PRIME

Technology Whitepaper

PHY, MAC and Convergence layers

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1 Introduction

Traditionally, the relationships between utilities and consumers have been rather limited. As long as the energy flowed where and when required, customers were satisfied and trusted all their energy supply decisions to their traditional providers. Additionally, market dynamics were null, generally based on regulated tariffs, so customer perception was that not much could be done about it.

But times have changed and will continue to evolve dramatically. Climate change concerns, growing reliability needs, increasing energy costs and technology advances are leading to a greater consumer involvement, which will redefine the relationship with the utilities. Customers are willing to become more active participants in the energy market. For this truly customer centric business, a new customer interface has to be built; an interface that will allow people make choices based on real time information.

Additionally as a response to the environmental, social and market demands on energy supply, utilities will have to build a new technologies-based grid that can meet all these challenges. The network we are building today has to meet the needs of tomorrow's customers. Improving performance to meet the growing utility marketplace requirements means innovating and integrating technology around the utility processes. And ICT will become a key piece in the future utility.

So this shift in consumer attitude and the technological evolution of the grid will be keys for the transformation of utilities business. Telecommunications, as a mean to interface with the customers and with the distributed assets, becomes a key enabler for this evolution.

PRIME (PoweRline Intelligent Metering Evolution) is a Physical and Mac layer standard definition based on up-to–date technologies, in order to guarantee that future market requirements are met and that utilities' investments are future proof. Prime is open, looking for different vendors' equipment interoperability, as a way to push for the growth of a new market so, that at the end of the day, all players will benefit from this approach.

PRIME is base on OFDM multiplexing in CENELEC-A band and reaches up to 130 kbps raw data rate.

2 PRIME initiative

2.1 Members and structure

PRIME project was launched by Iberdrola in order to assess the idea, define and test a new, future proof, PLC based, open standard that could meet the future requirements on customer real time interfacing and smart grid evolution.

Prime project structure consists of a Steering Committee chaired by Iberdrola and 4 working groups:

- Physical Layer
- MAC Layer
- Upper Layers
- Deployment & Field tests.

The project includes members from all relevant stakeholder groups in order to cover all the different activities involved: utilities, meter manufacturers, chip designers, integrators, etc. Prime project members are:

- Advance Digital Design
- Current Technologies International
- Iberdrola
- Landis & Gyr
- ST Microelectronics
- USyscom
- ZIV Medida

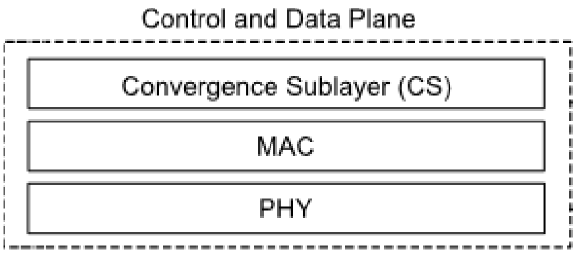
2.2 Project timeline

- **2007**
  - Pre-Prime: solution assessment & testing (200 meter-rooms in 3 towns).
  - 13/9: PRIME Project launching.
  - 31/12: Physical & Mac specifications available.
- **2008**
  - 28/2: Specifications made public.
  - 31/4: Prototypes available from three different vendors.
  - 31/7: Lab and grid testing completed.
  - 31/12: Medium size technical deployment & testing completed.
- **2009**
  - Deployment.

2.3 Key Features

PRIME defines lower layers of a PLC narrowband data transmission system over the electric grid. All the system has been created to be low cost and high performance.

The Figure below depicts the proposed communication layers and the scope of the specification. The proposed reference model is based on IEEE Std. 802.16 protocol layering.



The service-specific Convergence Sublayer (CS) classifies traffic associating it with its proper MAC connection. This layer performs the mapping of any kind of traffic to be properly included in MAC SDUs. It may also include payload header suppression functions. Multiple CSs are defined in order to accommodate different kinds of traffic into MAC SDUs.

The MAC layer provides core MAC functionalities of system access, bandwidth allocation, connection management and topology resolution. It has been defined for a connection oriented Master-Slave environment, and optimized for low voltage power line environments.

The PHY layer transmits and receives MAC PDUs between Neighbor Nodes. It is based on OFDM multiplexing in CENELEC A band and reaches up to 130 kbps raw data rate.

PRIME specifications take advantages of state of the art technologies and adapt them to the needed requirements, simplifying processes, overheads and others, to ensure performance, interoperability between devices and different implementations of elements in the system.

2.4 System Architecture

PRIME system is composed of subnetworks, each of them defined in the context of a transformer station. A subnetwork is a tree with two types of nodes, the Base Node and the Services Nodes.

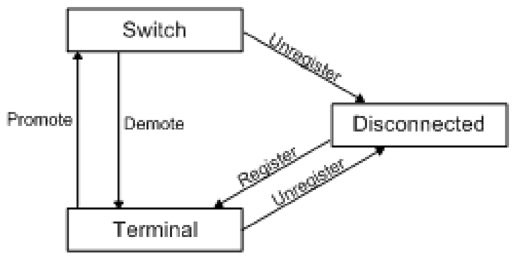
2.4.1.1 Base Node

The Base Node is at the root of the tree and acts as master node that provides connectivity to the subnetwork. It manages the subnetwork resources and connections. There is only one Base Node in a subnetwork. This Base Node is initially the subnetwork itself, and other nodes should follow a process of registering in order to enroll them to this subnetwork.

