breaker
- Charging elect. vehicle

TI Technologies for Smart Grid Solutions

Microcontrollers ARM-Based				Complementary Analog		
16-bit	32-bit real-time	ARM 32-bit	ARM +	Low-power RF	Analog	Saving power
MSP430™	**C2000™**	**Stellaris® M3**	**ARM 9, OMAPL1x**	**CC**	**OPA, THS, ADC**	**TPS, UCC**
Ultra-low power	Real-time MCU ADC, Flash	Industry std. low power	Industry std. High Perf GPP	RF SoC transceiver	Amp, LD, PGA ADC, DAC	AC/DC, DC/DC, LDO
Up to 25 MHz	Protocol stack & modem	< 100 MHz	Accelerator	433 to 2500 MHz	Full range	Full range
Flash 1KB to 256KB	Embedded Flash f. upgrade	Flash 256kB with path to 2MB	MMU	Flash for SoC	Various technologies	Ultra low-power high efficiency
RTC, ADC, MPY, USART	Appropriate peripherals	Multi-serial port encryption Analog integration	USB, LCD MMC, EMAC, LINUX/WinCE	Appropriate peripherals		
Measurement metrology MCU	PLC Modem Multi- modulation S-FSK/OFDM PRIME/G3	Smart Grid application processor	Data Concentrators/ Power Analytics	Mesh-RF ZigBee®, WM-Bus	Measurement PLC	Metering saving power

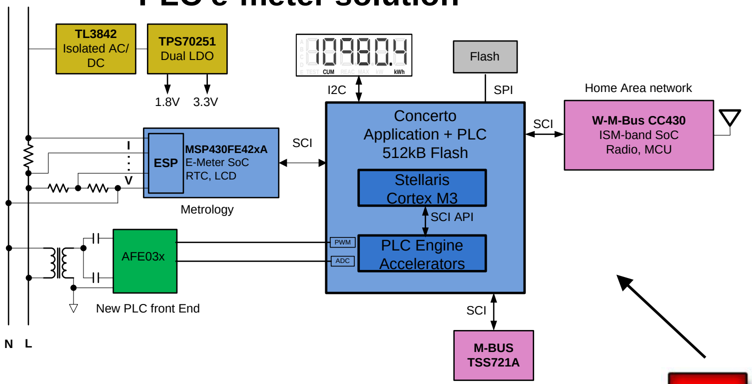



Smart Grid Business Unit

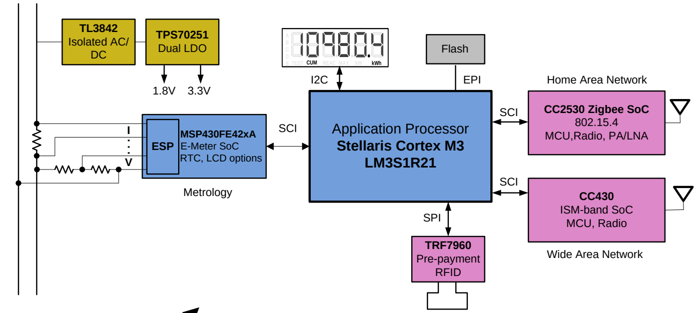
Marketing, BD, System/Application, Software team, Standardization & Government relations support

Examples of TI’s System solutions for Smart Grid

PLC e-meter solution



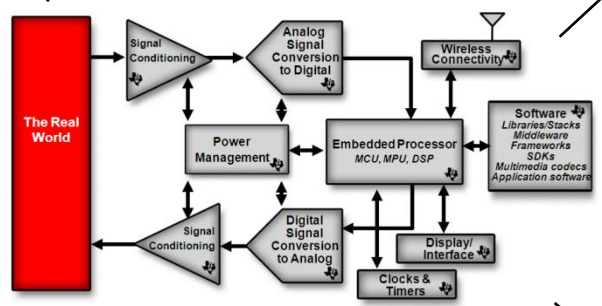
RF e-meter solution



Software:

Metrology: Single Phase, 2-Phase, 3-Phase

Security / Encryption, DLMS, RTOS

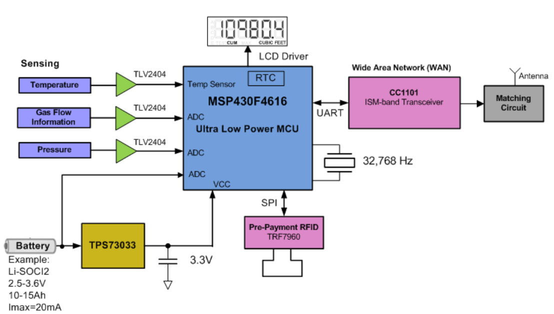


Software:

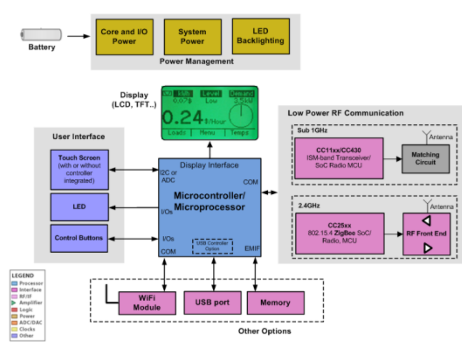
Wired Communications: SFSK, PRIME, G3, Flex OFDM, KNX

Wireless Communications: WMBUS, SEP 1.0/2.0, Sub 1GHz, 802.15.4g

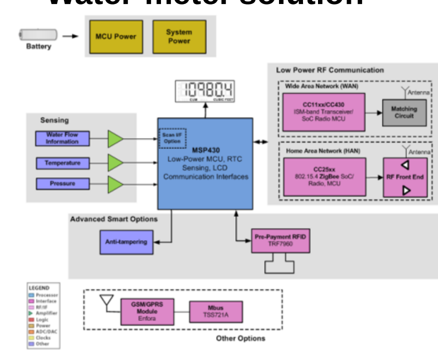
Gas-meter solution



In-Home Display



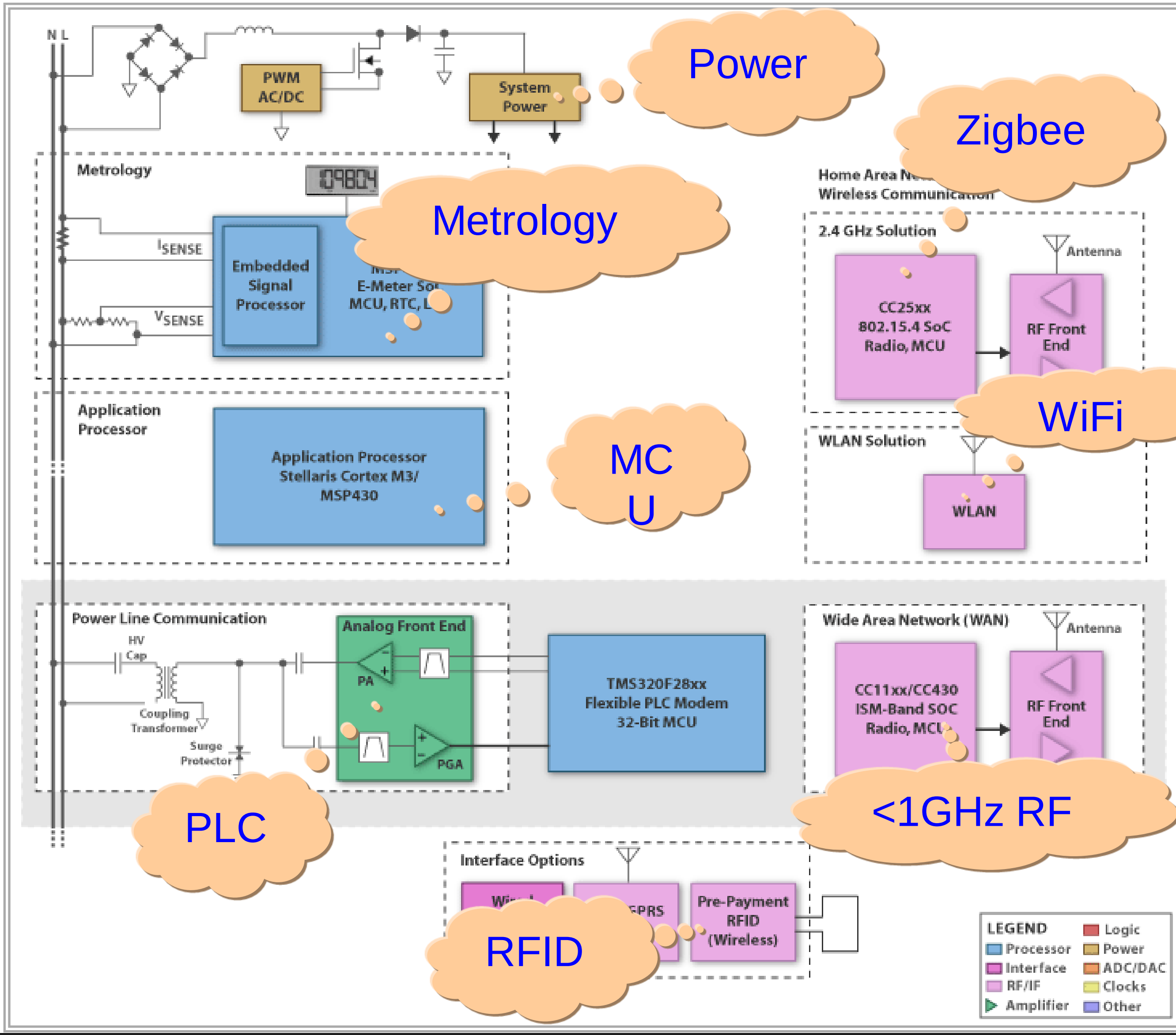
Water-meter solution



TEXAS INSTRUMENTS

TI can offer: Smart meter architecture

- HW
  - •MCU
  - •RF & RFID
  - •PLC
  - •Power
  - •Analog
- SW
  - •Metrology
  - •Zigbee
  - •PLC
  - •WMBUS
- expertise
  - •RF
  - •PLC
  - •metrology
  - •ARM
  - •security
  - •support



TI PLC Development & Roadmap

PLC for Smart Meter Application

Market

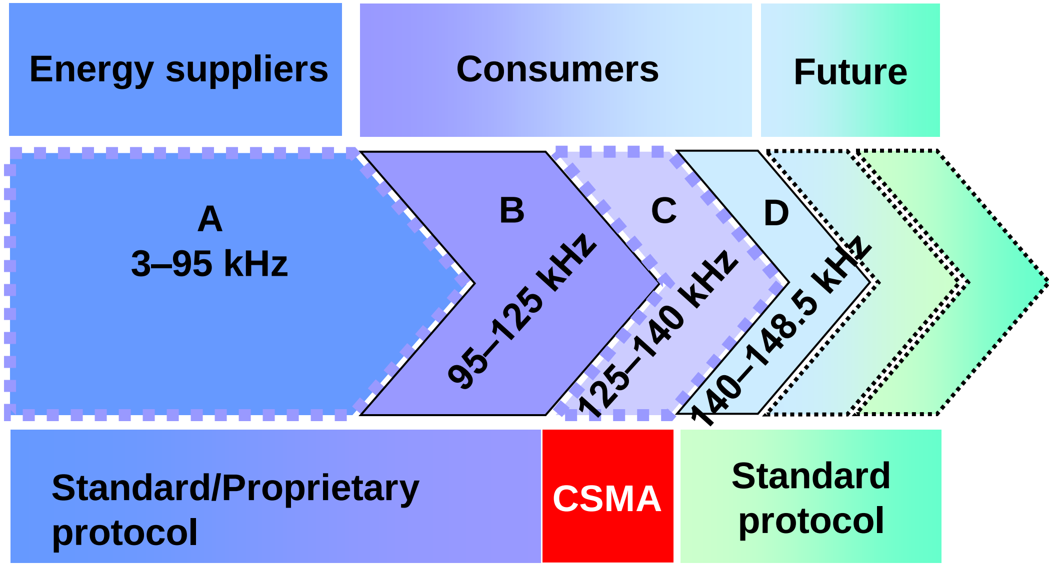
- Research reports ~**250M** installed smart meters by 2015
- Europe and North America are leading with Asia growing fast
- PLC is the most adopted communication technology in Smart Meters: 60% share

Popular PLC for Smart Meter Standards:

-IEC-61334 S-FSK/G1, PRIME, G3, G.9955, P1901.2

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 CEPRI
  - 3–500 kHz single-band not regulated

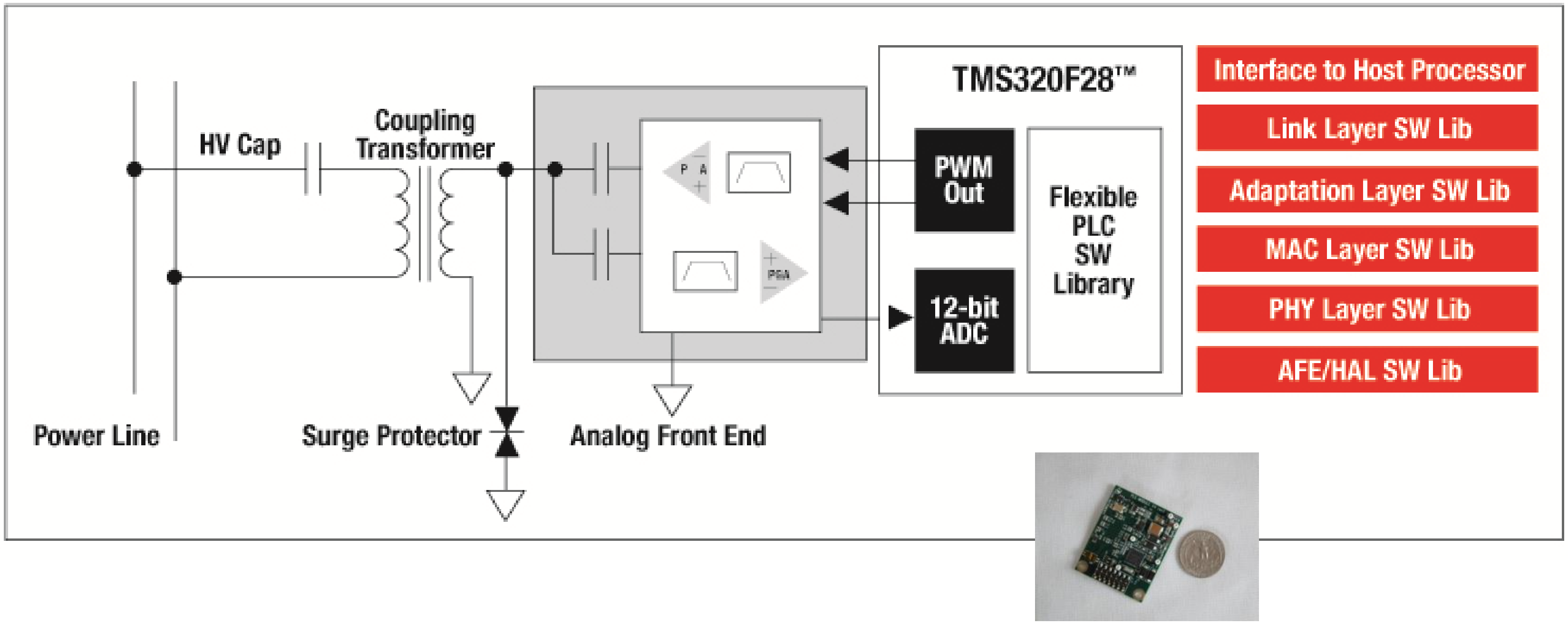
15

IEC61334, PRIME, G3 and IEEE P1901.2

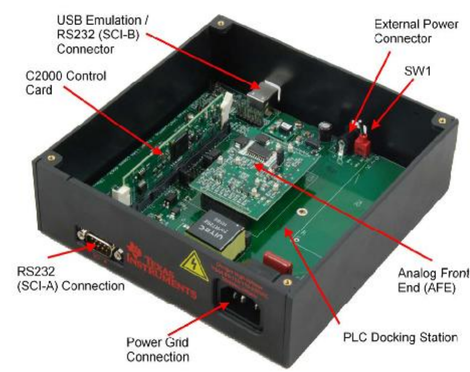
Parameter	IEC61334 S-FSK	PRIME(OFDM)	G3(OFDM)	P1901.2(OFDM)
Modulation Size	Spread Frequency Shift Keying	DBPSK / DQPSK/D8PSK	DBPSK / DQPSK/(D8PSK)	DBPSK/DQPSK/D8PSK/ Coherent Modulation
Forward Error Correction	N/A	Rate ½ Convolutional Code	Outer RS + inner rate ½ convolutional code	Outer RS + inner rate ½ convolutional code
Data Rate	2.4Kbps	21, 42, 64, 84, 64Kbps (w/ coding)	20.36,/34.76/(46) Kbps (with coding)	Scalable up to 250Kbps
Band plan	CENELEC-A	Continuous 42-89 KHz (defined for LV scenario)	36-91 KHz with tone masking for SFSK	CENELEC-A, FCC band
ROBO Mode	No	No	Yes	Yes
Tone Mask	No	No	Yes	Yes
Adaptive Tone Map	No	Yes	Yes	Yes
MAC	IEC61334 MAC	PRIME MAC	802.15.4/G3 profile	802.15.4 based
Convergence Layer	IEC61334-4-32	IEC61334-4-32/IPv4	6LoWPAN/IPv6	6LoWPAN/IPv6
Meter Application	COSEM/DLMS	COSEM/DLMS, IP	COSEM/DLMS, IP	COSEM/DLMS, IP

