Analysis of standards for Low frequency narrow band power line communication for smart grid applications

For P1901.2

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AGENDA ITEMS

- 14 - Proposed network architecture
  - Review of existing solutions/standards.

- 17 – Review of PHY main features alternatives
  - OFDM parameters and Operating Frequency
  - Synchronization
  - Modulation Schemes
  - Coding and error correction

- 18 – Review of MAC main features alternatives
  - Challenges of NPLC for SG
  - Beacon vs. Non-Beacon Configurations
  - Mesh vs tree network topology
  - CSMA-CA vs SFN

- 19 – Coexistence and evolution
**Review of existing solutions/standards**

- Proposed rules for evaluation:
  - Is it based on OFDM?
  - Is it under 500kHz?
  - Is it an open standard?

<table>
<thead>
<tr>
<th>Name</th>
<th>Modulation</th>
<th>Freq Range</th>
<th>Open standard</th>
</tr>
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<tbody>
<tr>
<td>Aclara TWACS</td>
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<td>&lt;20kHz</td>
<td>Patented</td>
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<tr>
<td>G3</td>
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<td>Open</td>
</tr>
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<td>LonWorks</td>
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<td>IAd</td>
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<td>&lt;100kHz</td>
<td>Patented</td>
</tr>
<tr>
<td>PRIME</td>
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<td>&lt;100kHz</td>
<td>Open</td>
</tr>
<tr>
<td>Watteco WPC</td>
<td>✗</td>
<td>&lt;100kHz</td>
<td>Patented</td>
</tr>
<tr>
<td>Ytran DCSK</td>
<td>✗</td>
<td>&lt;100kHz</td>
<td>Patented</td>
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</table>
Summary of G3-PLC Solution

- **Application layer**
  - Compliant with ANSI C12.19/C12.22, IEC 62056-61/62 (DLMS/COSEM), and other international standards

- **Transport and network layers**
  - IPv6 enables potential services: SNMP, TFTP, etc.
  - 6LoWPAN adaptation layer associates the IEEE 802.15.4-based MAC layer to IPv6
    - Compression of IP header, fragmentation, routing, and authentication

- **MAC layer**
  - Plug-and-play network management chooses “the best path” (full mesh support)
  - Time-domain and collision management
  - IEEE 802.15.4-2006 MAC layer
  - CSMA/ARQ

- **Physical layer**
  - Support of internationally accepted bands from 10kHz to 490kHz (FCC, CENELEC, ARIB)
  - Multilayer error encoding/decoding
    - Viterbi, convolutional, Reed Solomon, and CRC16
  - 8PSK, QPSK, BPSK, ROBO, and Messaging modes
  - Adaptive tone mapping, notching, and modulation
G3-PLC PHY Architecture

- Adaptive tone mapping/notching for optimal bandwidth utilization
- Robust mode of operation to improve communication under noisy channel conditions
- Two layers of forward-error correction (FEC) for robust data communication
- Two-dimensional time and frequency interleaving
G3: Encapsulation of Application Data Through Protocol Layers

**IPv6/UDP layer**
- 207 bytes of load-profile data
- 3 bytes of COSEM application layer
- 8 bytes of IPv6 COSEM wrapper
- 8 bytes of UDP header
- 40 bytes of IPv6 header

**6LoWPAN layer**
- IPv6 and UDP headers are compressed to 2 and 4 bytes, respectively

**IEEE 802.15.4 MAC layer**
- MAC layer may segmentize the frame depending on channel characteristics (modulation and number of used tones)
- MAC header and FCS (CRC16) are added to the payload

**PHY layer**
- Frame control header (FCH) is added to construct the PHY frame
- FCH carries important information about PHY frame (duration, modulation, tone map)
PRIME Alliance: History

- Mar 2010
  - 23 members, including;
    - 8 Principal Members and 17 Regular Members

- October 12th, 2009
  - PRIME Alliance Field Test Proves Successful interoperability for multi-vendor Metering

- May 29th 2009
  - First PRIME ALLIANCE meeting was held

- May 12th, 2009
  - PRIME Alliance launched.