2.4.1.2 Service Nodes

Any other node of the subnetwork is a Service Node. Service Nodes are either leafs of the tree or branch points of the tree. These nodes start in a disconnected state and follow certain procedures to establish network connectivity. Each of these nodes is one point of the mesh of the subnetwork. These nodes have two responsibilities: connecting themselves to the subnetwork and switching the data of their neighbors in order to propagate connectivity.

Service Nodes change their behavior dynamically from “Terminal” functions to “Switch” functions and vice-versa. Changing of functional states occurs based on certain pre-defined events in the network.



The three functional states of a Service Node are:

- **Disconnected**: Service Nodes start in a disconnected state. In this state a node is not capable of communicating or switching the traffic of another node. The primary function of a Service Node in this state is to search for an operational network in its proximity and to try to register itself to it.

- **Terminal**: In this state a Service Node is capable of communicating its traffic by establishing connections, but is not capable of switching the traffic of any other node.

- **Switch**: In this state a Service Node is capable of performing all Terminal functions. Additionally, it is capable of forwarding data to and from other devices in the subnetwork. It is a branch point in the tree.

3 PHY Layer

3.1 Main features

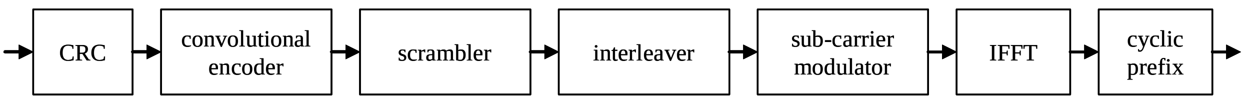
PRIME PHY layer is designed to transmit and receive over power lines which were originally devised for distribution of power at 50-60Hz AC. The use of this medium for communications at higher frequencies presents some technically challenging problems:

- Distribution networks are usually made of a random variety of conductor types, and terminating into loads of different impedances. Such a network has an amplitude and phase response that varies widely with frequency. Furthermore, the channel characteristics can also vary with time as the loads on the network change.

- Interference also affects power lines. Electric appliances with different kind of motors, switching power supplies and halogen lamps produce impulse noise that reduces the reliability of communication signals. Due to attenuation, the noise is also location dependent.

PRIME PHY layer uses a combination of approaches that ultimately allow for robust high speed, low cost communications over power lines. A simple yet powerful scheme which is based on adaptively modulated Orthogonal Frequency Division Multiplexing (OFDM), along with forward error correction and data interleaving.

A block diagram representation of a PHY transmitter is shown:



On the transmitter side, the PHY layer receives its inputs from the Media Access Control layer. If decided by higher layers, the PHY frame after the CRC block is convolutionally encoded and interleaved (however, it will always be scrambled). The output is differentially modulated using a DBPSK, DQPSK or D8PSK scheme. The next step is OFDM, which comprises the IFFT (Inverse Fast Fourier Transform) block and the cyclic prefix generator.

3.2 Transmission technique

One of the main novelties of PRIME is that it uses an OFDM approach instead of traditional single carrier solutions that have been used in the past for narrowband power line communications.

OFDM is well known in the literature and in industry. It is currently used in xDSL technologies, terrestrial wireless distribution of television signals (DVB-T, DVB-H and more), and has also been adapted for IEEE's high rate wireless LAN Standards (802.11a and 802.11g). In less than twenty years, in fact, OFDM has developed into a popular scheme for virtually all new telecoms standards: WiMAX, DAB, DRM, 3G cellular telephony, UWB, MoCA, Broadband over Power line...

Technically speaking, OFDM is a digital multi-carrier modulation scheme, which uses a large number of closely-spaced orthogonal subcarriers to carry data. To obtain high spectral efficiency, these subcarriers typically overlap in frequency, but the mathematical property of orthogonality allows recovering each of the subcarriers separately at the receiver, so in practice subcarriers don't interfere with each other as would be the case with traditional FDM.

Each subcarrier is modulated with a conventional modulation scheme at a low symbol rate, maintaining data rates similar to conventional single-carrier modulation schemes in the same bandwidth. In practice, OFDM signals are efficiently generated and detected using the well-known Fast Fourier Transform (FFT) algorithm.

The primary advantage of OFDM over single-carrier schemes is its ability to cope with severe channel conditions -for example, attenuation of high frequencies in long power lines, narrowband interference and frequency-selective fading due to multipath- without complex additional mechanisms (e.g. equalization filters). Channel equalization is simplified because OFDM may be viewed as using many slowly-modulated narrowband signals rather than one rapidly-modulated wideband signal.

Additionally, low symbol rate makes the use of a guard interval (or cyclic prefix) between symbols affordable, rendering it possible to handle time-spreading and eliminate inter-symbol interference (ISI). For low frequencies like the ones PRIME uses, multipath is not a critical issue so cyclic prefixes will not waste a significant part of OFDM symbols.

PRIME decided to choose OFDM for it automatically solved, in an elegant way, three main problems already mentioned:

- Less precision is required for receiver synchronization, having a direct impact in cost.