TI PLC Programmable Solution

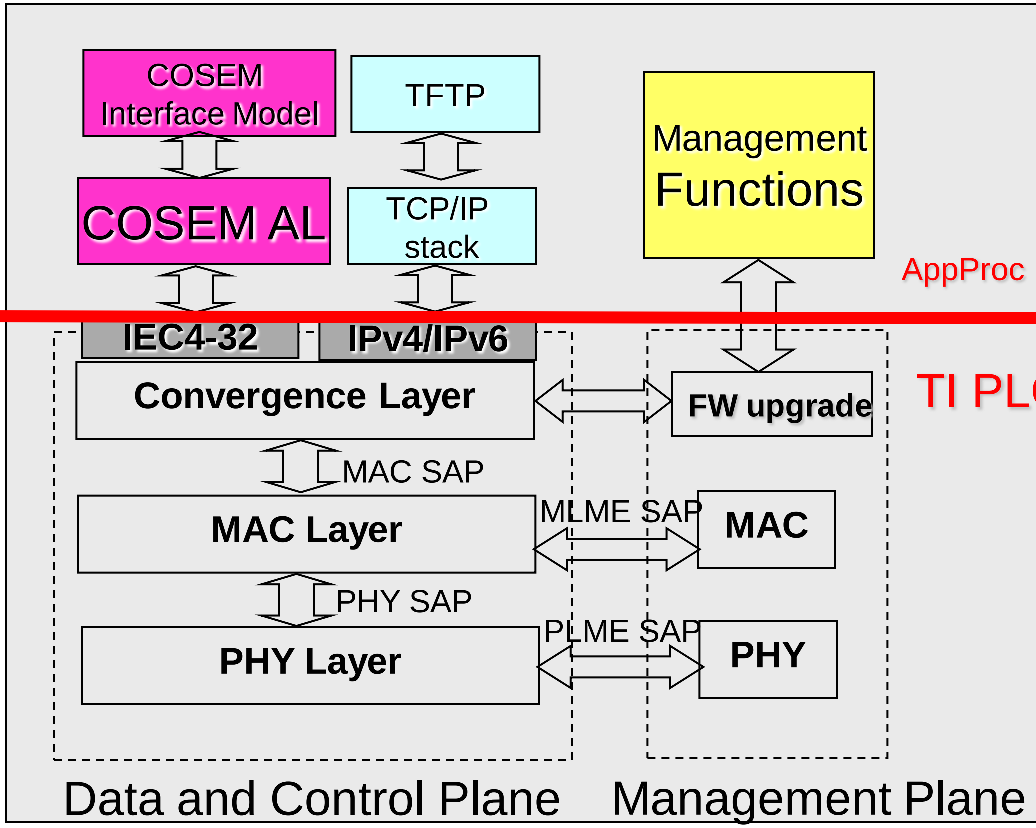
TI Narrowband PLC Solution
Flexible, scalable and easy to customize



- **Flexible Hardware**: Single HW Digital + AFE support
  - Frequency (0-500KHz)
  - C2000 family: F28335, F2806x, F28035(piccolo-B), Concerto
  - **Conformance Certified: PRIME Alliance Certification Lab**
- **plcSUITE SW Package**:
  - Multiple standards: PRIME, G3, P1901.2, IEC61334 (S-FSK)
  - Certified SW Libs, APIs
- **FlexOFDM:** Further Feature Enhancements

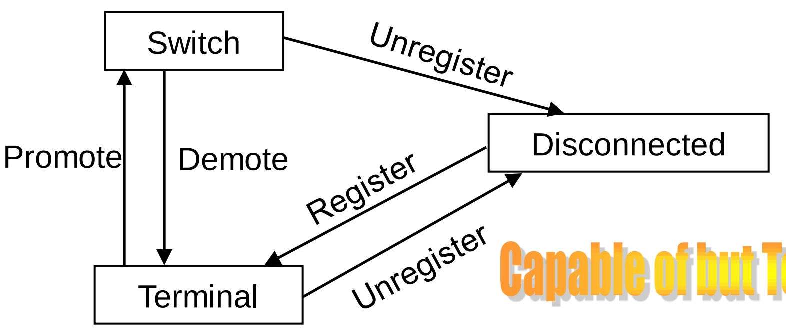


PRIME



Features

- Terminates @ IEC4-32 LLC in F28069
- CENELEC-A band
- BPSK, QPSK, 8PSK, **ROBO**
- IPv4/IPv6*, automatic network formation
- Resources Usage:
  - MIPS: ~60MHz Peak
  - RAM/FLASH: 90KB RAM, 220KB
- Room for eMeter App in F28069
- ROBO tested for crossing LV/MV transformers

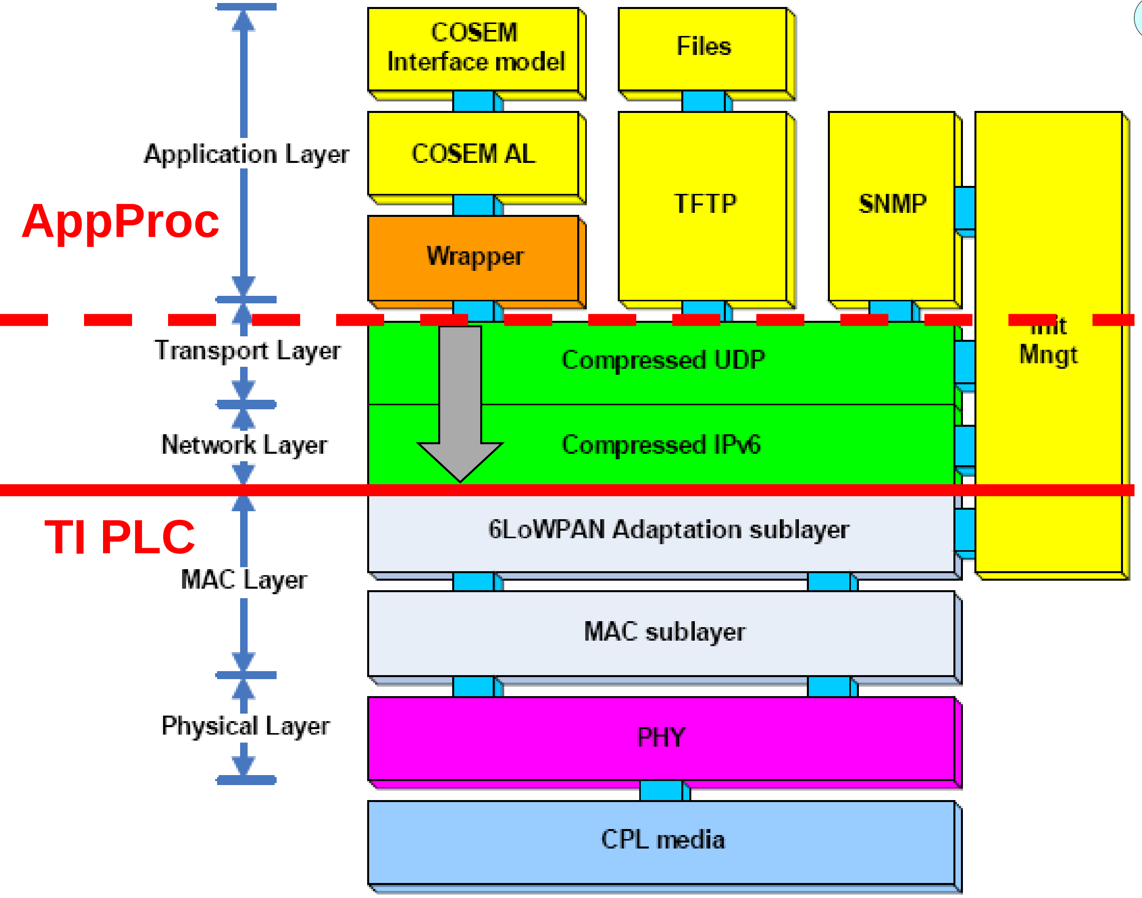


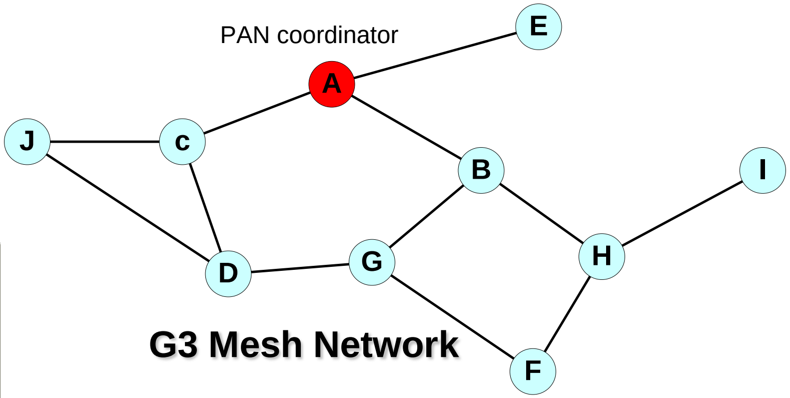
Capable of but Terminal and Switch

Quality

- Prime Conformance Certified
- Interoperable with 4 major DC vendors: Current, ZIV, Ormazabal, Nucleus.
- Mass deployment in Iberdrola grid

G3





G3 Mesh Network

Features

- Terminates @ 6LoWPAN layer (or IPv6/UDP)
- CENELEC A, B, C, D, FCC
- Automatic Mesh network
- System Resources
  - MIPS: peak ~90 MHz, avg 60MHz
  - RAM/Flash: 80KB/220KB
- Both eMeter and **mini-concentrator** configure
- DC Support with ARM926

Quality

- PHY test vectors IOT with MAXIM
- ERDF G3 Conformance Test Ready
- WW Field Tests: LV/MV transformer crossing, LV/LV field tests

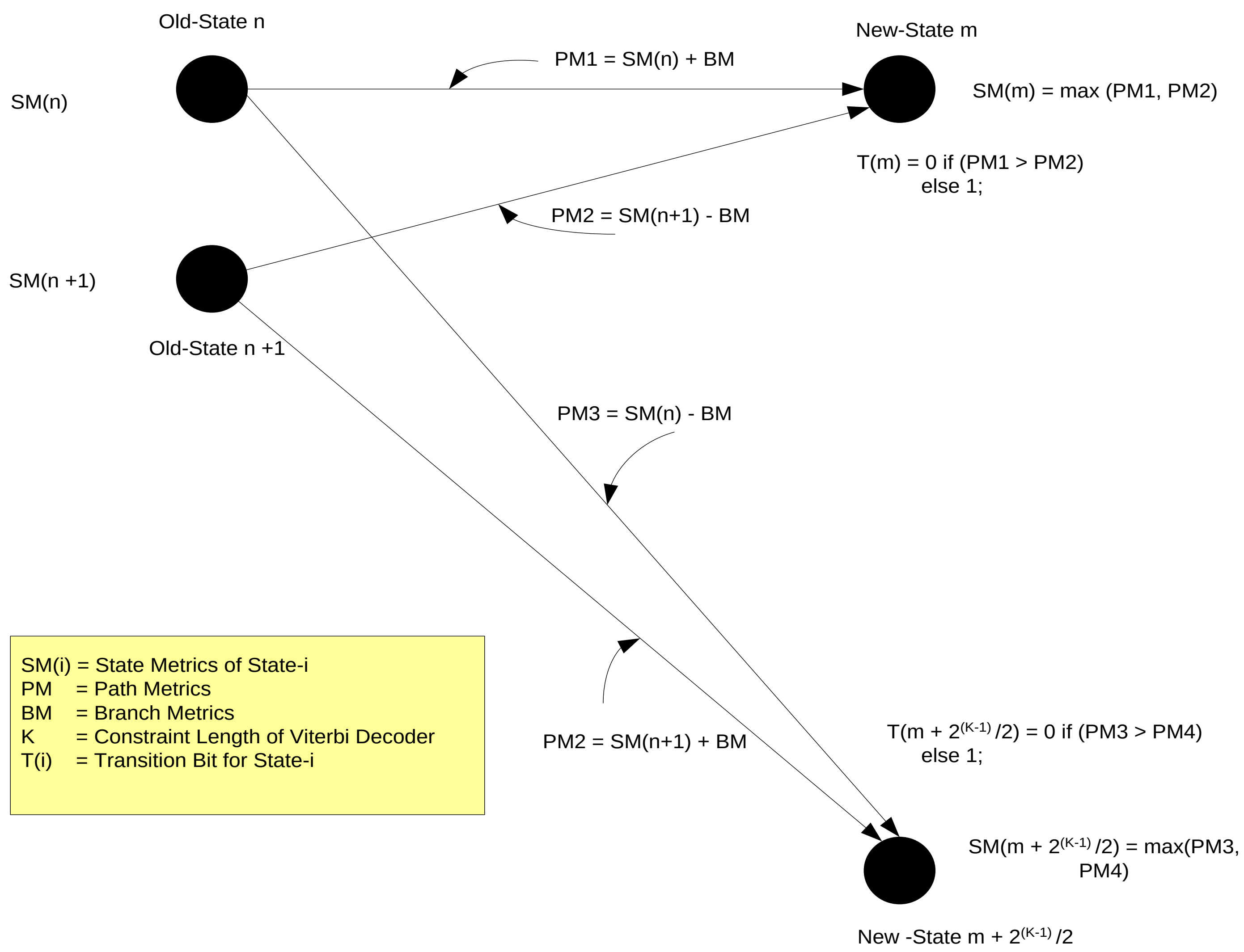
HW Architecture

Application-Specific MCU – What is it?

- ASIP – Application-specific instruction set processor
  - Provides ***special instructions*** to accelerate PLC computations
    - ***FEC*** computations (Viterbi acceleration, Galois field arithmetic)
    - ***FFT/IFFT*** acceleration
    - ***Complex arithmetic***
    - ***Security engine*** (CRC, other instructions to accelerate AES computations)
  - Provides instructions to accelerate frequently used computations

- Benefits
  - ***Competes with custom ASIC*** in terms of cost and power dissipation while ***achieving full software programmability***
  - Reduces MIPS, clock frequency, program memory size
  - Lower cost and power than a general purpose DSP / MCU
  - Ability to evolve implementations as PLC standards evolve

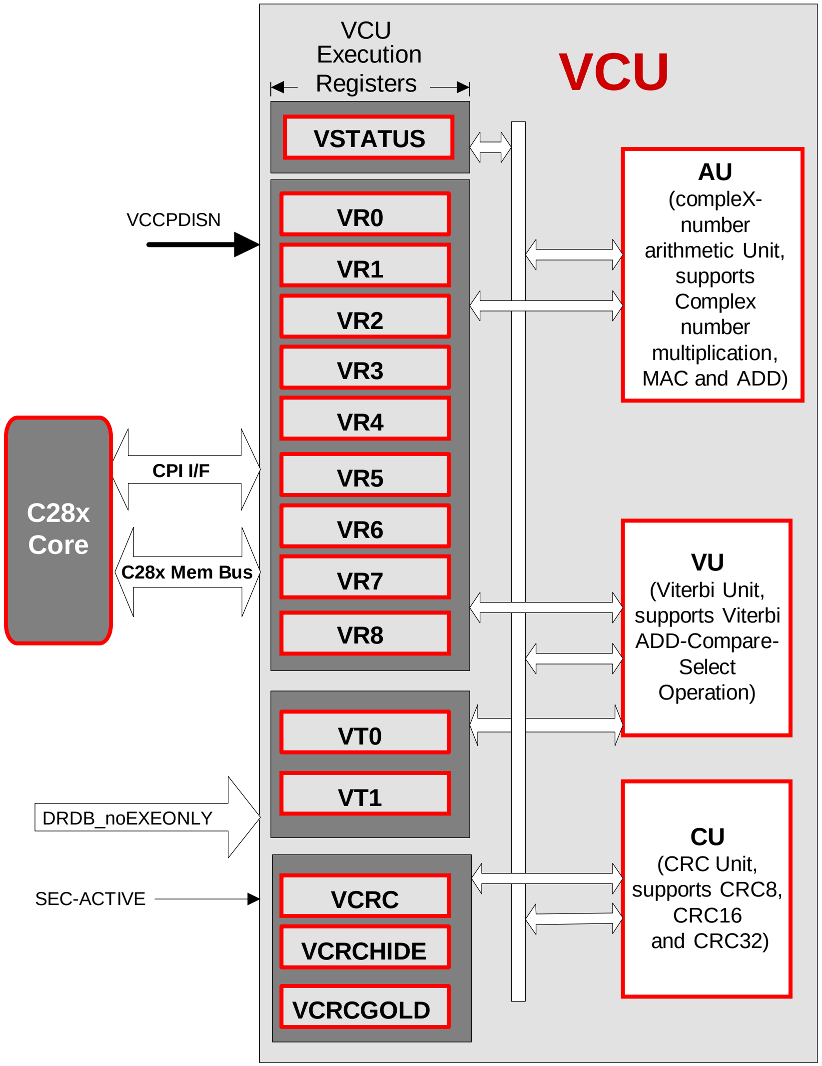
Application-Specific VITERBI Instructions

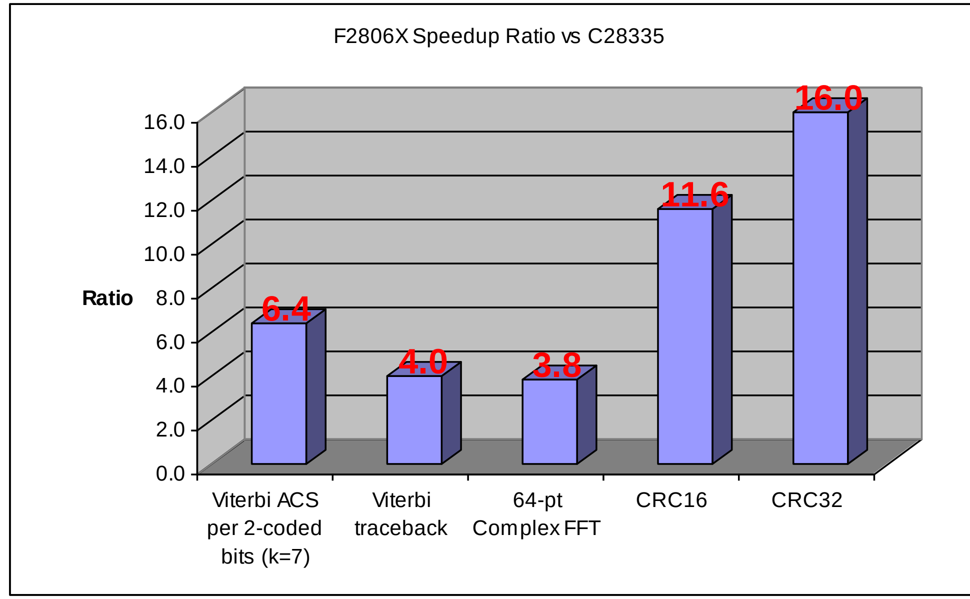


SM(i) = State Metrics of State-i
PM = Path Metrics
BM = Branch Metrics
K = Constraint Length of Viterbi Decoder
T(i) = Transition Bit for State-i

TI VCU Accelerates Communications

(Viterbi, CRC and Complex Arithmetic ASIP)





VCU-II Further Enhancements (in-progress)