<table>
<thead>
<tr>
<th>Company Name</th>
<th>Type</th>
<th>Membership</th>
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<tbody>
<tr>
<td>1. ADD</td>
<td>Semiconductor</td>
<td>Principal Member</td>
</tr>
<tr>
<td>2. CURREN GROUP</td>
<td>Distribution Manag.</td>
<td>Principal Member</td>
</tr>
<tr>
<td>3. EERDROLA</td>
<td>Utility</td>
<td>Principal Member</td>
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<tr>
<td>4. TRON</td>
<td>Meter Manufacturer</td>
<td>Principal Member</td>
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<td>5. LANDIS+GYR</td>
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<tr>
<td>6. STMICROELECTRONICS</td>
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</tr>
<tr>
<td>7. TEXAS INSTRUMENTS</td>
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<td>8. ZIV GROUP</td>
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<td>9. CEZ MERENI</td>
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<tr>
<td>10. CIRCUTOR</td>
<td>Meter Manufacturer</td>
<td>Regular Member</td>
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<td>11. FUJITSU MICROELEC.</td>
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<td>12. SKRA-METREGA</td>
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<td>Regular Member</td>
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<td>13. ORBIS</td>
<td>Meter Manufacturer</td>
<td>Regular Member</td>
</tr>
<tr>
<td>14. TRI (TAWAIN POWER)</td>
<td>Utility</td>
<td>Regular Member</td>
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<td>15. ADD grup (MOLDOVA)</td>
<td>Meter Manufacturer</td>
<td>Regular Member</td>
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<tr>
<td>16. EDP</td>
<td>Utility</td>
<td>Regular Member</td>
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<td>17. NUCLEO</td>
<td>Distribution Automation</td>
<td>Regular Member</td>
</tr>
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<td>18. SAC</td>
<td>Distribution Automation</td>
<td>Regular Member</td>
</tr>
<tr>
<td>19. SADEMCOM</td>
<td>Meter Manufacturer</td>
<td>Regular Member</td>
</tr>
<tr>
<td>20. SOGECAI</td>
<td>Meter Manufacturer</td>
<td>Regular Member</td>
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<td>21. APATOR</td>
<td>Meter Manufacturer</td>
<td>Regular Member</td>
</tr>
<tr>
<td>22. INDRA</td>
<td>System Integrator</td>
<td>Regular Member</td>
</tr>
<tr>
<td>23. JANZ</td>
<td>Meter Manufacturer</td>
<td>Regular Member</td>
</tr>
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</table>
PRIME Structure (I)

- **PRIME** is the specification of a solution for Power Line Communications in the CENELEC A-Band using OFDM modulation.
- This solution is oriented to provide a low cost and very robust communication channel in applications such as Automated Meter Management.
- The average transmission rate for the PHY layer is around **70 kbps** and the maximum is **128 kbps** using a bandwidth of 47.363 kHz located on the high frequencies of the CENELEC A-Band (41.9 to 88.8 kHz).
- The design is based on international and recognized standards with specific improvements and modifications to fit into this specific environment.
PRIME Structure (II)

- PRIME provides a complete specification of the data and control planes, as well as of the Management Plane.
- The service-specific 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.
  - It may also include pay-load header suppression functions.
  - Multiple Convergence sublayers are defined to accommodate different kinds of traffic into MAC.
- The MAC layer provides functionalities like system access, bandwidth allocation, connection establishment/maintenance and topology resolution.
- The PHY layer transmits and receives MPDUs between neighbor nodes.
PRIME: Convergence Layer (CL)

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.
PRIME system is composed of sub networks, each of them defined in the context of a transformer station. A sub network is a tree with two types of nodes, the Base Node and the Service Nodes.

The Base Node is at the root of the tree and acts as a master node that provides connectivity to the subnetwork. It manages the subnetwork resources and connections.

Any other node of the subnetwork is a Service Node. These nodes have two responsibilities: connecting themselves to the sub network and switching the data of their neighbors in order to propagate connectivity.

The MAC layer provides all necessary features to manage PRIME networks and sub networks: addressing, synchronization (beacon management), dynamic management of the network structure (promotion and demotion of terminals), device registration management, connection setup and management, channel access arbitration, distribution of random sequences for deriving encryption keys, multicast group management...
PRIME: PHY Layer Overview

- PLC: frequency fading -> error bursts
  - Separate adjacent bits using interleaving
  - Adjacent coded bits are mapped onto non-adjacent data subcarriers

- OFDM symbol + cyclic prefix

- Cyclic prefix

- Sub-carrier modulator

- IFFT

- OFDM freq allocation

- Convolutional Encoder (optional)

- Scrambler

- Interleaver (optional)

- CRC

- [0010..010]
On the transmitter side, the PHY layer receives its inputs from the Medium Access Control layer.

