PRIME v1.4 White Paper

Prepared by the PRIME Alliance Technical Working Group

Abstract:

Summary of improvements and new features introduced by PRIME specification, version 1.4.

This paper presents an overview of PRIME specification v1.4 and some of its unique features. Robust modes enable reliable communications over harsh and exceptional power line channels, and bandwidth extension gives more flexibility and data rates when there are available channels up to 500 kHz, which enables both robustness and high throughput. This is one step forward, after having reached field-proven maturity with PRIME v1.3.6. Now the PRIME Alliance is extending the scope of PRIME, turning it into a global technology, developing new flexible features to cope with "harsh" corner cases in Europe and to provide an adaptable, robust technology for smart grid applications.

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1 Introduction to PRIME v1.4

Power line communication (PLC) is a generic term for the technology that uses power lines as a communication medium. PLC applications have a traditional presence in automated meter reading (AMR) systems, as a founding component of the advance meter infrastructure (AMI) needed for Smart Metering and smart grid deployments. The biggest advantage of using PLC is that no additional wiring is required other than the pre-existing power lines. One of the most important requirements for PLC applications is that all of the components need to be reliably connected all the time in any environmental conditions and must be resilient to any noise or unintended interference. Therefore, special care must be taken to make systems work in harsh environments with the availability and performance needed in each application where PLC is used.

PRIME (PoweRline Intelligent Metering Evolution) PLC technology (ITU G.9904) is an OFDM (Orthogonal Frequency Division Multiplexing)-based technologies to address the challenges of smart grids in existing Low Voltage and Medium Voltage electricity grids [1, 2]. The PRIME technology was developed within the PRIME Alliance and it is now approved as international standard ITU G.9904. The PRIME Alliance (http://www.prime-alliance.org/) is an ecosystem of companies focused on the development of a new open, public and non-proprietary telecom solution which will support not only Smart Metering functionalities but also the progress towards the smart grid. Iberdrola was one of the first utilities to deploy PRIME in large scale to prove the high performance of PRIME systems in the Spanish grid and in other countries. Other utilities worldwide (Energa-Operator, EDP, Gas Natural Fenosa, etc.) do have operational PRIME deployments today (15+ as of November 2014).

PRIME specification has been the major achievement of PRIME Alliance. With it, more than 26 different vendors are able to provide PRIME certified products. PRIME v1.3.6 is the protocol version today successfully deployed in millions of Smart Meters on field. Within the active PRIME Technical Working Group, PRIME specification has anyhow experienced an important evolution in order to improve system performance with two important features, robust modes and FCC/ARIB band extension. PRIME v1.4 will add [3] a set of new modes called “robust modes” (as an example within CENELEC-A band, the addition of robust modes provides more reliable communications up to 14.5 dB gain compared to PRIME v1.3.6 but lower data rates with 5kbps and 10kbps) and will extend the frequency coverage up to 500 kHz to achieve higher data rates in environments where such extended frequencies can be used.

These developments would have not been possible without extensive channel measurements performed by the PRIME Technical Working Group, to validate the performance of PRIME robust modes. The two new transmission modes are Robust DBPSK and Robust DQPSK, which add four OFDM symbol repetitions after the already existing PRIME v1.3.6 convolutional encoder. Headers with increased robustness are combined with longer preambles (=8.192ms) for protection from power line impulse noise. These robust modes enable communication in low signal to noise ratio environments, improving the excellent results obtained in PRIME deployments all over the world. One of the unique features of the PRIME robust modes is that the repetition is done at the OFDM symbol level instead of the bit level, so more time domain diversity can be achieved. Bandwidth extension to 500 kHz is intended to provide higher data rates up to 1Mbps for those applications and areas where other frequency bands are applicable (America and Asia, other applications such as automotive communications). PRIME bandwidth extension also incorporates the robust modes and longer preambles for reliable communications.

All these improvements come together with the necessary Media Access Control (MAC) layer adaptation. MAC layer is a fundamental part of PRIME specification. The improvements of MAC layer allow full backward compatibility of any development compliant with PRIME v1.3.6, ensuring full support of the sound solutions being provided by the multiple active vendors in PRIME ecosystem. Most of the new features in PRIME specification MAC layer are also consequence of the experience acquired during the last four years of worldwide field deployments, where a huge number of PRIME networks have been analyzed.