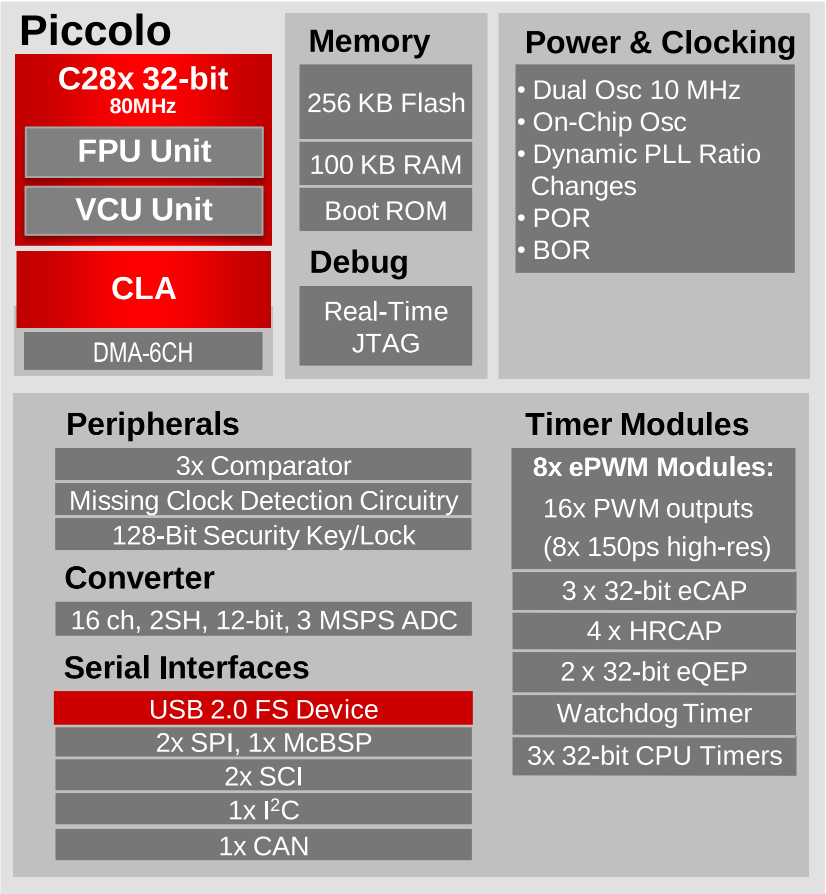
- **Reed-Solomon: 4x enhancements**
- **Viterbi: 6x faster then VCU-I**
- **FFT: 2x speed-up than VCU-I**

F2806x – New *Piccolo* Series

Performance
- **80 MHz** C28x 32-bit CPU
- **Floating Point Unit**
- **VCU (Viterbi, Complex Math, CRC)**
- **Control Law Accelerator**
- Full software compatibility with previous generations
- **6 Ch DMA**

Features
- **Core**
  - C28x 32-bit CPU
    - Single cycle 32-bit MAC
  - 80MHz Performance
  - **Floating Point Unit**
  - **VCU (Viterbi, Complex Math, CRC)**
- **Control Law Accelerator**
  - Extra 80 MIPS Performance
  - Floating Point
- **Memory**
  - Flash: 128, 256 KB
  - RAM: 36, 68, 100 KB
- **Highlights**
  - Single 3.3V supply
  - High accuracy on-chip oscillators (10MHz)
  - Three analog comparators with 10-bit reference
  - 150ps resolution on PWM frequency
  - 12-bit ratio-metric ADC
  - 2 x Quadrature Encoder Pulse (eQEP) Unit
  - CAN 2.0B up to 16 mailboxes
  - **USB 2.0 FS Device**

Markets: Power Line Modem, UPS, Motion and Low End Drives



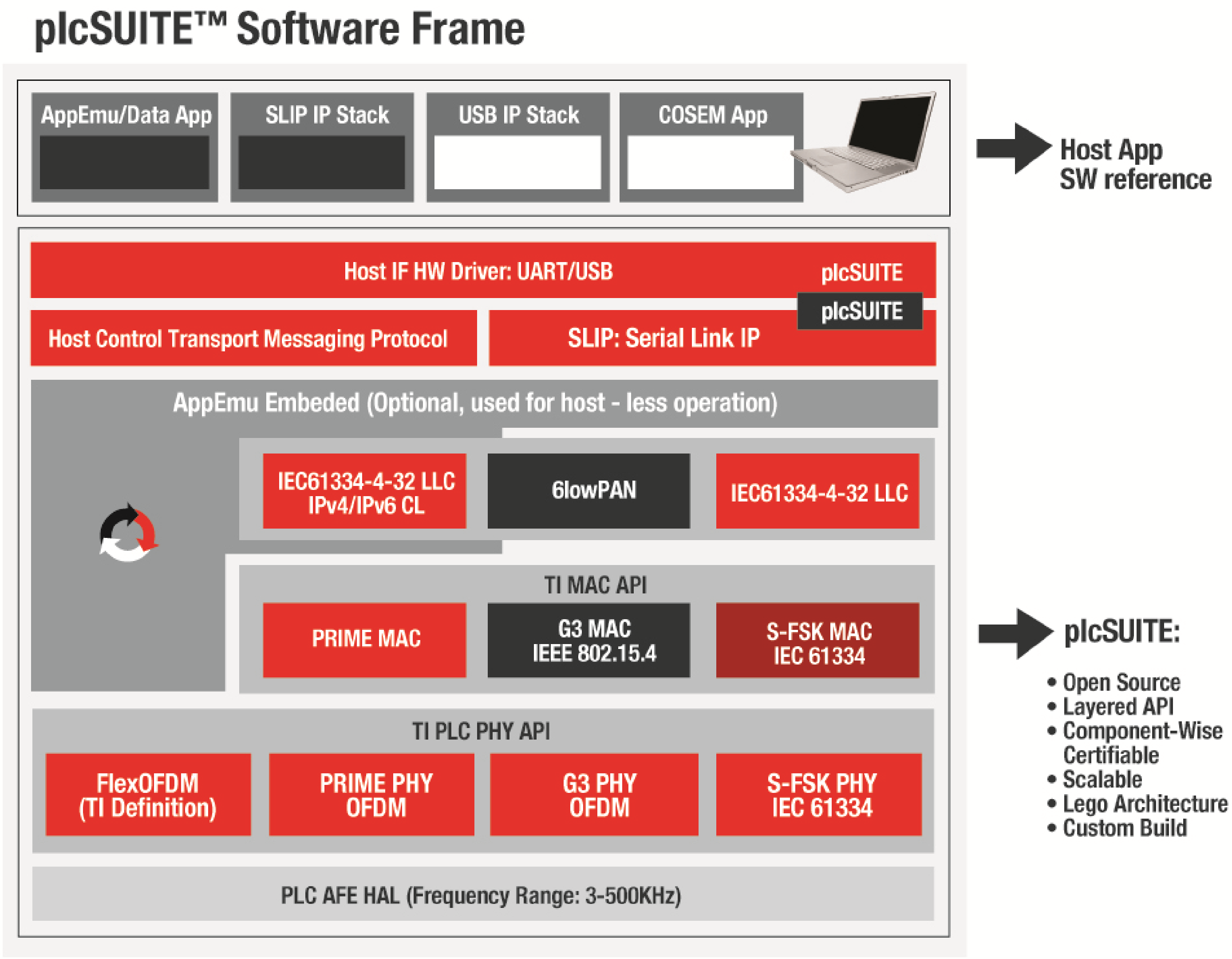
105C/125C and Q100

Packages: 80-pin LQFP*, 100-pin LQFP

*USB available 1Q'11

plcSUITE

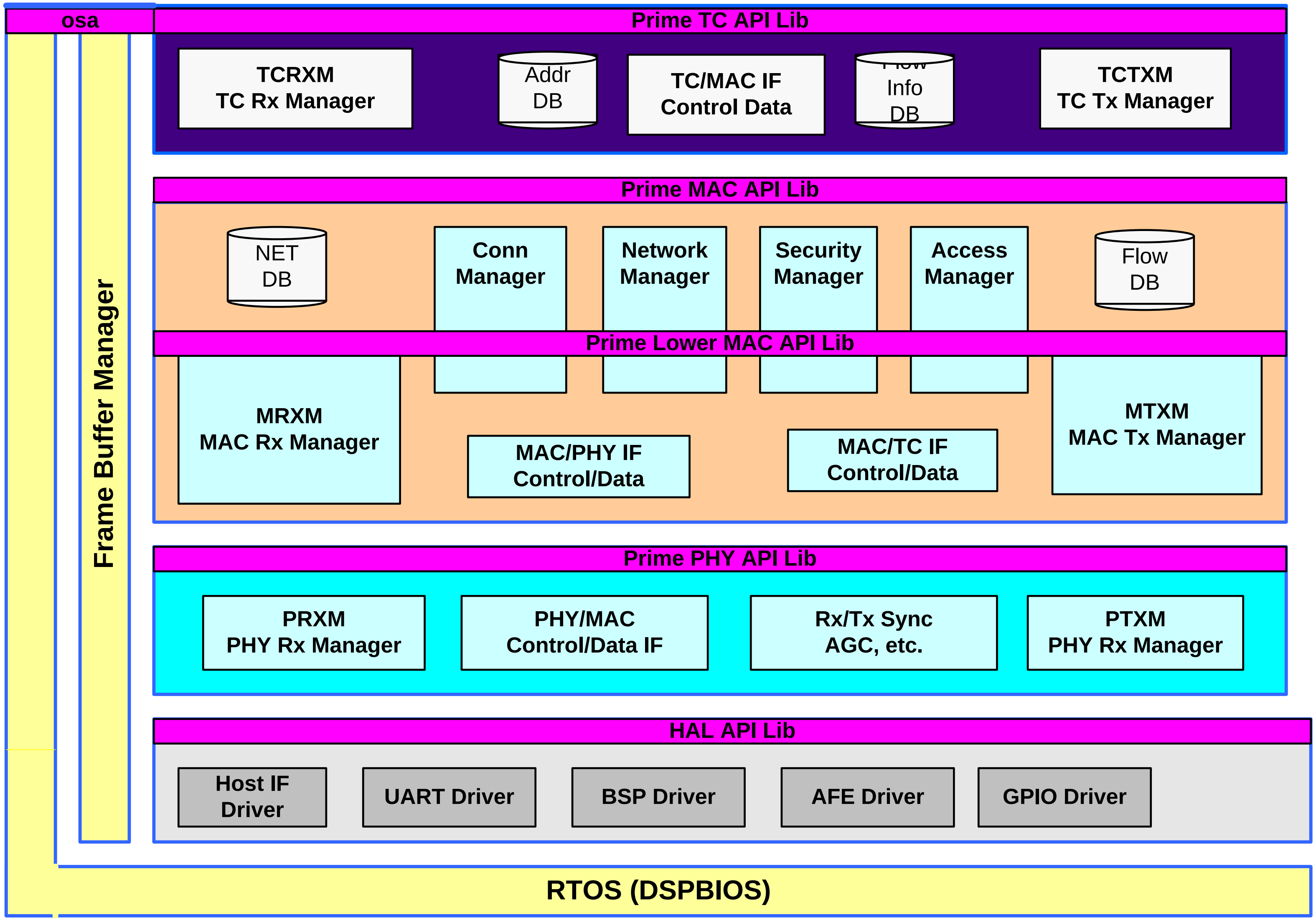
TI plcSUITE Software Framework



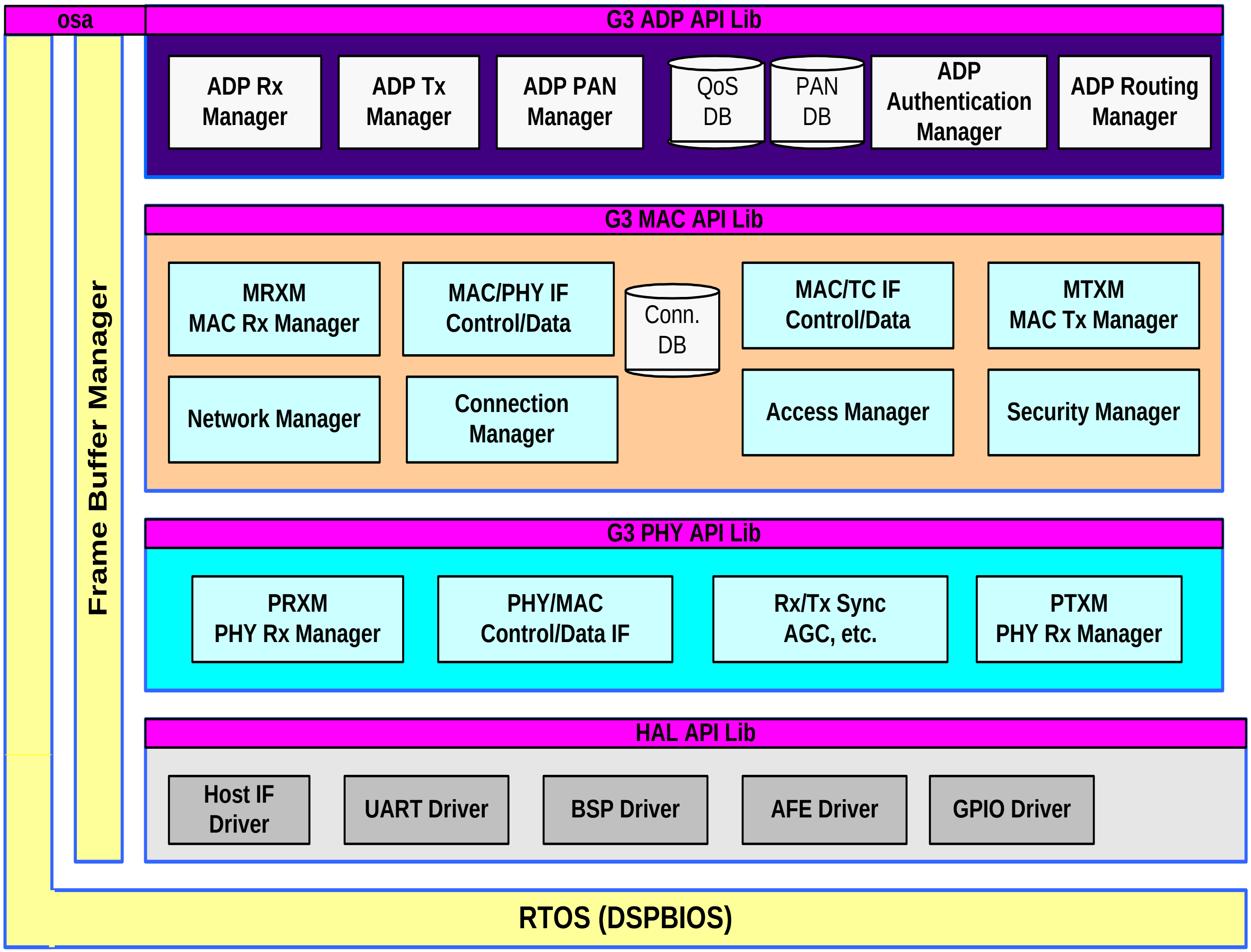
plcSUITE:

- Open Source
- Layered API
- Component-Wise Certifiable
- Scalable
- Lego Architecture
- Custom Build

TI Prime SW Stack



TI G3 SW Stack



PLC SW Framework

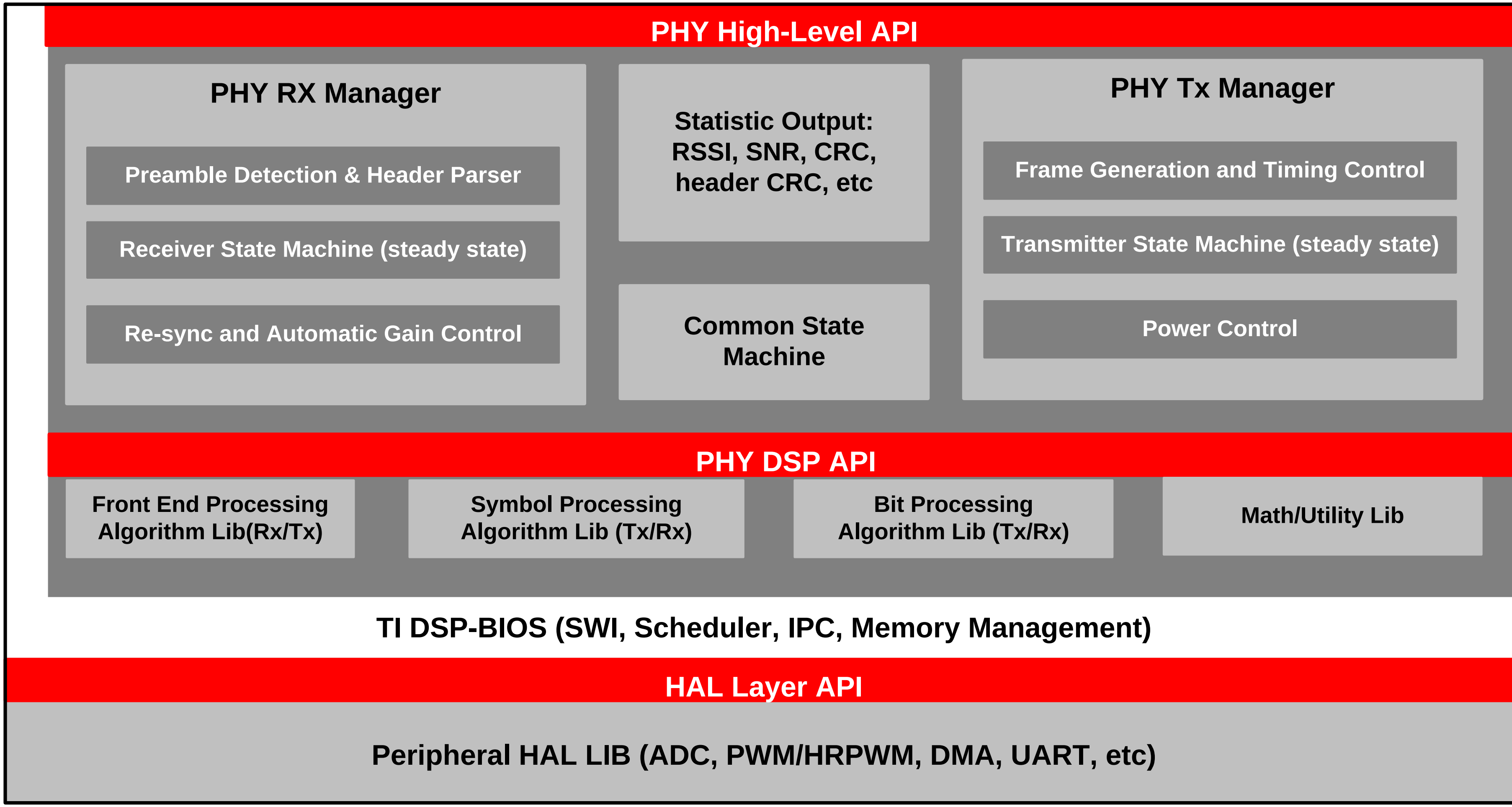
- Single SW Framework supporting Prime, G3, flexOFDM, (SFSK)
- RTOS (DSP BIOS) for Scheduling
  - Multi-threading (different priorities from deadlines): HWIs, SWIs, Task
  - Inter-thread communications: semaphores, mailbox message queues, mutex
  - OS timer: sleep, timeout callback
- PLC Functional Libraries with Standard APIs (Independent of OS or HW Platform)
  - PHY, MAC, CL libraries for PRIME
  - PHY, MAC/ADP libraries for G3
  - PHY library for flexOFDM
- HAL Abstraction with Standard APIs (Same interface for discrete AFE or AFE031, F28335, F2806X)
  - AFE (ADC, ePWM, eCAP, DMA)
  - Peripherals (SPIs, UART, I2C, McBSP, GPIOs)
- Host Message Protocol (Interface to application processor)
- Embedded meter emulation application
- Enable customers to intercept at different layer as desired (e.g. at PHY layer, Host application layer), provides:
  - Functional libraries
  - DSP application examples code: Interface to PHY
  - Host application example code: Interface to Host