If decided by higher layers, the PPDU (Physical layer Protocol Data Unit) after the CRC block is *convolutionally encoded* and then 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.
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OFDM parameters and Operating Frequency

- An advantage of OFDM is its ability to cope with severe channel conditions without complex additional mechanisms (e.g. equalization filters)

- Baudrate is proportional to the bandwidth and the modulation used

- Size of the symbol
  - is proportional to the sampling frequency and the number of sub-carriers
  - increases the robustness in case of impulsive noise

- Coding increases the robustness but also increases the complexity and the power consumption
**PRIME: PHY layer, OFDM parameters and operating Frequency**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base band clock</td>
<td>250kHz</td>
</tr>
<tr>
<td>Symbol length</td>
<td>2240 μs</td>
</tr>
<tr>
<td>Preamble length</td>
<td>2048 μs</td>
</tr>
<tr>
<td>Number of data subcarriers</td>
<td>84 (header)</td>
</tr>
<tr>
<td>Number of pilot subcarriers</td>
<td>13 (header)</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>488,28125 Hz</td>
</tr>
<tr>
<td>Frequency Band</td>
<td>(47kHz) 42 – 89 KHz (CENELEC A)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>DBPSK</th>
<th>DQPSK</th>
<th>D8PSK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convolutional Code (1/2)</td>
<td>On</td>
<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>Info bits per subcarrier</td>
<td>0,5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Info bits per OFDM symbol</td>
<td>48</td>
<td>96</td>
<td>96</td>
</tr>
<tr>
<td>Raw data rate (kbps approx)</td>
<td>21,4</td>
<td>42,9</td>
<td>42,9</td>
</tr>
<tr>
<td>MAX MSDU length with 63 symbols (bits)</td>
<td>3016</td>
<td>6048</td>
<td>6040</td>
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</tbody>
</table>
PRIME: PHY layer, frame structure

### Preamble
- Is used at the beginning of every PPDU for synchronization purposes.
- A linear chirp signal meets all the requirements.

### Header
- The header is composed of 2 OFDM symbols, which are always sent using DBPSK modulation and FEC (convolutional coding) ‘On’.
- The first two OFDM symbols (header) are composed of 84 data subcarriers and 13 pilot subcarriers.

### Payload
- 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 to provide the best compromise between throughput and efficiency in the communication.
- This includes deciding whether or not FEC (convolutional coding) is used.
- After the header, 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 stream from each field must be sent msb first.
**G3: PHY layer, OFDM parameters and operating Frequency**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Base band clock</td>
<td>400kHz</td>
</tr>
<tr>
<td>Symbol length</td>
<td>735 μs</td>
</tr>
<tr>
<td>Preamble length</td>
<td>715 μs x 9.5 = 6792 μs</td>
</tr>
<tr>
<td>FCH symbols (Header) length</td>
<td>735 μs x 13 = 9555 μs</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>36</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>1562.5 Hz</td>
</tr>
<tr>
<td>Frequency band (54.7 kHz)</td>
<td>35.9 – 90.6 kHz (CENELEC A)</td>
</tr>
<tr>
<td>RS DQPSK</td>
<td>2,423 kbps – 5,592 kbps</td>
</tr>
<tr>
<td>RS DBPSK</td>
<td>3,271 kbps – 20,009 kbps</td>
</tr>
<tr>
<td>RS DBPSK Robust</td>
<td>12,10 kbps – 34,16 kbps</td>
</tr>
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</table>
## PRIME/G3: PHY layer, OFDM parameters

<table>
<thead>
<tr>
<th></th>
<th>PRIME</th>
<th>G3</th>
<th>PRIME/G3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base band clock (kHz)</td>
<td>250</td>
<td>400</td>
<td>0.62</td>
</tr>
<tr>
<td>Symbol length (ms)</td>
<td>2.24</td>
<td>0.735</td>
<td>3</td>
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<tr>
<td>Preamble length (ms)</td>
<td>2.048</td>
<td>6.792</td>
<td>0.3</td>
</tr>
<tr>
<td>Header length (ms)</td>
<td>4.48</td>
<td>9.555</td>
<td>0.469</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>97</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Subcarrier spacing (Hz)</td>
<td>488.2</td>
<td>1562.5</td>
<td></td>
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<tr>
<td>Frequency band (kHz)</td>
<td>47</td>
<td>54.7</td>
<td></td>
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<tr>
<td>Min Baud rate</td>
<td>21.4</td>
<td>2.423</td>
<td>8.84</td>
</tr>
<tr>
<td>Max Baud rate</td>
<td>128.6</td>
<td>34.16</td>
<td>3.76</td>
</tr>
</tbody>
</table>
Synchronization

- **PRIME preamble**
  - Uses a chirp signal of 2,048 ms and constant envelope
  - A single frequency that evolves from 42kHz to 89kHz

- **G3 preamble**
  - 9.5 identical OFDM symbols, 6.792 ms

- **Conclusion**
  - In PRIME, the energy is focused on a single frequency at every single time.
  - In G3, the energy is spread in 36 subcarriers
  - SNR=2.048/6.792*36=10.85=> 20.7 dB
  - **PRIME can synchronize a signal 20.7 dB more attenuated than G3**
Modulation Schemes

- G3 uses DBPSK & DQPSK
- PRIME uses DBPSK, DQPSK & D8PSK
Modulation Schemes
Coding and error correction

- G3 uses
  - DQPSK with RS+CC(1/2)  12.1-34.1k
  - DBPSK with RS+CC(1/2)  3.2-20k
  - DBPSK with RS+CC(1/2)+RC(1/4)  2-5k (Robust mode)
  - In FCH (Header) nor RC, CC, RC, only CRC5

- PRIME
  - DBPSK with CC(1/2,1)  21.4-42.9k
  - DQPSK with CC(1/2,1)  42.9-85.7k
  - D8PSK with CC(1/2,1)  64.3-128.6k

- Conclusion
  - PRIME uses 3 times more energy symbol to avoid impulsive noise
  - G3 needs RS and 4 repetitions to avoid impulsive noise
  - RS increases 50% the size and energy consumption of the chip
  - Alternative CC (1/4,1/8)?
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Challenges of NPLC for SG

- NPLC for SG
  - Be able to cover last mile LV-LV & MV-LV
  - Robust 100-500 nodes
  - Frequent periods of short duration in which the network topology changes
  - Wide range of impedance changes in very short periods of time
  - Large range of attenuation changes
  - Links between nodes are asymmetrical and noisy
Beacon vs. Non-Beacon Configurations

- **Beacon Configuration**
  - Continuous upgrade of the network structure
  - Proactive routing
  - Reduced polling optimizes channel bandwidth
  - Children may sleep during the inactive portion of the frame
  - Children don’t have to poll for data, beacon notifies them
  - Children get a quick response time when data is available

- **Non-Beacon Configuration**
  - No overhead of periodic beacons
  - Parent on at all times to receive communication
  - Data can be polled at any time
  - Allows Peer2Peer communication to eventually build full “mesh”
Beacon Configuration

- **Parent**
  - Energy Detection Scan to detect channel performance
  - Beacons to define Superframe
  - Supports Active and Inactive periods. Sleep mode during Inactive periods
  - Beacon announces pending (out to Device) communication

- **Child**
  - Passive Scan to discover Parent
  - Associates to Parent (Join) and receives 16 bit address
  - Synchronizes to beacon, communicates during active period
  - Beacon notifies child of pending data, Child polls Parent to extract it
  - Sleep mode when not in use
**Beacon in G3/PRIME**

- G3 does not use beacons
- **PRIME**
  - A Frame is comprised of one or more Beacons, one Shared-Contention Period (SCP) and zero or one Contention-Free Period (CFP).
  - SCP channel access does not require any arbitration.
  - SCP avoid collisions using CSMA-CA mechanism
  - CFP channel access needs devices to request allocation from the Base Node
Mesh vs Tree network topology: G3 Mesh network routing

- Mesh network routing employs reactive routing based in AODV (Ad Hoc On Demand Distance Vector Routing)
  - Ad Hoc (Network is unknown at start-up)
  - On Demand (Determines route to destination only when needed)
  - Distance Vector (Only the final destination and the next hop are stored at each node. Relies on a distributed protocol to handle routing)
- Flooding (repeated broadcasts) determines paths from source to destination in the mesh
- Route Replies determines viable paths in the mesh while Routing tables record known paths determined by AODV
- Self healing upon route failure
  - Reliable and robust. Failed router will reinitiate discovery and find an alternative path
Mesh vs Tree network topology: PRIME tree network routing

Base Node transmits Beacons (BPDU): BC₀

Switch transmits its own Beacon (BPDU): BC₁

Switch Node
S=(1,0)
T=(0,3)

Terminal Node
T=(0,1)

Switch Node
S=(2,0)
T=(0,4)

Terminal Node
T=(0,2)

Terminal Node
T=(1,1)

Terminal Node
T=(1,2)

Terminal Node
T=(2,1)

BC₄ transmitted by S(2,0)
Mesh vs Tree network topology: G3/PRIME network routing

- Mesh network routing of G3
  - Convenient for lighting, industrial and building automation applications
  - Reactive routing increases the latency of transmission
  - Discovery process increases the traffic

- Tree network routing of PRIME
  - Convenient for European AMM application
  - Proactive routing decreases the latency of transmission
  - Passive discovery process decreases the traffic
CSMA-CA vs SFN

- **CSMA-CA**
  - Traditional and robust access algorithm
  - Low efficiency for transmission

- **SFN**
  - Unicast cooperation
    - We can have gains if relays use MISO codes
    - We can be opportunistic and require low overhead through randomized coding
    - Some of the diversity benefits are lost to be opportunistic
    - In broadcast applications opportunistic approaches are also rewarded with gains...
  - Multicast cooperation
    - Signal superposition could be seen as cooperation rather than collision
Coexistence and evolution
OFDM with no OFDM

- Notching and bit loading
  - Increase the complexity of all the OFDM nodes
  - Decrease performance

- TDM using superframes
  - Increase the complexity of only the OFDM base node
  - Provide coexistence with other OFDM systems but bit loading could be necessary
Coexistence and evolution
OFDM evolution alternatives

- Single band OFDM system 40-500kHz
  - incredibly high overhead, thus resulting in an inefficient transmission.
  - the injected power of the injected signal would be distributed along the whole bandwidth, resulting in less power for the whole bandwidth, whereas the noise would be incremented in the same proportion.
  - More complex implementation for service nodes

- Multiple band OFDM system 50kHz x 9
  - replication of the existing OFDM channel in 9 new locations,
  - all of them with the same bandwidth and structure as the original one, but in different frequency ranges.
  - Each one of these frequency ranges would be called an “OFDM channel”
Coexistence and evolution
PRIME evolution example

- Suggested channels (including guard intervals)
  - 42 to 97 kHz (CENELEC A-band) -> CHANNEL 0 (PRIME 1.3)
  - 100 to 150 kHz -> CHANNEL 1
  - 150 to 200 kHz -> CHANNEL 2
  - ...
  - 450 to 500 kHz -> CHANNEL 8
Coexistence and evolution
PRIME evolution example

Advantages of this solution are listed below:

- **Legacy**: this solution would be compatible with the legacy PRIME
- **Scalable** solution:
  - the current PRIME structures would be applied to the new channels with low effort
- **Smart increase of the complexity**: small changes in the Service Nodes
  - Most of the implementation changes and cost increase would be on the Base Node side.
  - The Base Node should be able to transmit beacons in all 9 channels at the same time, and to process the information received through these 9 channels with the same performance as the current solution.
- Increase performance of the network: the overall **speed** of the network would be **increased** because the effective transmission rate of the Base Node would be increased.
  - Each branch of the PRIME network could be assigned to a specific channel, thus effectively dedicating those frequencies to a limited number of devices in the network.
  - The traffic would be consequently lower, reducing the number of collisions and optimizing the network usage.
  - OFDM Channel **distribution indoor/outdoor for coexistence**
- Never change a running system:
  - this extension could be implemented with a few changes in the existing PHY layer (additional techniques such as notching and bit loading should be implemented)
  - leaving the **MAC layer almost unchanged**.