- Extended symbol duration in OFDM leads to robustness against *impulsive* noise, as it can only hit a small portion of a symbol in time domain.

- The best exploitation of the available spectrum is possible; this is a critical issue for bandwidth-limited channel like the one we will use (see below).

3.3 Frequency band

From the beginning, an important choice for PRIME was to select a frequency band that would:

- Allow cheap equipment implementations,

- Have acceptable channel behavior for transmission and reception over power lines, and

- Would be future proof. This means the frequency range should not be significantly impaired in the foreseeable future by other services (e.g. radio).

The natural choice for the above needs became evident as in Europe there is already a normalized frequency band which use *“shall be restricted to electricity suppliers and their licensees”,* this is defined in EN50065-1 and it is called CENELEC-A band. It goes from 3 kHz up to 95 kHz. In the US the FCC Part 15 allows the use of up to 500 kHz, so PRIME would also be compatible to it.

CENELEC-A band is an answer to the three questions that were posed, as this frequency range:

- Will allow for the cheapest possible solution. The usage of MHz-bands is currently more expensive for state of the art implementations. The digital-audio industry has been using components in kHz-bands for many years.

- Is already extensively tested for power line communications, both in measurements and field trials.

- Gives a regulatory certainty, which is critical for future proof systems.

Furthermore, PRIME decided to concentrate on a subset of frequencies of the CENELEC-A band. Many measurements of channel characteristics performed in CENELEC-A band show that the spectrum of interest should be located between approximately 45 kHz and 90 kHz:

The final frequency usage of the PRIME OFDM signal is:

- The first subcarrier is centered at 41992.1875 Hz.

- The last subcarrier is centered at 88867.1875 Hz.

- So the signal uses more than 47kHz bandwidth and still comfortably fits inside the “best” part of CENELEC-A band.

3.4 Subcarrier spacing

The inverse of the subcarrier spacing equals the duration of the OFDM symbol (the IFFT interval, actually), so a shorter subcarrier spacing will imply longer symbol duration that will be helpful in providing enough energy to overcome possible impairments caused by impulsive events. This is in fact one of the most powerful features of PRIME OFDM signal, so the shortest subcarrier spacing (within limits) should be favored.

PRIME performed a detailed measuring campaign over different power lines in more than 180 places in three Spanish cities, selecting various cable types, age, distances and topologies. An extensive database was recorded with signals using 13, 26, 48 and 96 subcarriers (which have a roughly similar implementation cost). The results showed the advantage of choosing the 96 subcarrier scheme, which on the other hand is considered an already high enough number. Simulations with higher number of subcarriers did not offer greater advantages.

PRIME OFDM signal presents these features:

- The subcarrier spacing is exactly 488.28125 Hz.
- With the available bandwidth this implies 97 subcarriers. 96 of them will be used for data.
- The IFFT interval length is 2,048 ms plus a cyclic prefix of 0,192 ms.

For a proposed clock of 250 kHz, the parameters of PRIME OFDM signal would be:

Base Band clock (Hz)	250000
Sub-carrier bandwidth (Hz)	488.28125
Number of data subcarriers	96 (Payload)
Number of pilot subcarriers	1 (Payload)
FFT interval (samples)	512
FFT interval (µs)	2048
Cyclic Prefix (samples)	48
Cyclic Prefix (µs)	192
Symbol interval (samples)	560
Symbol interval (µs)	2240

3.5 Power levels

PRIME will have to comply with EN50065-1 limits. But additionally PRIME defines a Transmit PSD measurement setup which will be used to establish compliance: the power amplifier shall be capable of injecting a final signal level in the transmission node of 120dBµVrms (1Vrms) when connected to a certain artificial mains network.

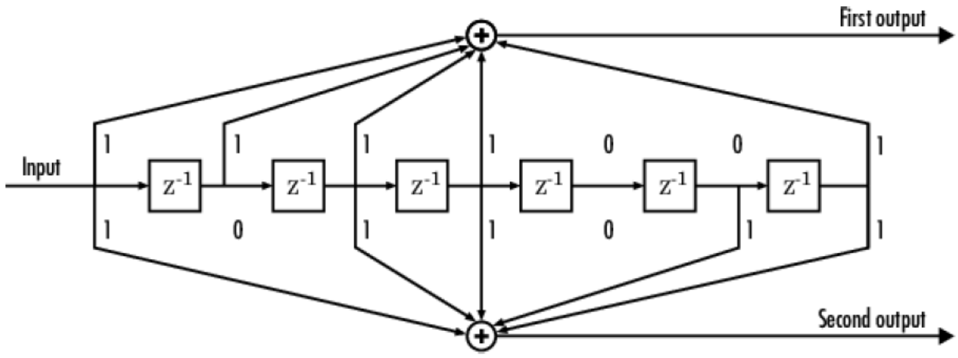
3.6 Forward error correction

Further to the inherent robustness of the uncoded OFDM signal itself, it is fundamental to be able to perform some sort of channel coding for cases in which SNR will be low.