TI plcSUITE Host Interface Messages

Message Type	PRIME Standard	G3 Standard	Description
0x00	DATA TRANSFER	DATA TRANSFER	Application specific Data messages
0x01	GET_SYSTEM_INFO	GET_SYSTEM_INFO	Get system (HW/SW) info
0x02	GET_PHY_PIB	GET_PHY_PIB	Get PHY PIB attributes from PLC device
0x03	GET_MAC_PIB	GET_MAC_PIB	Get MAC PIB attributes from PLC device
0x04	SET_INFO	SET_INFO	Set certain configuration to PLC device
0x05	SHUTDOWN	SHUTDOWN	Reset PLC device
0x06	SETUP_ALARM	SETUP_ALARM	Setup alarm notifications
0x07	ALARM	ALARM	Alarm Notification
0x08	NW_REGISTER	NETWORK_START	Initiate network registration process
0x09	NW_UNREGISTER		Initiate network un-registration process
0x0a	CONNECT	CONNECT	MAC Initiate connection setup process
0x0b	DISCONNECT	DISCONNECT	MAC Initiate connection teardown process
0x0c	LOAD_SYSTEM_CONFIG	LOAD_SYSTEM_CONFIG	Load system configuration data
0x0d	SET_MAC_PIB	SET_MAC_PIB	Set MAC PIB attributes from PLC device
0x0e	CLEAR_PHY_PIB	CLEAR_PHY_PIB	Clear certain PHY PIB attributes.
0x0f	CLEAR_MAC_PIB	CLEAR_MAC_PIB	Clear certain MAC PIB attributes.
0x10	ATTACH	ATTACH	PRIME CL-432 Establish Request and Confirm
0x11	DETACH	DETACH	PRIME CL-432 Release Request and Confirm
0x12		DISCOVER	Network Discovery
0x13	FIRMWARE_UPGRADE		FW Upgrade process.
0x0e - 0x7f	Reserved		
0x80 - 0xfe	Diagnostic messages		
0xff	Reserved		

- >90% Common Messages
- Easy migrate from PRIME to G3 or vice versa

TI Helps for Fast SW Development/Port



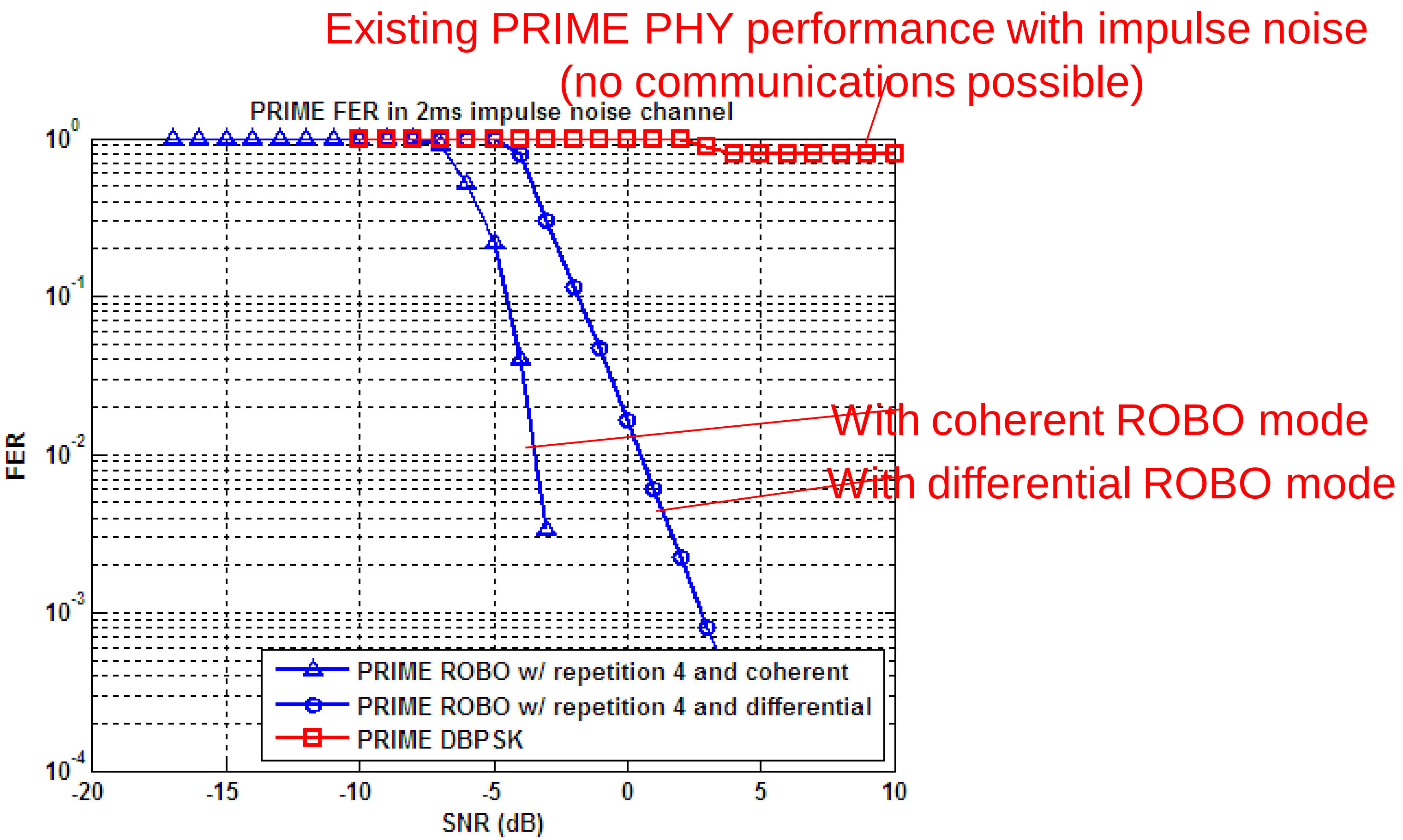
All SW LIBs with Cycle Counts Available TODAY!!!

TI PLC FlexOFDM

TI FlexOFDM Definition: Customizable OFDM

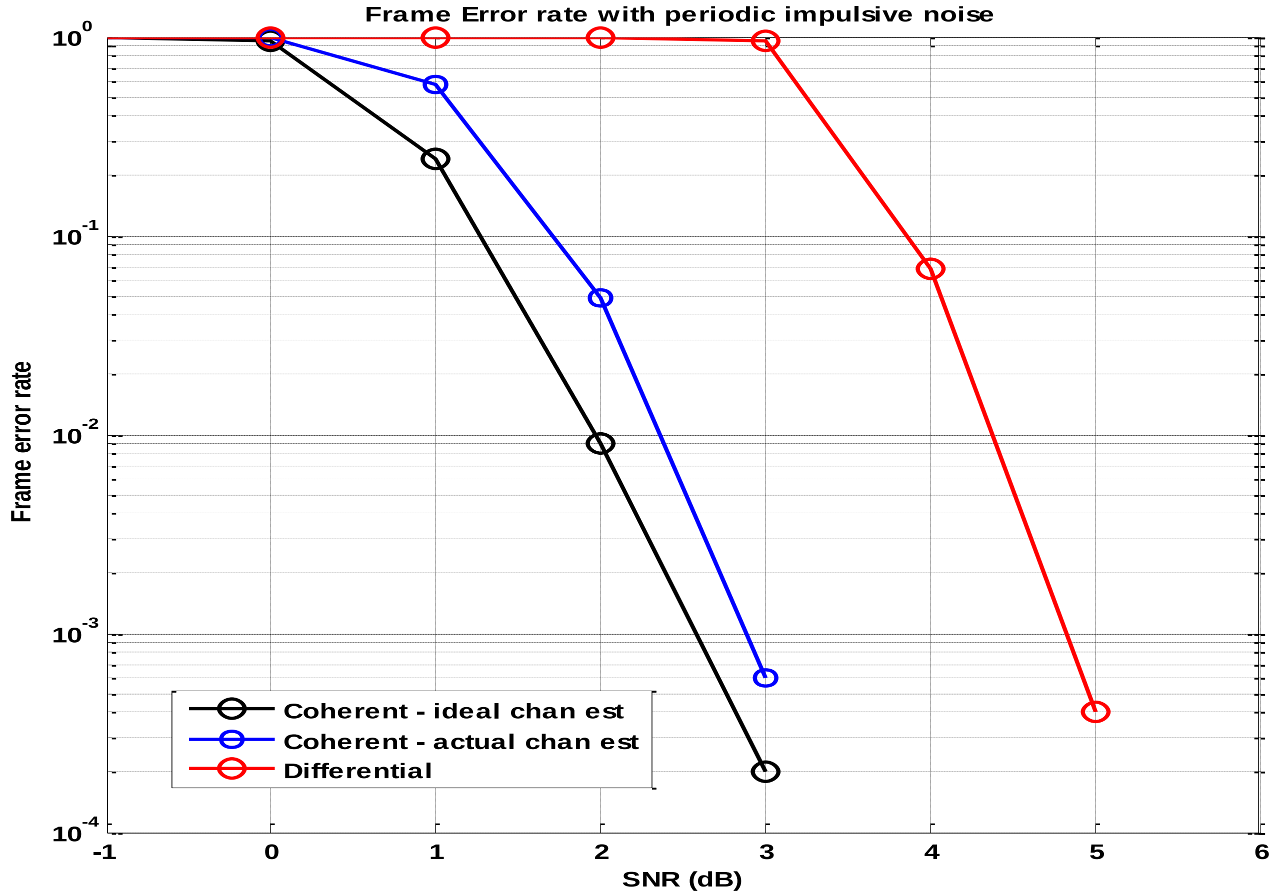
- **Frequency Band/Bandwith Flexibility:**
  - Any frequency channel: 0-500KHz, Any channel BW (today limited to 12KHz)
  - Automatic channel scan for channel quality measurement and monitor
  - Flexible Analog Front End: AFE031, AFE032, AFE033
- **Flexible PHY Layer: Best of G3/PRIME and more …**
  - Fully automated adaptive tone map and tone mask (P1901.2 contribution)
  - Coherent modulation with pilots embedded (P1901.2 optional feature)
  - Provision for longer preamble sequence for harsh line condition
  - Optional more repetitions in the header
  - Configurable block inter-leaver sizes
  - Zero-Crossing interference cancellation
  - Others to come
- **Flexible MAC Layer: Best of G3/PRIME/802.15.4e and more**
  - CSMA/CA baseline
  - Customizable GTS schedule for multiple applications: DC-DC msg/SEP2.0
  - Multiple routing (AODV, LOAD, RPL, etc): p2p/p2mp, star, tree, mesh
  - Closely coupled with PHY FlexOFDM PHY features: ATM, etc.

Performance in Impulse Noise Channel



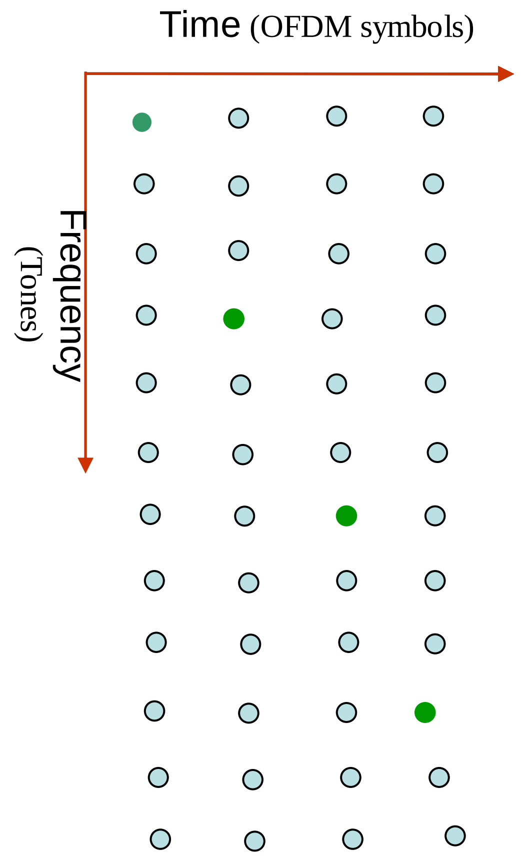
- PRIME interleaver is 2ms
  - PRIME DBPSK gives error floor with this impulse noise
  - With ROBO mode with repetition 4, will give longer interleaver
  - TI gives flexibility to provide ROBO mode
  - TI differential ROBO gives 0dB SNR for 1e-2 FER
  - TI coherent ROBO gives -3dB SNR for 1e-2 FER

Gain from coherent modulation - Example



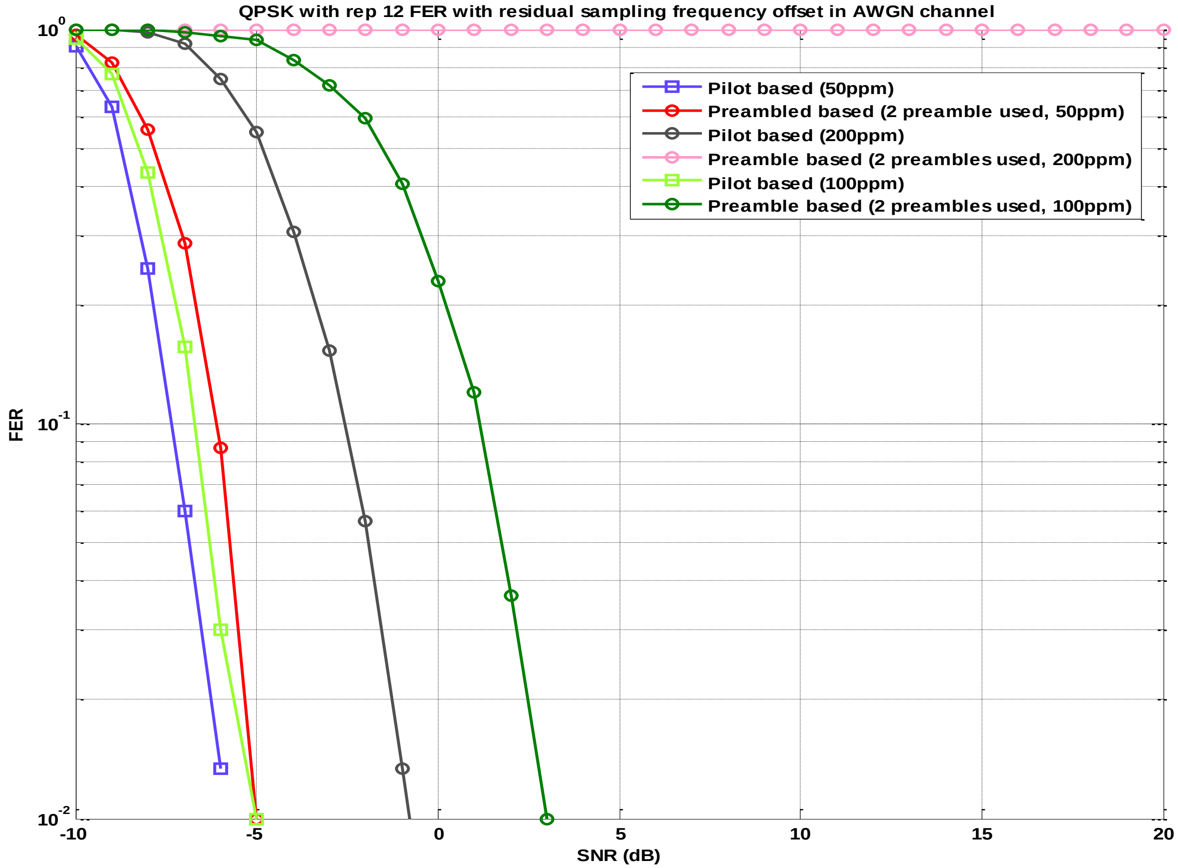
- With realistic impulsive noise model, coherent modulation gives more than 2 dB improvement for FEC without repetitions
- Gain is even greater with more repetitions

Pilots



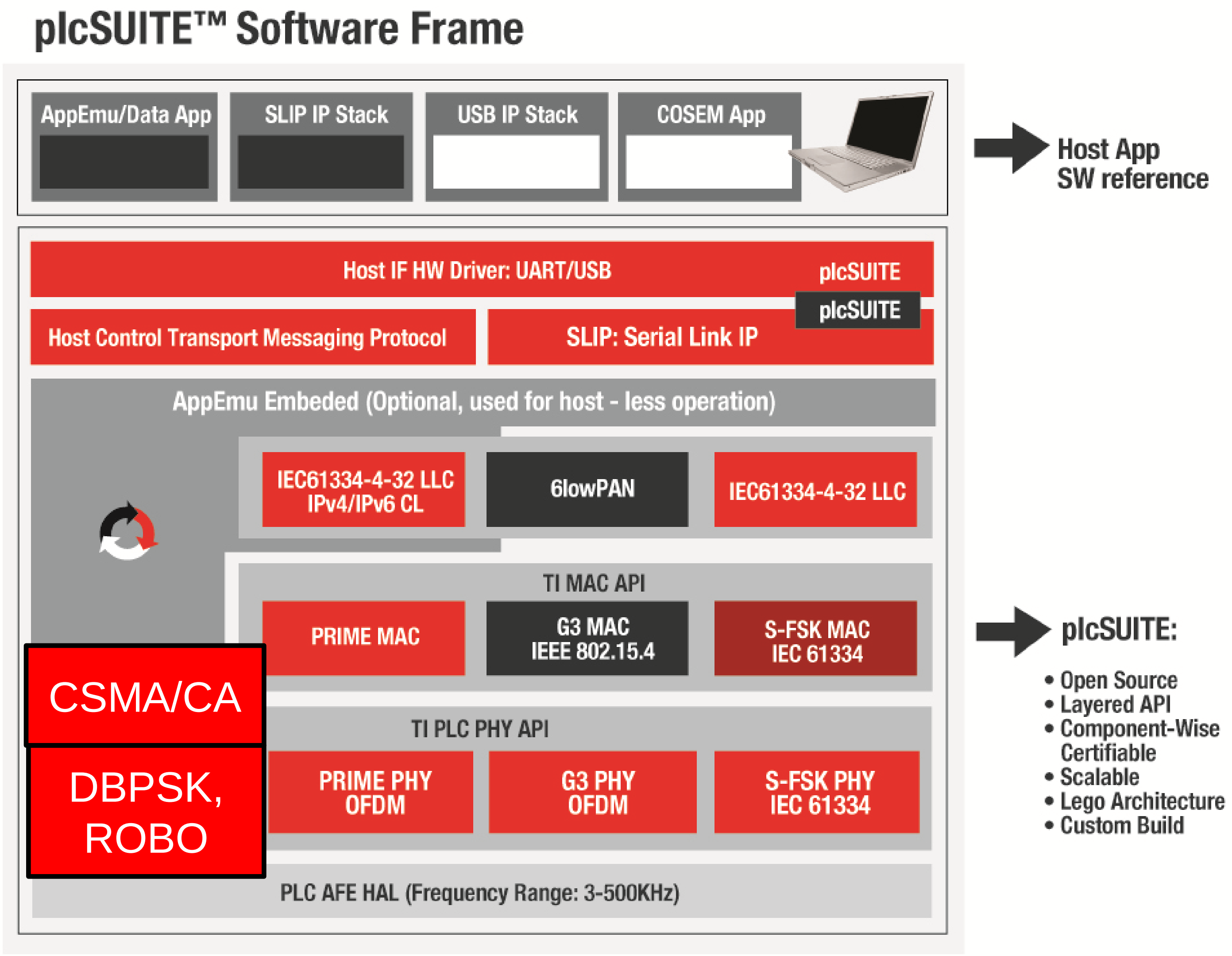
- Green circles denote pilots, grey denote data
- Regular time-frequency pilot structure enables channel estimation, sampling frequency offset estimation