Apart from those features derived from the new physical layer (PHY) requirements, main new features of the MAC layer in PRIME specification v1.4 are oriented to reduce the overhead of the channel by means of increasing the size and flexibility of the frame, and reducing the number of control packets. For example, data packets and ALIVE packets are used to inform about the quality of each link, and decisions about the modulation scheme are taken considering this information. In this article, we describe some important features of robust modes and FCC/ARIB band extension.

2 Main features of PHY Layer

2.1 PHY Frame formats

The PRIME specification v1.4 defines two types of PHY frames named frame of Type A and Type B. The structure of the PRIME PHY frame of Type A is shown in Figure 1**Error! Reference source not found.**. Each PHY frame of Type A starts with a preamble lasting 2.048 ms, followed by 2+M OFDM symbols, each lasting 2.24 ms. The first two OFDM symbols carry the PHY frame header while the remaining M OFDM symbols carry the payload. The value of M is signaled in the header and is at most equal to 63.

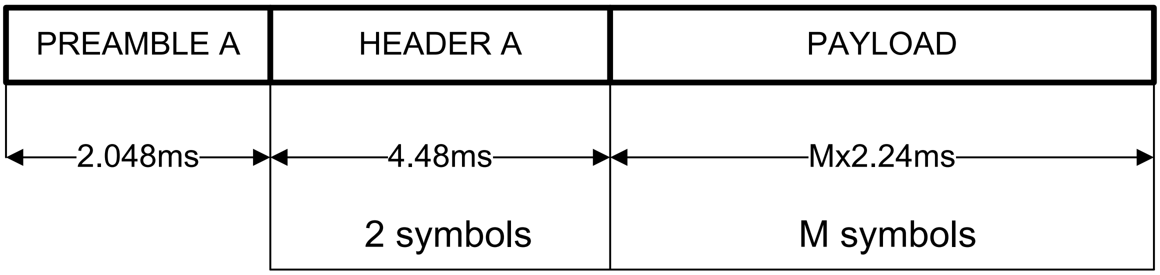

Figure 1 - PHY frame of Type A

The structure of the PHY frame of Type B is shown in Figure 2. Each PHY frame of Type B starts with a robust preamble lasting 8.192 ms, followed by 4+M OFDM symbols, each lasting 2.24 ms. The first four OFDM symbols carry the PHY frame header while the remaining M OFDM symbols carry the payload. The value of M is signaled in the header, and is at most equal to 252.

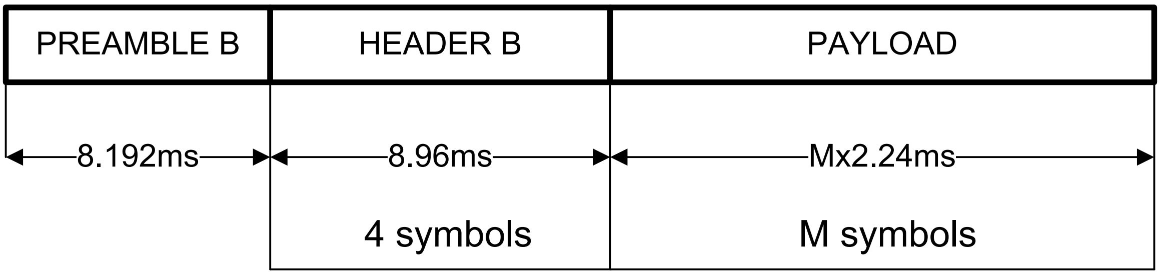

Figure 2 - PHY frame of Type B

The frame of Type A corresponds to the physical layer protocol data unit (PPDU) defined in PRIME v1.3.6.

The frame of Type B is a new type of PPDU and it includes a more efficient header specially designed to support the robust transmission modes. Furthermore, PHY header Type B has several advantages:

1) It can signal 4 times more symbols than a Type A header, as robust PPDUs are expected to be longer.
2) It provides padding up to 8 times bigger than Type A header.
3) Its CRC is 12 bits instead of 8 bits, reducing the possibility of false positives in the PHY layer by 16 times.