PRIME performed real measurements (as said before) in a big number of different scenarios. Block coding and convolutional coding techniques were specifically analyzed. Results showed that simple convolutional coding performed consistently better than several proposed block codes. The explanation for this seems clear: generally block codes are fully effective for a given underlying noise model, and behave much worse for any deviating noise scenario. Convolutional coding on the other hand is able to cope with a broader range of noise patterns. The variability of noise profiles is seen to be very much noticeable in different locations, so it seems sensible to rely on the coding scheme that would give acceptable results in most of the cases.

It is important to notice that a certain amount of measurements performed quite well in the absence of coding, especially for binary constellations in higher SNR scenarios. So, the mechanism of coding is optional and the decision will be taken by upper layers that will adaptively decide on whether to use it or not.

The selected encoder is a ½ rate binary non-recursive, non-systematic convolutional encoder with constraint length k=7 and a free distance of 10. A smaller constraint length was analyzed but the decrease in performance was not thought to be worth the cost savings.



Additionally to convolutional encoding it is necessary to perform interleaving: because of the frequency fading (narrowband interference) of typical power line channels, OFDM subcarriers at the receiver generally show different amplitudes. Deep fades in the spectrum may cause groups of subcarriers to be less reliable than others, thereby causing bit errors to occur in bursts rather than be randomly scattered. Interleaving is applied along with convolutional encoding to randomize the occurrence of bit errors prior to decoding. At the transmitter, the coded bits are permuted in a certain way, which makes sure that adjacent bits are separated by several bits after interleaving. PRIME uses three different interleaving schemes depending on the constellation itself.

3.7 Scrambler

An additive scrambler is always used to avoid the occurrence of long sequences of identical bits. By randomizing the bit stream, crest factor at the output of the IFFT is reduced. This is a cheap but helpful mechanism to decrease Peak to Average Power Ratio of the OFDM signal, which could otherwise reach dangerous values.

3.8 Digital modulation

The power line channel between any two links has a different amplitude and phase response. Furthermore, noise on the power line is local to the receiver. PRIME optimizes the data rate on each link by means of an adaptive approach i.e. PRIME allows for choosing from three different digital modulations.

It is important to note that amplitude sensitive modulations are not used in PRIME. The real measurements performed also compared different modulation schemes: BPSK, QPSK, 8PSK and 16QAM, both in absolute and differential variants. The differential schemes were further evaluated both in time domain and frequency domain differential modulation. As a result, frequency domain differential modulation proved to be superior in virtually all channels, and it was seen that the benefits of implementing 16QAM over 8PSK were negligible. Best results were of course offered by differential BPSK; however QPSK and 8PSK performed quite acceptably in a sensible portion of the measurements, so it was considered useful to have these modulation schemes available. The fact that just PSK modulations are used simplifies the design and reduces cost.

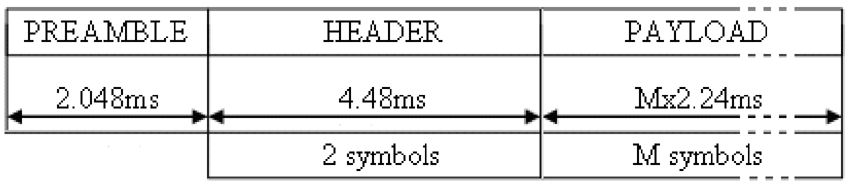
For payload symbols in which 96 subcarriers are used for data we have the following numbers depending on the modulation scheme and coding option (FEC on/off):

	DBPSK		DQPSK		D8PSK	
Convolutional Code (1/2)	On	Off	On	Off	On	Off
Information bits per subcarrier N_{BPSC}	0.5	1	1	2	1.5	3
Information bits per OFDM symbol N_{BPS}	48	96	96	192	144	288
Raw data rate (kbps approx)	21.4	42.9	42.9	85.7	64.3	128.6

The unmodulated payload is modulated as a multicarrier differential phase shift keying signal with one pilot subcarrier and 96 data subcarriers that comprise 96, 192 or 288 bits per symbol. The pilot subcarrier is used inside each OFDM symbol to provide phase reference for the frequency domain differential modulation.

3.9 Frame format

The frame format is shown below:



3.9.1.1 Preamble

Every transmission starts with a fixed Preamble. This is a crucial element for synchronization purposes. The use of OFDM symbols for the Preamble is not appropriate.

In order to get a robust synchronization, a type of signal was selected with a constant envelope signal, in order to allow sending a maximum of signal energy. Additionally, the Preamble needs frequency agility to avoid that frequency selective attenuation could suppress it, and excellent autocorrelation properties are needed.

A well-known class of signals which perfectly fulfills the above requirements is the linear chirp. The waveform of the Preamble is therefore:

$$S_{CH}(t) = A \cdot rect(t/T) \cdot \cos\left[2\pi\left(f_0 t + 1/2\mu t^2\right)\right]$$

where T= 2048μs, f_0= 41992 Hz (start frequency), f_f = 88867 Hz (final frequency), and μ= $(f_f - f_0)/T$.

3.9.1.2 Header and payload

Just after the Preamble, 13 pilot subcarriers are inserted in each of the first 2 OFDM symbols to provide enough information to estimate the sampling start error and the sampling frequency offset. These two symbols form the header. The header is modulated DBPSK with 84 data subcarriers that comprise 84 bits per symbol. The header is always sent using FEC (convolutional coding) 'On'.

However the payload is DBPSK, DQPSK or D8PSK encoded, depending on the SNR available to achieve the desired BER. The MAC layer will select the best modulation scheme using information from errors in the last frames. The system will then configure itself dynamically to provide the best compromise between throughput and efficiency in the communication. This includes deciding whether or not FEC (convolutional coding) is used. Each OFDM symbol in the payload carries 96 data subcarriers and one pilot subcarrier. Each data subcarrier will have a bit-load of 1, 2 or 3 bits.

The fields that form the header and payload are shown below (bits transmitted before encoding):

HEADER						PAYLOAD			
PROTOCOL	LEN	PAD_LEN	MAC_H	CRC_Ctrl	FLUSHING_H	MSDU	FLUSHING_D	PAD	
4	6	6	54	8	6	8xM	8	8xP	bits

- HEADER: it is composed of the following fields:
  - PROTOCOL: contains the transmission scheme of the payload.

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
DBPSK	DQPSK	D8PSK	RES	DBPSK_F	DQPSK_F	D8PSK_F	RES	RES	RES	RES	RES	RES	RES	RES	RES

  Where RES means "Reserved" and the suffix "_F" means FEC is 'On'.
  - LEN: defines the length of the payload in OFDM symbols. Thus a maximum of 63 OFDM symbols will be transmitted in one payload.
  - PAD_LEN: defines the length of the PAD field in bytes.
  - MAC_H: MAC layer Header. It is included inside the HEADER symbols to protect the information contained.

- CRC_Ctrl: the CRC_Ctrl(m), m = 0..7, contains the CRC checksum over PROTOCOL, LEN, PAD_LEN and MAC_H field (PD_Ctrl). The polynomial form of PD_Ctrl is expressed as follows: $\sum_{m=0}^{69} PD\_Ctrl(m)x^m$

  The checksum is calculated as follows: the remainder of the division of PD_Ctrl by the polynomial $x^8 + x^2 + x + 1$ forms CRC_Ctrl(m), where CRC_Ctrl(0) is the LSB. The generator polynomial is the well-known CRC-8-ATM.
- FLUSHING_H: flushing bits needed for convolutional decoding. All bits in this field are set to zero to reset the convolutional encoder.

* PAYLOAD:
  - MSDU: Uncoded MAC layer Service Data Unit.
  - FLUSHING_D: flushing bits needed for convolutional decoding. All bits in this field are set to zero to reset the convolutional encoder. This field only exists when FEC is ‘On’.
  - PAD: Padding field. If the last OFDM symbol is not completed, the padding data must be inserted.

4 MAC Layer

4.1 Addressing

Each node has a universal MAC address - 48 bits (the EUI-48; IEEE Std 802-2001). Each manufacturer assigns this address during manufacturing process and it is used to universally identify a node during network registration process.

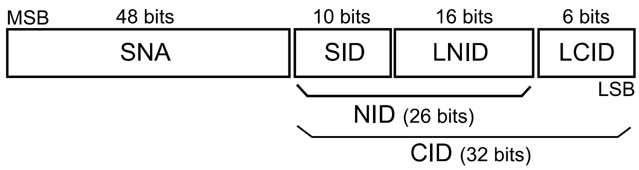
Each subnetwork has only one Base Node, so the EUI-48 of the Base Node identifies its subnetwork uniquely. This EUI-48 is called the Subnetwork Address (SNA).

The Switch Identifier (SID) is a unique identifier of 10 bits for each Switch Node inside a subnetwork. The subnetwork Base Node assigns SID during the promotion process. A Switch Node is universally identified by the pair of SNA and SID. SID = 0 is reserved for the Base Node.

During registering process, a node receives its Local Node Identifier (LNID), which is a 16 bits long identifier. The LNID uniquely identifies a node within the nodes served by a Switch. A combination of LNID received during initial registration and SID of switch which facilitates connection of device in reference, is called NID. The NID identifies a node in a subnetwork. Any node is universally identified by the pair of SNA and NID. LNID = 0 is reserved for Switch Node.

During connection establishment a local connection identifier (LCID) is reserved. This field, which is 6 bits long, identifies specific connection in a node. The combination of NID and LCID is called CID. CIDs uniquely identify connections in a subnetwork. Any connection is universally identified by the pair of SNA and CID.

The full addressing structure and length is represented herewith:



Additionally, multicast and broadcast addresses are used for transmission of data and control information. There are several broadcast and multicast address types, depending on the context associated with traffic flow.

Each Service Node has a level in the topology. The nodes that are connected directly to the Base Node have level 0. The level of any Service Node not directly connected to Base Node is the level of its Switch Node plus one.

4.2 Starting and maintaining subnetworks

A Base Node is primarily responsible for setting up and maintaining a subnetwork. In order to execute its task, the Base Node performs the following:

- **Beacon transmission.** The Base Node and all Switch Nodes in the subnetwork broadcast beacons at fixed intervals of time. The Base Node always transmits exactly one beacon per frame. Switch Nodes transmit beacons with a frequency prescribed by the Base Node at the time of their promotion.

- **Promotion and demotion of terminals and switches.** All promotion requests, generated by Terminal Nodes on receipt of a *Promotion Needed PDU*, are directed to the Base Node. The Base Node maintains a table of all Switch Nodes in the subnetwork and allocates a unique SID to new incoming requests. In case of receipt of multiple promotion requests, the Base Node can, at its own discretion, reject some of those requests. Likewise, the Base Node is responsible for demoting any registered Switch Nodes. The demotion may either be initiated by the Base or be requested by the Switch Node itself.

- **Device registration management.** The Base Node receives registration requests from all new devices trying to be part of its managed subnet. Base Nodes process each received registration request and respond with an Accept or Reject message. Each accepted registration is allocated a unique NID to be used for all subsequent communication within the subnetwork. Likewise, the Base Node is responsible for de-registration of any registered Service Node. De-registration may either be initiated by the Base or be requested by the Switch Node itself.

- **Connection setup and management.** The MAC layer is connection oriented, implying that data exchange is necessarily preceded by connection establishment. The Base Node is always required for all connections in the subnet, either as an end-point of the connection or as a facilitator of the connection.

- **Channel access arbitration.** The usage of channel by devices conforming to this specification maybe controlled (i.e. contention-free) at certain times and open (i.e. contention-based) at others. The Base Node prescribes which usage mechanism shall be in force at what time and for what duration. Furthermore, the Base Node is responsible for assigning the channel to specific devices during contention-free periods of access.

- **Distribution of random sequence for deriving encryption keys.** All control messages in the MAC specification are required to be encrypted before transmission. Besides control messages, data transfers maybe optionally encrypted as well. The encryption key is derived from a 128 bit random sequence. The Base Node periodically generates a new random sequence and distributes it to the entire subnetwork, thus helping maintain security infrastructure of the subnetwork.

- **Multicast group management.** The Base Node maintains all multicast groups in the subnetwork. This implies processing of all join and leave requests from any of the Service Nodes and creation of unsolicited join and leave messages as a result of application requests.

4.3 Channel Access

PRIME devices will be used for specific core-utility applications. Unlike traditional data applications, these kinds of applications generate small bursts of traffic, which may have real-time delay requirements.

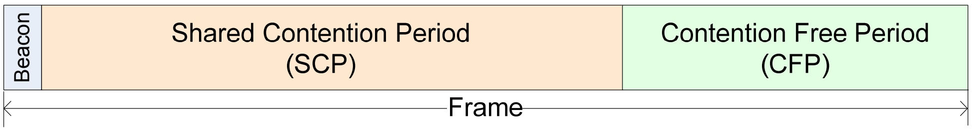
With the given nature of traffic in network, a Time Division Multiplex (TDM) scheme allocating fixed time-slots to each device in the network would mean waste or underutilization of resources. Also, due to the time required for setup processes, dynamic allocation of TDM slots would compromise the real-time requirements for some of the applications. For these reasons it is good to have a CSMA/CA based channel access scheme. At the same time, there may be cases where bulk data transfer is needed from/to the devices. This would be a justification for TDM because CSMA/CA may create unwanted collisions.

Channel Access concept for PRIME subnetwork is comprised of both Carrier Sense Multiple Access (CSMA/CA) and Time Division Multiplex (TDM). Time is divided into composite units of abstraction for channel usage, called frames. Base Node and Service Nodes in a subnetwork can access channel in either the Shared Contention Period (SCP) or they may request for dedicated Contention-Free Period (CFP).

Access of channel in CFP needs devices to make allocation requests to Base Node. The Base Node, depending on present status of channel usage, may grant access to the requesting device for specific duration or may deny the request.

Access of channel in SCP does not require any arbitration. The transmitting devices however need to respect the timing boundaries of the SCP within a frame. The composition of a frame in terms of SCP and CFP is communicated in every frame as part of beacon.

A frame is comprised of one or more Beacons, one Shared Contention Period and zero or one Contention Free Periods (CFP). When present, the length of CFP is indicated in the *Beacon PDU*.



4.4 Switching

In a subnetwork, the Base Node cannot communicate with every node directly. For purposes of scalability and range extension, switching function is defined as an integral part of MAC layer. As mentioned earlier, devices that forward traffic are called Switch Nodes. All Service Nodes in a subnetwork are capable of acting as Switch Nodes, thus enabling full coverage over the low voltage network.

Switch Nodes do not necessarily need to connect directly to the Base Node. They may attach to other Switch Nodes and form a cascaded chain. There is no limitation to the number of Switch Nodes that may connect to a Switch Node down the cascaded chain, thus contributing significantly to range extension and scalability.

Switch Nodes are primarily responsible for:

- Transmitting *Beacon PDUs* at fixed intervals to help:
  - New Service Nodes synchronize to the network.
  - Existing Service Nodes stay synchronized to the network.
  - Transmit control information to connected devices.

- Relaying data and control packets to/from the devices in their domain from/to the Base Node.

Switch nodes do not perform any control functions except for transmitting Beacons. All control functions including initial registration and subsequent connection setups are centralized in the Base Node. This has the following advantages:

- The complexity of Service Nodes is kept low, thus making a low cost implementation possible.

- The Base Node has detailed information of the entire subnetwork and not just the immediately connected devices. Thus it is able to better manage shared network resources.

Switch Nodes repeat traffic to/from the Base Node such that every node in the subnetwork is effectively able to communicate with the Base Node. Switch Nodes selectively forward traffic that originates from, or is addressed to, one of the Service Nodes in its control hierarchy. All other traffic is discarded by Switches, optimizing traffic flow in the network.