Pilots+coherent modulation + more reptitions → Better header performance



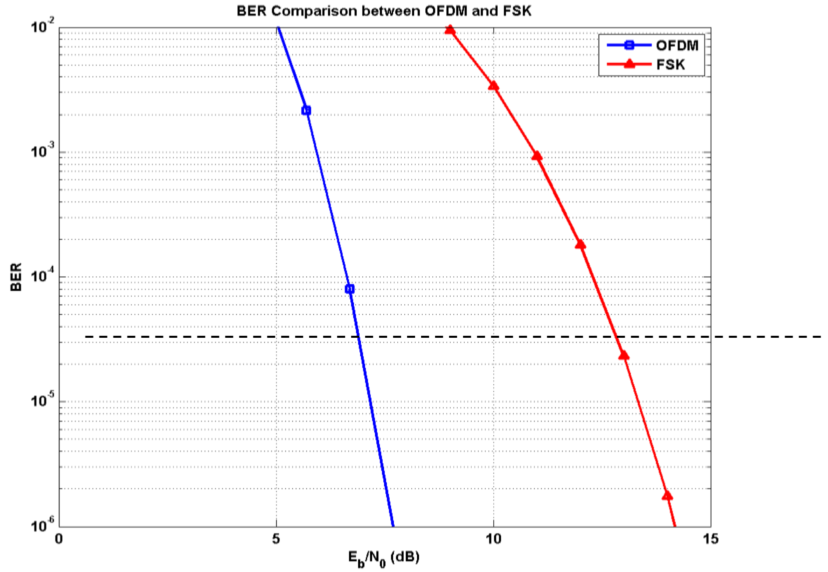
- Enables header decoding below -5 dB even with realistic crystals

PLC-Lite in plcSUITE



FlexLite/FSK Comparison (1)

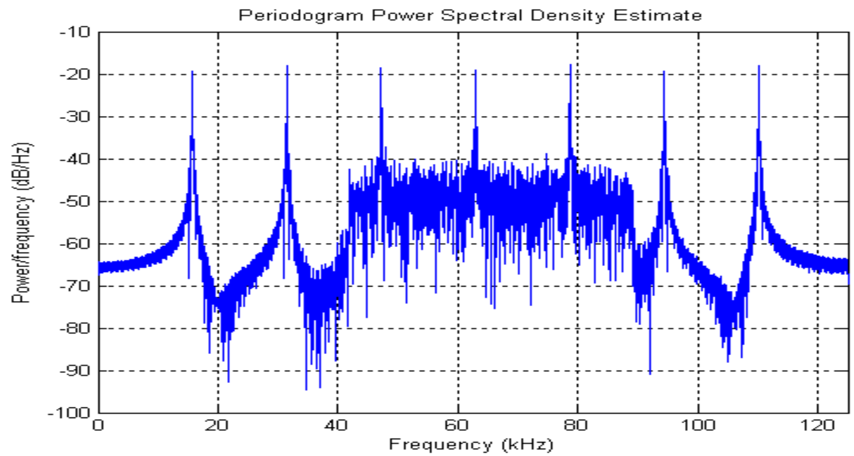
- **AWGN performance:** OFDM performance in all white Gaussian noise (AWGN) 7dB better than FSK
  – FSK has to inject 2 times the signal amplitude compared to OFDM to get same performance



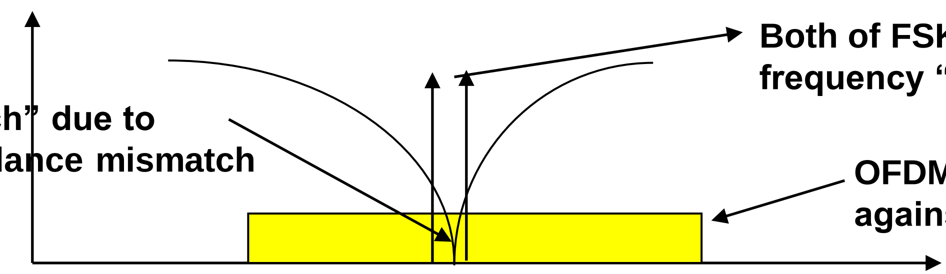
Standards: Multiple PLC standards are using OFDM
– PRIME, G3, ITU G.9955, ITU G.hnem/IEEE1901.2

FlexLite/FSK comparison (2)

- **Resilience to interference**: OFDM resilient to narrow band interference



- **Frequency diversity:** FSK may suffer from lack of frequency diversity



FSK carriers need to be separated by a large frequency spacing to have the frequency diversity against notches in frequency domain

- An “X” kHz spacing at around 144 kHz FSK needs to be “10X” kHz at 1.8 MHz to have the same robustness to frequency selective fading

TI PLC Standard Activities

OFDM PLC Alliances and International Standards

- **G3 Alliance – EDF/ERDF + 3 SC vendors + 3 meter manufacturers**
  - Cenelec A and FCC 145.3 – 478 KHz. LV/MV network
  - Interoperability, mesh network , band plan in discussion
  - Full scale deployment on French grid in 2014-2015. Worldwide applicability
- **PRIME Alliance – Iberdrola + 3 SC vendors + 3 meter manufacturers**
  - CENELEC A band, LV access network
  - PHY and MAC are stable. Tree topology, adding PHY ROBO mode for impulse noise
  - Full scale deployment on Iberdrola grid in 2012-2013. Worldwide applicability.
- **IEEE P1901.2**
  - Interoperable with G3 Cenelec A and G3 FCC. Band plans: Cen A, Cen B, FCC 145.3-478 KHz
  - Sub-banding, coherent modulation, mesh network, beaconing, channel models, coexistence in discussion.
  - Draft in progress. International standard expect in 2012
- **ITU-T G.hnem**
  - Coherent modulation, synchronous beacons, full FCC band, robust preamble, MV/LV
  - Not interoperable with G3 although G3 and PRIME Cen A are G.hnem Annexes
  - Draft complete. International standard in 2012.
- **SAE J2931-3 (EV – EVSE communications)**
  - Based on G3 (TI/Maxim). Band plan: Cen B/C/D and full FCC
  - EMC testing completed at Ford. Testing at EPRI and DOE in August 2011. IPv6. 6lowPAN, SEP2.0 supported.
- **ISO / IEC JWG CI for EV PLC, IEC 15118-3**
  - HomePlug Green PHY and G3/P1901.2 are under consideration.
  - European automakers leaning towards HPGP, but auto qualified production chipsets not available

TI active participation in the Smart Grid Initiatives

PAP15

15.4G

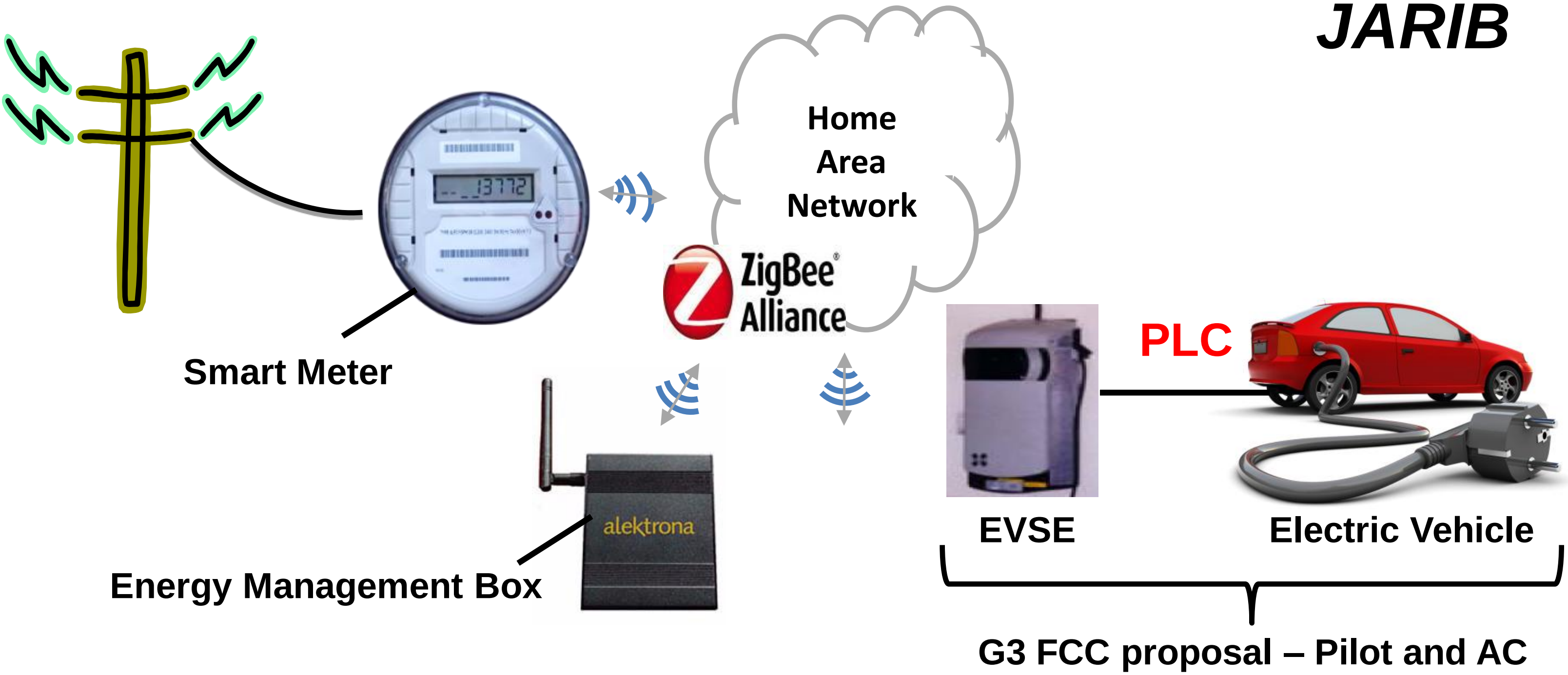
TI Standard Participation & Contribution

- **TI Contributes to IEEE, ITU, and ISO standards**
- **TI Participates in Industry Alliances**
  - PRIME, G3, WiFi-WFA, Zigbee, others
- **TI ITU-T G.hnem Accepted Contributions**
  - Pilots and coherent modulation: TI proposed add pilots to enable coherent modulation
  - Interleaver: TI proposed block interleavers of length at most 10 ms (half of zero crossing)
  - FEC: TI proposed concatenated coding as opposed to LDPC
  - Tone spacing: TI proposed changing to multiple of PRIME / G3 tone spacings
  - Preamble structure: TI proposed adding channel estimation symbols to aid in synchronization
- **TI P1901.2 Technical Contributions:**
  - Pilots – TI proposed adding pilots to enable coherent modulation
  - Beacon – TI proposed adding optional beacon mode with multiple beacon slots and CAP slots
  - PHY operation in multiple tone masks – TI proposed defining PHY operation in multiple tone masks
  - Channel modeling for A/B/C/D band parameters – TI lead channel model work
  - MAC operation in multiple tone masks – TI proposed multiple-tone mask operation in the MAC, combining ideas in 15.4 beacon mode with other features. Under discussion

TI Activity in PLC for EV/EVSE

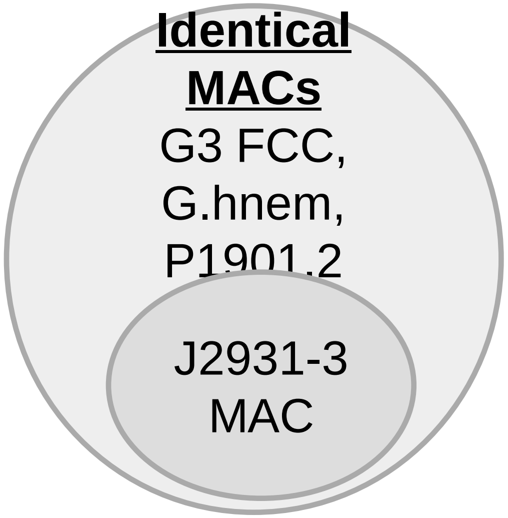
SAE ISO/IEC

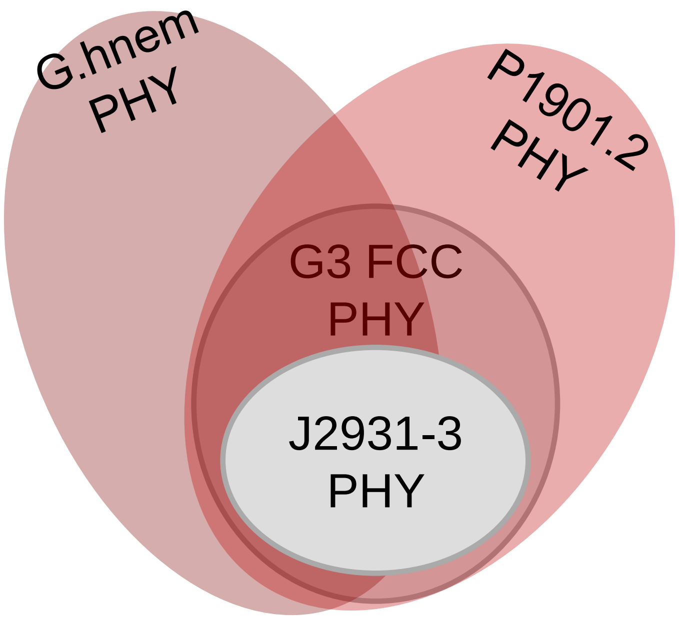
JARIB



- Multiple successful tests made with G3 – FCC
- TI brings additional experience on Home Area Network Communication: LPRF or PLC
- TI can address the full system **Meter to Car** communication

SAE, G3 FCC, P1901.2, G.hnem Situation





- IEEE P1901.2 PHY is superset of G3 FCC
  - Incremental updates and features (interleaver, preamble, others)
- SAE J2931-3 PHY is G3 FCC subset
- MAC's are identical and based on 802.15.4 for large mesh network
  - J2931-3 MAC can be simplified for point-to-point operation
  - MAC should be stable. Evolutionary enhancements (routing, networking, etc..) will be done at Layer 3
- NB OFDM SDO's include IEEE, ITU-T
- NB OFDM Alliances: G3-PLC, PRIME Alliance
- IPV6 and SEP 2.0 supported
- Up to 300 Kbps with G3 FCC
- G3 FCC is open technology
- G3 advantage is thru transformer communications and support for large networks

