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

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

Smart Meters

- Electricity meter
- Gas meter
- Water meter

Smart homes and buildings

- In home display
- Thermostats
- Smart Appliances
- Circuit Breaker
- Charging elect. vehicle
## TI Technologies for Smart Grid Solutions

### Microcontrollers
- **16-bit**
  - MSP430™
    - Ultra-low power
    - Up to 25 MHz
    - Flash 1KB to 256KB
    - RTC, ADC, MPy, USART
    - Measurement metrology MCU
- **32-bit real-time**
  - C2000™
    - Real-time MCU
    - ADC, Flash
    - Protocol stack & modem
    - Embedded Flash
    - Flash f. upgrade
    - Appropriate peripherals
    - PLC Modem
    - Multi-modulation S-FSK/OFDM PRIME/G3

### ARM-Based
- **ARM 32-bit**
  - Stellaris® M3
    - Industry std. low power
    - < 100 MHz
    - Flash 256kB with path to 2MB
    - Multi-serial port encryption
    - Analog integration
    - Smart Grid application processor
- **ARM +**
  - ARM 9, OMAPL1x
    - Industry std. High Perf GPP
    - Accelerator
    - MMU
    - USB, LCD
    - MMC, EMAC, LINUX/WinCE

### Complementary Analog
- **Low-power RF**
  - CC
    - RF SoC transceiver
    - 433 to 2500 MHz
    - Flash for SoC
    - Multi-serial port
    - Encryption
    - Data
    - Concentrators/Power Analytics
- **Analog**
  - OPA, THS, ADC
    - Amp, LD, PGA
    - ADC, DAC
    - Full range
    - Various technologies
    - Measurement PLC
- **Saving power**
  - TPS, UCC
    - AC/DC, DC/DC, LDO
    - Full range
    - Ultra low-power
    - High efficiency
    - 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**
- **New PLC front End**
- **AFE03x**
- **Concerto Application + PLC**
- **512kB Flash**
- **Stellaris Cortex M3**
- **APL Engine Accelerators**
- **M-Bus TMS521A**

**RF e-meter solution**
- **Application Processor**
- **Stellaris Cortex M3 LM3S1R21**
- **Radio**
- **MCU**
- **BiM-M-Bus CC430**

**Gas-meter solution**
- **Software:**
  - Metrology: Single Phase, 2-Phase, 3-Phase
  - Security / Encryption, DLMS, RTOS

**In-Home Display**
- **Software:**
  - Wired Communications: SFSK, PRIME, G3, Flex OFDM, KNX
  - Wireless Communications: WMBUS, SEP 1.0/2.0, Sub 1GHz, 802.15.4g

**Water-meter solution**
- **Software:**
  - Metrology: Single Phase, 2-Phase, 3-Phase
  - Security / Encryption, DLMS, RTOS
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

---

**Power**

**Zigbee**

**Metrology**

**MCU**

**WiFi**

**<1GHz RF**

**PLC**

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

Quality
- Prime Conformance Certified
- Interoperable with 4 major DC vendors: Current, ZIV, Ormazabal, Nucleus.
- Mass deployment in Iberdrola grid
G3

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
  – *Cometes 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-I

- **AU** (compleX-number arithmetic Unit, supports Complex number multiplication, MAC and ADD)
- **VU** (Viterbi Unit, supports Viterbi ADD-Compare-Select Operation)
- **CU** (CRC Unit, supports CRC8, CRC16 and CRC32)

VCU-II Further Enhancements (in-progress)
- Reed-Solomon: 4x enhancements
- Viterbi: 6x faster than VCU-I
- FFT: 2x speed-up than VCU-I

<table>
<thead>
<tr>
<th>Function</th>
<th>F2806X Speedup Ratio vs C28335</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viterbi ACS per 2-coded bits (k=7)</td>
<td>6.4</td>
</tr>
<tr>
<td>Viterbi traceback</td>
<td>4.0</td>
</tr>
<tr>
<td>64-pt Complex FFT</td>
<td>2.8</td>
</tr>
<tr>
<td>CRC16</td>
<td>11.6</td>
</tr>
<tr>
<td>CRC32</td>
<td>16.0</td>
</tr>
</tbody>
</table>
### 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