Each Switch Node maintains a table of other Switch Nodes that are connected to the subnetwork through it. Maintaining this information is sufficient for switching purpose because traffic to/from Terminal Nodes will also contain identity of their respective Switch Nodes.

4.5 Retransmissions

The power line channel at PHY operational frequencies can experience impulsive noise. While the duration of this noise is very short, it is bound to cause problems for any data on the channel. For this reason, to enable better application layer efficiency, a retransmission scheme is specified within the MAC.

Implementing ARQ functions is not mandatory for conformance to PRIME specifications. Thus, there is provision for low cost Switch Nodes that choose to not implement any ARQ mechanism at all. Intermediate Switch Nodes that do not implement ARQ are required to transparently bridge traffic.

The ARQ mechanism is that of “Selective Repeat”. It provides an efficient performance as compared to other commonly used ARQ schemes.

Each packet has an associated unique packet identifier. Packet identifiers have values within the range of module 256.

4.6 Security

The security functionality provides privacy, authentication and data integrity to the MAC layer through a secure connection method and a key management policy. While devices may choose not to encrypt data traffic, it is mandatory for all MAC control messages to be encrypted with a specific security profile. Additionally, the *Beacon PDU* and *Promotion Needed PDU* are also transmitted non-encrypted.

Several security profiles are provided to manage different security needs, which can arise in different network environments Current version of the specification enumerates two security profiles and leaves scope for adding up to two new security profiles in future versions.

Communications having Security Profile 0 are based on transmission of MAC SDUs without any encryption. This profile shall be used by communication that does not have strict requirements on privacy, authentication or data integrity.

Security Profile 1 is based on 128 bit AES encryption of data and its associated CRC. This profile is specified with the aim of fulfilling all security requirements:

- Privacy is guaranteed by the encryption itself and from the fact that the encryption key is kept secret.
- Authentication is guaranteed by the fact that each node has its own secret key known only by the node itself and the Base Node.
- Data integrity is guaranteed by the fact that the payload CRC is encrypted.

Key management policies define three different *Working Keys*, derived from two *Master Keys*, two *Secret Keys* and a *Key Diversifier*.

4.7 MAC PDU format

There are different types of MAC PDUs, for different purposes.

4.7.1 Generic MAC PDU

Most of subnetwork traffic is comprised of Generic MAC PDUs (GPDU). They are used for most purposes: data and control. They are generally used for any operation of the subnetwork, except for those cases in which special operations require a specific PDU.

The GPDU is composed of the Generic MAC header, one or more MAC packets and the calculated CRC. Including more than one packet is an optional feature which is called “packet aggregation”.

Generic MAC header	Packet 1	Packet 2	….	Packet N	CRC

4.7.1.1 Generic MAC Header

The generic MAC header is 3 bytes in length and contains information which is applicable to all packets contained in a single burst. This information includes:

- Direction of transmission, specifying if the burst is from Service Node to Base Node (downlink) or from Base Node to Service Node (uplink).
- Level of originating device in overall network hierarchy.
- 8 bits of header check sequence.

4.7.1.2 Packet structure

Each packet contains a header and payload:

Packet header	Packet payload

The packet header is 6 bytes long and contains specific information on:

- Source/destination of packet.
- Contents of the packet i.e. if it contains MAC signaling information or data.
- Transmission priority of contents, associating them to QoS mappings.
- Length of contents.
- Sequencing information used for acknowledgements.

The three bytes in Generic MAC Header and the first four bytes of the first Packet header form the *MAC Header* from PHY perspective. It is important information so it is especially protected.

4.7.2 Promotion Needed PDU

The Promotion Needed PDU (PNPDU) is transmitted by Service Nodes in disconnected state when they do not receive Beacons for a fixed period of time. The PNPDU is broadcast with most robust modulation scheme. Any Service Nodes in Terminal state that receive PNPDU initiate a promotion process. On successful completion of promotion process, the receiving Service Node transits to Switch state and starts transmitting beacons that will help inclusion of this new device in subnetwork.

Due to the fact that it is always transmitted by unsynchronized nodes, so it is subject to create collisions, it is a special header to reduce its size.

4.7.3 Beacon PDU

Beacon PDU is transmitted by every Switch Node in the subnetwork, including the Base Node. The purpose of this PDU is to circulate information on channel access frame structure to all devices that are part of this subnetwork. The contents of a beacon transmitted by Base Node and each Switch Device include:

- Security profile used the subnetwork.
- Source address (SID) of the device generating beacon.
- Subnetwork Address (SNA) of this subnetwork.
- Level of beacon source in subnetwork hierarchy.
- Details of frame structure to be followed for the duration of frame that starts with this beacon.

4.7.4 MAC control packets

Control information of the MAC is transported using MAC control packets. Downlink control packets are sent by every Switch Node (and Base Node) to communicate control information to one of its nodes, or to all of them. Uplink control packets are sent by Service Nodes to communicate with the Switch Node they depend on, or with the Base Node.

There are several types of control messages. The payload of the packet contains the information carried by the control packets. This information is different depending on the type of the packet.

Type	Packet name	Packet description
1	REG	Registration management
2	CON	Connection management
3	PRO	Promotion management
4	BSI	Beacon Slot Indication
5	FRA	Frame structure change
6	CFP	Contention Free Period request
7	ALV	Keep Alive

Type	Packet name	Packet description
8	MUL	Multicast Management
9	PRM	PHY Robustness Management
10	SEC	Security information

5 Convergence Layer

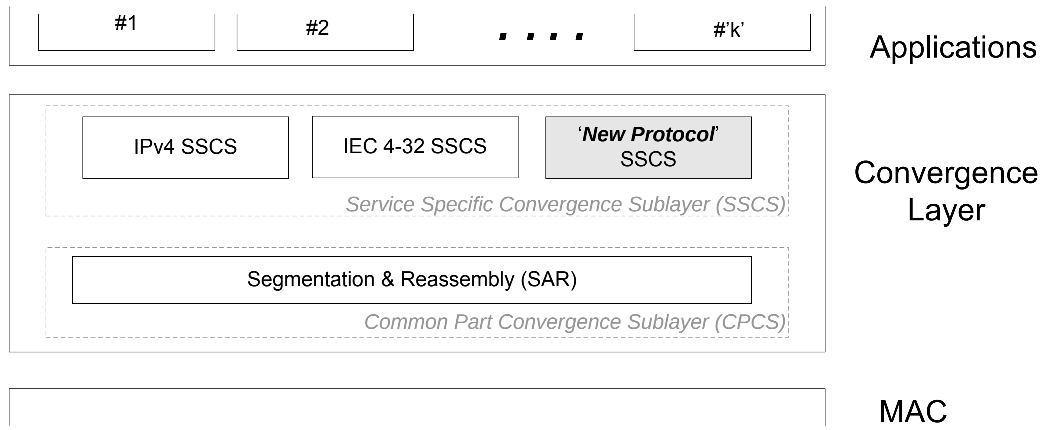
5.1 Introduction

The Convergence Layer (CL) classifies traffic associating it with its proper MAC connection. This layer performs the mapping of any kind of traffic to be properly included in MAC SDUs, providing access to the core MAC functionalities of system access, bandwidth allocation, connection management and mesh topology resolution. It may also include payload header suppression functions.

The convergence layer is separated into two sublayers:

- The Common Part Convergence Sublayer (CPCS) provides a set of generic services.
- The Service Specific Convergence Sublayer (SSCS) contains services that are specific to one application layer.

There are a number of SSCS, typically one per application, but only one common part.



Several CLs are defined in order to accommodate different kinds of traffic into MAC SDUs, namely, IP convergence layer as a very useful and universal access to PRIME, and IEC 61334-4-32 as a link towards metering systems.

5.2 Common Part Convergence Sublayer

Currently there is only one such service. It is segmentation and reassembly (SAR).

The SAR segments convergence layer SDUs that are larger than a specific size into fixed size segments. The segmented data is reassembled at the destination SAR before being forwarded to applications. PRIME specifies a uniform segment size for all convergence layers, thus making it possible to have low complexity implementations.

5.3 IPv4 Convergence Layer

The IPv4 convergence layer provides an efficient method of transferring IPv4 packets over the PRIME network.

A Service Node can pass IPv4 packets to either the base, or to other Service Nodes:

- The Base Node acts as a router between the PRIME subnet and the backbone network. The base could also act as a NAT.
- Current implementation supports only a single route.
- The Service Nodes may use statically configured IPv4 addresses or may use DHCP to obtain IPv4 addresses.
- Each Service Node registers its IPv4 address and EUI-48 address with the Base Node.
- Service Nodes query the Base Node to resolve an IPv4 address into a EUI-48 address. This requires a dedicated connection to be established to the base for address resolution.
- The convergence layer performs the routing of IPv4 packets. That is, the convergence layer will decide if the packet should be directly sent to another Service Node, or forwarded to the configured gateway.
- IPv4 convergence layer in PRIME is connection oriented. Once address resolution has been performed, a connection is established between the source and destination Service Node for the transfer of IP packets. This connection is maintained while there is traffic being transferred and may be removed after an inactive period.
- Optionally TCP/IPv4 headers may be compressed. Compression is negotiated as part of the connection establishment phase.
- Broadcasting and multicasting of IPv4 packets is supported in PRIME.

5.4 IEC 61334-4-32 Convergence Layer

This convergence layer supports the same primitives as the IEC 61334-4-32 standard. The IEC 61334-4-32 SSCS provides convergence functions for applications that use IEC 61334-4-32 services.

Implementations conforming to this SSCS in PRIME offer all LLC services specified in Section 2 of IEC 61334-4-32 (1996-09 Edition) specification. Additionally, PRIME IEC 61334-4-32 SSCS provides some extra services that help to map this connectionless protocol to the connection oriented nature of PRIME MAC.

In this SSCS, a Service Node can only exchange data with the Base Node and not to other Service Nodes:

- Each IEC 61334-4-32 SSCS establishes a dedicated PRIME MAC connection to exchange unicast data with the base.
- The Service Node is responsible for initiating this connection to the Base. The Base cannot initiate a connection to a Service Node.
- Once the connection has been established, the Base Node will always initiate all data transfers with the Service Node.