TI PLC Field Test Experience

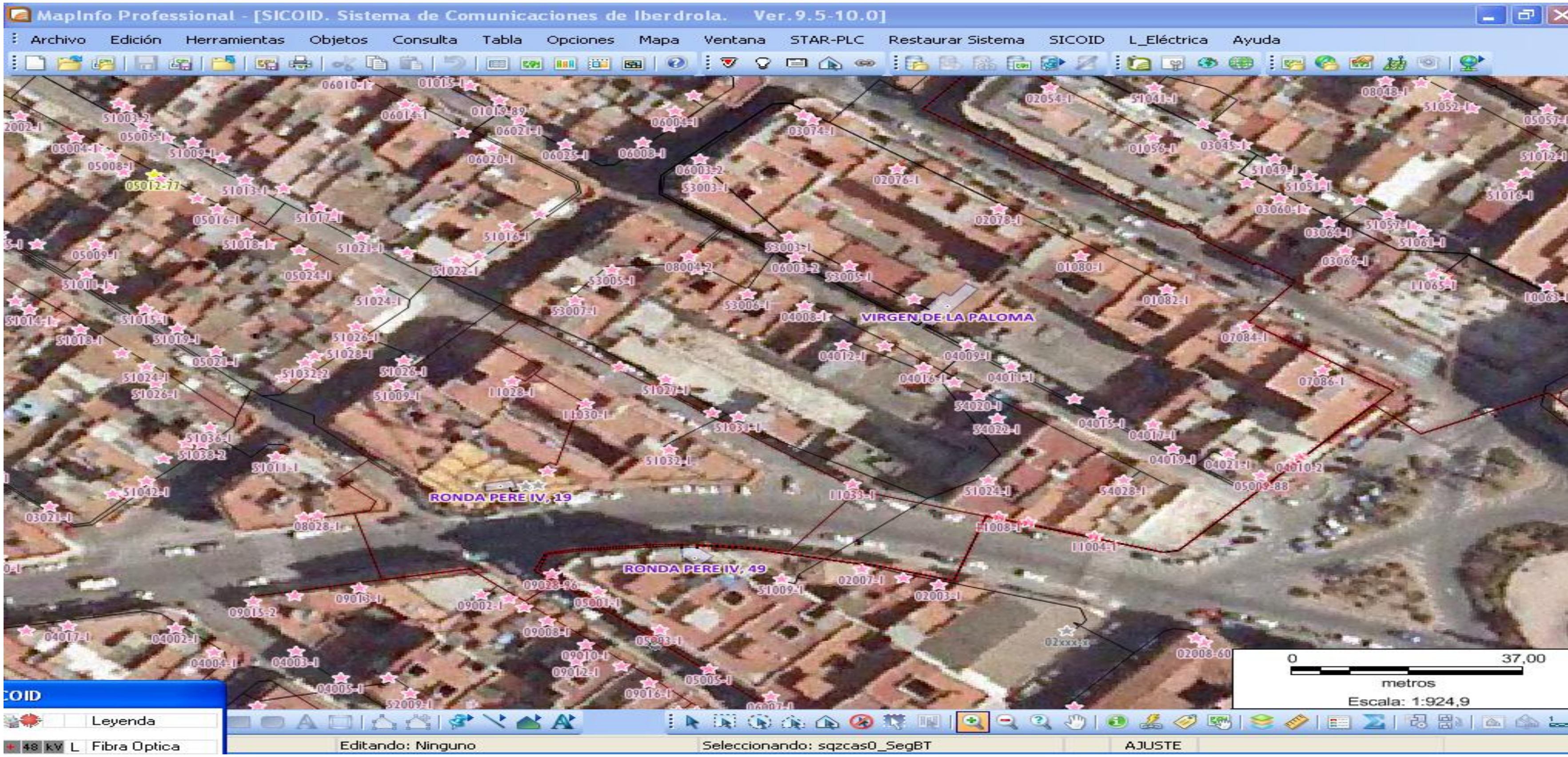
Field Test Scenarios

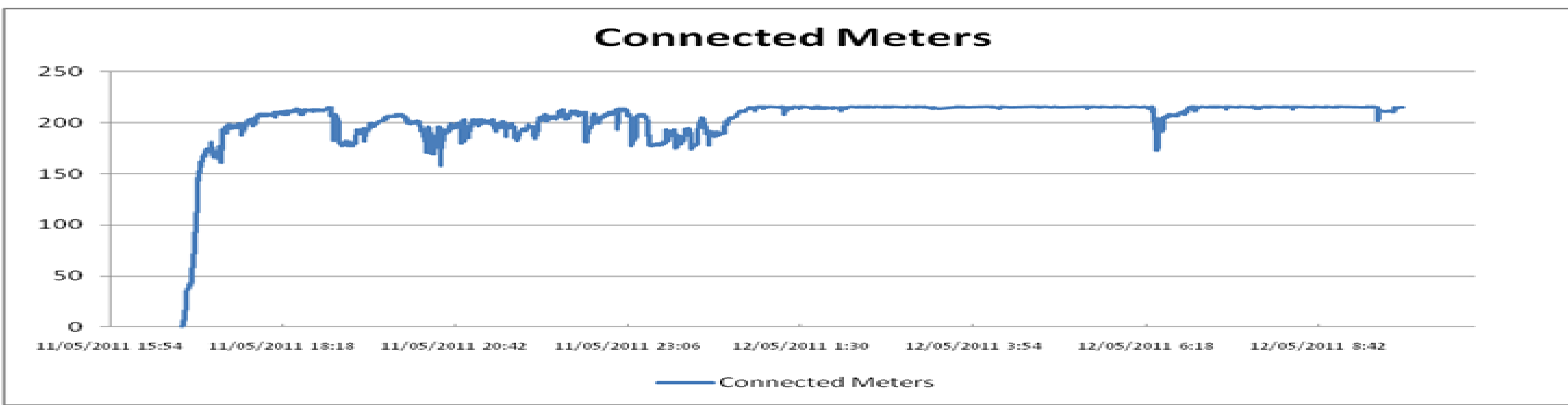
- LV side of transformer to eMeter
- Crossing MV/LV transformer(s) to eMeter
- Street Lighting applications
- Solar applications
- Electrical Vehicle(EV) to Electrical Vehicle Service Entity (EVSE) Communications

TI PLC Field Tests For last 180 Days

Where	When	Band/NW	Software	Results
Southern US	May 2010	CENELEC-A LV/MV	PRIME+ROBO	Channel and noise in Cenelec band
Japan	Aug 2010	CENELEC-A + FCC, MV/LV	PRIME+ROBO+subband	Cenelec + FCC band demonstration with cap bank
Southern US	Nov 2010	FCC, MV/LV	PRIME+ROBO+subband	Good SNR for MV-MV comm MV/LV and LV/MV communication do not have enough SNR to support communication on entire FCC / ARIB bandwidth
Central Indiana	Dec 2010	FCC, MV/LV	PRIME+ROBO+subband	
Milan	Feb 2011	CENELEC-A, LV/LV	PRIME+ROBO	Passed all the LV/LV test cases
Milwaukee, WI	Mar 2011	CENELEC-A+FCC, MV/LV	G3-CENELEC A +flex OFDM	Passed with the erasure channel with actuators
Southern US	Mar 2011	FCC, LV/LV, LV/MV	G3-FCC with flexible masks	Channel and noise captures Confirm flexOFDM tests about insufficient SNR
Hiroshima, Japan	April 2011	FCC, LV/LV	G3-FCC with flexible masks	Passed all the LV/LV test cases except the WHT case.
Beijing, China	Apr 2011	FCC, LV/LV	G3-FCC with flexible masks	Achieved up to 200m in out-door grid to meter tests Challenges in in-door tests
Spain	2011	CENELEC-A, LV/LV	PRIME	Official field deployment for hundreds of meters
Mexico City, Mexic	May 2011	CENELEC+FCC, LV/LV	PRIME and G3-FCC	Successfully pass 2 circuit-breakers for G3-FCC, PRIME has difficulty
Turkey	June 2011	CENELECA, LV/LV	PRIME & G3-CENELC	Successfully pass all test cases competitor either pass or fail

TI PRIME Based 220 Meters in Burriana, Spain



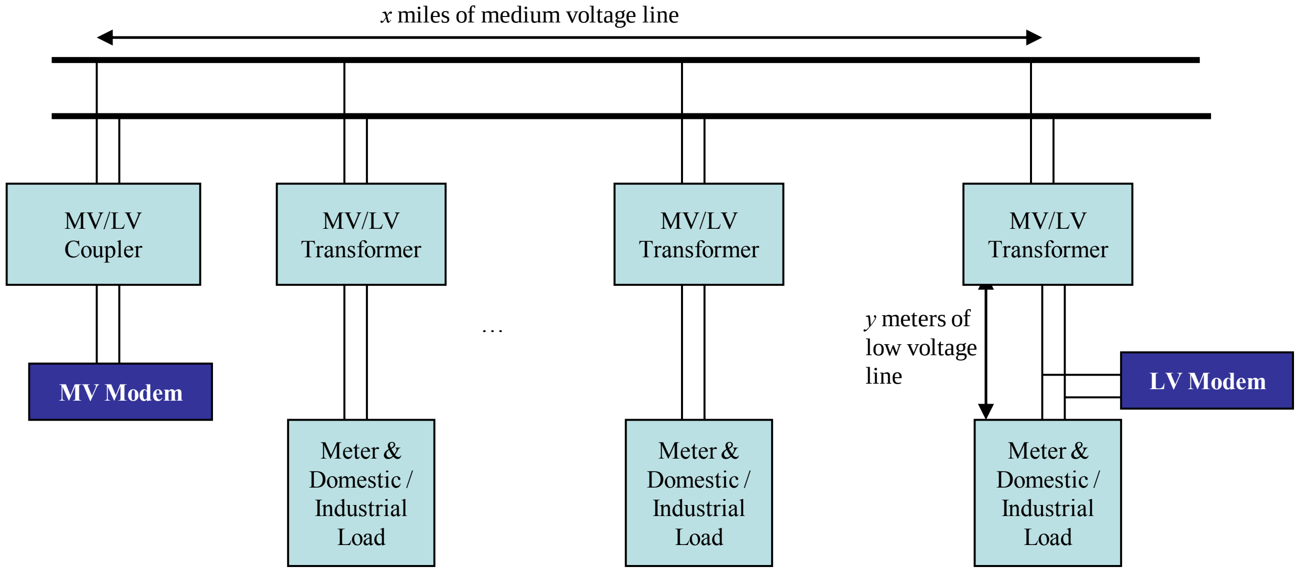


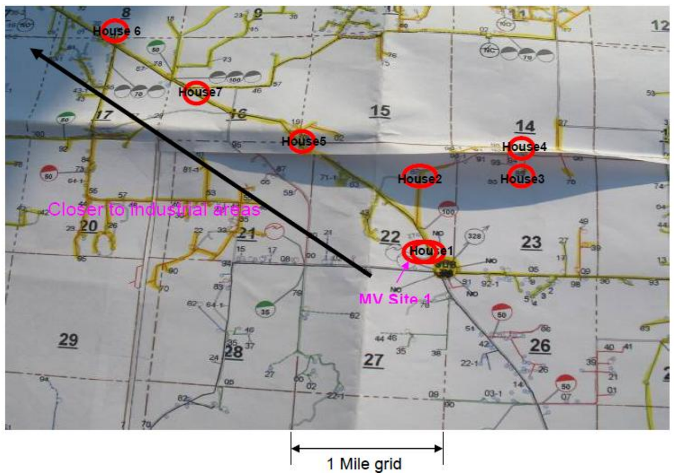
MV/LV Transformer Tests in US grid

- Successfully crossed MV/LV transformer in US grid

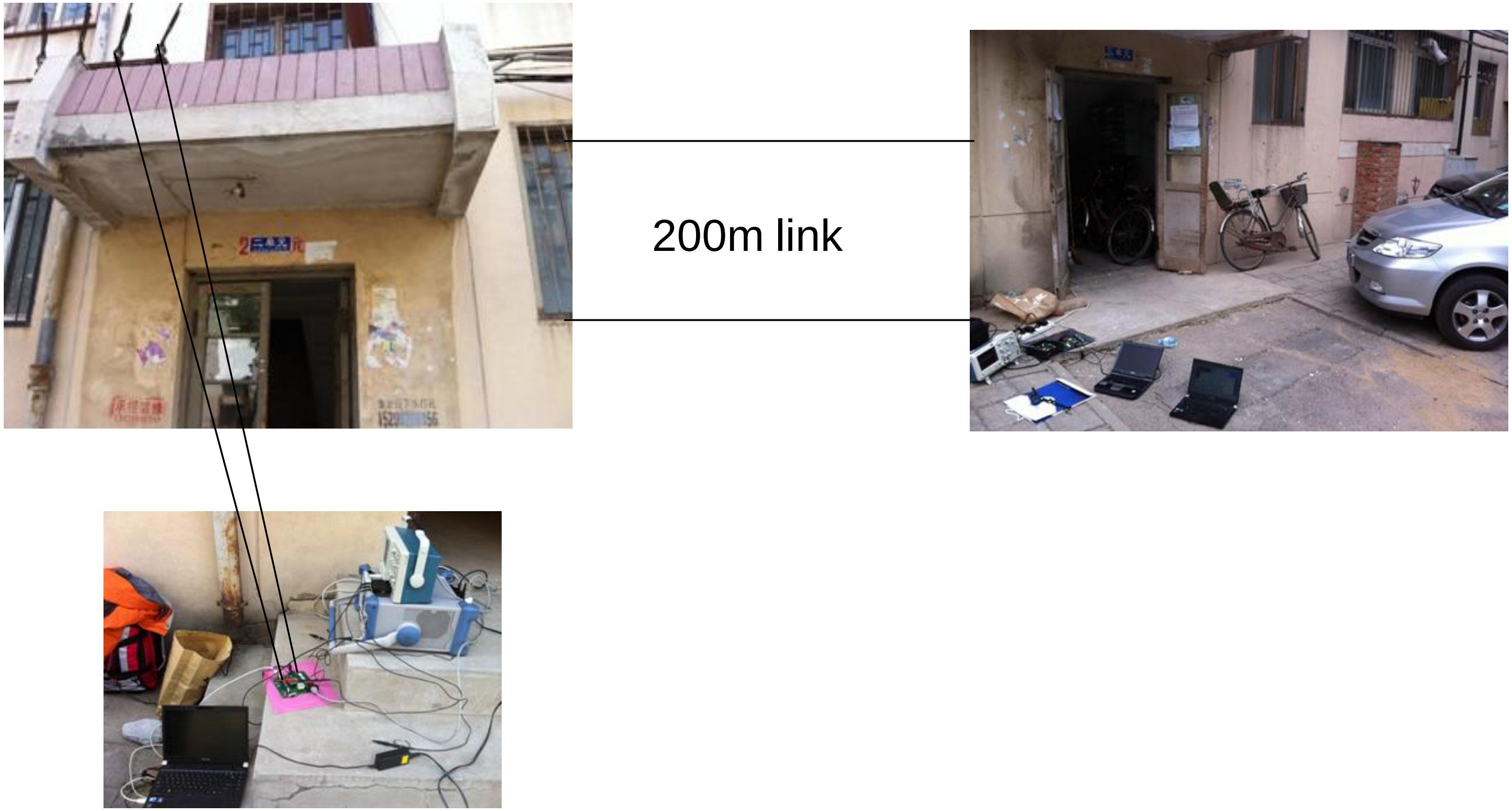
- PHY data rates 1.5 - 20 kbps at a distance of 1.6 mi
- LV-LV results upto 350m distance

MV-LV results up to 3km distance



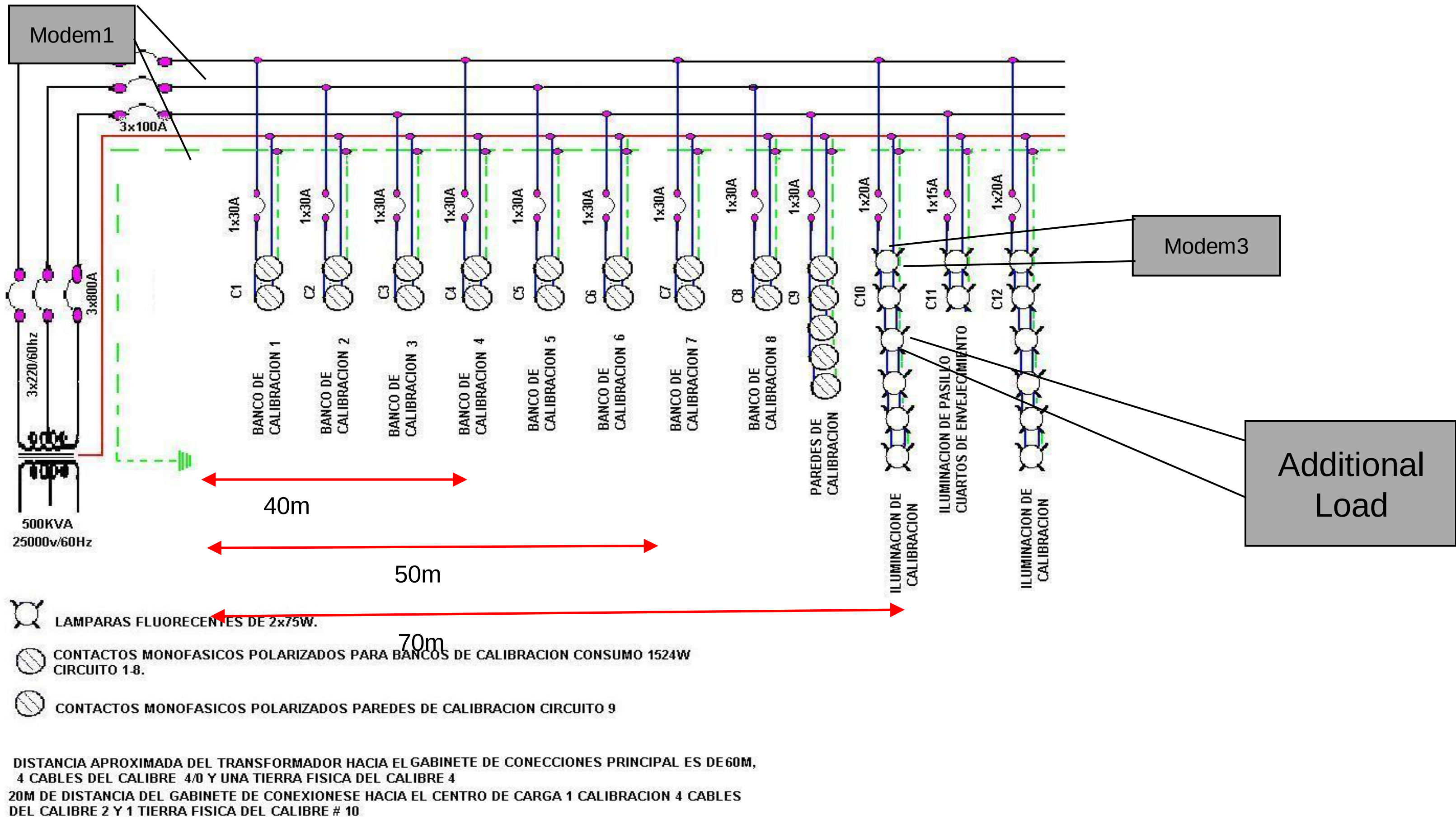


LV-LV Tests in China Grid (Apr. 2011)



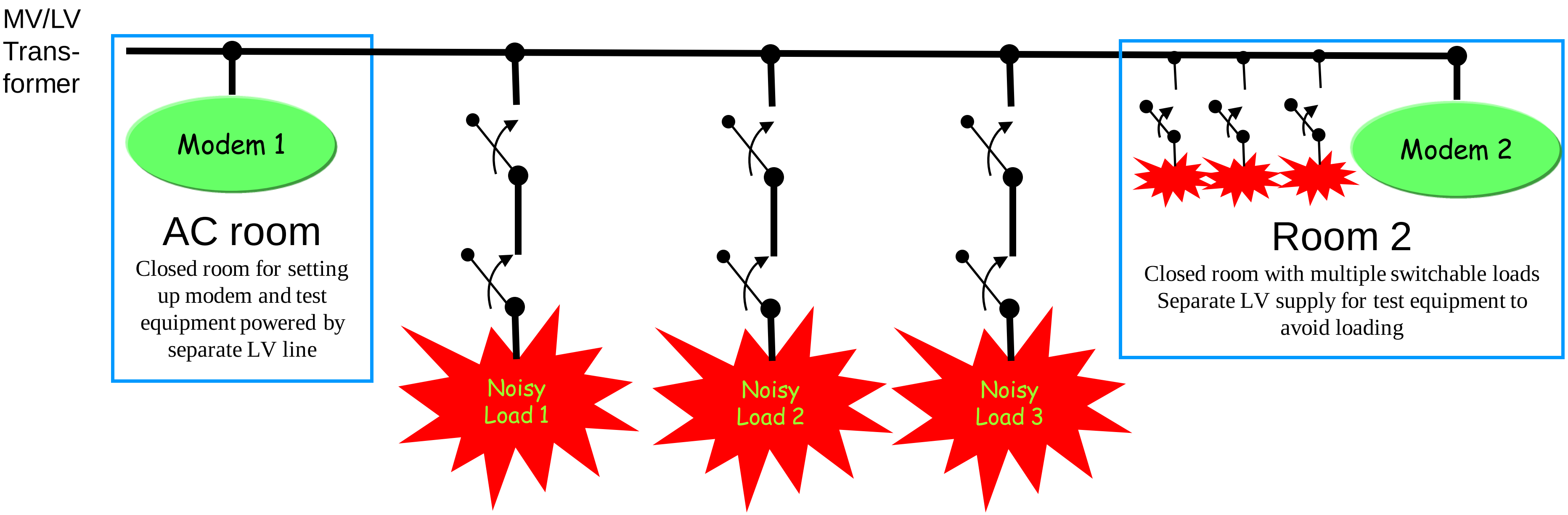
- Connection made in each apartment building for variant distance for CENELEC & FCC
- Tested both day time (light load) and evening/night time (heavy load)
- Achieved upto 200m even at evening time (high noise and attenuation)