<table>
<thead>
<tr>
<th>Piccolo</th>
<th>Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C28x 32-bit 80MHz</strong></td>
<td>256 KB Flash</td>
</tr>
<tr>
<td>FPU Unit</td>
<td>100 KB RAM</td>
</tr>
<tr>
<td>VCU Unit</td>
<td>Boot ROM</td>
</tr>
<tr>
<td>Debug</td>
<td>Real-Time JTAG</td>
</tr>
<tr>
<td>CLA</td>
<td>DMA-6CH</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power &amp; Clocking</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Dual Osc 10 MHz</td>
</tr>
<tr>
<td>• On-Chip Osc</td>
</tr>
<tr>
<td>• Dynamic PLL Ratio Changes</td>
</tr>
<tr>
<td>• POR</td>
</tr>
<tr>
<td>• BOR</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Peripherals</th>
</tr>
</thead>
<tbody>
<tr>
<td>3x Comparator</td>
</tr>
<tr>
<td>Missing Clock Detection Circuitry</td>
</tr>
<tr>
<td>128-Bit Security Key/Lock</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 ch, 2SH, 12-bit, 3 MSPS ADC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Serial Interfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>USB 2.0 FS Device</td>
</tr>
<tr>
<td>2x SPI, 1x McBSP</td>
</tr>
<tr>
<td>2x SCI</td>
</tr>
<tr>
<td>1x I²C</td>
</tr>
<tr>
<td>1x CAN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Timer Modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>8x ePWM Modules:</td>
</tr>
<tr>
<td>16x PWM outputs (8x 150ps high-res)</td>
</tr>
<tr>
<td>3 x 32-bit eCAP</td>
</tr>
<tr>
<td>4 x HRCAP</td>
</tr>
<tr>
<td>2 x 32-bit eQEP</td>
</tr>
<tr>
<td>Watchdog Timer</td>
</tr>
<tr>
<td>3x 32-bit CPU Timers</td>
</tr>
</tbody>
</table>

**105C/125C and Q100**

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

*USB available 1Q’11

---

---

---
TI plcSUITE Software Framework

plcSUITE™ Software Frame

- AppEmu/Data App
- SLIP IP Stack
- USB IP Stack
- COSEM App

Host IF HW Driver: UART/USB
Host Control Transport Messaging Protocol
SLIP: Serial Link IP

AppEmu Embedded (Optional, used for host - less operation)

- IEC61334-4-32 LLC IPv4/IPv6 CL
- 6lowPAN
- IEC61334-4-32 LLC
- TI MAC API
- PRIME MAC
- G3 MAC IEEE 802.15.4
- S-FSK MAC IEC 61334

TI PLC PHY API
- FlexOFDM (TI Definition)
- PRIME PHY OFDM
- G3 PHY OFDM
- S-FSK PHY IEC 61334

PLC AFE HAL (Frequency Range: 3-500KHz)

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

Host App SW reference
TI Prime SW Stack

- **Frame Buffer Manager**
  - **Prime MAC API Lib**
    - TCRXM (TC Rx Manager)
    - MRXM (MAC Rx Manager)
  - **Prime Lower MAC API Lib**
    - PRXM (PHY Rx Manager)
  - **Prime PHY API Lib**
    - PTXM (PHY Rx Manager)
  - **HAL API Lib**
    - Host IF Driver
    - UART Driver
    - BSP Driver
    - AFE Driver
    - GPIO Driver

- **RTOS (DSPBIOS)**
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

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

- >90% Common Messages
- Easy migrate from PRIME to G3 or vice versa
TI Helps for Fast SW Development/Port

PHY High-Level API

- **PHY RX Manager**
  - Preamble Detection & Header Parser
  - Receiver State Machine (steady state)
  - Re-sync and Automatic Gain Control

- **PHY Tx Manager**
  - Frame Generation and Timing Control
  - Transmitter State Machine (steady state)
  - Power Control

- **Statistic Output**
  - RSSI, SNR, CRC, header CRC, etc

- **Common State Machine**

**PHY DSP API**

- **Front End Processing Algorithm Lib (Rx/Tx)**
- **Symbol Processing Algorithm Lib (Tx/Rx)**
- **Bit Processing Algorithm Lib (Tx/Rx)**
- **Math/Utility Lib**

**TI DSP-BIOS (SWI, Scheduler, IPC, Memory Management)**

**HAL Layer API**

- **Peripheral HAL LIB (ADC, PWM/HRPWM, DMA, UART, etc)**

---

**All SW LIBs with Cycle Counts Available TODAY!!!**
TI PLC FlexOFDM
TI FlexOFDM Definition: Customizable OFDM

• **Frequency Band/Bandwidth 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
• Green circles denote pilots, grey denote data

• Regular time-frequency pilot structure enables channel estimation, sampling frequency offset estimation
Pilots + coherent modulation + more repetitions → Better header performance

- Enables header decoding below -5 dB even with realistic crystals
PLC-Lite in plcSUITE

plcSUITE™ Software Frame

Host IF HW Driver: UART/USB
Host Control Transport Messaging Protocol
SLIP: Serial Link IP

AppEmu Embedded (Optional, used for host - less operation)

IEC61334-4-32 LLC IPv4/IPv6 CL
6lowPAN
IEC61334-4-32 LLC

TI MAC API

PRIME MAC
G3 MAC IEEE 802.15.4
S-FSK MAC IEC 61334

TI PLC PHY API

PRIME PHY OFDM
G3 PHY OFDM
S-FSK PHY IEC 61334

PLC AFE HAL (Frequency Range: 3-500KHz)

CSMA/CA
DBPSK, ROBO

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

Host App SW reference
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

![Power Spectral Density Estimate](image)

- **Frequency diversity**: FSK may suffer from lack of frequency diversity
  - Both of FSK carriers may suffer from the frequency "notch"
  - OFDM has a frequency diversity against frequency "notches"
  - 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

• **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
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

- 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
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
<table>
<thead>
<tr>
<th>Where</th>
<th>When</th>
<th>Band/NW</th>
<th>Software</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern US</td>
<td>May 2010</td>
<td>CENELEC-A LV/MV</td>
<td>PRIME+ROBO</td>
<td>Channel and noise in Cenelec band</td>
</tr>
<tr>
<td>Japan</td>
<td>Aug 2010</td>
<td>CENELEC-A + FCC, MV/LV</td>
<td>PRIME+ROBO+subband</td>
<td>Cenelec + FCC band demonstration with cap bank</td>
</tr>
<tr>
<td>Southern US</td>
<td>Nov 2010</td>
<td>FCC, MV/LV</td>
<td>PRIME+ROBO+subband</td>
<td>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</td>
</tr>
<tr>
<td>Central Indiana</td>
<td>Dec 2010</td>
<td>FCC, MV/LV</td>
<td>PRIME+ROBO+subband</td>
<td></td>
</tr>
<tr>
<td>Milan</td>
<td>Feb 2011</td>
<td>CENELEC-A, LV/LV</td>
<td>PRIME+ROBO</td>
<td>Passed all the LV/LV test cases</td>
</tr>
<tr>
<td>Milwaukee, WI</td>
<td>Mar 2011</td>
<td>CENELEC-A+FCC, MV/LV</td>
<td>G3-CENELEC A +flex OFDM</td>
<td>Passed with the erasure channel with actuators</td>
</tr>
<tr>
<td>Southern US</td>
<td>Mar 2011</td>
<td>FCC, LV/LV, LV/MV</td>
<td>G3-FCC with flexible masks</td>
<td>Channel and noise captures Confirm flexOFDM tests about insufficient SNR</td>
</tr>
<tr>
<td>Hiroshima, Japan</td>
<td>April 2011</td>
<td>FCC, LV/LV</td>
<td>G3-FCC with flexible masks</td>
<td>Passed all the LV/LV test cases except the WHT case.</td>
</tr>
<tr>
<td>Beijing, China</td>
<td>Apr 2011</td>
<td>FCC, LV/LV</td>
<td>G3-FCC with flexible masks</td>
<td>Achieved up to 200m in out-door grid to meter tests</td>
</tr>
<tr>
<td>Spain</td>
<td>2011</td>
<td>CENELEC-A, LV/LV</td>
<td>PRIME</td>
<td>Official field deployment for hundreds of meters</td>
</tr>
<tr>
<td>Mexico City, Mexico</td>
<td>May 2011</td>
<td>CENELEC+FCC, LV/LV</td>
<td>PRIME and G3-FCC</td>
<td>Successfully pass 2 circuit-breakers for G3-FCC, PRIME has difficulty</td>
</tr>
<tr>
<td>Turkey</td>
<td>June 2011</td>
<td>CENELECA, LV/LV</td>
<td>PRIME &amp; G3-CENELC</td>
<td>Successfully pass all test cases competitor either pass or fail</td>
</tr>
</tbody>
</table>
TI PRIME Based 220 Meters in Burriana, Spain

Connected Meters
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 up to 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 Combinations and FER Percentages

<table>
<thead>
<tr>
<th>Load</th>
<th>CEN A (40-90kHz)</th>
<th>CEN A with tone mask (40-90kHz with 60-77kHz not transmitting)</th>
<th>CEN B (98-122kHz)</th>
<th>CEN B/C (98-138kHz)</th>
<th>FCC Low (145kHz-310kHz)</th>
<th>FCC High (310-478kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Load</td>
<td>ROBO: 0% FER</td>
<td>ROBO: 0% FER</td>
<td>ROBO: 0% FER</td>
<td>ROBO: 0% FER</td>
<td>ROBO: 0% FER</td>
<td>ROBO: 0% FER</td>
</tr>
<tr>
<td></td>
<td>DBPSK: 100% FER</td>
<td>DBPSK: 100% FER</td>
<td>DBPSK: 50% FER</td>
<td>DBPSK: 0% FER</td>
<td>DBPSK: 100% FER</td>
<td>DBPSK: 100% FER</td>
</tr>
<tr>
<td>Additional Load</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>ROBO: 0% FER</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
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
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

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

- **Test Categories:**
  - 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:

- **Linear Chain Network**
  - Base Node
  - Service Node 1
  - Service Node 2
  - Service Node 3
  - Service Node 4

- **Single Hop Network**
  - Base Node
  - Service Node 1
  - Service Node 2
  - Service Node 3
  - Service Node 4

- **Hybrid Network**
  - Base Node
  - Service Node 1
  - Service Node 2
  - Service Node 3
  - Service Node 4
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
  - $A=75\text{dB}$ attenuation measured with 0 BER/FER
    - The received level is $1\text{Vrms} \times 10^{(-75/20)} \approx 200\mu\text{Vrms}$
    - 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
Receive side analog specifications:

**Switchable Attenuator**
Gain: 1 or 1/2

**Rx Active Filter**
- Pass-band gain 1
- In-band ripple upto 6 dB
- 35 dB rej @ 270 kHz
- In-band noise: 30 uV

**PGA**
- Gains 1, 4, 16, 64

**ADC**
- Quantization noise: 0.3 mV
- Max input signal 3V p-p