4) It is smaller than Type A header by means of reducing MAC layer information, so that it can be encoded in 4 symbols after repetition (1 symbol before repetition). Type A header uses 2 symbols without repetition mechanism.

Depending on channel conditions, the transmitter can use the frame of Type B to take advantage of its greater robustness or the frame of Type A which has a reduced overhead permitting to obtain higher transmission efficiency.

Both Type A and Type B PHY frame defined by PRIME v1.4 support FCC/ARIB band extension, that is, robust modes are available in combination with frequency band extension.

2.2 Robust Modes

In order to cope with very harsh environments, which may be found in specific countries and application conditions, additional optional robust transmission modes have been introduced in the PRIME specification v1.4. These modes have been designed to improve the system robustness against both impulsive noises and interfering noises. In particular, all the portions (preamble, header and payload) of the PHY frame of Type B have been enhanced introducing a repetition factor of four.

2.2.1 Preamble extension

The PRIME v1.4 preamble is based on a linear chirp signal which has three important features:

1) Constant signal envelop. The preamble can provide a higher energy level compared to the OFDM signal composing the rest of the frame.
2) Flexible frequency definition. The preamble can be defined on different frequency intervals.
3) Excellent autocorrelation properties.

To give additional robustness against impulsive noises to the Type B preamble, the chirp sequence composing one preamble symbol $S_{PS}(t)$ is repeated four times resulting in a preamble length of about 8.192ms. The last preamble symbol has a phase inversion which can be used by the receiver for accurate frame synchronization.

In the case of multiple channel bands, each preamble symbol $S_{PS}(t)$ is composed by the concatenation of two or more sub-symbols $S_{SS}(t)$. The number of sub-symbols corresponds to the number of active channels concurrently used. Each sub-symbol contains a chirp signal defined on the frequencies of one of the active channels.

To reduce spurious spectral emissions and to avoid signal distortion due to the frequency discontinuities, the head and tail samples of each sub-symbol are shaped and overlapped with the adjacent sub-symbol. This approach gives the maximal freedom in defining the channels allocation maintaining the constant signal envelop and the good autocorrelation properties of the single channel preamble.

2.2.2 Repetition encoding

The forward error correction (FEC) mechanism of the PRIME v1.4 robust transmission modes are composed by the concatenation of a convolutional encoding and a repetition encoding, as shown in Figure 3.

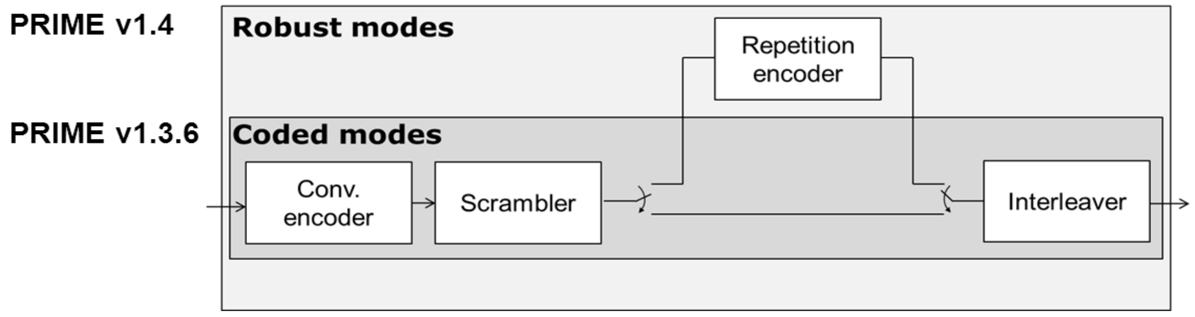

Figure 3 - Block scheme of the PRIME v1.4 robust modes FEC mechanism

The PRIME v1.4 repeater block repeats the convolutional encoded bit sequence associated to an OFDM symbol by a factor of four. Since each repeated sequence is placed on a different OFDM symbol, the time diversity of the system increases with consequent improvement of the resilience to the impulsive noise bursts. Furthermore, thanks to a cyclic shift of the repeated sequences, each bit replica is placed on a different frequency giving frequency diversity to the system. This results in a strong improvement of the system performance in case of narrow-band interferers as well as channel notches. A pictorial description of the PRIME v1.4 repetition encoding is given in Figure 4.

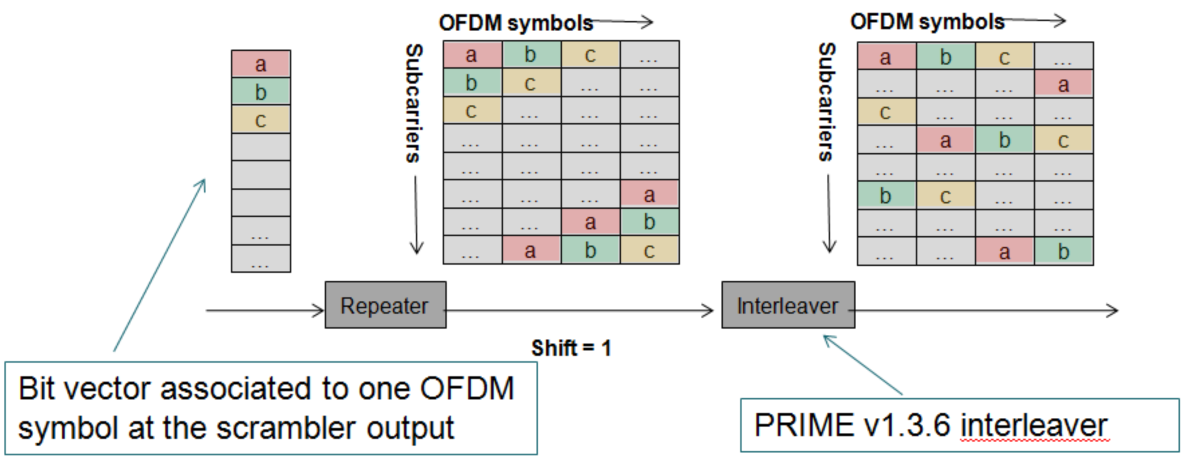

Figure 4 - Repetition encoding description.

The especially designed repetition encoding of the PRIME v1.4 permits to obtain the above enhancements (time and frequency diversity) maintaining a symbol-based interleaver. This solution has three important advantages compared to the alternative solution of increasing the interleaver block size:

1) It has a lower complexity, memory requirement and cost;
2) It facilitates the PRIME v1.3.6 backward compatibility since the same interleaver can be reused to decode PRIME v1.3.6 and PRIME v1.4 frames;
3) It does not increase the decoding latency since each OFDM symbol can be processed immediately.

In order to permit the choice of the best trade-off between robustness and throughput, both DBPSK and DQPSK modulations are supported in the case of the robust transmission modes. In fact, the use of the DQPSK modulation reduces the throughput loss due to the repetition encoding while maintaining the advantage of both time and frequency diversity.

According to the simulation results performed during the specification definition by the PRIME Technical Working Group members, the robust DBPSK mode permits to enhance the system performance of about 4 dB in case of additive white Gaussian noise permitting a reliable communication with a signal-to-noise power ratio of 0 dB (1% of frame error rate with a payload of 256 Bytes). The performance enhancement is much higher in more disruptive scenarios. For example, in the case of a notched channel, a performance gain higher than 6 dB has been measured and in case of impulsive noises, a maximum gain of 14.5 dB was achieved. These results were based on the measured channels in electrical grids from PRIME Technical Working Group.

2.3 FCC/ARIB frequency band extension

The PHY of PRIME originally specified an OFDM modulation scheme in the CENELEC A band (3 kHz up to 95 kHz), which is intended for distribution grid operations according to EN 50065-1. The successful adoption of PRIME technology in many CENELEC regulated countries has provoked an increasing demand outside Europe with the consequent evolution of the specification.

PRIME v1.4 extends the system band up to 500 kHz, multiplying by eight the bandwidth originally available. The use of this extended frequency range is subject to applicable local regulations, e.g. EN 50065-1 in Europe, or FCC part 15 in the US.

2.3.1 Concept

PRIME v1.4 PHY specification uses the frequency band from 41.992 kHz to 471.6796875 kHz. This range is divided into eight channels, which may be used either as single independent channels or “NCH” of them concurrently as a unique transmission / reception band. Figure 5 shows PRIME v1.4 channel allocation.

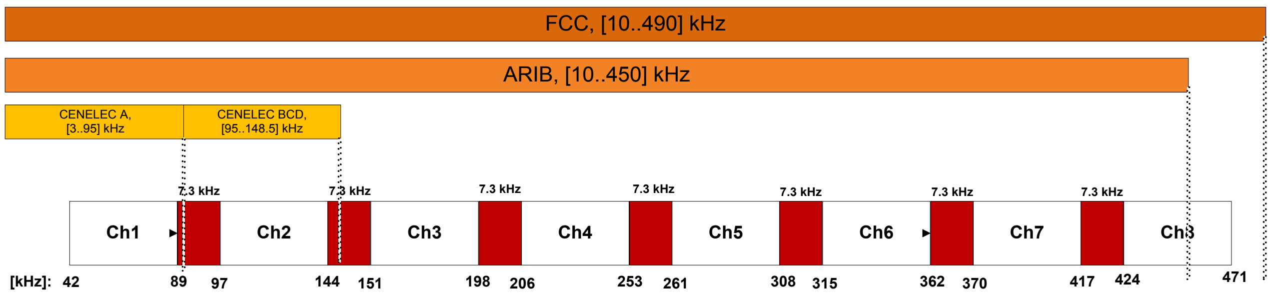

Figure 5 - PRIME v1.4 FCC / ARIB frequency band extension

OFDM modulation is specified in each channel, with data signal loaded on 97 equally spaced subcarriers, transmitted in symbols of 2240 us, of which 192 us are comprised of a short cyclic prefix. Adjacent channels are always separated by guard intervals of fifteen subcarriers (7.3 kHz).

The new PRIME v1.4 PHY layer refers to the PRIME v1.3.6 header as “Type A”, extending the concept of this header for the band extension by including more MPDU bytes in the two header symbols that are transmitted in the additional available channels.

2.3.2 Features

PRIME v1.4 provides extremely high flexibility since the eight available channels can be combined in many different ways, constituting “bands”. The amount of supported bands and their configuration is called “band plan” and is managed by the MAC layer.

Combining multiple channels into a band allows PRIME v1.4 to achieve baud rates ranging from a minimum of 5.4 kbps (one channel in the most robust mode) to a maximum of 1028.8 kbps (eight channels in the less robust mode). These rates are shown in **Error! Reference source not found.**.

Table 1 - PRIME v1.4 data rates

Sub-carrier modulation scheme	DBPSK			DQPSK			D8PSK	
Convolutional code (1/2)	On	On	Off	On	On	Off	On	Off
Repetition Code	On	Off	Off	On	Off	Off	Off	Off
Raw data rate (kbps)	N_{CH}x5.4	N_{CH}x21.4	N_{CH}x42.9	N_{CH}x10.7	N_{CH}x42.9	N_{CH}x85.7	N_{CH}x64.3	N_{CH}x128.6

N_{CH} = Number of active channels [1..8]

The typical noise behavior in a standard power line channel favors transmission in higher channels. A possible use case, combining e.g. three upper channels (Ch5, Ch6 and Ch7) in DQPSK_CC would provide a raw baud rate of 128 kbps.

The service nodes contain a set of specific preconfigured bands. This so called band plan is deployment specific. The PRIME conformance tests define which bands are mandatory for a service node. The MAC section of the PRIME v1.4 specification lists some basic rules how service nodes shall search through the different bands of the plan to automatically determine the band to operate in.

3 Main features of MAC Layer

3.1 MAC Frame Format and Channel Access

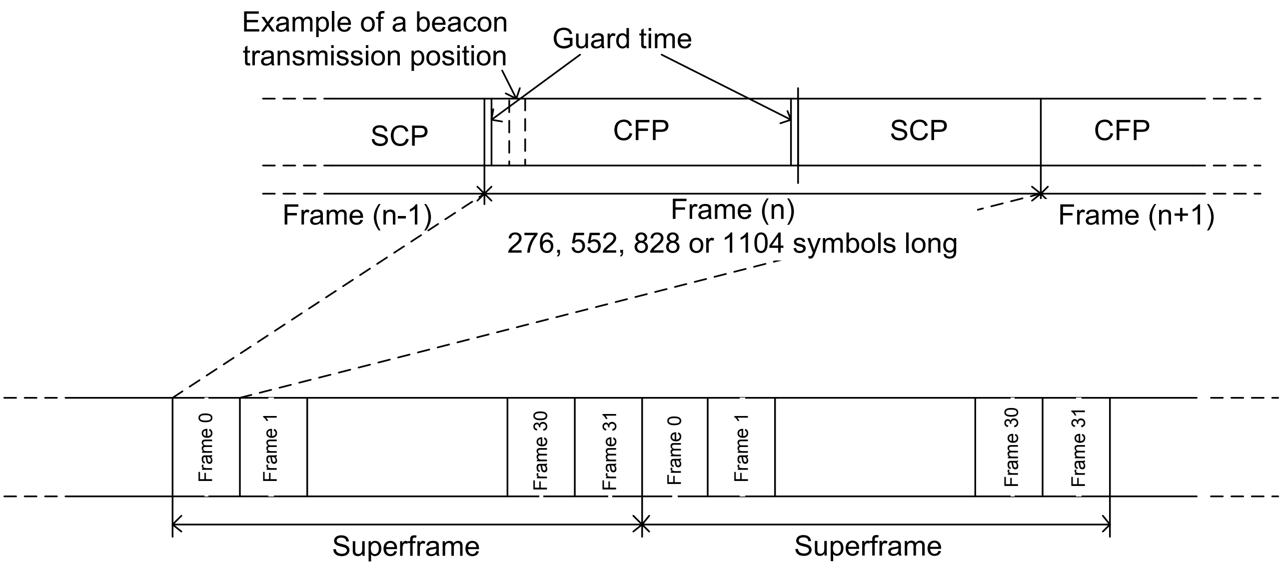

Figure 6 - MAC Frame Format

The new robust PHY Frames (Type B) are longer and thus imply a different channel usage. Beacons using robust modulation are up to four times longer than beacons using non-robust modulation. To sustain throughput the MAC introduces two new features:

- The MAC frame length is flexible and it can be 276, 552, 828 or 1104 symbols long. The frame length is commanded by the base node. The longer frames reduce the portion of time which is used for beacon transmission, thus increase throughput, at the cost of slower network convergence. Base nodes select an optimal policy depending on the amount of robust mode transmission in the network.
- To support the different beacon lengths, the beacon slot concept was revised. Beacon slots and contention free area (CFP) are merged in PRIME v1.4 to a single CFP at the beginning of the MAC frame. Beacon positions are defined in symbols since frame start. The base node is responsible to reserve contention free period for the beacons from the MAC CFP area. This specification enhancement gives base nodes the ability to schedule beacons optimally and, thereby, minimize the amount of time reserved for beacon transmission.

Changes to the frame structure and the beacons can be initiated by the base node using control messages.

The robust PHY Frames of Type B use a longer preamble. The preamble length has an important influence in determining channel occupancy. An adjustment of the parameters used in the CSMA-CA algorithm was necessary. To maintain the efficiency in networks which do not use robust modulations, two sets of parameters are defined. Depending whether robust mode transmissions are used in a PRIME network, the base node commands the service nodes to use one or the other parameter set. The information which parameter set a service node shall use is propagated through the network as part of the beacons.

3.2 Modulation selection

The Robustness-management (RM) mechanism is reworked to support the new robust mode modulations. It is designed to select the most suitable transmission scheme from the eight available ones (Robust DBPSK, Robust DQPSK, DBPSK_CC, DBPSK, DQPSK_CC, DQPSK, D8PSK_CC and D8PSK). Depending on the transmission channel conditions, the nodes shall decide either to increase the robustness or to select faster transmission modes for generic DATA packets. MAC control packets are not subject to this mechanism and are transmitted in Robust DBPSK, Robust DQPSK or DBPSK_CC.

By default, decision about applicable transmission mode is taken locally. That is, dynamic adaptation of the transmission mode is performed taking into account link level channel information, which is exchanged between any pair of nodes in direct vision (parent and child). As an exception to this rule, a Base Node may decide to disable dynamic robustness-management and force a specific transmission mode in the Service Node(s). This static configuration shall be fixed during registration.

The robustness-management mechanism comprises two main features:

- Link quality information, which is embedded in the packet header of any Generic packets.
- Link level ACK-ed ALIVE mechanism.

3.2.1 Link quality information embedded in the packet header

All Generic packets convey link quality related information. Four bits in the packet header are used by the transmitting device to notify the other peer of the weakest modulation scheme that the transmitter considers it could receive by that specific peer. The transmitting device calculates this value processing the received packets sent by the other peer.

Whenever a node receives a Generic packet from a peer, it shall update some info related to the transmitting peer. Basically, the modulation scheme the transmitter considers it could receive (4-bit value comprised in the transmitted header) and, at the same time, the receiving node shall reset a timestamp used to check if this information is valid or not.

Whenever a node wants to transmit DATA to an existing peer, it shall check validity of the robustness-management information it stores related to that peer:

- If the robustness-management information is out of date: The node shall transmit using the most robust modulation scheme available for the PHY frame type in use. Note: the first time a node sends DATA to a peer, RM information is automatically considered to be “out of date” and consequently the most robust modulation scheme available shall be used.
- In case robustness-management information is valid: The modulation scheme previously stored by this node can be used for transmission.

3.2.2 Link level ACK-ed ALIVE mechanism

The ALIVE procedure has been modified to work hand in hand with the new RM mechanism. It defines repetitions that are performed in every hop, both down- and up-link. A device transmitting ALIVE packets shall use this fact to assume a delivery failure if it does not receive the corresponding ACK packet. In this case the transmitting device shall re-transmit the packet: the first repetition shall be performed with the same robustness, which will be successively increased after every link level repetition. Once the maximum number of repetitions is reached, the least robust modulation in which the node can transmit could be stored, even if the repetitions were due to the ACK packets, the robustness-management information should correct a change to a more robust modulation than needed.

The device receiving the ALIVE packets, on reception of a packet being sent more than twice, shall send the ACK packet with at least the same robustness as the received packet.

The ALIVE packets shall be transmitted in one of the following encodings: DBPSK_CC, Robust DQPSK and Robust DBPSK. The robustness increase should be performed in that order.

The new ALIVE procedure has, in addition to support RM, further benefits. The new ALV packet contains information of the quality of each link. This information provides the Base Node with accurate information of the whole network.

- All these new features have some bandwidth cost, lower than having independent robustness management packets. To make this cost even lower some optimizations have been added. Maximum ALIVE time has been increased by 8, so a network can manage more devices than a PRIME v1.3.6 network. If all of the nodes were robust it could hold twice as nodes as today is holding with the same ALV bandwidth.
- Switch Nodes update their ALIVE time each time they switch an ALIVE to nodes depending on them, decreasing the need of performing ALIVE operations with them and in the same time they will be more robust to collisions and the networks will be more stable.
- When ARQ data packets or some control packets are received from the Base Node the receiving Terminal Node updates the timer for the ALIVE expiration.

3.3 Multicast switching simplification

In PRIME v1.3.6, the nodes did have to maintain the multicast table to switch the appropriate multicast traffic. The issue is that the cost of maintaining such a table and state machine is very memory intensive. This has been addressed with a new mechanism which is introduced in PRIME v1.4. The procedure to start switching multicast traffic is the same as it was in PRIME v1.3.6, just listen to a MUL_JOIN packet, that does not require too many memory. When all the nodes depending on the switch have left the group, instead of the Switch Node having to know it, the Base Node will send a control packet to explicitly stop switching multicast traffic for a group.

4 Backward compatibility

4.1 PHY backward compatibility mechanism

PRIME specification v1.4 is an extension of v1.3.6. The inclusion of new features, such as additional robust modes and a new PHY frame type (Type B), implies that PRIME v1.4 compliant devices shall be able to support the following scenarios:

1) Homogeneous networks which do implement neither the new frame type (Type B) defined in PRIME v1.4 nor the additional robust modes (Robust DBPSK, Robust DQPSK). This case corresponds to PRIME v1.3.6 networks.

2) Homogeneous networks which implement PRIME v1.4 new frame type (Type B) as well as the additional robust modes (Robust DBPSK, Robust DQPSK).

3) Mixed networks, composed of a combination of devices described in points (1) and (2) above.

Mixed networks (scenario 3) require a specific mechanism that provides coexistence for PRIME compliant devices using different PHY frame formats.

For that purpose a backward compatible PHY frame ("BC frame") has been defined. Its format is shown in Figure 7:

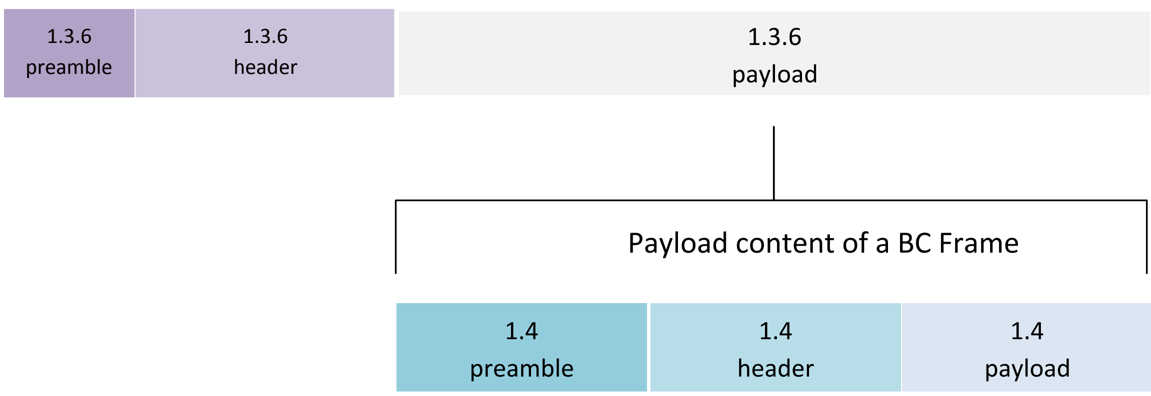

Figure 7 - Backward compatible PHY frame

The BC frame is just a prefix (a PRIME v1.3.6 preamble followed by a predefined v1.3.6 header) encapsulating a standard v1.4 Type B frame in its payload.

This prefix can be detected by PRIME v1.3.6 devices, achieving two critical goals. First, the header in the prefix specifies the length of the appended v1.4 frame in the payload – that is, a PRIME v1.3.6 device will know exactly how long the channel is busy and will not try to access it. Second, the predefined value in the header is configured in a way that makes PRIME v1.3.6 devices to discard the whole BC frame.

By means of this mechanism, devices supporting the Type B frames defined in PRIME v1.4 are allowed to use them in mixed networks without colliding with PRIME v1.3.6 devices, which are not able to decode Type B frames.

This feature is especially useful to provide connectivity between PRIME v1.3.6 clusters under severe and exceptional noise conditions. The connectivity can be achieved by means of PRIME v1.4 capable nodes acting as bridges between clusters. This is the most common use case in PRIME v1.4 / PRIME v1.3.6 mixed networks.

4.2 MAC backward compatibility mechanism

PRIME v1.4 includes MAC backward compatibility features which provide a seamless transition of PRIME v1.3.6 networks to PRIME v1.4 networks. PRIME v1.4 service nodes start operating in PRIME v1.4 compatibility mode when the base node indicates it through its Beacons. Compatibility mode supports the coexistence of PRIME v1.3.6 and PRIME v1.4 service nodes.

PRIME v1.4 compatibility mode provides an easy transition mechanism in case there are hard-to-reach meters in an existing PRIME v1.3.6 network. By upgrading some meters in a harsh environment network to PRIME v1.4, the robust modulations can be used to increase connectivity. The design of the compatibility mode is based on this kind of use cases. In these scenarios the benefits from PRIME v1.4 compatibility mode outweigh the performance limitations by far.

5 Conclusion

This paper has presented an overview of the PRIME v1.4 specification and some of its unique features. Robust modes enable reliable communications over harsh and exceptional power line channels, and bandwidth extension gives more flexibility and data rates when channels up to 500 kHz are available, to provide both robustness and high throughput.

With installed smart meters approaching 5 million, PRIME confirms it is a proven technology that performs in large-scale, future-proof smart grid deployments. With PRIME v1.4, the scope of PRIME is extended for global smart grid applications. This unleashes new opportunities of added-value services that strongly improve the business case and fit the requirements of the evolving smart grid network beyond traditional utility smart metering business.

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