Mexico LV-LV Test (April, 2011)



Load	CEN A (40-90kHz)	CEN A with tone mask (40-90kHz with 60-77kHz not transmitting)	CEN B (98-122kHz)	CEN B/C (98-138kHz)	FCC Low (145kHz-310kHz)	FCC High (310-478kHz)
Normal Load	ROBO: 0% FER DBPSK: 100%FER	ROBO: 0% FER DBPSK: 100% FER	ROBO: 0% FER DBPSK: 50% FER	ROBO: 0% FER DBPSK: 0% FER DQPSK: 10% FER	ROBO: 0% FER DBPSK: 100% FER	ROBO: 0% FER DBPSK: 100% FER
Additional Load	N/A	N/A	N/A	ROBO: 0% FER DBPSK: N/A	N/A	N/A

Japan – Mar 2011



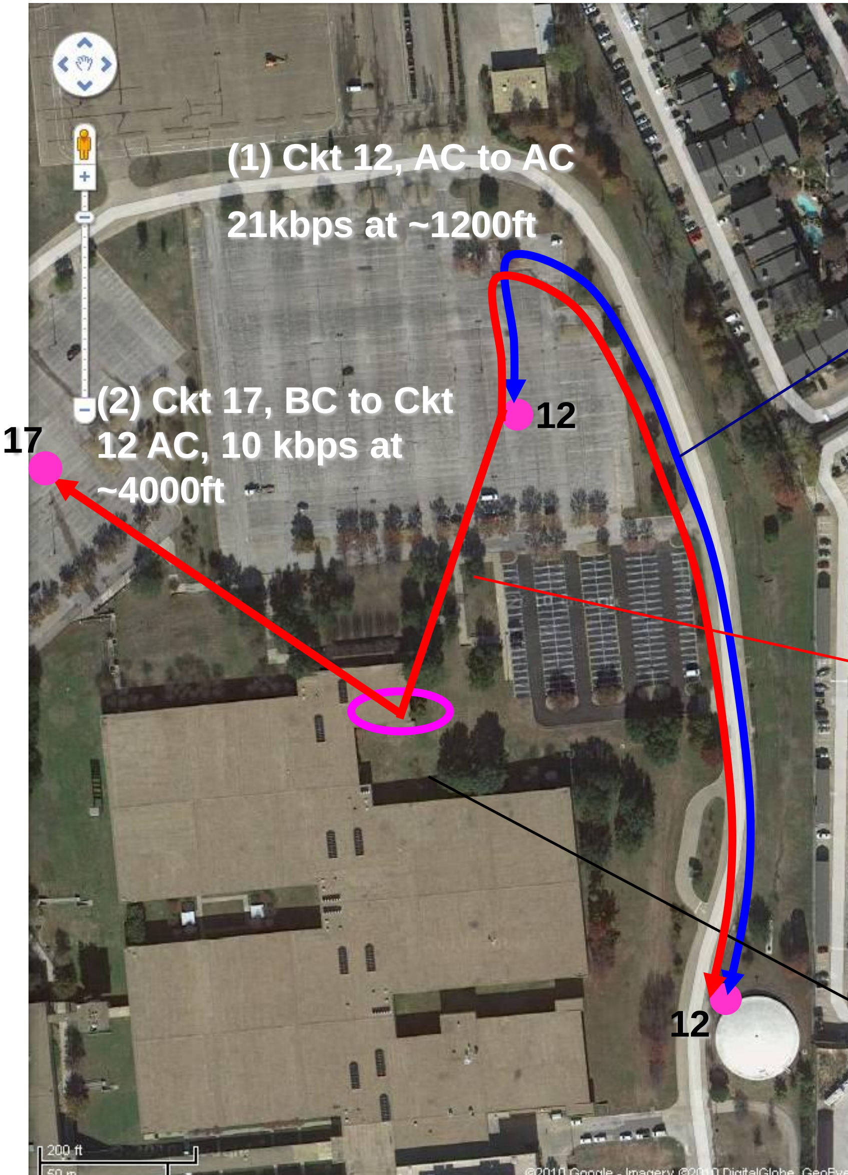
- Test G3-FCC PHY communication between two modem separated by 100m, with three switchable taps at 25, 50, 75m from AC room
  - Noisy load equipment can be connected to taps. Typical load tried = space heater "Kotatsu"
- Many switchable loads at receiver in Room 2
  - plate heater, space heater, microwave oven, TV, DVD player, …
- Results from tests using TI G3-FCC modems
  - Adding load equipment at Room 2 is the main challenge (tap loads impact SNR, but effect of loads in Room 2 more dramatic)
  - G3-FCC with 168.75 kHz bandwidth offers good performance for most loads, except for the case of IHT-only load
  - For IHT-only load, G3-FCC with 93.75 kHz bandwidth offers good performance
  - Reverse direction (room 2 -> AC room) is good for all loads tested. No problems with thermal shutdown

LV-LV Tests in Turkey

- Lab tests
  - With 200m extension cable, 34kbps achieved with G3 DQPSK
  - With 200m extension cable and contact noise (with hair dryer, etc), 34kbps achieved with G3 DQPSK

- Factory tests
  - With 350m distance, 20kbps achieved with PRIME DBPSK (Factory machine off)
  - With 350m distance, 20kbps achieved with PRIME DBPSK (Factory machines on)
    - File transfer is also ok

Street Lighting Applications



- Ckt breaker 12, phase AC to AC, was tested in CENELEC A band (PRIME)

  21kbps at ~1200ft

- Ckt 17 phase BC to Ckt 12 phase AC was tested in FCC band (170-184 kHz)

  10kbps at ~4000ft (=1.2km)

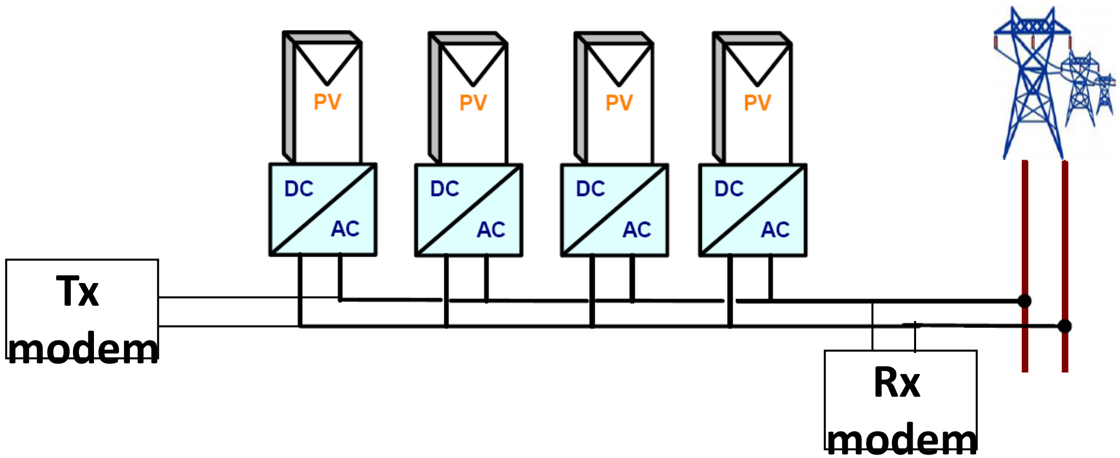
Circuit breaker room that feed light poles

Courtesy of Google

Texas Instruments

Solar Applications

- Communicate between a transmitter on 4 solar panels on the rooftop to a receiver ~25 m away on power line.



- Inverter switching frequency has harmonics of 20 kHz
- Achieved error free communication of 42 kbps

Communication Across DC Charger Cable

- DC charger setup and connection of TI modem

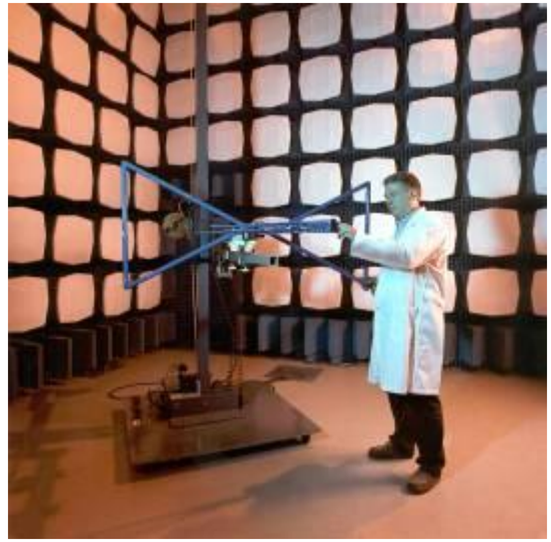
- Demonstrated 42 kbps in DC+/gnd configuration with charger on
- Expect at least 21 kbps in DC+/- configuration with Li-ion batteries (lower current ripple during charging)

TI PLC Certification and Lab Test

TI PLC is PRIME Certified

PRIME ALLIANCE
Certification process

- Passed PRIME Conformance Test
- **PHY: 100%**
- **MAC:** 100%
- **CENELEC:** 100%
- Certification performed by Tecnalia/KEMA laboratory in Spain

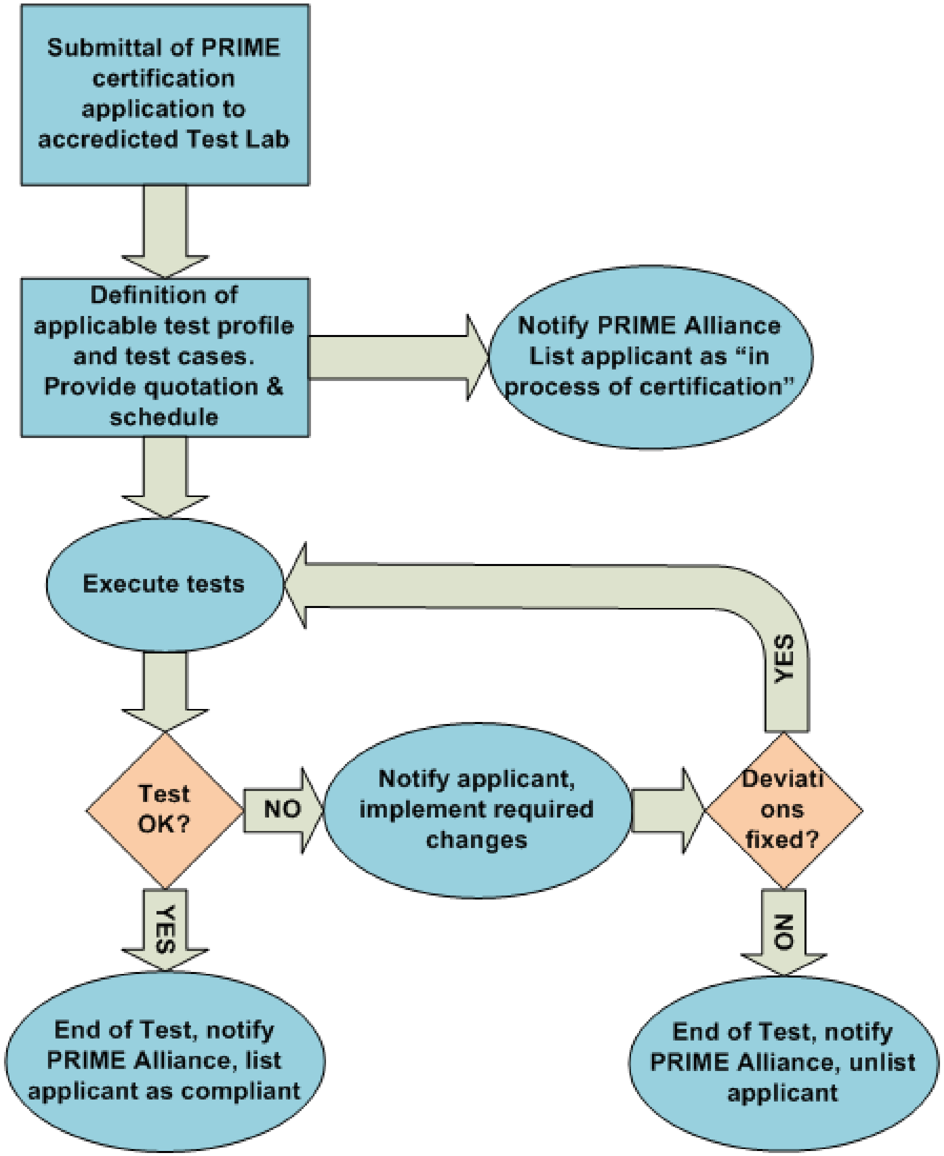


tecnalia

DUT:	MAC: cd:cd:cd:cd:cd:cd				
CODE	**DESCRIPTION**	**RESULT**	**EXPECTED**	**VEREDICT**	**COMMENTS**
	2.2 PHY Test Cases: Functional Category				
2.2.1	Verify error free communication (0% FER) when communicating directly over the LISN stated in the PRIME PHY Spec (2Ohm) and output level 120 dBuV, PPDU length 256 bytes	2000 frames measured with TI's tool	at least 1996 frames	OK	
2.2.2	Verify error free communication (0% FER) when communicating directly over the LISN stated in the PRIME PHY Spec (2Ohm) and output level 120 dBuV, PPDU length 256 bytes	2000 frames measured with TI's tool	at least 1996 frames	OK	
2.2.3	Verify error free communication (0% FER) when communicating directly over the LISN stated in the PRIME PHY Spec (2Ohm) and output level 120 dBuV, PPDU length 256 bytes	2000 frames measured with TI's tool	at least 1996 frames	OK	
2.2.4	Verify error free communication (0% FER) when communicating directly over the LISN stated in the PRIME PHY Spec (2Ohm) and output level 120 dBuV, PPDU length 256 bytes	2000 frames measured with TI's tool	at least 1996 frames	OK	
2.2.5	Verify error free communication (0% FER) when communicating directly over the LISN stated in the PRIME PHY Spec (2Ohm) and output level 120 dBuV, PPDU length 256 bytes	2000 frames measured with TI's tool	at least 1996 frames	OK	
2.2.6	Verify error free communication (0% FER) when communicating directly over the LISN stated in the PRIME PHY Spec (2Ohm) and output level 120 dBuV, PPDU length 256 bytes	2000 frames measured with TI's tool	at least 1996 frames	OK	
2.2.7	Verify error free communication (0% FER) when communicating directly over the LISN stated in the PRIME PHY Spec (2Ohm) and output level 120 dBuV, PPDU length 256	2000 frames measured with TI's tool	at least 1996 frames	OK	
2.2.8	Verify error free communication (0% FER) when communicating directly over the LISN stated in the PRIME PHY Spec (2Ohm) and output level 120 dBuV, PPDU length 256 bytes	2000 frames measured with TI's tool	at least 1996 frames	OK	
2.2.9	Verify error free communication (0% FER) when receiving input signal of 122 dBuV	2000 frames measured with TI's tool	at least 1996 frames	OK	
2.2.10	Verify Zero Crossing detection		50Hz nx1000 / 60Hz nx833	N/A	skipping this test from the certification process until there is a window to modify the PRIME spec
	2.4 PHY Test Cases: Signal Quality category				
2.4.1	Verify that the EVM of the received signal at output level of 120 dBuV is above 17dB.	18.002 dB (505) measured with TI's tool	>17 dB	OK	
2.4.2	Verify that the EVM of the transmitted signal output level of 120 dBuV is above 17dB.	17.99 dB (504)	>17 dB	OK	

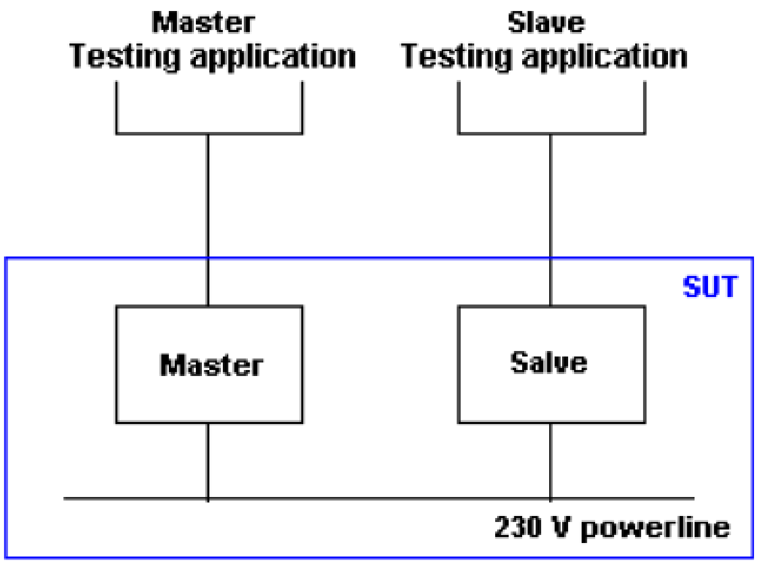
PRIME Certification Procedures

- **Test Categorices:**
  - EMC
  - PHY
  - MAC
  - CS Layers



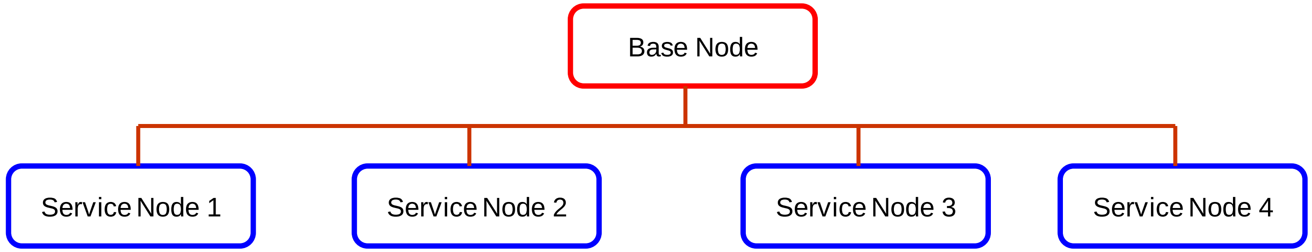
G3 Certification Procedures

- **WS3 Focuses on PHY Interoperability Test Process**
  - Tests of the digital part of the PHY layer at the simulator level
  - Tests of the complete PHY layer at the simulator level
  - Plug fest
- **ERDF Technical Lab Tests**
  - PHY Tests
  - Data Link Layer Tests
  - Upper Layer Tests
- **PHY Tests Example**
  - Conformance to standard
  - Dynamic range
  - Harmonics measurements
  - Robustness against impulse noise
  - Robustness against white noise
  - Robustness against sinusoidal noise
  - ….

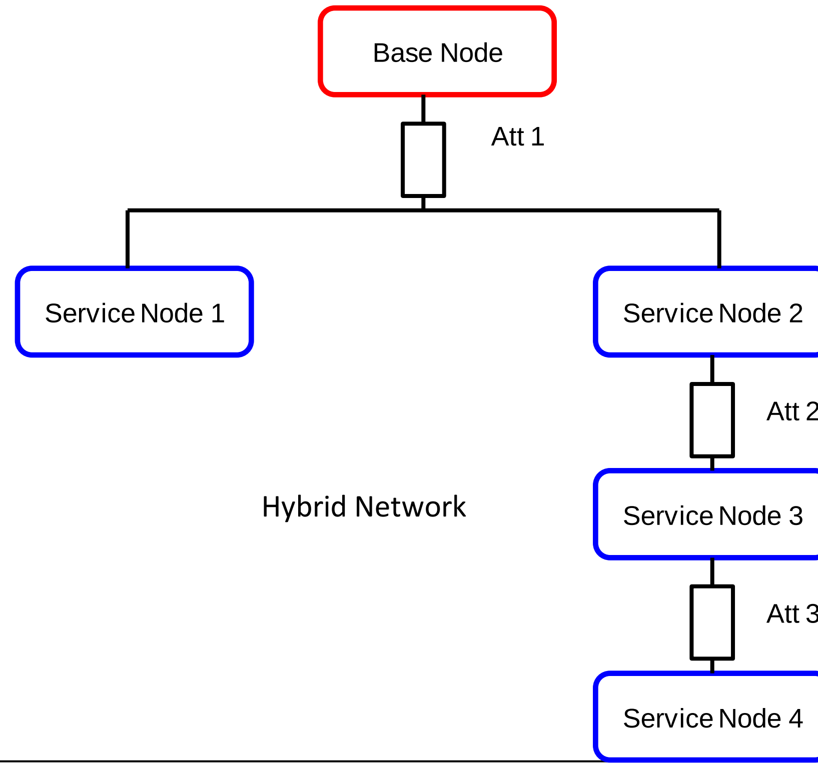


Network Registration Test

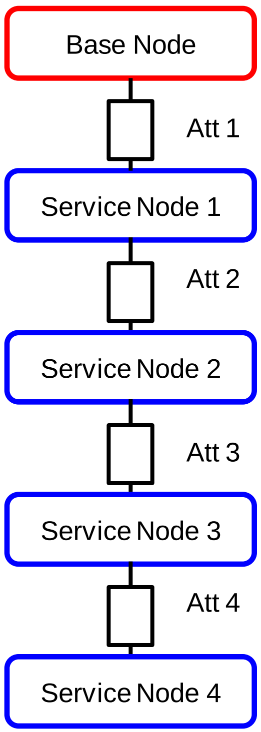
Network registration test for the following scenarios were performed successfully



Single Hop Network



Hybrid Network



Linear Chain Network

PRIME Modem: PHY Test & Validation

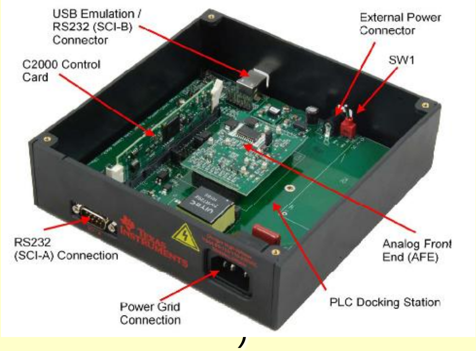
PC

PRIME Tx Model in MATLAB
Adds impulse
noise,,interference

Rohde & Schwarz AMU

Plays back Matlab test vectors
Adds channel distortion, noise

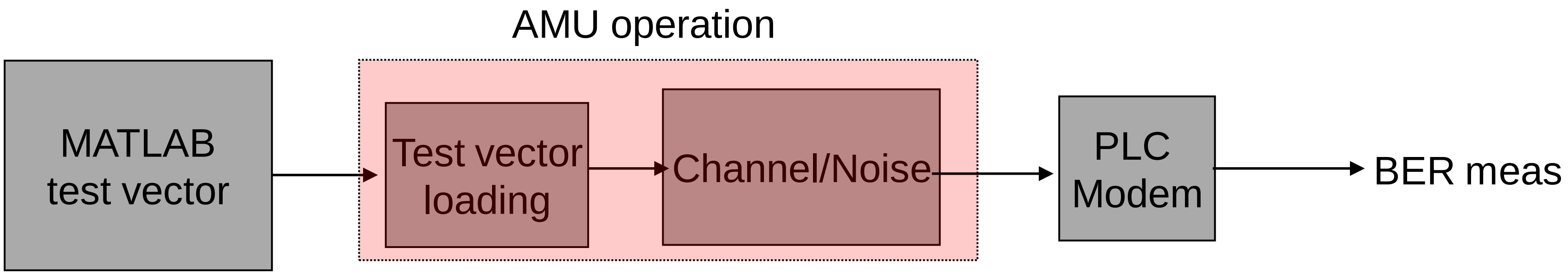
PLC Modem



PC

Display

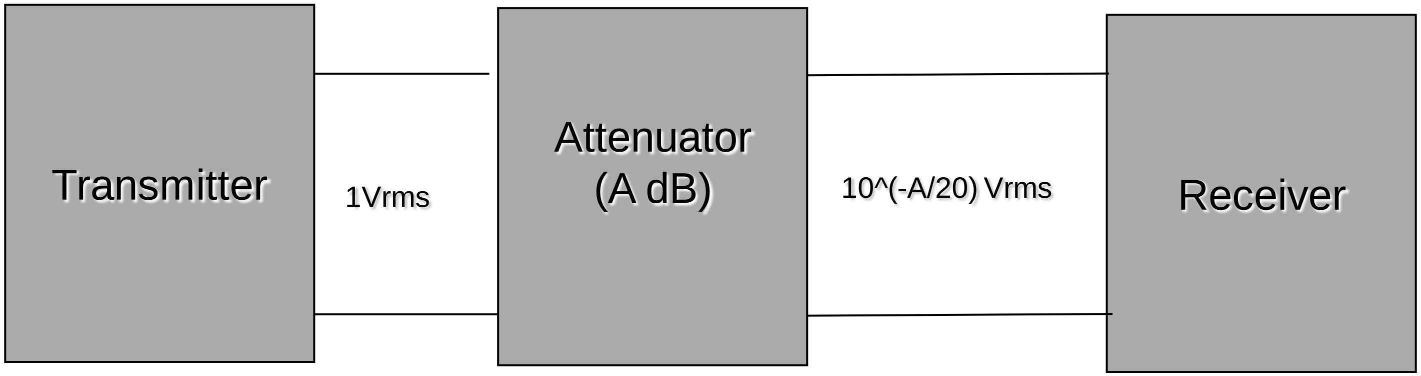
PHY Validation



- Generate test vectors in MATLAB
  - PRIME transmit signal generated using software model
  - Add narrowband interferers and / or impulse noise in MATLAB
- Load test vectors on AMU, add impairments models and play
  - Background noise: white/colored
  - Multipath distortion using line-impedance channel model
- Receive signal in analog + digital board
- Compare results against MATLAB

VALIDATION: Measured LAB BER = MATLAB simulated BER

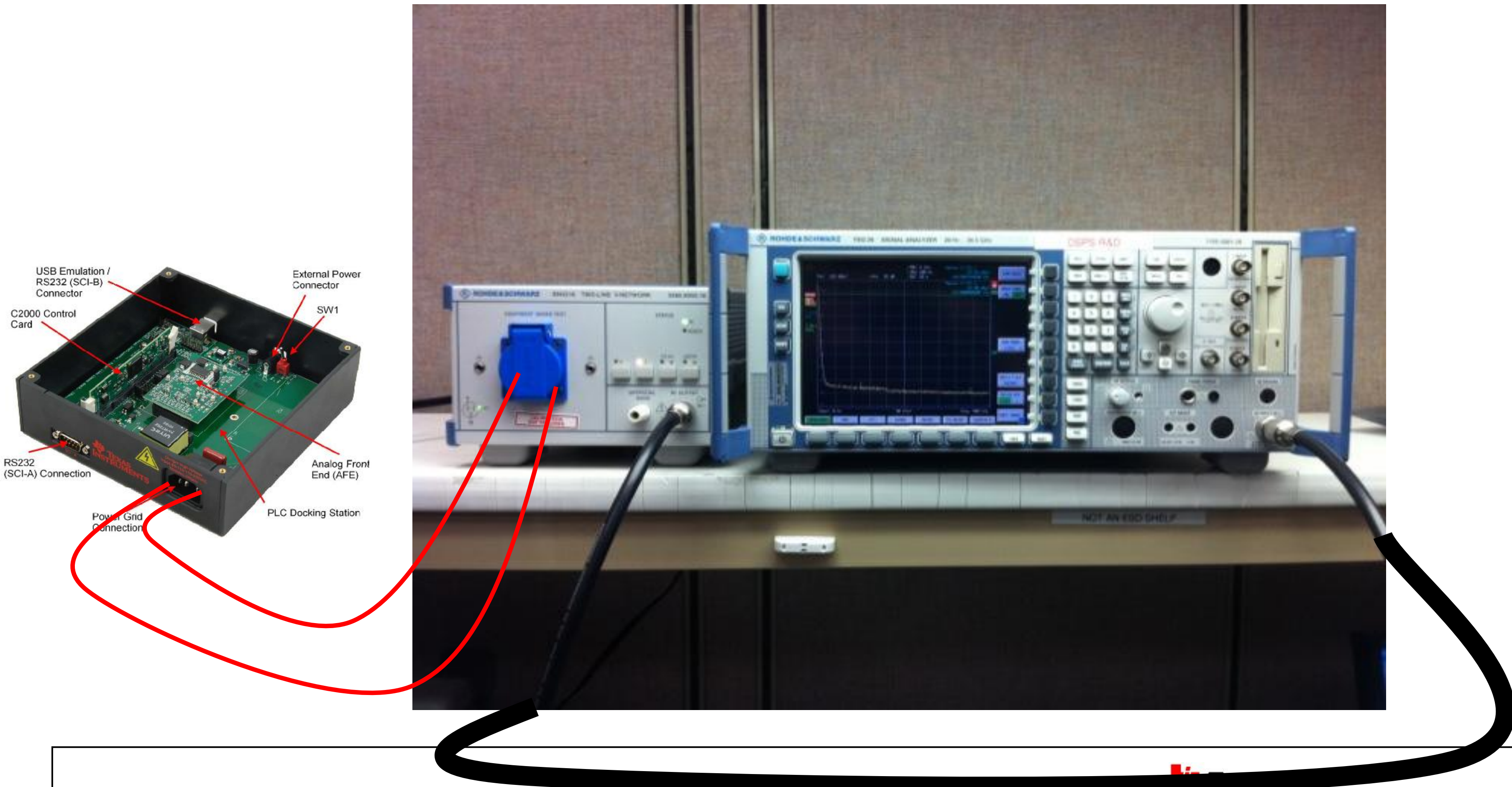
PHY Validation



- Transmitter set to transmit 1Vrms
- No power line connection
  - Direction connection with an attenuator
- DBPSK + FEC with 235byte transmitting
- Test results
  - A=75dB attenuation measured with 0 BER/FER
    - The received level is 1Vrms*10^(-75/20) = ~200uVrms
    - Attenuation was verified with a spectrum analyzer

LISN Measurements in TI Lab

- Follow the procedure in EN 50065-1
- Measurements on R&S FSQ-26 doing both RMS and quasi-peak measurements
- TI uses R&S ENV 216 for LISN
- Measurement Setup:

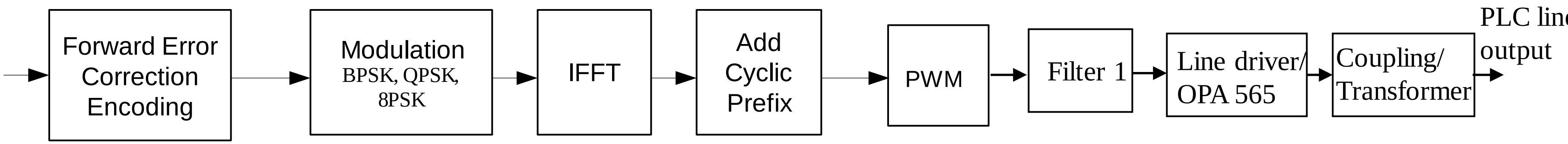


Network Validation

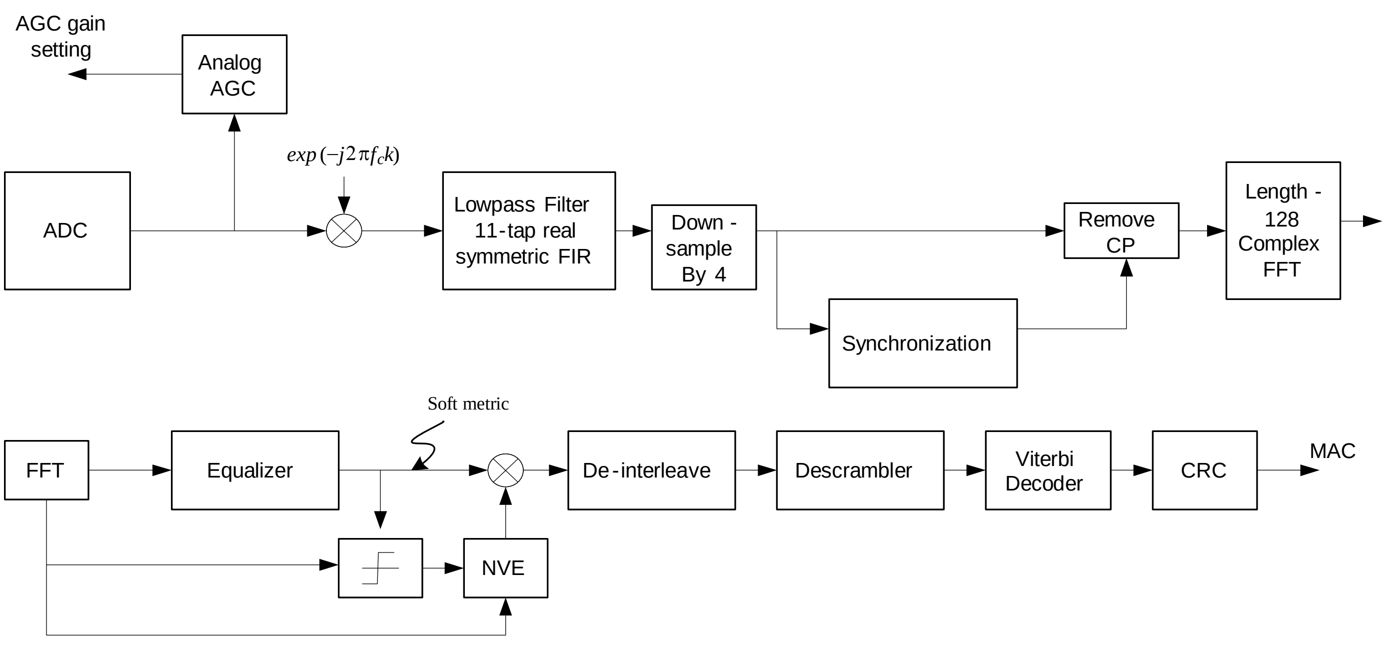
- Data Concentrator
- Meters
- Multi-level Network
  - Registration
  - Connection
  - Long/short Cycle Test
  - Firmware Upgrade

PRIME PHY Transmit Chain

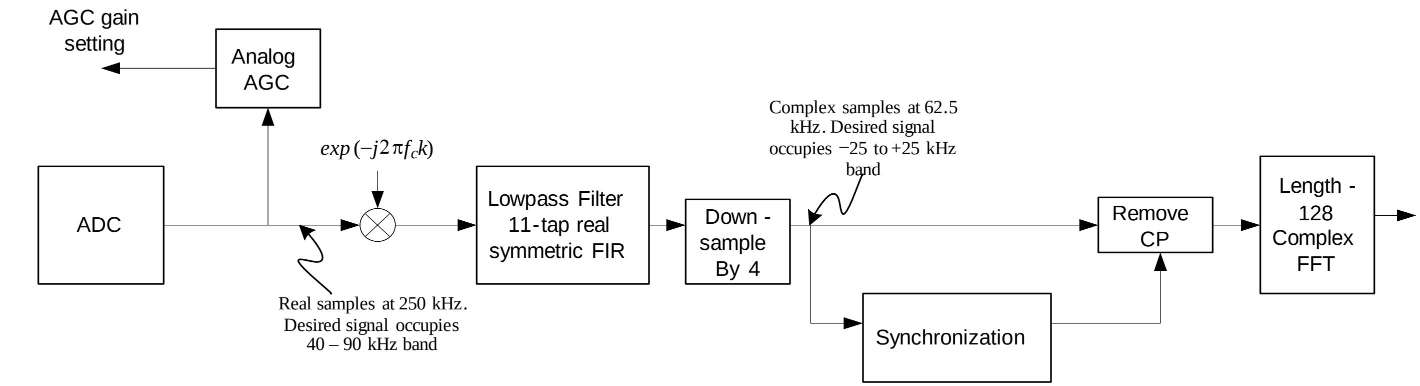
- Transmit side block diagram

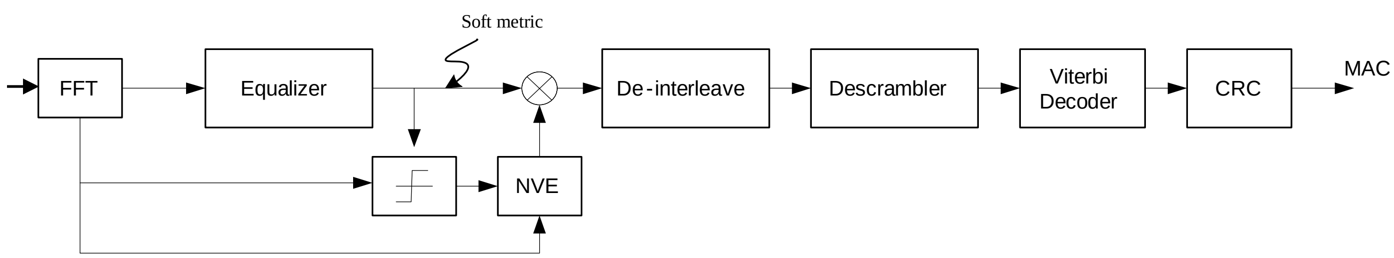


- Receive side block diagram



PRIME PHY Receive Chain





Receive side analog specifications: