

Bachelor's Degree in Engineering in Telecommunication Technologies

Bachelor's Final Project

Viability of PRIME Hybrid (PLC+RF) technology in low-voltage Smart Grid networks across different topologies.

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Madrid
2021 -2022

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Viability of PRIME Hybrid (PLC+RF) technology in low-voltage Smart Grid networks across different topologies

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Abstract

1. Introduction

The electrical grid has been gradually experiencing a crucial evolution over the last decade. Energy supply and demand management have become more complicated with the proliferation of new techniques and technologies that are altering consumer behaviour patterns. Higher proportions of non-renewable generation and the increase of distributed generation also contribute to the shifting environment. Moreover, the strive to provide consumers with personalized product offers and almost real-time information regarding their consumption patterns created the need for highly efficient communication technologies that work in tandem with the generation, transmission and distribution parts of the electrical grid.

This study focuses on the distribution side of the electrical grid, which is the most diverse part of the three above and presents the highest variation in possible topologies and telecommunication deployments. It is effectively an example of the last mile problem, where data needs to be collected from a high number of end-users (electricity meters) and aggregated before being transferred "upstream".

Particularly, the communication alternative discussed in this paper focuses on the low-voltage part of the distribution network. This communication can be done using powerlines that are already in place (PLC), with wireless alternatives (RF) or with other minoritary solutions out of scope of this study. Several organizations have proposed communication standards to lay some common specifications to facilitate interoperability across devices from different manufacturers. One of such organizations is PRIME Alliance, which has historically focused on publishing PLC

standards. However, a hybrid (PLC+RF) alternative is currently being proposed.

In this paper, we use an already existing PLC communications simulator and modify it to include the RF possibility and the combined hybrid option. Thus, making it possible to compare PLC or RF only deployments with hybrid architectures.

2. State of the Art

PRIME is a communications standard with a global presence that can operate in MV and LV networks. More than 20 million smart meters have been deployed worldwide implementing these communication specifications. Currently, it only has published PLC specifications. The basis for PLC is that it makes use of existing powerlines originally deployed for energy distribution as a communication channel for metering information. This presents a clear advantage in cost reduction. Furthermore, orthogonal frequency division multiplexing (OFDM) is also a marked improvement over other previously proposed single-carrier alternatives.

The network established by PRIME has a tree-like topology. A base node located in the MV/LV transformer acts as a network coordination unit at the base of the tree. Service nodes are located in the different branches and can act as switches - relaying information - or they can be simply end-nodes (terminal).

All communication is orchestrated by the base node which establishes two distinct communication periods that are continuously repeated. This periodic repetition of the two communication slots (contention-free period and shared contention period) is called a MAC Frame. This communication scheme originally devised for PLC is also incorporated in the PRIME Hybrid version as it only incorporates an additional PHY layer to the original PLC PRIME layer structure.

Other communication alternatives used to gather energy consumption information are Wi-SUN alliance deployments and LTE rollouts. The Wi-SUN Alliance is an organization that operates similarly to the PRIME Alliance. The differentiating factor is that their proposed standards primarily promote wireless communications - namely an RF mesh network. These networks are orchestrated by border routers acting as personal area network coordinators. Within these PANs, individual nodes

have multi-hop capabilities and can relay messages to other nodes in the network. LTE networks use the architecture conceived by 3GPP (initially designed for voice, video, and browsing) to poll end nodes. Generally, they require less initial planning in areas with widely available LTE coverage but may encounter cost problems due to the use of a regulated spectrum and the higher cost of end nodes.

3. Hybrid Network Simulation Tool

The hybrid simulation tool is built on top of SimPRIME, a tool developed by J. Matanza for PLC network simulations. The software used is OMNeT and Matlab. OMNeT is used for the description of communication layers and the simulation of messages and events. Matlab is used for the PLC channel simulation.

This paper adds several modules to the SimPRIME simulator. There are three main contributions. The first one is the adaptation of the MAC layer to the dual PHY architecture. Some considerations have been included regarding how the node chooses which PHY to use for transmission. A combiner module is the second addition to SimPRIME. It has been included between the MAC and the two PHY layers. Finally, an RF PHY layer added has been implemented according to the 802.15.4 standard required by the PRIME Hybrid specifications.

The simulation builds a network of nodes organized into several parallel branches - all parameters regarding branch and node numbers can be adjusted accordingly - and collects information regarding throughput, polling times, and network topology metrics.

The PLC channel is simulated using attenuation matrices generated in Matlab while the wireless environment is implemented with the INET library commonly used for OMNeT simulations. All transmission parameters such as bitrate, data lengths, and layer specifications like alive timers have been selected based on the corresponding values indicated by either 802.15.4 or PRIME Hybrid specifications.

Some node behaviour regarding hybrid messaging is not fully detailed by the PRIME specifications and a possible approach has been suggested in this paper. This is mainly relevant in the decision taken by the MAC layer of which PHY to use. In brief, it has been determined that all nodes will be initialized with a

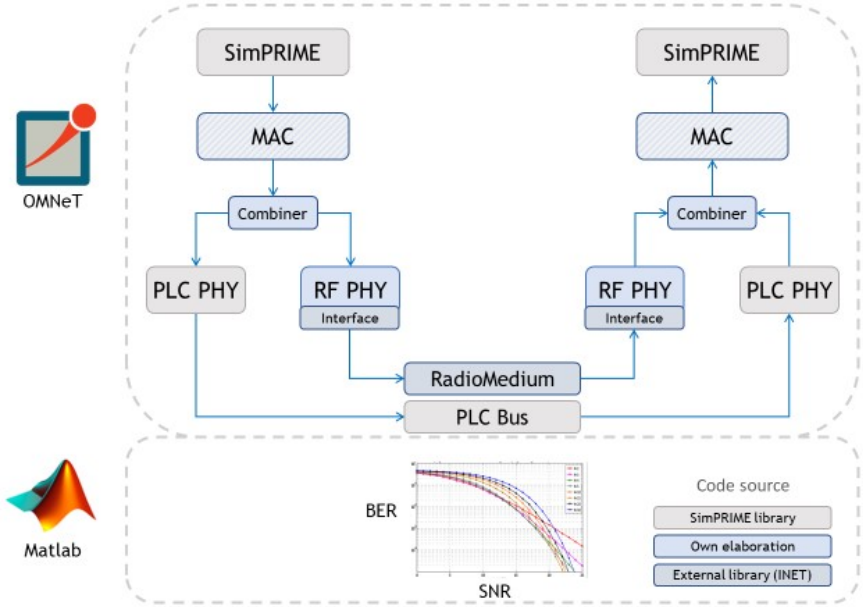

Figure 1: Hybrid simulation architecture

transmission preference and they will give preference to this mode for all uplink communication. Downlink communication will be done according to the respective preference of the receiving nodes.

The simulation tool developed can produce two different types of outputs. The first one is a logical tree depicting the final converged network. The second one is a list of several metrics indicating the polling time of all nodes (TTR), roundtrip times and application layer throughput.

Three different topologies with varying node densities have been simulated. For each density scenario - low, medium, and high - branch separations of 30 and 70m have been run. For each of these density and branch separation pairs, five different logical node distributions have been simulated. Thus, a total number of thirty scenarios (three densities, two branch separations, and five logical node distributions) have been constructed.

The five logical node distributions represent the communication preference that is initially set for each of the nodes present in the simulation. The first two scenarios have only non-hybrid nodes. One being only PLC and the other one with

only RF. The other three distributions (hybrid A, B, and C) are constituted of all hybrid nodes. The difference between the three is the initial node communication preference. Distribution A is initialized with 90% of nodes having a PLC preference. Distributions B and C present a 50% and 10% initial assignation of PLC preference to hybrid nodes respectively. It should be noted that hybrid nodes can transmit and receive via either channel (PLC or RF). This parameter only sets their initial uplink communication preference that nodes will attempt to use to establish a connection.

4. Results and conclusions

The result tables obtained indicate some key network behaviours and an overall conclusion that is applicable to the three kinds of logical deployments studied.

The network behaviours observed indicate that wireless networks have more problems in the initial convergence phase, usually taking longer to converge and having a more unstable network whilst doing so. The reason for this is that a single promoted switch has nodes from several different branches that immediately connect to it - as opposed to PLC where only nodes in the same branch register when a switch is promoted. This higher initial rate of registration causes a funnel and fewer switching points, resulting in a slightly more unstable network with a few critical switches. The consequence of this is that upon a switch's failure (possible due to the hidden node problem), more nodes are disconnected. The network eventually recovers with nodes requesting new promotions, but the overall convergence time is higher. Additionally, roundtrip times also take longer. This is because as nodes in parallel branches share the same channel (which does not happen in PLC), the channel sensing algorithm must attempt transmission more times than in the PLC case. This causes overall roundtrip times to be lengthened.

A second conclusion extracted from the results is that nodes that are registered to the subnetwork via hybrid switches may regularly miss beacons in some cases. With the current logic implemented within the MAC layer, this can happen when a terminal node can only listen to one of the two types of beacons (either RF or PLC) that are alternatively sent by the switch. A switch will send beacons through

RF or PLC depending on the distribution of nodes that are registered to it. These beacons indicate the terminal nodes when the SCP and CFP start and by missing them, some nodes will not try to access the channel via CSMA during that MAC Frame. For example, an RF node registered to a switch in another branch, will not receive PLC beacons sent by that node. This causes hybrid TTR times to be much higher.

It should be noted that the previous two conclusions are a reflection of the simulator's performance. Certain approaches have been taken when designing MAC behaviour which may be implemented in a different manner in real field deployments. Overall, this means that the previous two points apply only to the results within the scope of the current simulator. These conclusions do not apply directly to the performance of PRIME Hybrid specification as a whole.

Finally, a general conclusion is that MAC parameters represent the most sensible group of parameters of all. They are the ones that influence the results the most when they are altered. This is due to both PHY layers being similarly orchestrated as they share the same MAC layer and overall behaviour.

Nevertheless, there is room for improvement within the simulator. New functionalities can be included, namely topology variations (node clusters, irregular distributions) and support for a larger number of nodes. Additionally, the process of setting up and running the simulator could also be simplified to enable its usage in a wider array of environments. Currently, it is not easy to configure and set up, leading to less transparency regarding its results.

All in all, this study presents improvements over the previous PLC-only simulator by incorporating new RF and hybrid functionalities. Moreover, it presents initial findings regarding the comparison between PLC, RF and hybrid alternatives. Finally, some possible improvements are also proposed for future work.

Viabilidad de la tecnología PRIME Híbrida (PLC + RF)
para distintas topologías de redes inteligentes de baja tensión

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Resumen

1. Introducción

Durante la última década, la red eléctrica ha sufrido cambios graduales orientados principalmente a la mejora de las comunicaciones a lo largo de esta. La gestión de la oferta y demanda energética ha aumentado en complejidad con la proliferación de nuevas tecnologías que están modificando los hábitos de consumo de los clientes finales. Además, una mayor proporción de generación renovable y el aumento de la generación distribuida también han contribuido a este entorno cambiante necesitado de tecnologías de comunicación efectivas.

Por otro lado, los consumidores requieren productos cada vez más personalizados a sus perfiles de consumo y se han desarrollado herramientas para que los clientes puedan visualizar su consumo casi a tiempo real. Todos estos avances promueven el desarrollo de tecnologías de comunicación implementadas sobre las redes de transporte y distribución de energía y que mantengan en constante comunicación los agentes de generación y de consumo eléctrico. Por ejemplo, para la recolección de datos de consumo de los contadores eléctricos.

Este estudio está enfocado en la red de distribución. Esta es la parte más heterogénea de la red y donde encontramos la mayor variabilidad de topologías y despliegues. Esta red de distribución, con su gran capilaridad presenta un importante reto de recolección de datos de un gran número de usuarios y de su correspondiente agregación en multitud de puntos distribuidos geográficamente.

En particular, el estudio se centra en la red de bajo voltaje. Las comunicaciones en este entorno se pueden hacer mediante tecnología PLC. Esta tecnología

hace uso de los cables de electricidad para transportar datos a través de estos usando OFDM. Otra posibilidad de comunicación en este entorno usando medios inalámbricos (RF) u otras tecnologías minoritarias que quedan fuera del alcance de este documento.

Hay distintas organizaciones cuyo objetivo es desarrollar especificaciones comunes para facilitar que los fabricantes desarrollen productos compatibles entre sí. Una de estas organizaciones es PRIME Alliance. Históricamente, ha publicado estándares de comunicación PLC. sin embargo, actualmente se está discutiendo la implementación de una propuesta híbrida (PLC + RF).

En este estudio, se desarrolla un simulador de comunicaciones híbridas en el entorno de las redes de bajo voltaje. En concreto, se utiliza un simulador PLC desarrollado por J. Matanza y se modifica para incluir funcionalidades RF e híbridas. De esta manera, se consigue tener una herramienta que hace posible una comparación entre despliegues simples de PLC o RF frente a despliegues híbridos.

2. Estado del arte

PRIME es un estándar de comunicaciones que está presente a nivel global. Puede operar en redes de media y baja tensión y actualmente cuenta con más de 20 millones de contadores inteligentes desplegados. Por ahora todas las especificaciones publicadas se centran en tecnología PLC. El punto de partida de esta tecnología es el uso de la red eléctrica existente como medio de comunicación. Esto presenta importantes ventajas en cuanto a costes de despliegue. Además, el uso de OFDM también representa una mejora importante respecto a otras alternativas con frecuencias de portadora únicas.

La red propuesta por PRIME tiene una estructura de árbol. Un nodo base, se ubica en el transformador de media a baja tensión y actúa como agregador de datos en la base del árbol. El resto del árbol está compuesto por "nodos de servicio". Estos pueden actuar de dos maneras distintas. Pueden retransmitir información (switches) o ser simples receptores finales (terminal).

El nodo base organiza toda la comunicación presente en la red mediante el uso de periodos de transmisión llamados tramas MAC. Estas tramas MAC están

divididas en dos trozos, llamados “shared contention period” y “contention free period”. Este esquema de comunicaciones desarrollado para PLC se incorpora en la opción híbrida. La principal novedad que incorpora PRIME Híbrido es la inclusión de una nueva capa PHY de RF para la comunicación inalámbrica.

Existen también otras alternativas para la recopilación de datos de consumo eléctricos. Algunos ejemplos son las opciones propuestas por Wi-SUN Alliance - especialmente orientadas a redes inalámbricas - y despliegues que hacen uso de la red LTE. La Wi-SUN Alliance funciona de una manera similar a PRIME Alliance, proponiendo estándares unificados con la intención de que los fabricantes los adopten y facilitar futuros despliegues, minimizando posibles problemas de compatibilidad. En particular, las redes inalámbricas propuestas tienen una topología de malla en la cual todos los nodos están capacitados para retransmitir mensajes, haciendo de estas alternativas muy robustas y tolerantes a fallos. Por otro lado, la alternativa LTE utiliza la red desplegada originalmente para comunicaciones de terminales móviles para encuestar a contadores inteligentes. Esto presenta algunas ventajas de cobertura y planificación en áreas con amplia cobertura y densidad de torres. Sin embargo, puede presentar costes de despliegue y mantenimiento adicionales.

3. Herramienta de Simulación de Redes Híbridas

La herramienta de simulación desarrollada ha sido implementada sobre el código de SimPRIME, un simulador creado por J. Matanza para experimentar con despliegues de redes PLC. Los programas utilizados para el desarrollo son OMNeT y Matlab. El primero se usa para la programación de las distintas capas de comunicación y la gestión de eventos. Matlab aporta la modelización del canal PLC.

Este estudio añade o modifica tres módulos a la herramienta SimPRIME previa. Además, utiliza herramientas externas de la librería INET para simular el canal inalámbrico. El primer módulo modificado es la capa MAC. Aquí se hacen las adaptaciones necesarias para poder incluir una segunda capa PHY a la arquitectura. El segundo módulo incluido es el “Combiner”, que hace de enganche entre la capa MAC y la PHY dual. Finalmente, se ha desarrollado la capa PHY sigu-

iendo el estándar 802.15.4 tal y como se indica en las especificaciones de PRIME Híbrido.

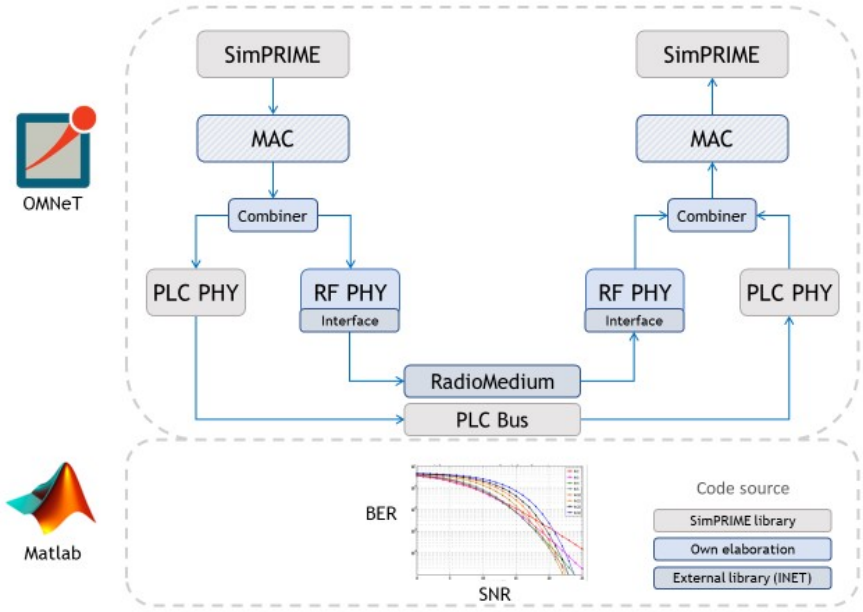

Figure 2: Arquitectura del entorno de simulación híbrido

La simulación construye un escenario compuesto por nodos de servicio distribuidos en distintas ramas paralelas, todas conectadas a un mismo nodo base. Todos los parámetros son ajustables, incluyendo el número de nodos y de ramas y las distancias entre ellos. Se recoge información sobre organización de la red y su topología lógica, además de tiempos de encuestado de nodos y tasas de transferencia efectivas.

El canal PLC se simula mediante matrices de atenuación generadas por Matlab. En cambio, para el entorno inalámbrico se hace uso de herramientas de la librería INET mencionada anteriormente. Todos los parámetros usados para particularizar la transmisión como velocidad y potencia de transmisión o temporizadores a nivel MAC son ajustables.

Como aportación adicional, hay áreas de las especificaciones híbridas que no describen con pleno detalle el funcionamiento lógico de los nodos. Para estos casos, se han propuesto posibles alternativas de implementación. El caso más importante

de esto es la decisión de qué capa física utilizar a la hora de transmitir paquetes. El sistema diseñado es que cada nodo híbrido se inicializa con una preferencia PLC/RF. Todas las comunicaciones iniciadas por un nodo se harán teniendo en cuenta esta preferencia. En caso de no obtener respuesta, probará con el modo de comunicación alternativo. Sin embargo, para responder a nodos que dependan de él, un nodo híbrido siempre utilizará el mismo medio a través del cual haya recibido las peticiones originalmente.

El simulador desarrollado produce dos resultados principales. En primer lugar, un esquema de la topología lógica presente cuando converge la red. En segundo lugar, distintas métricas como tiempos de encuestado, latencias a nivel de aplicación y tasas efectivas de comunicación.

Se han simulado tres topologías distintas. Estas se diferencian por una densidad variable de nodos en función del escenario - densidad baja, media y alta. Para cada una de estas topologías se ha probado dos escenarios distintos. El primero con separación de 30m entre ramas, y el segundo con una separación de 70m. Además, para cada uno de estos pares densidad, separación, se han simulado cinco distribuciones lógicas de nodos distintas. Esto significa que se han realizado un total de treinta escenarios de simulación distintos (tres densidades, dos separaciones de rama, y cinco distribuciones lógicas de nodos) además de los escenarios básicos de prueba.

Las cinco distribuciones lógicas de nodos se han establecido para representar la preferencia de comunicación que se establece inicialmente en cada uno de los nodos. Las primeras dos distribuciones están compuestas únicamente por nodos no híbridos. Es decir, la primera contiene nodos PLC y la segunda nodos RF únicamente. Las tres distribuciones restantes (híbridas A, B, y C) están formadas por nodos híbridos. La diferencia entre las tres se encuentra en su configuración inicial. La distribución híbrida A se inicializa con un 90% de los nodos con preferencia de transmisión PLC. Las distribuciones B y C disminuyen esta preferencia inicial a un 50% y 10% de los nodos respectivamente. Es importante resaltar que un nodo híbrido es capaz de transmitir y recibir mensajes en cualquiera de los dos canales (PLC y RF). Este parámetro de preferencia inicial, únicamente es-

tablece el canal de preferencia que los nodos utilizarán en primer lugar para sus comunicaciones hacia el resto de la red.

4. Resultados y conclusiones

Los resultados obtenidos nos indican ciertas claves sobre los comportamientos de las redes y una conclusión general aplicable a todos los escenarios estudiados. Los comportamientos observados indican que el caso inalámbrico presenta más problemas que el PLC en la fase inicial de convergencia de la red. Normalmente, las redes RF tardan más en converger y presentan un comportamiento más inestable durante este proceso. Esto ocurre porque un nodo que es promocionado en una red RF puede alcanzar a nodos desconectados en ramas paralelas. Esto no ocurre en el caso PLC, donde un nodo solo puede conectarse a switches de su misma rama. Es debido a esta conexión inicial más acelerada por lo que se crean puntos críticos en la red que hacen de embudo de tráfico. Esto tiene como consecuencia que un fallo en uno de estos switches - que puede ser debido al problema del nodo oculto - resulta en un mayor número de nodos terminales desconectados. La red se recupera más adelante con los nodos desconectados pidiendo nuevas promociones. Sin embargo, el tiempo de convergencia se ve afectado y resulta ser mayor para estos casos. Además, los tiempos "roundtrip" de aplicación son mayores. Esto ocurre porque nodos RF que se encuentren en ramas paralelas comparten el mismo canal de transmisión. Esto no ocurre en PLC, donde cada rama resulta ser un único canal. De esta manera, el algoritmo CSMA debe escuchar el medio más veces en el caso RF que en el caso PLC. Esto causa el incremento de los tiempos de "roundtrip"

Una segunda conclusión importante obtenida a partir de los resultados híbridos es que nodos terminales registrados a la red mediante nodos híbridos pueden llegar a perder beacons en algunos casos. Según la lógica que hay actualmente implementada en la capa MAC, este comportamiento puede darse cuando un nodo solo es capaz de escuchar uno de los dos tipos de beacons (PLC o RF) que puede enviar el switch. Los switches transmiten beacons en función de la proporción de nodos registrados a ellos. Los nodos terminales se sirven de estos beacons para identificar sus periodos de transmisión. En caso de no recibir un beacon, un nodo no

tratará de acceder al canal mediante CSMA durante esa trama MAC. Por ejemplo, un nodo RF registrado a un switch en una rama paralela no podrá recibir todos los beacon PLC enviados por este. La consecuencia de esto es el aumento de los tiempos de encuestado de nodos de la red

Es importante resaltat que las dos conclusiones previas se han obtenido a partir de los resultados del simulador. Esto implica que las decisiones de implementación tomadas, particularmente las relacionadas con la capa MAC, pueden ser aplicadas de manera distinta en escenarios de campo reales. La consecuencia principal de esto es que los dos puntos anteriores únicamente aplican a los resultados dentro del marco del simulador. No son un reflejo absoluto del rendimiento de las especificaciones de PRIME Híbrido.

Finalmente, una conclusión general es que los parámetros de la capa MAC son los que más afectan a los resultados de la simulación. Alteraciones en estos parámetros causan cambios significativos tanto para casos RF, como para casos PLC. Esto se debe a que ambas capas PHY están coordinadas por una misma capa MAC y comparten la manera de operar.

El simulador resultante presenta también posibles áreas de mejora. Sería posible añadir nuevas funcionalidades como nuevas topologías (clusters de nodos, distribuciones irregulares), o optimizar el código para soportar un mayor número de nodos por escenario. Además, el proceso de preparación y ejecución del simulador también podría simplificarse para facilitar su uso. Actualmente, no es sencillo de ejecutar y esto tiene como consecuencia una menor transparencia sobre sus resultados.

Como conclusión, este documento presenta mejoras sobre el simulador de PLC anterior mediante la incorporación de nuevas funcionalidades RF e híbridas. Además, muestra también comparaciones básicas entre las tecnologías PLC, RF e híbrida. Finalmente, propone posibles mejoras y cambios a desarrollar sobre el trabajo realizado.

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1 Introduction

1.1 The electrical grid's current trajectory

The electrical grid is a system composed of many interconnected pieces. Each of these pieces interacts with the others and contributes to achieving the network's ultimate goal: managing energy supply and demand to accommodate individual demand schedules with centralized and distributed generation. This system is highly complex, and its three main stages - generation, transmission, and distribution - are continuously evolving.

The electrical system has a global presence. However, it cannot be envisioned as one homogeneous unit, but rather as a set of interconnected networks. Even though they have different characteristics (topologies, physical magnitudes, standards) there are some challenges and threats that are common to all networks.

As described in [1], these challenges include planning inefficiencies, periodic consumption patterns with high peak-valley differences, congestion and losses in transmission and distribution. Most of these boil down to the one factor that distinguishes electrical energy from other commodities: electricity cannot be stored efficiently in large quantities, thus supply must equal demand at all times. From this fact, several problems arise which require that the whole system be resilient and managed with low latencies. Resilience is key because any failure in the system has immediate consequences that can be felt at other points in the network. Low latency allows decisions to be made with up-to-date information, facilitates fault correction, and improves automation capabilities [2].

These problems are not new to the industry. However, the scale at which they are now occurring and other factors, such as the increasing share of renewable energy generation, require the incorporation of new solutions. The set of new solutions and improvements designed to improve the network - which are mainly based on telecommunication services - is nowadays known as the *Smart Grid*.

Special attention will be dedicated to the distribution stage of the electrical network. Particularly, low-voltage (LV) distribution networks. This part of the

network consists of lines with voltage levels below 1kV. They are the most diverse part of the network as its topology highly depends on the individual population and service area [2]. For now, it is important to state that MV/LV transformers[1] are part of the distribution networks and are feeding LV lines, connecting them to the MV grid. Thus, given the network's topology, secondary substations are placed in a prime location to boost MV and LV digitization.

Key Smart Grid applications at LV distribution include Demand Response (DR) and Automatic Meter Infrastructure (AMI). Both of these features make use of bidirectional communications within the network. DR uses these interactions to facilitate more efficient generation and consumption patterns. AMI allows utilities to collect information automatically from electricity meters.

This communication can be done with different technologies such as powerline communication (PLC) or wireless radio-frequency communications (RF). PLC is currently one of the most widespread communication technologies for LV networks. PLC's biggest advantage is that information travels through an already existing medium, the powerlines, which means that no additional infrastructure rollout is required [3]. However, it is not the best technology for all scenarios due to the possibility of noisy channels, non-dense populations and unsuitable electric rollouts. In such scenarios, RF communications may be a superior technology. A few reasons why RF may be more suitable in some instances are emission regulations, and high variability of attenuation depending on the communication scenario. High regulations ensure that communications take place in a controlled noise environment whereas a high range of possible attenuation means that RF will be suitable in at least some scenarios.

It is at this point where this study will focus. Both technologies have provided positive results independently [4]. However, they both have their weaknesses. The merging of both of them in a hybrid solution provides a more flexible and reliable network. PRIME Alliance[2] has merged them into a hybrid standard solution: PRIME Hybrid.

[1]Device that reduces voltage to adequate levels for distribution amongst households, small businesses and medium-sized industrial customers

[2]PoweRline Intelligent Metering Evolution

We will delve deeper into this standard set by PRIME Alliance in section 2. For now, it can be established that this paper aims to study the viability of the PRIME Hybrid solution for different LV network topologies. To achieve this, a simulation framework based on the PRIME simulator described in [5] will be developed. The simulator will be expanded to include the newest version of PRIME specifications and RF capabilities. Finally, an economic comparison will be done with other rollout alternatives (such as the Wi-SUN alliance and/or LTE).

The expected results are a comprehensive comparison of PRIME Hybrid performance across different scenarios and a high-level analysis of the cost-benefit structure of the different rollout alternatives.

1.2 Motivation

1.2.1 Metering evolution in the Spanish market

In December 2007, the Spanish government approved the required legislation [6] "by which all electrical invoices from January 2008 onward must be modernized". In this document, the Government imposes on utility companies the duty to replace all qualifying electricity meters. The measuring equipment would qualify for replacement if contracted power was lower than 15kW[3].

The reason behind this metering overhaul was to install more up-to-date electricity meters. These meters would have hourly discrimination and remote management capabilities. The legislation was updated again in 2012 [8] to revisit the intermediate milestones while maintaining the final deadline. The final schedule and milestones were: substituting 35% of meters before 2015; another 35% before 2017; and the final 30% before 2019.

According to a report published by *Comisión Nacional de los Mercados y la Competencia (CNMC)*, [4] the outcome of this metering renovation initiative was a success. By December 31st 2018, 99.04% of new meters had already been installed [9]. This modernization brought several new crucial tools to the table. The most

[3]Average contracted power for a Spanish household is 4kW with an average monthly consumption of 270kWh [7]

[4]Spanish equivalent of European Securities and Markets Authority (ESMA)

prominent ones are the automatic readings of users' electric consumption, and more flexible tariff offers (for example hourly price discrimination).

Nowadays, energy companies are faced with new challenges to improve the overall performance of the electrical grid and increase their operating efficiency. Players must keep updating and renewing their equipment to achieve higher network efficiency and operating flexibility. The final goal is to have a grid with bidirectional communication, automated operations control, and the ability to efficiently collect information generated by meters and other sensors connected to the network. To face these upcoming challenges, the Spanish Government has kept-up legislative pressure to innovate. Electric meters must be renewed again before their regulatory life of 15 years [10].

1.2.2 Scope of the study within the metering evolution

At this point is where the present study comes into play. Energy utilities are currently considering different network improvement options. One of these alternatives is the introduction of PRIME Hybrid technology as a means of communicating with smart meters. In addition to studying the case of the Spanish grid - where PLC communications have already been successfully introduced - PRIME Hybrid will also be tested for other geographies.

Network topologies for Brazil and the United States will be simulated. These countries have fundamentally different characteristics to those of the Spanish electrical system. For example, where PLC installation is concerned, Spain was an attractive network for this kind of rollout. Spain's fit with PLC technology is mainly due to the high client to substation ratio (around 100 clients per substation)[5]. Higher ratios imply fewer capital expenditures per household when deploying the technology which decreases the overall cost of updating the whole grid. This ratio is lower in both the US and Brazil (the former with around 2 clients per substation and the latter sitting in between the US and Spain) [11]. In these cases, RF may provide a more viable alternative to PLC due to potentially easier

[5] A higher number of supply points per substation significantly reduces the scale of the required rollout and its total cost. In this context, the substation is referring to MV/LV transformers which are sometimes called *secondary* substations

installations, higher ranges and lower costs. A combination of the two technologies (PRIME Hybrid) may be the most suitable choice. This is the starting point for our analysis and the motivation to create a simulation tool with capabilities to obtain results comparing RF, PLC and the combination of the two in PRIME Hybrid. These comparisons will be established across different network scenarios and topologies.

1.3 Objectives of the study

This project has three main objectives. The PRIME Hybrid simulation tool will be developed to reach meaningful conclusions in all three goals.

- Consider the viability of a PRIME Hybrid solution (PLC + RF).
- Understand the possible discrepancies and grey areas within the specification that arise when combining PLC and RF standards. A potential approach to these unclear points will be proposed.
- Examine the effectiveness of a PRIME Hybrid solution by simulating a network under different working conditions.

The development of the simulation tool is not an objective in itself. It will be crucial in reaching the objectives listed above but it will be considered as a means to an end, a tool used to reach the main conclusions. Further explanation is provided below regarding how to achieve the proposed goals.

Viability of hybrid solution. Before diving fully into the development of the simulation tool, an analysis will be done regarding the compatibility of the different standards. The possibility of combining the protocol stacks of PLC and RF needs to be studied and understood. To achieve this, an explanation is provided regarding the newest PRIME standard (v1.4) and how to include an RF PHY layer in its protocol stack.

Gray areas in standards. The merging of PLC and RF is not expected to be seamless. Any decisions taken in the process that are not fully detailed in

current standards will be laid out and discussed. For example, if the node's choice to use PLC or RF is dynamic, several possible decision parameters will be considered.

Effectiveness of Hybrid solution. Simulations will help measure the results of hybrid communications and how they compare to PLC and RF individually. Some expected results are network latencies, throughput and availability.

1.4 Roadmap of the study

The study is structured in three main parts. The first part consists of chapter 2. In this chapter, the current communications environment for low-voltage (LV) networks is described. Several sections within this chapter describe the PRIME Alliance and its standards in detail, followed by the RF standard used for PRIME Hybrid. In order to provide valid viability benchmarks, other non-PRIME technologies such as Wi-SUN and LTE are also described.

The second main part of the study is comprised of chapter 3. This chapter discusses the simulation tool used to recreate the PRIME Hybrid communications environment. The framework and tools used are described in detail to provide the reader with a conceptual overview of how the simulation works and its limitations.

The final part of the study consists of chapters 4 and 5. The former chapter is further divided into two sections. First, we describe how the simulation scenarios are chosen and what their equivalent would be on the field. We also describe the different metrics that are obtained from the simulation and why they are relevant for the viability study. Then, still, within chapter 4, we compare PRIME Hybrid with standalone RF and PLC networks to comment on the obtained results. The latter of the two chapters extends this comparison to non-PRIME options such as Wi-SUN Mesh and LTE. This comparison is done across different topologies and scenarios.

2 State of the Art of Low-Voltage Network Communications

The academic field concerning Smart Grids and their applications has seen a substantial rise in popularity in recent years. It is certainly relevant to base the present paper on available conclusions and published work. This section is organized as follows. First, some background is provided on PRIME Alliance in section 2.1. Then, PLC and RF standards are discussed separately in sections 2.2 and 2.3. The combination of both standards is discussed in section 2.4. This hybrid model will be the one tested in the developed network simulation tool.

After discussing the different options offered by PRIME Alliance, two additional communication alternatives are presented in sections 2.5 and 2.6: Wi-SUN RF Mesh and LTE. These two alternatives will be used as a comparison benchmark for the PRIME Hybrid simulation outcomes. Thus, some prior knowledge of them is beneficial to establish valid comparison metrics.

Finally, various additional papers addressing the current state of the art are mentioned for additional reference and an overall conclusion is provided. This section aims to lay the groundwork for the final cross-technology comparison that will be performed with the simulation results.

2.1 PRIME Alliance

PRIME Alliance (PoweRline Intelligent Metering Evolution) is a worldwide organization whose main goal is to support smart metering and smart grid functionalities. They strive to pursue this by developing and maintaining standardized telecommunication solutions which are publicly available. It was created in 2009 and up until today, solutions with PRIME standards have been applied globally (Spain[6], Portugal, Poland, Brasil...) with high levels of success [12].

PRIME Alliance is organized into different committees and technical working groups which are responsible for promoting PRIME and developing the standards

[6]In Spain, PRIME solution represents the most widely adopted standard

and specifications respectively. It is in constant communication and cooperation with utilities regarding their respective rollouts, allowing the alliance to integrate information gathered from current deployments whilst providing benefits to utilities. These benefits include access to documentation, insights regarding specifications and direct access to PRIME members and industry-leading manufacturers.

Discussion regarding this organization is relevant because the PLC standard and hybrid solution used in the simulation are based on PRIME Alliance information.

2.2 PRIME v1.3 and v1.4

PRIME is a power line communication (PLC) standard with a presence throughout the globe. It is based on OFDM (orthogonal frequency division multiplexing) technology and it can operate in MV and LV networks. It was developed for "Advanced Metering, Grid Control and Asset Monitoring applications". One of its key benefits is the achieved interoperability between different manufacturers which has resulted in more than 20 million smart meters deployed worldwide [12].

The standard was updated to PRIME v1.4 in 2014 [13] and adds additional robustness options and extended frequency coverage (up to 500kHz from the prior 90kHz) to the previous version PRIME v1.3.

2.2.1 PRIME v1.4 in detail

As previously described, PLC communications make use of existing power lines that were originally deployed for energy distribution. This presents an inherent advantage of minimal deployment costs but comes hand in hand with some challenging problems.

The following paragraphs present a general overview of the PRIME standard with further detail regarding its drawbacks; followed by a deeper dive into both the PHY and MAC layers.

2.2.1.1 Standard overview

A PRIME network has a tree-like topology. The terminal nodes are located in branches that are all connected to the main distribution panel where the base node (network coordinator) is located. These branches may differ highly from each other and present different physical characteristics, including various cable types and variable impedances. Furthermore, loads may not be constant over time and interference (non intentional emissions from loads) also affects communications.

Initially, one of the main advantages introduced by PRIME was the usage of OFDM in contrast to the single carrier alternatives previously common in narrowband power line communications. Orthogonal frequency division multiplexing encodes the data by using several carriers per frequency channel. Thus, increasing the overall spectral efficiency of communications. It also has additional advantages such as higher data rates and higher resilience to interference. These advantages are further detailed in [14] and [15] and also discussed in chapter 3 of [5]. Overall, according to the specifications, OFDM is chosen because of its adaptability to frequency-selective channels, its robustness to impulsive noise [7], and its higher spectral efficiency.

According to [14], since its conception, PRIME sought to use a frequency band that met the following criteria:

- Allow for inexpensive implementations of equipment
- Have predictable and acceptable channel behaviour for both transmission and reception
- Be unlikely to be at odds with other technology standards and services in the future

The chosen frequency band was CENELEC-A which comprises the 3kHz-95kHz spectrum. Compatibility in the US is also assured by FCC Part 15 which allows the use of up to 500KHz. As mentioned in 2.2, PRIME v1.4 has increased the

[7] FEC availability which provides error-correction capabilities and higher symbol duration make errors less likely to happen due to short noise impulses

supported frequencies to 3kHz-500kHz (EN 50065 1:2001+A1:2010 by European regulations) [16].

The scope of the specification covers three communication layers: Convergence Layer (CL), Media Access Control (MAC) Layer, and Physical (PHY) Layer. We will mainly focus on the latter two layers as the CL's function is to classify traffic from higher layers and associate it with the proper MAC connection.

2.2.1.2 PHY Layer

The PHY specification makes use of the frequency band from 41.992KHZ to 471.68KHz. This is separated into eight channels that can be used in an independent or combined manner. Moreover, each of these channels is further divided into 97 carriers, which are transmitted using a symbol length of 2240μs. There are also guard intervals separating the different channels (7.3KHz).

Several blocks comprise the PHY layer according to the PRIME v1.4 specifications. We will briefly cover their functionalities. Their implementations within the simulation tool are explained in section 3.3.

The MAC Protocol Data Unit (MPDU) is received by the PHY frame and a Cyclic Redundancy Check (CRC) is appended to it. Then, a convolutional encoding is performed, followed by an optional forward error correction (FEC). Afterwards, scrambling and interleaving are performed. Depending on the different settings of these steps, the transmitter configuration may be referred to as "robust mode". CRC and FEC are used as measures to reduce and correct possible bit errors. Scrambling prevents long sequences of bits of the same value whilst the interleaver makes the transmission more robust to bursts of noise.

All in all, PRIME v1.4 defines two types of PHY frames (A and B). Both types consist of a preamble, a header and the payload with the main difference between them being the increased robustness of the type B frame. This is due to the increased number of symbols present in each of the three parts due to the different possible configurations of the previously described modules (CRC and FEC). Type A permits higher transmission efficiency at a cost of higher sensitivity to noise and interference. The robust mode defined by the type B frame is better

suited to harsh environments.

A PHY frame is composed of three parts: preamble, header, and payload. Parameters regarding these three parts are different for frames A and B and are shown in table 1. The preamble is used for synchronization purposes and lasts longer in robust mode. The header and payload are composed of several OFDM symbols. The header contains the pilot and data subcarriers. There are eight possible channels and each one contains 13 pilot subcarriers. Between every pilot, there are seven data subcarriers. The third part is the payload, which is made up of M OFDM symbols. This M parameter is specified in the header so receiving nodes know when the transmission ends.

	Preamble	**Header**	**Payload**
Type A Frame	2.408ms	4.48ms (2 symbols)	M x 2.24ms (M symbols)
Type B Frame	8.192ms	8.96ms (4 symbols)	M x 2.24ms (M symbols)

Table 1: Type A & B PHY frame formats

Further detail of these characteristics can be found in both the PRIME specifications and in [13]. Moreover, section 2.2.2 provides some additional details regarding compatibility and advances from the previous version (1.3) to the current one (1.4).

2.2.1.3 MAC Layer

The PRIME standard defines two kinds of network nodes: Base Node (BN) and Service Node (SN). The base node manages the network and coordinates the responses from a pool of service nodes. This BN is usually located in the MV/LV transformer (see section 1.1). A network is comprised of multiple SN registered to one BN. Thus, the network is managed by a BN which periodically polls SN to obtain updated information on all devices connected to the network. Figure 3 shows the three possible states of a SN. The initial state for these nodes is "Disconnected". In this state, a node will not communicate data and it will try to register to the network (by transmitting REG type packages to the BN). Once connected to the network, the node is now in "Terminal" mode, and is now able to transmit

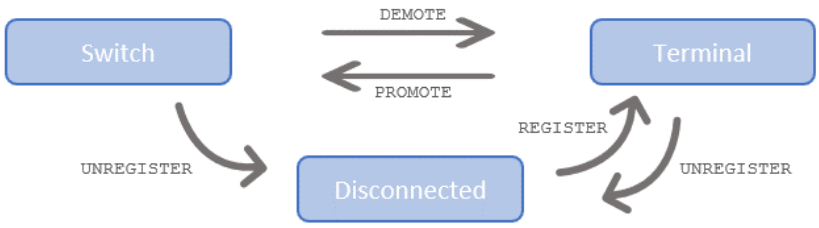

Figure 3: Node Functional State Diagram

data upstream. If needed (for example, a node downstream cannot communicate directly with the base node), a node can be promoted to "Switch". In this third state, it can forward information downstream and relay responses upstream. A visual example of a possible logical topology is presented in figure 4

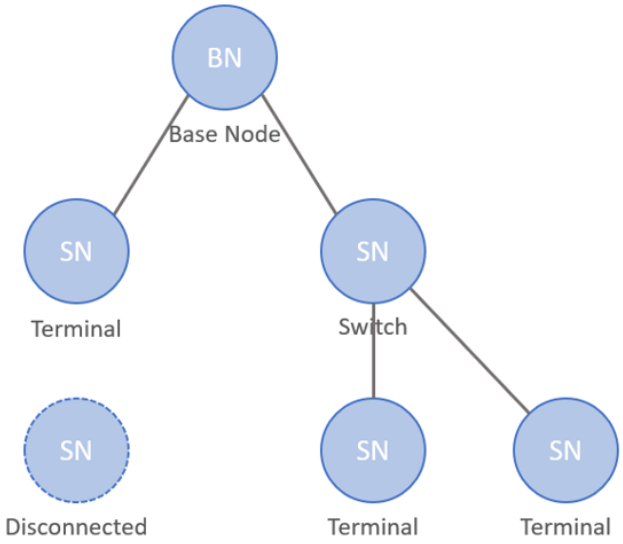

Figure 4: Example of PRIME Logical Topology

The addressing structure defined by PRIME has several pieces. First and foremost, each node has a 48-bit unique and universal MAC address. This address is called EUI-48 and in the case of the BN, it uniquely identifies the subnetwork (subnetwork address, SNA). The second piece is the switch identifier (SID). This

is assigned by the BN to each of the switches present in its network during the promotion process. Naturally, a switch is then universally identified by the combination of SNA and SID. When a terminal node is registered to the subnetwork, it is also assigned a local node identifier (LNID). Both SID and LNID unequivocally identify a given node within a specific subnetwork (node identifier, NID). Finally, a local connection identifier (LCID) is assigned to a specific connection within a node. In a similar manner to prior logic, the 31-bit CID (connection identifier) identifies a single connection inside a given network. Figure 5 shows the address structure described by the standards

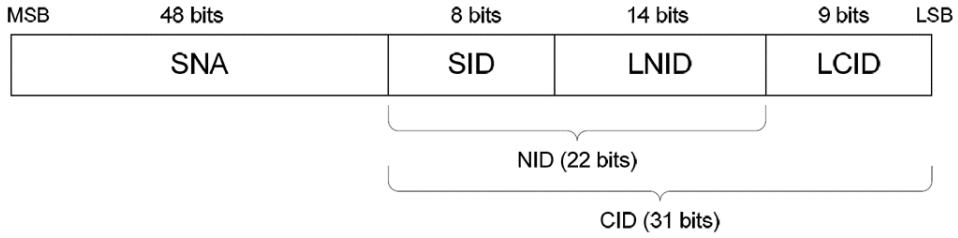

Figure 5: PRIME Address Structure

The MAC layer also manages the logic involved with the channel access. This is very convenient for the present paper as the Hybrid structure uses the same MAC for two different PHY layers (RF and PLC). This is further detailed in section 2.4. PRIME v1.4 specifies abstract time units - called MAC Frames - that divide the channel usage into several slots [16]. We can distinguish two parts in each frame:

- **Contention Free Period**: within this part of the frame, only devices that have been granted explicit permission by the Base Node are allowed to transmit. Several devices may be authorized to transmit within the same CFP and they are provided with start and end times for their channel usage.

- **Shared Contention Period**: in this second part of the frame, devices may use the channel freely as long as they comply with CSMA CA[8] and transmit

[8]Carrier-sense multiple access with collision avoidance. The nodes sense the channel to check if it is idle before beginning their transmission. Implementation of this algorithm is specified on page 82 of [16]

all their intended data within the given SCP.

Some additional notions to take into account are the existing guard times after each of the two periods and the concepts of beacons and super-frames.

Beacons are protocol data units (PDU) that contain administrative and operational information about the current subnetwork. They are transmitted by both the Base Node and Switch Nodes at the beginning of every MAC frame. Technically beacon slots are considered to be within the CFP. All service nodes track these BPDUs (beacon PDUs) as they facilitate network synchronization by relaying information such as frame length and type of frames used in the network.

Base nodes in large networks may not transmit beacons in every MAC frame to allow other nodes to communicate within the given CFP. However, they must use their beacon slot at least once every several MAC Frames (32). This grouping of MAC Frames is defined as a super-frame. All specifications regarding MAC Frame structure are shown in figure 6.

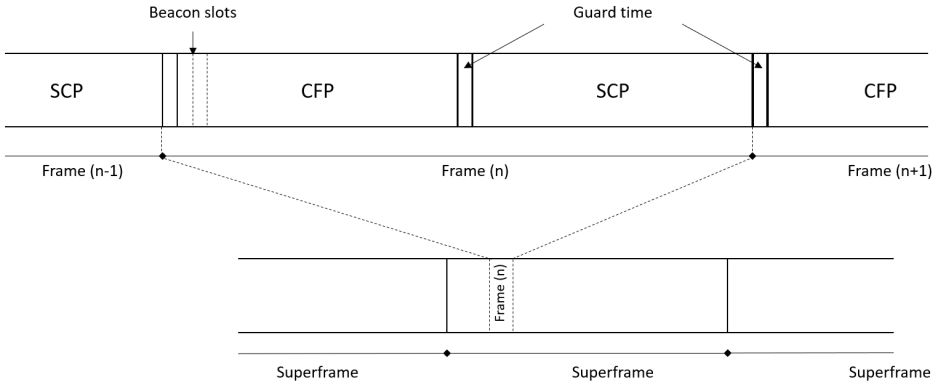

Figure 6: MAC Frame Structure

2.2.2 Backwards compatibility considerations for PRIME v1.4

As referenced earlier, PRIME v1.4 build upon its previous version by extending frequency coverage up to 500KHz and adding several robust communication modes. Backwards compatibility with PRIME 1.3 deployments is possible however some

limitations must be considered. We will discuss them briefly because they are relevant for the simulation tool developed as we have used the existing SimPRIME tool [17] which was developed for v1.3. Thus, some legacy features are to be expected. The changes that may affect the most are the flexible MAC frame length and beacon slot optimization introduced in v1.4. Standards point out that to ensure backwards compatibility a fixed frame length of 276 symbols must be used and up to five beacon slots may be reserved within them. This is described in detail in [3] and in p.187 of [16].

2.3 Wireless RF, standard 802.15.4

IEEE 802.15.4 is a standard developed for low-rate wireless networks. It was first devised in 2003 and it has been updated continuously over the years with its latest revision being in 2020. The goal of this standard since its inception was the creation of inexpensive, low-power wireless communications.

802.15.4 defines a physical layer (PHY) and a medium access control layer (MAC). It describes two types of devices that can participate in the network: full-function devices (FFD) and reduced-function devices (RFD). The difference between them is that a FFD can participate in the network by serving as a personal area network (PAN) coordinator. On the other hand, RFD is intended to serve only for simple applications. One FFD is assigned to multiple RFD at a time, however, the inverse is not true. One RDF can only have one FFD assigned at one time. Thus, the FFD plays the part of the network coordinator described in the PRIME standard. It should be noted however, that in a typical mesh topology deployment, all nodes may relay messages to each other even if they are not considered FFD.

Several papers such as [18] and [19] have performed analysis regarding the implementation of this standard in smart utility networks (SUN). The combination of this with PLC communications is discussed in the following section.

The crucial part of this standard in regards to the current study is its PHY layer. To construct the PRIME Hybrid layers, we need two PHY layers, one of which is based on 802.15.4. This is described in the PRIME specifications for

hybrid data transmission, [20].

To be more precise, the standard defines multiple possible PHY layers that can be applied to a variety of cases and frequency bands. According to the directives described in PRIME Hybrid specifications, we have focused on the guidelines provided by Chapter 19 of [21] - SUN FSK PHY[9]. Parameter values and options are also enumerated in PRIME Hybrid specifications and are detailed in appendix C. In short, the standard lays out several key parameters used for modulation, the convolutional encoder, FEC, interleaver, sensitivity, and transmission rates. All of which are later encoded into the simulator.

2.4 PRIME Hybrid

The combination of both PLC and RF technologies is the latest tendency promoted by PRIME Alliance. The expected benefits of this combination have been laid out in previous sections (see section 1.3) and are a key focus of the current study.

The basis of this hybrid solution is the addition of RF specifications into the PRIME v1.4 protocols stack. This will allow nodes to communicate with each other whether they are PLC-only, RF-only or hybrid nodes containing both technologies.

The combination of both specifications is achieved by integrating both PHY layers under the same MAC layer (defined by PRIME v1.4). This allows for a fully hybrid solution that will include the best of both alternatives.

All in all, a hybrid network is in direct opposition to the idea of having two parallel individual networks, one RF and one PLC. Theoretically, two superposed networks could achieve the same result without the complications of developing and adjusting to a new standard. This parallel network option may seem logical at first. However, this alternative implies effectively doubling the number of physical nodes to be able to reach a final node that would not be reachable by just having one technology available. On large scales, duplicating node deployment and production is more expensive than developing a hybrid node that adjusts to both behaviours.

[9]Smart Utility Network Frequency Shift Keying PHY. Specifically, the draft indicates the use of Chapter 20 of an older version of [21]. The most up to date version (cited) has the corresponding PHY layer described in Chapter 19.

Figure 7 provides a simple example of a possible hybrid topology. The objective is to be able to reach terminal nodes of both kinds by using any kind of path (PLC, RF or both). This can be done by using hybrid and simple (non-hybrid) nodes.

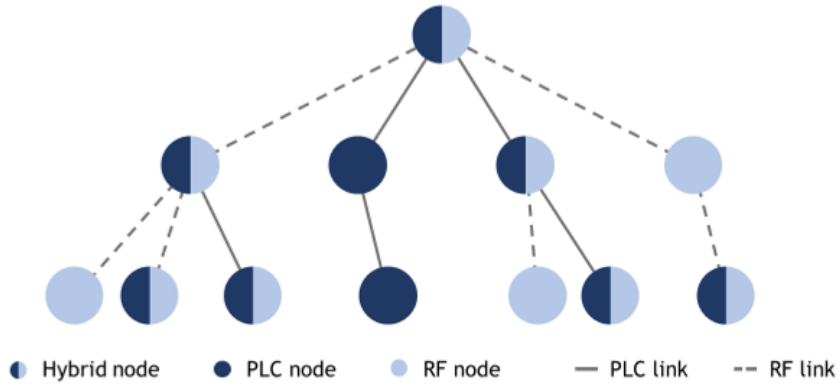

Figure 7: Hybrid Network Example

To be able to achieve this kind of medium interoperability, the specifications propose a dual PHY architecture. This rather uncommon layout - suitable for preexisting PLC and RF simple (non-hybrid) deployments - is laid out in [20]. Moreover, several papers such as [4] and [22] provide some additional insight on the matter. For instance, in the latter paper, the author points out two main advantages of the hybrid system. The first one is a less complicated deployment footprint - by only having to develop and account for a single MAC layer instead of installing two separate nodes. The second advantage is the usage of a common routing system which according to the author simplifies implementation.

The layers defined by the specifications are shown in figure 8. In the following two subsections, we will provide some examination of the MAC and PHY layers. Mainly, how the standard describes their behaviour and the connectivity between them. The logic illustrated in these sections will be applied later when building the simulation model (see Section 3).

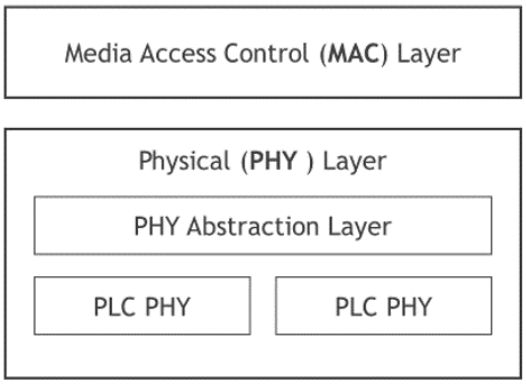

Figure 8: PRIME Hybrid Layer Definition

2.4.1 PHY layer considerations

PRIME Hybrid makes use of the PHY defined by PRIME v1.4 (PLC PHY). In addition, the following consideration is included: "the PHY layer can use an RF PHY to ensure the communication of the entire network when the media conditions or the characteristics of the device require it. At each point-to-point connection, the MAC layer can select the PHY layer, and the bands or channels available in it, that are most convenient to ensure the best communication".

Parameters for the PLC PHY are defined in a similar manner and structure to version 1.4 (the backwards compatibility is even described in reference to 1.3). With regards to the RF PHY, specifications state that PRIME nodes supporting RF communications must adhere to the SUN FSK PHY standard noted in section 2.3. For each parameter referenced in the requirements, PRIME states how the statement should be implemented according to five categories. These categories are Informative (I), Normative (N), Selection (S), Extension (E), and Not Relevant (N/R). For example, for the preamble field of the RF standard 802.4.15, PRIME assigns a "Selection" category where it fixes the preamble length attribute to eight. For reference, a few example rows of the table are provided in table 2

Clause	Title and remarks/modifications	Statement
20.1	Introduction	N
20.2.1.1	Preamble field. The attribute [...] shall be set to eight	S
...	...	...
...	...	...
20.5	Mode switch mechanism for SUN FSK. Mode [...] shall not be used	N/R

Table 2: RF PHY Parameter Specifications for PRIME Hybrid

2.4.2 MAC layer considerations

There are no new node states introduced at a MAC level. In a similar manner to section 2.2.1.3's description, nodes can be in one of three states: disconnected, terminal, switch. There is still only one base node (BN) per subnetwork and all other nodes are service nodes (SN).

However, the incorporation of dual channels and the ability to alternate between them raises important questions regarding for example registration processes and communication periods (CFP slot allocation for example). This section addresses all the points delineated by PRIME. However, the specifications leave room for interpretation and some implementations are left to the reader. These will be explained in detail in section 3.4 where we also point out how they have been implemented within the simulation.

Regarding the registration process, a SN can only be registered to the subnetwork through one medium. This means that simple (non-hybrid) nodes may only be part of a network if they are connected through another simple node of their kind or a hybrid node. Thus, if a node that is registered through PLC attempts to register via RF, it will be unregistered in PLC and re-registered in RF. Regarding beacon transmissions, simple nodes that act as switches only transmit beacons in their respective mediums. However hybrid nodes may do so in both RF and PLC. Promotions may also be requested in either medium. For example, a hybrid node may request a promotion to switch (because it received a promotion request from a node downstream) in RF. It will then be linked to the BN via RF and may transmit data downstream in either medium - according to the preferences of terminal nodes that logically depend on the said hybrid node.

In conclusion, simple (non-hybrid) nodes may function regularly in all cases.

Hybrid nodes may switch their communication method upstream depending on their current medium preference, this implies a new registration procedure. Moreover, hybrid nodes (that have been promoted to switch) will accommodate whichever communication preferences downstream nodes indicate. These will be invariable for simple nodes but may be variable for hybrid nodes.

2.5 Wi-SUN Alliance

Wi-SUN Alliance is a global association that operates in a similar manner to PRIME Alliance (section 2.1). Its mission statement is to promote a unified set of standards for wireless communications (power levels, data rates, modulations, frequency bands and other parameters). They focus on wireless deployments and they operate in compliance with IEEE Standard 802.15.4g [23].

This standard builds upon the regular 802.15.4 by including new PHY layers (and their corresponding MAC modifications) for smart neighbourhood networks. These additional PHY descriptions are mainly designed to support "outdoor low-power low-data-rate, wireless, smart metering ubiquitous network (SUN) applications under multiple regulatory domains".

A conventional Wi-SUN field-area network (FAN) is divided into several personal area networks (PAN). Within these PANs, a topology similar to the one described in section 2.3 is set up. Several terminal devices are assigned to one coordinator within the PAN. Coordinators act as routers by gathering information sent upstream by terminal devices and sending traffic from central systems downstream [24]. They play a similar role to Base Nodes defined by PRIME.

Overall, within a FAN network, a node may assume one of three different roles: Border Router, Router, and Leaf nodes. Border Routers are located at PAN edges. They keep track of routing tables within their corresponding PAN and provide connectivity to the network. These are similar to Base Nodes in PRIME standards. Router nodes provide upwards/downwards packet forwarding and addressing functionalities. Finally, Leaf nodes are the end devices. These Leaf nodes may have multi-hop capabilities and a mesh network topology can be established with Router nodes acting as switches and Leaf nodes as terminal

devices [25].

Performance results of Wi-SUN deployments are publicly available. There are Wi-SUN white papers [26] and publications by several authors ([27], [28], [29], and [30]) that both theoretical and field performance results. These numbers will be used for a viability comparison with the PRIME Hybrid simulation results.

2.6 LTE

Long Term Evolution (LTE) project was conceived within 3GPP[10]. It aimed to plan for the eventual growth and expansion of the UMTS[11] network. The purpose of this expansion was to increase data rates while simplifying network architecture and overall energy consumption. Within this network, user equipment (UE) connects to wireless towers, called eNodeB. These eNodeB provide connectivity to the Evolved Packet Core (EPC) which serves as network backhaul whilst providing additional services (location, subscriber policy and mobility management) [31].

LTE networks comprise an interesting option for supporting automatic meter infrastructure (AMI). Low latency and preexisting widespread coverage over residential areas are promising attributes. However, LTE was initially designed for communications with larger data streams and different overall characteristics. For example, voice, video, and web browsing.

The allocation of resources in LTE communications is not always optimal for AMI. For example, in LTE, eNodeBs assign the totality of a specific frequency band to each user[12]. This may cause some inefficiencies as smart metering applications require significantly different performance metrics (for example, they are more tolerant to high latencies). Namely, AMI communications present small packet sizes, a large number of nodes, and coordinated (or organized in time) transmission

[10] 3rd Generation Partnership Project. Unification of several standard development organizations. Created in 1998 with the goal of producing technical specifications and reports for 3G mobile networks.

[11] Universal Mobile Telecommunications Service (3G). network. Preceded by GSM (2G) and succeeded by LTE (4G). Some of its most important improvements were soft handover (SHO), higher data rates, and an increased array of services. It also introduced more flexible cells where coverage radius is affected by the number of connected user equipments (UEs).

[12] If OFDM is used. OFDMA is also supported which also assigns users in both time and frequency domains.

requests [32]. Several papers have addressed this issue and solutions such as using the LTE control signalling for AMI data transmission [33] or designing a new scheduler for the LTE medium access control [34].

On the whole, several add-ons and improvements have been proposed to make LTE a more adequate option for AMI applications. One such example is the NB-IoT (Narrowband Internet of Things) specification which was developed by 3GPP. Its essential characteristics include low development cost, higher density per cell, and great penetration indoors and underground [35]. Another example that is less applicable to the current case is LTE-M (LTE for Machines) which is optimized for higher bandwidth and faster speeds.

This technology also has publicly available results that can serve as a valid benchmark and comparison for the hybrid simulation outputs. Papers such as [36], [37], and [38] provide adequate metrics to perform the necessary comparisons.

2.7 Conclusion

All in all, a hybrid alternative tackled in this study is a relatively new idea. Few field results combine wireless and cable communications that can be used as reference points.

However, the idea has been proposed and discussed in several papers such as [4, 22, 39]. Most of these papers stay at a theoretical level when discussing the hybrid approach. A well-documented example of a simulation and implementation of the technology is [39]. In this paper, the author sets up an outdoor experiment with street lamps controlled via PLC or RF. However, the proposed method does not allow a node to switch between the two technologies when needed. Instead, lamps are randomly assigned a transmission method (PLC or RF) and the experiment is run for that network configuration. Furthermore, the topology of the network and the number of connected nodes stays constant throughout the experiment.

These two characteristics are results that this study aims to alter and consider. By taking into account both of these parameters, obtained results will have interesting implications for network deployment and planning. Once this is achieved by the simulator in the following section, the final results will be compared with

the ones from the mentioned Wi-SUN and LTE papers to provide a credible comparison metric and viability discussion.

3 Hybrid Network Simulation Tool

3.1 Introduction

The current chapter describes the simulation tool developed for the testing of scenarios using PRIME specifications. This tool is based on the tool developed by the author in [5]. In that paper, the author presents a simulation environment for PLC PRIME communications. This study extends that code by adding RF and Hybrid functionalities.

Specifically, the objective that this tool aims to accomplish is the ability to analyze and compare PLC, RF and Hybrid network performance under several scenarios. These scenarios include different node distributions - both physical and logical - channel characteristics and even node and architecture parameters. Out of all possibilities, we will focus on varying physical topologies (node layout), and the logical distribution of PLC, RF and Hybrid nodes. Section3.3 provides a comprehensive layout of the simulation tool's architecture and further details regarding the overall approach. Numerical values for all parameters are detailed in appendix C.

Although the results obtained are plausible and well-grounded, it is important to acknowledge the limitations that this simulator may have and the differences that exist between theoretical and practical approaches. Some parameters have been decided based on existing deployments, comparable simulations, and the author's judgement. These decisions are fully reported in section 3.4. Expected simulation outputs and calculated metrics are defined in section 3.5. Moreover, the code presents some inherent limitations and there are areas for improvement and further expansion. These aspects are discussed in section 3.6 together with proposals for future work and possible improvements.

3.2 Preexisting simulation tool

SimPRIME [17] is developed and described in [5]. Its main feature as opposed to similar simulation frameworks is the combination of both physical and network

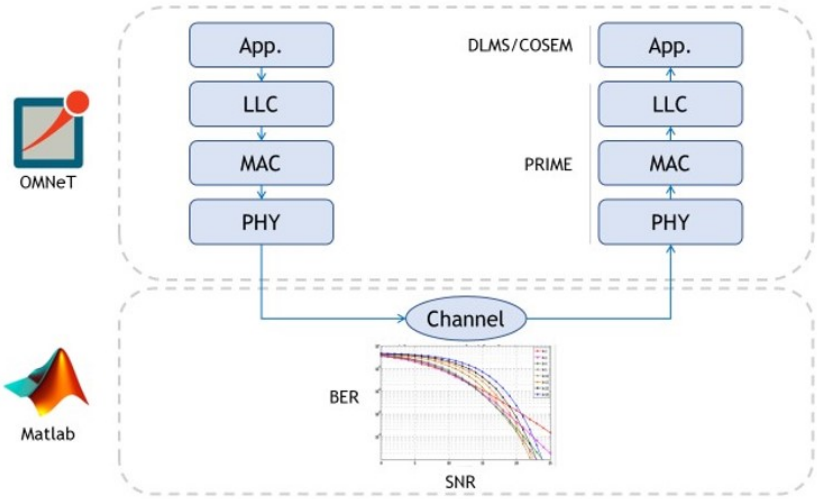

Figure 9: SimPRIME architecture

characteristics. Prior works had not always treated these two entities as a whole, which could lead to partial results.

SimPRIME's architecture is reflected in figure 9. All channel considerations are contemplated via Matlab whilst all other characteristics are taken into account within OMNeT+. All protocol layers and behaviour defined by PRIME standards are coded in C++ within the network simulation tool. For every transmission, BER is computed using the Matlab tool as a function of SNR. All calculations use the node's real position, channel characteristics, and message lengths to achieve a result that is as close as possible to a field environment.

The physical network topologies supported by the simulator are tree-like distributions. Parameters may be set for the number and length of branches, and the number of nodes per branch. Service nodes are then evenly distributed in each branch. An example of this layout is shown in figure 10.

The coded layers are PHY, MAC, and LLC layers according to PRIME standards. An application implementing DLMS/COSEM protocol is used at the topmost position of the stack. This abbreviation stands for Device Language Message Specification/Companion Specification for Energy Metering. It is a standard with

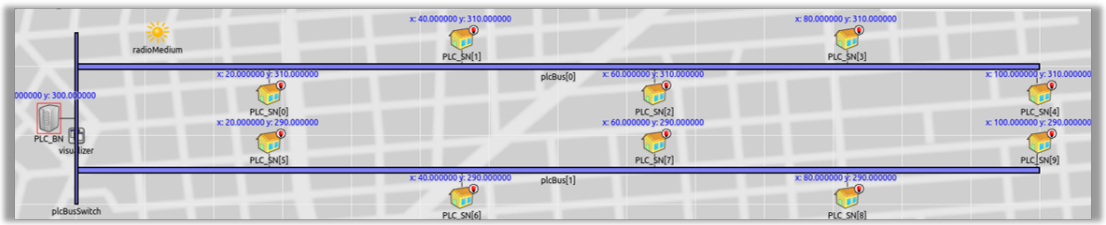

Figure 10: Example of node and branch distribution in simulator

a global presence used for smart energy metering, control and management. It is not uniquely used for electricity metering as it is also employed by gas, water, and heat utilities. DLMS is the application layer protocol whereas COSEM further defines the data model using an object-oriented approach. The messages interchanged in the simulation between BN and SN are represented in figure 11. This traffic pattern is similar to a daily read of the energy registers of a meter.

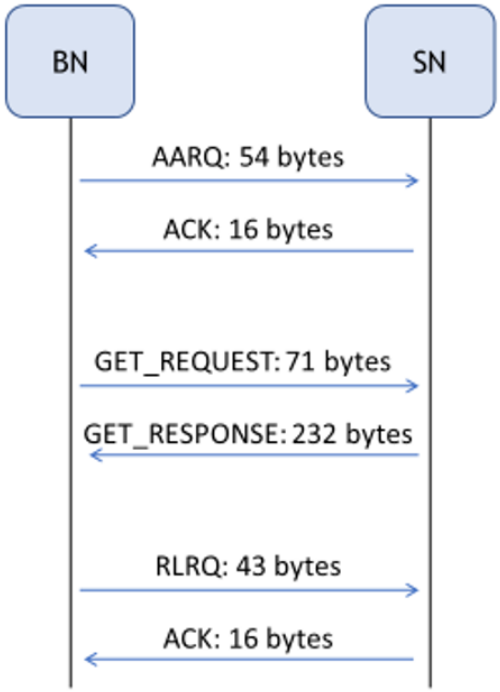

Figure 11: DLMS/COSEM communication flow

Metrics obtained as simulation results include registration and network conver-

gence times, switch promotion metrics and the number of switches, time to read all meters, and latency for application messages. These metrics are further detailed in 3.5.

All in all, these simulator is the basis for the developments that this paper presents. A new PHY layer has been designed, together with a new transmission channel (wireless). Logic has been introduced for nodes to be able to switch communication nodes if needed and also to deploy different types of networks such as all PLC, all RF, Hybrid, or a combination of the three.

3.3 Description of the simulation framework

The previous section describes the base code and simulator that was used as a starting point for the hybrid simulator. This section details the additions implemented to the preexisting architecture. First, in 3.3.1, a general overview of the system is presented, will mainly addressing the technologies used to simulate each part of the communications framework. Subsection 3.3.2 analyzes in detail the design of the channel modelling framework, also presenting an examination of different alternatives considered for simulating the channel. Finally, subsections 3.3.3 and 3.3.4 illustrate the development process and code structure of the newly-added layers.

3.3.1 Comprehensive explanation of simulation blocks

The general structure is very similar to SimPRIME's architecture. However, some differences have been included to accommodate PRIME Hybrid's new capabilities.

Figure 12 shows that both OMNeT and Matlab are used throughout the communication process. Additionally, there are three different code sources. SimPRIME code detailed in [5] and [17] is used for all upper layers. The MAC layer is modified to add some hybrid functionalities (for example, indicating within a given message which PHY layer to use in transmission). Combiner - the interface that combines PHY messages to offer the MAC layer one single downlink connection - and RF PHY are introduced and coded by the author as well as the channel

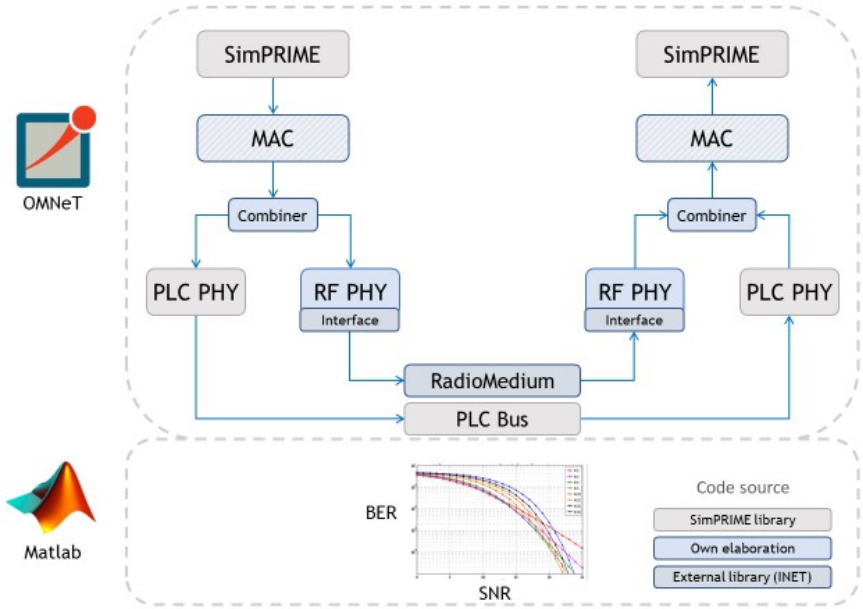

Figure 12: Hybrid simulation architecture

BER/SNR curves. INET [40] external library is used for the radio equipment and as the simulated radio medium for transmission[13].

As a general overview, a message is first generated by SimPRIME's application layer. When it reaches the MAC layer, a decision is taken to indicate whether the said message should be sent via cable or wireless mode (detailed in 3.4). The combiner then routes the message accordingly and the PHY layer transmits it. When a message is received, its SNR is computed with reception power and noise power. The corresponding BER is then obtained from the SNR/BER curves. These curves have been previously simulated in Matlab according to the different transmission possibilities (such as modulation and FEC type). We then simulate the packet error with the computed probability. Depending on this probability the packet may be considered to have errors, in which case it is dropped by the MAC.

Thus, the SNR/BER curves come into play for the error rate calculations. However, attenuation and collisions are not represented in those curves. Those considerations are taken into account in the PLC Bus and RadioMedium modules.

[13]The details regarding "Channel" and "RadioMedium" functionalities are explained in 3.3.2

3.3.2 Channel modelling

There are two distinct pieces used for the modelling: PLC Bus and RadioMedium. They both have the same goal of simulating channel attenuation and message collisions. However, they are used for different transmission mediums: cable and wireless respectively. The paragraphs below detail how each of these modules operates. It is important to keep in mind that the main objective of these tools is to provide a measure of reception power for each of the nodes in the network whilst also taking into account possible collisions. The determination of packet errors is performed later with the SNR calculation, which needs received power (and noise power) as an input.

3.3.2.1 PLC channel modelling - PLC Bus

This module is fully reutilized from SimPRIME. The code function gathers messages that are introduced in the cable and distributes them to all nodes. Attenuation for each transmitter-receiver pair of nodes is precomputed by Matlab and loaded onto OMNeT's simulation environment on initialization. This attenuation is primarily due to losses in the transmission medium (wire). The detail of the attenuation calculations is extensively explained in Chapter 3.3 of [5]. PLC Bus' message treatment is then reduced to simply discarding packages whenever a collision occurs in the wire. This should be infrequent as nodes implement a collision avoidance algorithm before starting transmissions. Several papers such as [41] and [42] have used this tool for their findings. The following paragraphs contain a brief examination of this module's operating principles.

Channel modelling is performed using a "Bottom-Up Approach". This concept was first developed by Banwell and Galli [43] and it provides a way to theoretically compute the PLC channel's transfer function for any link. To achieve this, full knowledge of the network's topology is needed, as it is the current case of the study. For the simulation, a network topology is entered into a Matlab function and the return value is a matrix with the dB attenuation values of each pair of nodes. This matrix is not symmetric as the attenuation "seen" when sending a message downstream *to* a node is not the same as the attenuation that is taken

into account when responding to that message and transmitting upstream *from* a node. An example matrix for 5 nodes (+1 base node) is represented in table 3. The main diagonal has a value of -1000 as a placeholder representing the attenuation from one node to itself (same row, same column). For example, in the indicated matrix, the attenuation for a message from the base node (row 1) to service node number three (column 4) would be 19.81 dB. However, a hypothetical response message would suffer an attenuation of 11.84 dB (row 4, column 1)[14].

Tx\Rx	**BN**	**SN1**	**SN2**	**SN3**	**SN4**	**SN5**
BN	-1000	-12.43	-17.11	-19.81	-22.84	-28.01
SN1	-5.23	-1000	-12.75	-15.77	-19.74	-22.23
SN2	-8.46	-5.84	-1000	-12.42	-16.22	-19.83
SN3	-11.84	-8.82	-6.73	-1000	-13.21	-16.09
SN4	-16.03	-12.26	-9.82	-7.27	-1000	-12.59
SN5	-17.44 dB	-14.65 dB	-11.74 dB	-8.85 dB	-6.34 dB	-1000 dB

Table 3: Example of PLC attenuation matrix

3.3.2.2 RF channel modelling - Radio Medium

In the case of wireless transmission, both tasks, attenuation and collisions are handled by INET's RadioMedium. This is an external library and several parameters such as the loss model can be introduced. For the purposes of our study, we chose to implement the simplest medium possible although other possible alternatives exist.

By the description provided by INET's API, RadioMedium "describes the shared physical medium where communication takes place. It keeps track of radios, noise sources, ongoing transmissions, background noise, and other ongoing noises. The medium computes when, where and how transmissions and noises arrive at receivers". Out of all possible subclasses of this RadioMedium, we chose to implement the class `Ieee802154NarrowbandScalarRadioMedium` with background noise and path loss models of `IsotropicScalarBackgroundNoise` and

[14]The matrix contains negative attenuations for negative for code purposes (As Rx is later computed as $Rx = Tx + Att.$, with $Att.$ having these negative values). The interpretation of cell SN1-BN would be that there is a 5.23dB attenuation for any message sent from SN1 to BN

Class	Parameter	Value	Justification
RadioMedium	type	Ieee802154Narrowband	Used for 802.15.4 by INET
BackgroundNoise	type	Isotropic	Constant noise over time and frequency domains for simplest model
	power	-96.616 dBm	Default INET value
PathLoss	type of pathLoss	BreakpointPathLoss	Simple attenuation model with parameters defined in 802.15.4
	breakpointDistance	8 m	
	l01	40.2	Assumptions for coexistence scenarios
	alpha1	20	
	l02	58.5	detailed in 802.15.4 specifications
	alpha2	33	

Table 4: Channel parameters chosen for simulation

`BreakpointPathLoss` respectively.

The `Ieee802154NarrowbandScalarRadioMedium` (`RadioMedium` in subsequent references) class, directly simulates a channel with the parameters described by the IEEE specifications for 802.15.4 [21]. It contains adjustable parameters which are mostly left with their default values (for example `ConstantSpeedPropagation`). The most relevant ones for this simulator are `backgroundNoise`, and `pathLoss`. The setting of all parameters is done following the process described in 2.3. This implies checking the reference table in the Hybrid documentation (reference table on page 54 of [20]) and cross-referencing it with the 802.15.4 standard First, the PRIME Hybrid document is checked for indications. Then, the correct section is consulted within the 802.15.4 document to select the parameter value. If a value is not specified by the Hybrid standard, it is left as the default value set by OMNeT (which have been fine-tuned by default for the `RadioMedium` class). Table 4 shows values of all relevant parameters that define the medium. All other parameters were left with their default INET values.

The parameters in `pathLoss` are obtained from an 802.15.4 reference document and they represent an attenuation model solely based on the transmitter-receiver distance for cases where there may be "coexistence". Coexistence is defined by the standard to be "issues regarding coexistence between IEEE 802.15.4 devices and other wireless IEEE-compliant devices". The channel model equation is then defined as:

$$d = 10^{\frac{(P_t - P_r - l01)}{\alpha_1}} \text{ for } d > d_{breakpoint}$$

$$d = 10^{\frac{(P_t - P_r - l02)}{\alpha_2}} \text{ for } d < d_{breakpoint}$$

3.3.3 RF PHY layer development

This layer is where the most significant part of the coding work done by the author is located. The full code for this layer is provided in appendix A. The PLC PHY layer is not discussed in this study because no changes were made from the SimPRIME version. PHY layer development is reviewed in four steps. First, we present how the initialization is done. Then, SNR/BER curves are explained. Finally, we show how messages are handled by the simulated PHY layer and all relevant parameters are displayed in a table.

3.3.3.1 PHY layer initialization

The PHY class is initialized by loading BER data from the SNR/BER curves simulated on Matlab. Then it sets its initial radio position parameters according to where the node is located in the network (positional coordinates). Afterwards, it identifies whether the node itself is set to communicate via RF (if the node has no RF capabilities because it is PLC-only, then this PHY is not instantiated). After this initialization, the regular operation mode starts with the handling of packets.

3.3.3.2 SNR/BER curves

Before detailing the packet treatment functionalities, a small note is provided regarding the computation of the SNR/BER curves on Matlab. These curves are obtained by creating dummy arrays in Matlab and simulating the sending and reception process with the incorporation of necessary PHY modules (FEC and interleaver) on both ends. The simulated channel introduces additive white

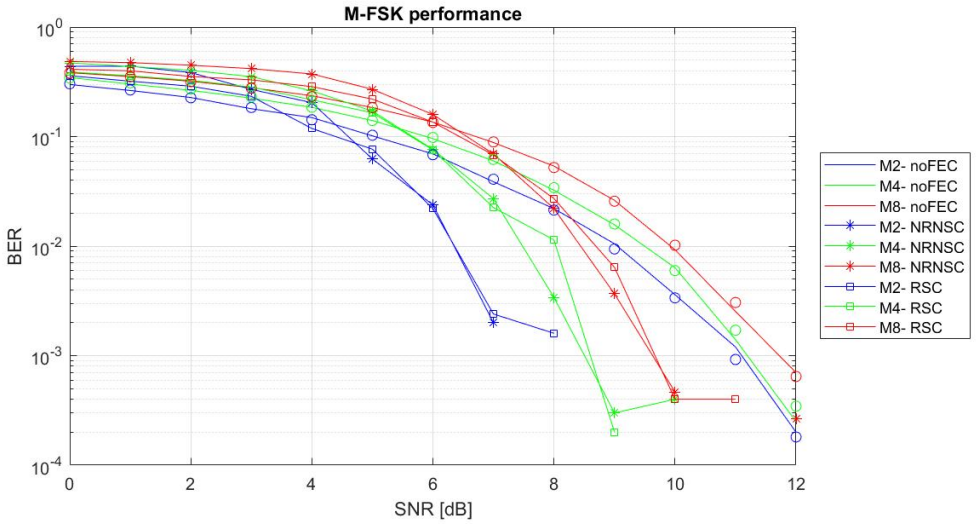

Figure 13: SNR/BER curves

gaussian noise (AWGN) [44] that takes SNR as an input. For the simulation, we enter an array of possible SNR values to obtain the final SNR/BER curves.

After the signal transmission and reception are simulated, the BER is computed by comparing the original signal to the final one after all reception steps are complete. This process is detailed on page 550 of [21] and figure 13 shows the resulting curves that are used in the simulation. NRNSC and RSC are two different types of FEC coding[15]. PRIME specifications indicate that the former should be the supported FEC coding mode.

Figure 13 shows the SNR/BER curves for different M-FSK modulations. Each colour represents a different transmission mode regarding the application of the different FECs. Lines are the simulated values, whereas the symbols (circles for noFEC, stars for NRNSC, and squares for RSC) represent the theoretical values). It can be seen that the simulated curves align correctly with the expected theoretical results. The baseline code for the theoretical results was provided by J. Matanza as it overlapped an approach taken by him in a similar case.

[15]Non-recursive and non-systematic code (NRNSC) and recursive and systematic code (RSC).

3.3.3.3 PHY layer message handling

When the PHY layer receives a message, it must first determine its source. Messages from the upper layer (combiner) are immediately sent to the INET radio interface. However, before leaving the PHY layer a simulation flag parameter is set within the message to indicate that it is transmitted via radio. This will be used by the combiner in reception to determine which PHY has received the message. The purpose of this flag (which is only code and not present as actual bits within the packet) is to emulate the communication primitives in real-world scenarios.

On the other hand, messages coming from the network undergo several steps before being sent to the upper layers (combiner and MAC). Mainly, the packet error simulation takes place at this point. If the message is considered to have arrived with errors, it is flagged as such and it will be later discarded by the MAC layer. To simulate the error, the SNR for the message is first computed. Reception power for the message and background noise - both simulated by the INET library - are needed for this step.

$$SNR = \frac{P_{Rx}}{P_{noise}}$$

This SNR is then inputted in the SNR curves from figure 13 and the BER is obtained. Most likely, the computed SNR is not the same as one of the discrete simulated SNR values. In this case, linear interpolation between the two closest values is performed to obtain an adequate BER value. With the BER value and packet length, we obtain a packet error rate.[16].

$$PER = 1 - (1 - BER)^{\text{packet length in bits}}$$

Then, a random number is sampled from a uniform distribution between 0 and 1. If this number is lower than the calculated PER, then the packet is flagged as erroneous. After this error treatment phase, the data is sent to the combiner. This

[16]The formula is "1" minus the probability that all bits within the sent packet are received without errors. A single bit is received correctly with probability $1 - BER$. Thus, assuming all errors are independent $(1 - BER)^n$ would be the probability that all n bits are without errors.

Class	Parameter	Value	Justification
Radio	type	Ieee802154Narrowband	Used for 802.15.4 by INET
	centerFrequency	867 kHz	Hybrid specs. reference to 802.15.4
	bandwidth	200 kHz	Table 20.6 SUN FSK in 802.15.4
	power	3.6 dBm (2.29 mW)	Section 20.6.11 SUN FSK in 802.15.4
	sensitivity	-94.01 dBm	Section 19.6.7 SUN FSK in 802.15.4
	bitrate	100 kbps	Table 20.6 SUN FSK in 802.15.4
	headerLength	16 bits	Table 20.6 SUN FSK in 802.15.4

Table 5: PHY parameters chosen for simulation

module simply receives the message and forwards it to the MAC. Its purpose is to ensure the MAC only has one downlink and uplink interface.

3.3.3.4 PHY layer parameter specification

In a similar manner to the method employed to customize the `RadioMedium`, the radio transmitter (`Ieee802154NarrowbandScalarRadio` class from INET) has been set up with the parameters shown in table 5[17]. As an example of parameter setting, the `centerFrequency` was chosen by consulting the reference table in PRIME Hybrid documentation. Said table, states that "the 863–870 MHz frequency band shall be supported". Thus, a centre frequency of 867MHz was chosen by cross-referencing the PRIME Hybrid specification with the possible band designations provided in the 802.15.4 standard[18].

3.3.4 Hybrid MAC layer adjustments

The code for the MAC layer was not changed significantly from the SimPRIME simulator. This is consistent with the desired architecture as the goal is to have one single MAC layer supporting both PHY options. Moreover, this MAC layer has no significant alterations compared to its PRIME v1.4 option. The adjustments and overall functionality of the MAC layer will be discussed in three steps. First,

[17]The footnote in section 2.3 addresses the discrepancy between chapter numbers and versions. For this table, the 802.15.4 version expressed in the Hybrid specifications (2017 and 2015) has been used for all applicable cases

[18]Moreover, this frequency matches the regulatory standards and the bands chosen by Iberdrola for its RF rollouts. However, as the simulation only takes into account one single radio channel, the effect of the frequency band is minimal on simulation results.

the initialization of all nodes is described. Then the message handling process, and finally, the chosen parameters are shown.

3.3.4.1 MAC layer initialization

Three main steps take place within a node's MAC layer initialization process. MAC (EUI-48) address determination, out-gate initialization, and parameter initialization.

The first step is to determine whether the present node is a BN or SN. When this choice has been taken (only one BN per subnetwork), the MAC address is assigned. To improve the readability of simulation results random numbers are not used here. Instead, a MAC address of "1" is given to the BN and all other nodes are given the previous node's address incremented by one. Thus, if we have two branches with five nodes in each branch, the BN will be assigned MAC 1. Then, nodes in the top (first) branch will be assigned addresses from 2 to 6 and nodes in the bottom branch will have addresses 7 to 11.

The second step is to initialize the out-gate. This means establishing the initial PHY layer preference. For non-hybrid nodes, this step is simple: they can only be assigned to one of the two PHY layers. However, hybrid nodes have to decide which PHY preference they start the simulation with. However, before taking this decision, a node must determine whether they are hybrid or not. These initialization decisions are taken by varying three parameters in the network configuration parameters: `oneOfEveryXNodesIsHybrid`, `oneOfEveryXRegularNodesIsRF`, and `oneOfEveryXHybridNodesIsRF`. The usage of each parameter is illustrated in figure 14.

The decision to choose `Y/N` in each `isHybrid` and `isRF` are computed by using the node's MAC address. The following equation is used to decide whether a node is hybrid or not:

$$\text{isHybrid} = \begin{cases} \text{yes} & \text{if } \texttt{MAC} \pmod{\texttt{oneOfEveryXNodesIsHybrid}} = 0 \\ \text{no} & \text{otherwise} \end{cases}$$

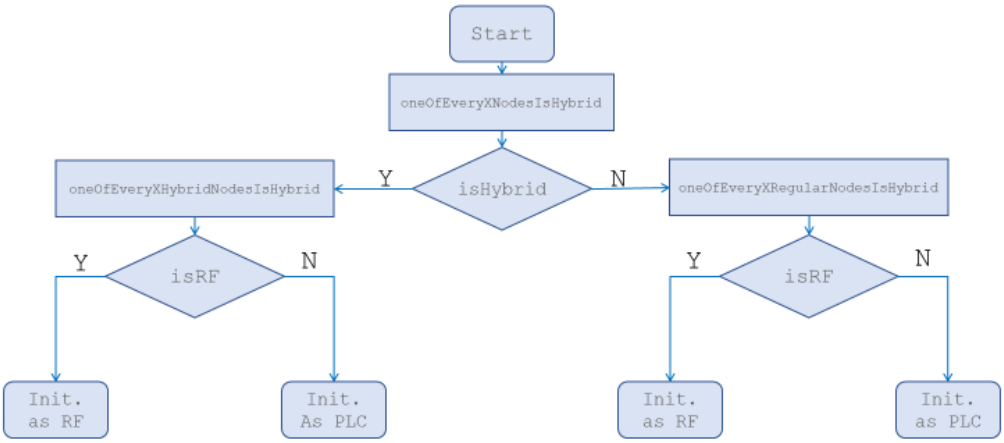

Figure 14: MAC initialization procedure

Afterwards, both hybrid and non-hybrid follow a similar path but the queried variable is different. In this case, either `oneOfEveryXHybridNodesIsRF` or `oneOfEveryXRegularNodesIsRF` is checked:

$$\text{isRF} = \begin{cases} \text{yes} & \text{if } \texttt{MAC} \pmod{\texttt{oneOfEveryXNodesIsRF}} = 0 \\ \text{no} & \text{otherwise} \end{cases}$$

This is implemented with this structure to provide higher simulation flexibility. For example, an architecture with 50% PLC-only nodes and the rest being hybrid initialized all with RF preference can be achieved by tuning the parameters as follows:

`oneOfEveryXNodesIsHybrid`= 2 50% of nodes are hybrid

`oneOfEveryXRegularNodesIsRF`= 0 all regular nodes are PLC

`oneOfEveryXHybridNodesIsRF`= 1 all hybrid have RF preference initially

The BN parametrization is done individually and does not affect the rest of the network. This is because we always want individual control of BN parameters as there will only be one for the whole network.

The third and final initialization step is the initialization of several parameters used during the simulation. For example, the list of registered nodes is initialized as emtpy[19], the time interval before requesting a promotion upstream is specified, and the number of alives without an answer before unregistering. All parameter values are detailed in 3.3.4.3.

3.3.4.2 MAC layer message handling

The message handling process is more complex than in the PHY case. However, as most MAC functionalities have remained unchanged from the previous simulator version, only an informative overview is provided of the general process. Moreover, an explanation of the two main additions included within the message handling code is also provided.

The general process involves determining the kind of message received. Upon receiving a new message, the MAC layer first determines whether it is a `SelfMessage` or not. `SelfMessage`s are simulation-only messages that serve as internal timers for the different functions performed by the MAC layer. One example of usage is the scheduling of alive timers. Whenever the BN receives an `ALV` message from a SN, it schedules a `SelfMessage` (timer) that will be received in `current simulation time` + `DEFAULT ALV TIME`. When this `SelfMessage` is received, it simulates the timer's expiration and subsequent actions can be taken.

The other possible message type is an external message. It can come from the network or the upper layers. These receive individual treatment according to the message type. Finally, whenever a message is ready to be sent, it is inserted into the transmission message queue and the CSMACA process is initiated. The implementation of this algorithm within the simulation code is described in detail in section 7.3.2.2 of [5] (and it has not been altered). Before a back-off period starts,

[19] All nodes have this empty list as service nodes may function as switches and register nodes in this list

the node checks that the message to be transmitted fits within the remaining MAC frame (see section 2.2.1.3). If it does not fit, the transmission will be delayed until the next MAC frame. If the transmission can be attempted, the back-off period starts. This period depends on the number of transmission attempts, and the priority of the message.

The two small modifications to the existing MAC layer message handling code are the combiner and communication preference parameters. The combiner module is located between the MAC and PHY layers and depending on the communication preference set by the MAC layer it relays a downlink message to the corresponding PHY layer. A certain node (either BN or SN promoted to switch) can know the communication preference of nodes downstream by checking its registered nodes list for their communication preference. This communication preference setting is explained in detail in section 3.4.

3.3.4.3 MAC layer parameter specifications

The parameters specified for the MAC layer are shown in table 6. These parameters correspond mainly to the timer values chosen to implement the keep alive and promotion processes. As these parameters are not self-explanatory, a concise description is provided.

Class	Parameter	Value	Justification
MAC Layer	defaultALVTime (BN only)	120s	PRIME Hybrid specs. p.275
	ALVNumChances (BN)	5	PRIME Hybrid specs. p.270
	interPromotionTime (BN)	50s	PRIME Hybrid specs. p.178
	ALVOffset (SN only)	60s	PRIME Hybrid specs. p.340
	numDisconnBeforePRN (SN)	5	Own implementation

Table 6: MAC parameters chosen for simulation

defaultALVTime time delta between ALV_REQ_B sent by BN.

ALVNumChances num. unanswered ALV_REQ_B required to unregister SN.

interPromotionTime time between two granted promotions by BN.

ALVOffset timer that is reset within SN with each received packet.

numDisconnBeforePRN num. of spent timers before SN requests promotion.

3.4 Addressing gray areas in standards

The main uncertainty within the specifications is the decision-making process of which PHY layer to use for transmission and reception. Should a hybrid node be listening in both mediums? Should a hybrid switch transmit beacons in both PLC and RF? If so, should they be part of different MAC frames? Questions such as these, are not fully laid out in the draft PRIME Hybrid specifications document currently available. For this reason, several assumptions have been made in these regards. Furthermore, a few additional simulation parameters have been specified by the author as detailed in the tables from previous sections.

Regarding the hybrid node behaviour, the most complete description is detailed on page 77 of [20] and it focuses mainly on PLC and RF channel usage by the different nodes. As the simulation only has one RF and PLC channel (see section 3.6 for limitations) this does not play a significant role. There are however a few behavioural descriptions that address questions not related to different channels. The main indication is related to beacon transmissions and the specifications dictate that a "PLC+RF base node may use one or two medium" (for beacon transmission). A second indication is that a service node may only be registered to the network through one medium. Should it start a second registration process via the second medium, it would lose its previous registration status. However, no further implementation details are provided for hybrid behaviour.

Thus, the determination of PHY layer preference for the packets sent by a hybrid node is done with the logic described in figure 15. If the node is not hybrid, the problem is non-existent, as the PHY layer is predetermined. However, if the node is hybrid then a distinction is made between uplink and downlink messages. An uplink message is always transmitted using whichever PHY was initially used for the node registration. Hybrid nodes may not communicate uplink via alternative channels. This is consistent with the second indication described above. However if the message is downlink, the PHY selection is more complicated.

Depending on the message type, a different process is followed. A message can

be GENERIC PDU or not. A GENERIC PDU message is a packet that is not a PN PDU (promotion needed) or BCN - PN PDUs are always relayed uplink so they should never reach this point of the logic tree. GENERIC PDU messages are transmitted according to the receiver node's preference. This preference has been previously registered similarly to ListRegNodes during the registration process of a downlink node. Non GENERAL messages are always BCNs and their preference is calculated with a personalized algorithm.

This algorithm is a simple procedure that calculates the percentage of beacons transmitted downstream according to the number of RF and PLC preferences of registered nodes. If a certain switch has five registered nodes with three of them having PLC preference and the two remaining ones having RF preference, it shall send a beacon via the PLC PHY 60% of the time. However, there is an imposed minimum of beacons transmitted in either medium in case all registered nodes have the same preference. For example, if 100% of nodes are registered with a PLC preference, the switch shall send an RF beacon from time to time in case a new (previously unseen or disconnected) RF-only node wants to join the subnetwork.

3.5 Simulation outputs

The simulation output has two main components: the PRIME network topology and several computed metrics. In this section, we show an example of a topology generated by the program and we comment on the meaning of the six obtained metrics. These metrics can be further divided into two categories: topology metrics and application traffic metrics.

An example of a topology is shown in figure 16. This tree is the resulting logical topology of a network composed of two branches of 100m in length with five nodes in each branch. In this case, all nodes were PLC-only nodes and some extra attenuation was artificially introduced between the third and fourth node in each branch to force promotions to happen in a controlled environment. The result shows two promoted SN with their corresponding switch identifiers (SID). All nodes have local node identifiers (LNID) that are dynamically assigned when

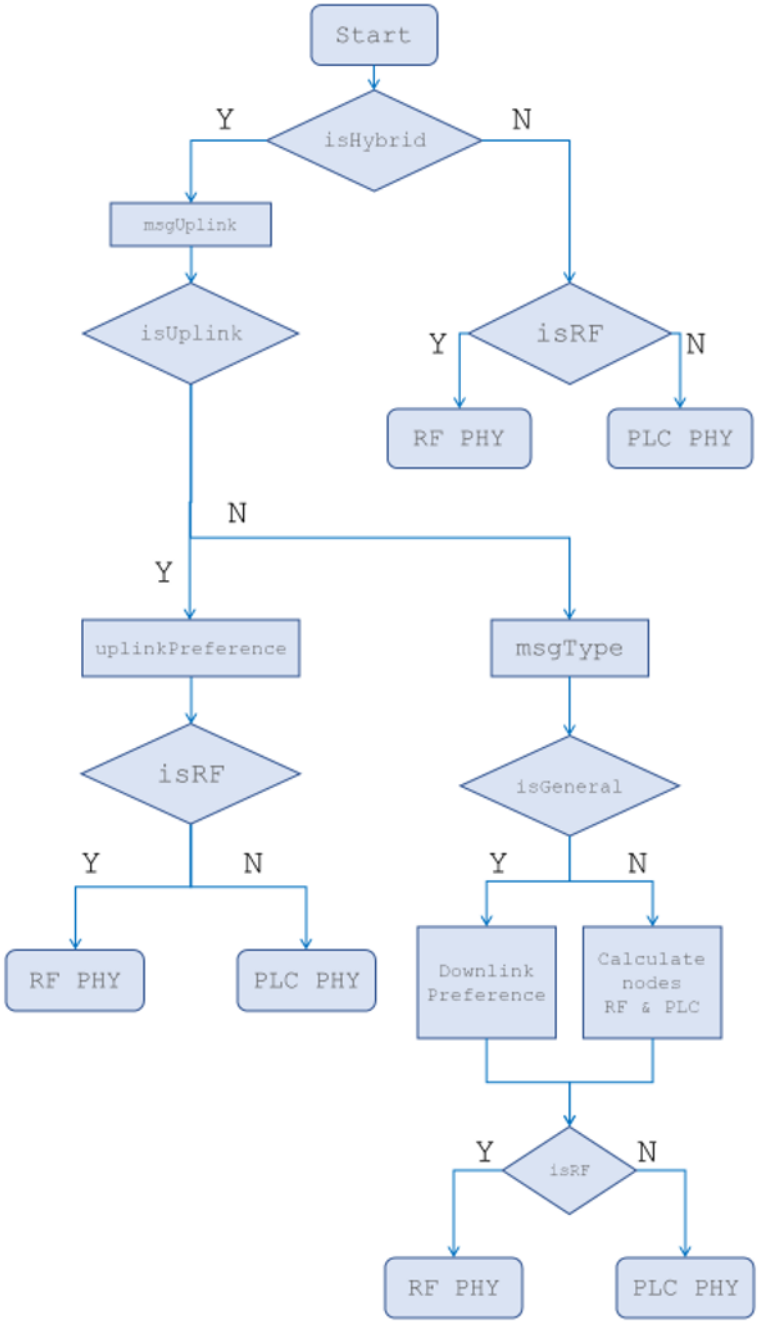

Figure 15: Determination of PHY layer preference for packets

joining the network.

```
The netwok logical topology is :
 -> I am node with SID = 0
    |
    |
    -> I am node with SID = -1 and LNID = 3
    |
    |
    -> I am node with SID = -1 and LNID = 4
    |
    |
    -> I am node with SID = -1 and LNID = 2
    |
    |
    -> I am node with SID = 1 and LNID = 1
        |
        |
        -> I am node with SID = -1 and LNID = 7
        |
        |
        -> I am node with SID = -1 and LNID = 8
    |
    |
    -> I am node with SID = 2 and LNID = 5
        |
        |
        -> I am node with SID = -1 and LNID = 10
        |
        |
        -> I am node with SID = -1 and LNID = 9
    |
    |
    -> I am node with SID = -1 and LNID = 6

```

Figure 16: Simulation result example: logical tree

Other topology results (topology metrics) are the number of registered nodes and MAC address of the registered node, number of switches and MAC address of switch node. The simulated application is DLMS/COSEM which is commonly used electric meter polling. The application traffic metrics obtained are time to read meters (TTR), application roundtrip latency, and throughput (application data bps). All metrics are recorded throughout the whole simulation period and will allow studying of network convergence times and other events that happen when the subnetwork is being configured (for example, promotion of a switch node followed by the registration of additional nodes). The topology metrics are self-explanatory, but the application traffic statistics require further definition to clarify what is being measured.

TTR All Meters - the time to read one meter is defined as the time difference between the sending of the AARQ (Application Association Request) and

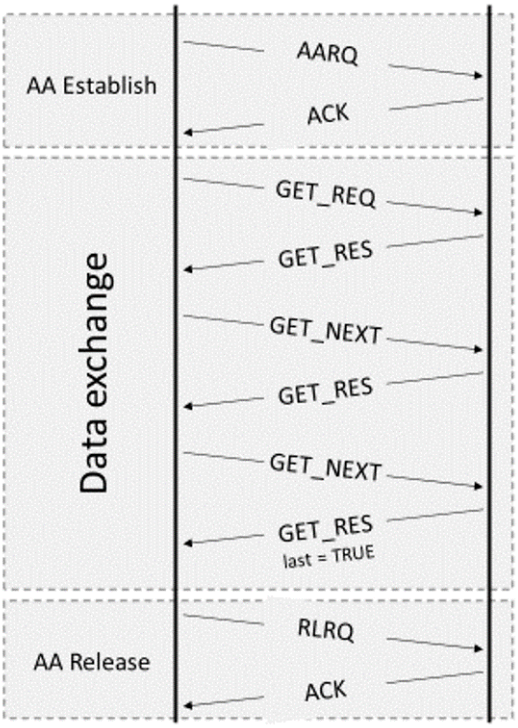

Figure 17: TTR metric: connection establishment and release

receiving the ACK for the RLRQ (ReLease ReQuest) [45]. Effectively, this means that reading one meter comprises the period of time between requesting a connection up to the point that this connection is released by the BN (see figure 17). The simulation implements sequential polling and TTR is defined as the time to read all meters currently registered. Some relevant parameters regarding packet sizes are shown in figure 11

Application roundtrip time - this is the time that passes since a `GET_REQ` message is created by the application layer until the response `GET_RES` is fully processed by the BN application layer again. A parameter that highly affects this metric (not strictly a latency in physical terms) is the simulated app processing time (both BN and SN) which for the simulation is set at 500ms.

Throughput - this metric indicates the effective data rate achieved during the simulation. Is computed by dividing the number of data bits - both sent and received - by the application roundtrip latency. A median value of all message exchanges is displayed.

3.6 Limitations of the simulation tool

In this last subsection of the simulation tool section, several known problems and limitations are highlighted. The goal of the program is to simulate field deployments as closely as possible, but an exact replication cannot be fully achieved. Three main limitations make this simulation differ slightly from real-world rollouts: the lack of several communication channels, noise and attenuation invariability, and node distribution.

For both RF and PLC, PRIME specifications contemplate the possible use of different communication channels, even describing in detail channel-hopping methods. This is not implemented in the simulation and thus, real-world results may be better than the metrics obtained in this study.

Secondly, noise and attenuation are constant for both cable and wireless options. Each of them are simulated following analytical procedures but throughout the simulation, they do not change. This is unrealistic when compared with real-world scenarios. PLC loads may vary depending on which devices are currently connected to the network and the power required by households. Wireless conditions may also vary due to weather conditions, construction works, external interference and other physical obstructions.

Finally, node configuration and network physical topology present limited deployment options. The only available configuration is several branches with an equal number of nodes in each branch. All nodes are equally spaced within the branch and all branches have the same distance between each other. Moreover, the simulation tool must be deployed in a virtual machine running Linux. RF environment simulation generates a multitude of events and simulations take a long time to complete, sometimes running into problems due to the limited capabilities of a virtual machine running on Windows. Effectively, this means that the maximum

number of nodes is capped at approximately 60 nodes.

All in all, these limitations narrow the number of possible scenarios that can be compared. However, they still allow for a realistic analysis of PRIME Hybrid technology and its performance.

4 Performance results

This section is divided into three parts. First, the scenarios that have been selected for testing are detailed and the reasoning behind the node layout choices is explained. Then, the different metrics for all simulations are shown in several tables. Finally, comments are provided explaining the most noticeable findings of the simulation.

4.1 Scenario description

Scenario selection has been done to test out different population densities and possible real-world layouts. As pointed out in section 1.2.2, client to substation ratio (effectively SN to BN ratio) varies significantly between the countries to test - namely Spain, Brazil, and United States. Thus, for a given powerline length, the number of nodes has been varied to change the node density within the scenario.

Moreover, for each physical topology selected we have tested five different logical node setups: all PLC, all RF, and three hybrid variations. These variations are achieved by changing the initial distribution of PLC/RF node preferences. The three variations are 90, 50, and 10% PLC nodes in initialization. The result is that in the first hybrid option, the majority of nodes are initialized with PLC transmission preference (they can receive both RF and PLC messages). In the second variation, this number is reduced to 50%. Finally, the third variation is comprised of mostly RF (hybrid) nodes at initialization (90%). The selected scenarios are detailed in table 7. For each scenario, table 8 shows the five possible variations described.

Scenario	**N. of branches**	**Branch length (m)**	**Nodes per branch**	**Tot. nodes**
Basic scenario	2-4	100	5	10-20
Low density	3	400	10	30
Medium density	3	400	15	45
High density	3	400	20	60

Table 7: Scenario Parameters

The following three sections detail the results of the proposed scenarios. Each

Variation	% PLC Nodes	% RF Nodes
All PLC	100	0
All RF	0	100
Hybrid A	90	10
Hybrid B	50	50
Hybrid C	10	90

Table 8: Scenario variations

table presents seven metrics. The first two columns are the time it takes for 50% of nodes to be registered and the convergence time for the network (95% of nodes registered). The third and fourth columns show the total number of switches and the percentage that they represent of the total network at convergence. TTR is the time to read all meters. App RT is the average time elapsed between an application layer sending a message and when it receives the response. One meter reading consists of several application messages (connection establishment included). Finally, the average throughput of these messages is represented in the last column. All scenarios simulated a time period of 1200 seconds.

4.2 Basic Scenario

Three alternatives to the basic scenario are shown. The first one with two branches and the other two, with four branches each. Branch separation is 20 meters for the first and second case and 70 meters for the last one. The purpose of this is to first have a simple benchmark scenario, followed by two slightly more complicated variations that differ only on the separation of their branches. This could represent a difference in service node density.

Basic scenario - 100m 2 branches of 5 hosts each branch. Branch separation 20m

	50% reg.	Conv.	# SW	SW%	Med. TTR	Med. App RT	Throughput
All PLC	8.3s	10.0s	0	0%	25.3s	1.2s	3.5kbps
All RF	9.4	22.4	1	10	26.2	1.3	3.4
Hybrid A	8.3	10.0	0	0	26.5	1.2	3.5
Hybrid B	8.8	32.9	1	10	26.1	1.2	3.5
Hybrid C	9.4s	22.4s	1	10%	26.1s	1.2s	3.5kbps

Table 9: Simulation results: Basic scenario - two branches

Basic scenario - 100m 4 branches of 5 hosts each branch. Branch separation 20m

	50% reg.	Conv.	# SW	SW%	Med. TTR	Med. App RT	Throughput
All PLC	10.8s	13.7s	0	0%	50.2s	1.2s	3.5kbps
All RF	13.1	83.2	2	10	102.3	1.3	3.4
Hybrid A	10.9	14.0	1	5	161.4	1.3	3.4
Hybrid B	13.7	47.8	1	5	114.3	1.3	3.4
Hybrid C	13.8s	69.3s	1	5%	72.7s	1.3s	3.4kbps

Table 10: Simulation results: Basic scenario - four branches 20m separation

Basic scenario - 100m 4 branches of 5 hosts each branch. Branch separation 70m

	50% reg.	Conv.	# SW	SW%	Med. TTR	Med. App RT	Throughput
All PLC	10.8s	13.7s	0	0%	50.0s	1.2s	3.5kbps
All RF	98.0	200.0	5	25	88.6	1.5	3.0
Hybrid A	10.8	13.9	3	15	66.3	1.3	3.4
Hybrid B	26.7	160.9	3	15	95.9	1.4	3.1
Hybrid C	218.5s	280.3s	3	15%	102.5s	1.5s	2.9kbps

Table 11: Simulation results: Basic scenario - four branches 70m separation

4.3 Low density scenario

The low-density scenario is run for two different base cases with different branch separations. It is seen that it mainly affects RF usage as nodes in parallel branches have higher difficulties communicating with each other.

For this more complex case, some TTR metrics in the higher separation case could not be computed. The reason for this is explained at the end of the chapter and in the overall conclusions.

Low density - 400m 3 branches of 10 hosts each branch. Branch separation 30m

	50% reg.	Conv.	# SW	SW%	Med. TTR	Med. App RT	Throughput
All PLC	17s	90s	4	13%	88s	1.3s	3.3kbps
All RF	220	631	8	27	300	2.1	2.0
Hybrid A	17	191	11	37	289	1.3	3.3
Hybrid B	120	590	17	56	284	1.5	2.8
Hybrid C	350s	882s	17	56%	231s	1.7s	2.5kbps

Table 12: Simulation results: Low density scenario - three branches 30m separation

Low density - 400m 3 branches of 10 hosts each branch. Branch separation 70m

	50% reg.	Conv.	# SW	SW%	Med. TTR	Med. App RT	Throughput
All PLC	17s	90s	4	13%	92s	1.3s	3.3kbps
All RF	355	621	14	47	199	2.1	2.1
Hybrid A	16	140	15	50		1.3	3.2
Hybrid B	223	504	15	50		1.3	3.2
Hybrid C	595s		16	53%	113s	1.9s	2.3kbps

Table 13: Simulation results: Low density scenario - three branches 70m separation

4.4 Medium density scenario

The medium density case shows two different result tables. Both of them are simulations with 400m branches and 15 nodes per branch. The first table has a separation of 30 meters between branches whereas, for the second one, branch separation is set to 70 meters.

For this medium density scenario, as in the previous case, some TTR metrics could not be obtained. Further comment on this is provided at the end of the chapter.

Medium density - 400m 3 branches of 15 hosts each branch. Branch separation 30m

	50% reg.	Conv.	# SW	SW%	Med. TTR	Med. App RT	Throughput
All PLC	24s	194s	6	13%	127.9s	1.4s	3.2kbps
All RF	255	475	8	18	361.7	2.1	2.1
Hybrid A	25	303	16	36		1.4	3.1
Hybrid B	190	483	15	33		1.3	3.4
Hybrid C	449s	732s	16	36%	417.5s	1.9s	2.2kbps

Table 14: Simulation results: Medium density - three branches. 30m separation

Medium density - 400m 3 branches of 15 hosts each branch. Branch separation 70m

	50% reg.	Conv.	# SW	SW%	Med. TTR	Med. App RT	Throughput
All PLC	24s	194s	6	13%	128s	1.4s	3.1kbps
All RF	383	537	14	31		2.6	1.7
Hybrid A	25	305	14	31		1.3	3.3
Hybrid B	198	439	13	29	213	1.5	3.0
Hybrid C	904s	1131s	16	36%	423s	1.8s	2.4kbps

Table 15: Simulation results: Medium density - three branches. 70m separation

4.5 High density scenario

The high-density case shows two different result tables. Both of them are simulations with 400m branches and 20 nodes per branch. The first table has a separation of 30 meters between branches whereas, for the second one, branch separation is set to 70 meters.

Again, there are cases for which no TTR metrics have been obtained. The reason for this is also laid out in the conclusions at the end of this chapter

High density - 400m 3 branches of 20 hosts each branch. Branch separation 30m

	50% reg.	Conv.	# SW	SW%	Med. TTR	Med. App RT	Throughput
All PLC	93s	299s	8	13%	185s	1.4s	3.0kbps
All RF	424	697	16	27	176	1.9	2.2
Hybrid A	195	302	14	23	466	1.6	2.7
Hybrid B	327	864	17	28		1.3	3.3
Hybrid C	763s	1075s	11	18%		1.7s	2.6kbps

Table 16: Simulation results: High density - three branches. 30m separation

High density - 400m 3 branches of 20 hosts each branch. Branch separation 70m

	50% reg.	Conv.	# SW	SW%	Med. TTR	Med. App RT	Throughput
All PLC	93s	299s	8	13%	180s	1.4s	3.0kbps
All RF	418	763	18	30		2.3	1.8
Hybrid A	195	639	17	28	252	1.6	2.6
Hybrid B	293		15	25		1.8	2.4
Hybrid C	590s		10	17%		1.8s	2.3kbps

Table 17: Simulation results: High density - three branches. 70m separation

4.6 Simulation result comparison of PRIME alternatives

Three main conclusions can be extracted from the previous tables. These conclusions explain most of the discrepancies observed within the results.

Firstly, when an RF network is establishing its logical tree, one single node being promoted to switch reaches more nodes than a PLC promotion would. This is due to the fact that nodes in parallel branches are reachable by radio but not by cable. This creates a problem for the recently-promoted switch node as it will receive messages from both upstream and downstream at the same time. Downstream nodes cannot sense the upstream nodes communicating and will deem the

channel empty when they want to transmit. This causes a traffic bottleneck and many collisions in the recently promoted node. This effect can be seen in figures 18 and 19[20]. The consequence of this behaviour (called the hidden node problem) causes disconnections in crucial switch nodes. The consequence of this is that RF nodes are initially connected via fewer switches, and these switches are in a complicated position communication-wise. Having fewer switches per terminal node causes the network to be highly dependent on these promoted nodes. If any of these nodes, were to fail, many terminal nodes would start requesting promotions again. This is the explanation for longer convergence times.

The second conclusion has to do with the logic implemented within the MAC layer for hybrid nodes. It explains the larger polling times that hybrid scenarios suffer. Any particular node sends information when it senses that the channel is idle during the SCP or CFP. The knowledge of these period timings is transmitted to all nodes via the beacons that are periodically sent by both the base node and switches. However, these beacons are not reaching all nodes adequately in hybrid cases. Figure 15 in section 3.5 shows how messages are relayed in hybrid cases: a switch node sends its beacon either via RF or PLC depending on the number of terminal nodes that are registered to the sender. Thus, RF nodes in other branches or simply nodes that can only hear one of the two types of beacons will some communication periods (MAC Frames). In the extreme case that there is only one RF node (for example in a parallel branch) per n PLC nodes, that particular RF node will miss n out of every $n + 1$ beacons (and thus, chances to communicate). Consequently, TTR metrics increase as it takes longer to poll all nodes.

Finally, an explanation for higher App RT can be linked with the channel sensing performed by RF nodes. The timer for measuring the roundtrip is started when the application layer sends its information to the LLC layer and stopped when it receives the corresponding response. The main contributor to this time is

[20]In these figures, gray circles indicate unregistered nodes, yellow houses are nodes registered via PLC, and antenna towers represent nodes registered via RF. Switch nodes are shown with blue boxes and their PLC and RF communication preference is indicated with white lines and a red circle with arrows respectively.

the MAC layer for two main reasons. The first reason is the processing time (set as 500ms for the simulation). The second reason is the channel sensing algorithm. RF nodes have a busier channel (shared with nodes from parallel branches). Thus, they will wait longer to transmit than PLC nodes. This long wait for transmission - which will happen in both the sender's request and receiver's response explains why the application layer takes a greater amount of time to receive the response.

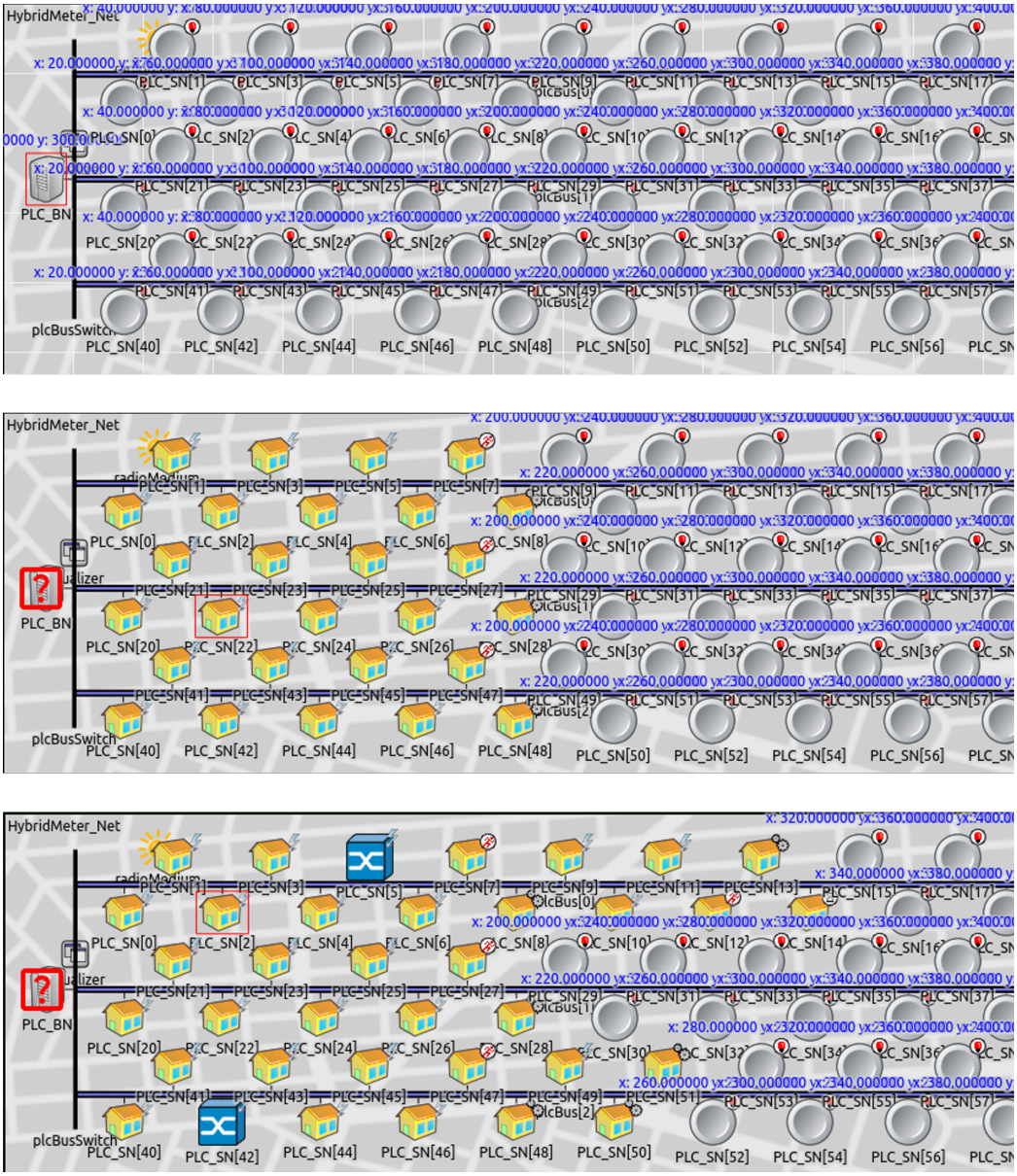

Figure 18: PLC initial registration sequence in simulator



Figure 19: RF initial registration sequence in simulator

5 Comparison with non-PRIME options

The previous section showed results from different alternatives to PRIME rollouts. In addition, a comparison across different possibilities was performed and some weaknesses of the RF alternative were highlighted. However, PRIME is not the only alternative there is regarding communication standards. In section 2, we presented two other possible alternatives that have been implemented in real-world deployments. These are LTE and Wi-SUN Alliance standards. In this section, we will compare PRIME rollouts with these two options. The comparison will focus on two main areas: cost and performance. The cost will include both deployment and operating costs whereas performance will be measured as a combination of throughput and other available metrics for each case. Data for LTE and Wi-SUN technologies is gathered from articles, papers, and technical specifications.

5.1 Cost comparison

Network cost has two main drivers, the physical architecture and deployment, and the maintenance costs of the network.

Deployment constitutes a high percentage of the costs of any network rollout. Each of the three cases presents unique characteristics in this regard. PLC requires a low upfront investment as the necessary powerlines used for communication are already in place. It does require upgrading the existing meters but this is also a factor for the RF and LTE cases. The element that stands out the most when performing a cost comparison is the need for LTE to use a licensed spectrum for communications which makes it significantly more expensive [46].

Moreover, deployment cost is also dependent on the type and number of devices deployed to cover the network. The number of terminal nodes is the same for all three options and corresponds to all the deployed smart meters. However, the necessary amount of data concentrator units may vary and it may affect costs in large scale deployments. With a constant number of devices across all technologies, higher individual device cost of LTE transceivers [46] makes this technology less viable from a purely economic point of view.

Logical network topology plays a key role in this aspect. LTE networks are usually set up using a star topology, with all nodes having a direct connection to the wireless tower base station. On the other hand, Wi-SUN deployments commonly use a mesh topology - with devices being able to communicate with each other and relay messages - whilst PRIME uses a tree-like topology. The main consequence of this difference is that LTE may have "black spots" in uncovered areas where it is impossible to establish a direct path between the end device and the base station [26]. However, this is highly unlikely in urban environments where coverage is widespread.

Maintenance within smart metering deployments is usually affected by device power consumption. Nodes are not always connected to a power source, thus their battery life and efficiency must be taken into consideration in some cases [38]. However, in the case of electric metering, this consideration does not have to be taken into account as most meters do not rely on battery life for operation [46].

All in all, a brief analysis of costs broken down into deployment and operating results in a clear disadvantage for LTE deployments. Whilst spectrum costs do not need to be directly financed by the company deploying smart meters, a mobile network operator (MNO) would most likely come into play. This implies paying the MNO for services and a certain dependence on possible standard changes and technology phase-outs.

5.2 Performance comparison

With limited data, it is difficult to provide accurate comparisons of throughput and other performance metrics. Published papers ([32], [47],[48]) provide estimations on how efficient the different network rollouts are, but more exact numbers are highly dependent on the network and are not always public. However, a limited qualitative comparison may be undertaken by measuring the three technologies against each other.

We will consider two comparison characteristics: throughput and scalability whilst also providing comments regarding the usage possibilities in different population densities. PLC networks are considered to have the lower peak data rates

[47] than the other two alternatives. Out of the other two alternatives, LTE networks usually present higher data rates with asymmetrical uplink and downlink speeds [48]. Scalability is even more dependent on the deployment environment. According to [32], tens of thousands of endpoints may be services by one single LTE base station with very high reading speeds. However, this is not applicable to all topologies and high attenuation environments, a more flexible and fault-tolerant mesh network may be more scalable.

All in all, there is no technology solution that fits all use cases. Whilst LTE has a larger range and other benefits such as higher speeds, it presents certain operating difficulties mentioned above that make RF and PLC more enticing. The choice between RF and PLC must also be made depending on the nature of the deployment. In rural areas, wireless communication may work better if households are not connected and the environment is adequate. Furthermore, a mix of PLC and hybrid can work in an urban environment where noise and attenuation characteristics are constantly changing.

6 Summary and Overall Conclusions

6.1 Summary

The electrical grid is gradually becoming a more interconnected and responsive system. This evolution is occurring to adapt to the changing environment of lower proportions of non-renewable (scheduled) generation, accommodating individual consumer profiles according to their demand patterns, and distributed generation alternatives among other transformations. Out of the three parts of the system, distribution is the most heterogeneous and thus, presents higher challenges when automatizing procedures. One main hurdle is the communication to and from the user endpoints. It is at this point, at the last mile of the electrical grid, that this study focuses. The goal is to provide a tool to simulate wired and radio communications between user endpoints (electric meters) and MV/LV transformers (effectively functioning as "traffic aggregators").

The main solutions mentioned in this paper that have currently been developed to tackle this problem are PLC, RF, and LTE communication with electric meters. Some examples of these implementations are PRIME Alliance's proposal of PLC standards and Wi-SUN Alliance's wireless alternatives. In this study, we implement a tool to study the viability of PRIME Hybrid. A newly proposed standard that combines PLC and RF alternatives into a single network rollout. This simulation will compare this new standard against non-hybrid PLC and RF rollouts whilst a comparison with Wi-SUN and LTE will be done with metrics obtained from published papers and external articles.

The simulator is built on top of a previously developed PLC simulator (J. Matanza). It uses OMNeT++ to describe the network topology and node behaviour whilst using Matlab simulations for channel attenuation and noise. The author's additions to this simulator were alterations to the MAC layer, the combiner module that is positioned between the MAC and the two PHY layers, the RF PHY, and the channel implementation with INET libraries,

By tuning certain parameters such as the number of nodes, length and number

of branches, and transmission parameters such as bitrate, power and sensitivity, the simulator can be tweaked to adjust to different scenarios. For this study, three main scenarios with different node density levels were tested. Each scenario had two possible branch topologies effectively making it six distinct scenarios. Each of these six scenarios was set up with five possible node configurations to test all PLC, all RF and several Hybrid options. It must also be noted that the resulting tool has some limitations regarding the maximum number of nodes that can be simulated at a time.

The results obtained indicate that wireless networks require additional time to converge when compared to PLC-only alternatives. The reason for this is the shared medium of all the nodes, including those that are located in parallel branches and would not interfere with each other in the PLC scenario. In addition to this, hybrid networks present a higher terminal to switch node ratio creating funnels, putting additional stress on the promoted switches (hidden-node problem) and causing additional instability in the initial stages of the network. Moreover, once the network has converged, radio nodes may take longer to access the medium for transmissions as, for the same reason as before, the channel is used a higher amount of time relative to the separate single cables of PLC.

Another important conclusion is that the logic used in the MAC layer needs to be reconsidered. At least, some additional experiments could be tested to improve the TTR increase problem explained in section 4.6. With the current MAC logic in the simulator, nodes registered via hybrid switches may miss some of the MAC Frames transmitted by those switches.

Regarding the comparison with Wi-SUN and LTE, the cost and deployment of a hybrid network would be very similar to the former one due to the similarity of their nodes and communication methods. It may be possible that costs are lower as some PLC-only nodes would not need any investment to start transmitting (antenna installation or other changes). LTE costs would be higher due to the equipment being more expensive and the use of licensed broadband spectrum. On the other hand, LTE presents higher data rates and wider coverage than the other two technologies. Nevertheless, metering applications are characterized by needing

lower throughput and not having strict latency requirements. Thus, depending on the characteristics of the rollout, one deployment may make more sense than the other.

In conclusion, this study provides a simulation tool to compare different hybrid and non-hybrid PRIME scenarios. It also advances some conclusions regarding the comparison of the two options whilst providing theoretical contrast with other alternatives.

6.2 Main conclusions, proposed improvements and limitations

The current study presents three key findings. First, it is an improvement over the previous simulator that allows testing scenarios across different technologies and the implementation of a PRIME Hybrid architecture.

The second set of conclusions reached is the description of RF and hybrid network behaviour when compared to PLC. We have stated that the network is more unstable at first, having more problems overall to achieve convergence. Node polling times are usually bigger, due to nodes in parallel sharing the same channel and possibly interfering with each other. In addition, nodes dependent on hybrid switches may miss beacons transmitted in the alternate communication channel, causing an increase in the overall polling times.

Finally, the MAC layer stands out as the most sensible piece within the network. Generally, required data rates for polling applications are not too high and the amount of information being transmitted is relatively low. This, coupled with lenient latency requirements means that channel conditions and transmitter bit rates make less of an impact than MAC characteristics and parameters. We could say that the results are highly sensitive to the variation of MAC values such as processing time, wait times between application messages and other values such as the number of alive chances.

However, there is room for future improvements to make this tool more accessible, support a higher amount of scenarios, and be more akin to real field deployments.

There are two main verticals upon which this tool can be improved. The first one is by adding new functionalities to the existing code. The current simulator only supports one kind of physical deployment. This is a specific - and not too large - number of nodes evenly distributed between a certain number of parallel branches. Most network rollouts present irregular node distributions and varying meter densities. Thus, the possibility of adding "node clusters" is an option for improvement. Another functionality that could be introduced is the variation of noise and attenuation characteristics while the simulation is taking place, instead of running in a fixed environment.

The second vertical of improvement would be making the simulator more accessible. Currently, it is necessary to install OMNeT within a Linux operating system. The installation process is lengthy and many problems may arise due to compatibility issues between libraries. Results also are produced in ".sca" or ".vec" files which are not easily transformed into excel or CSV formats. Thus, general packetization of the simulator with easily-introduced input variables and a pipeline for data outputs could improve the tool's usability.

The limitations presented by the simulation tool have been explained in detail in previous sections. There are three main points of friction. The first one is the inability to simulate multiple channels neither in RF nor PLC. Thus, channel-hopping is not accounted for within the simulations. The second limitation is that noise and attenuation are constant, and this is not the case neither in PLC nor RF deployments. Thirdly, the number of nodes supported by the simulator is extremely low compared with some possible field deployments.

All in all, this paper presents useful improvements over the previously developed SimPRIME simulator by adding new functionalities. However, some limitations have been addressed and also possible improvements can be implemented to make this tool even more useful for comparing communication technologies within low-voltage distribution networks.

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Appendices

A HybridMeter OMNeT

The main piece of code contributed is the development of the RF PHY layer. The code for this layer is thus represented in this appendix.

```
#include "RfPhysicalInterface.h"
#include <inet/common/InitStages.h>
#include <inet/common/ModuleAccess.h>
#include <inet/common/packet/chunk/FieldsChunk.h>
#include <inet/common/Ptr.h>
#include <inet/common/Units.h>
#include <inet/physicallayer/wireless/common/contract/packetlevel/SignalTag_m.h>
#include <MACMsg_m.h>
#include <omnetpp/cdisplaystring.h>
#include <omnetpp/cexception.h>
#include <omnetpp/clog.h>
#include <omnetpp/cmessage.h>
#include <omnetpp/cmodule.h>
#include <omnetpp/cobjectfactory.h>
#include <omnetpp/cpacket.h>
#include <omnetpp/cpar.h>
#include <omnetpp/csimplemodule.h>
#include <omnetpp/csimulation.h>
#include <omnetpp/cwatch.h>
#include <omnetpp/regmacros.h>
#include <omnetpp/simtime.h>
#include <PLCMAC.h>
#include <cmath>
#include "RFMessage_m.h"
#include "RFMessageChunk_m.h"


Define_Module(RfPhysicalInterface);
Register_Class(RfPhysicalInterface);

RfPhysicalInterface::RfPhysicalInterface() {
    // TODO Auto-generated constructor stub

}

RfPhysicalInterface::~RfPhysicalInterface() {
    // TODO Auto-generated destructor stub
}
```

```
void RfPhysicalInterface::initialize(int stage){

    if (stage == INITSTAGE_LOCAL) {

        EV << "I am initialized\n";
        // Load BER Curve Data
        loadBERCurveFile();

        // Statistics collection
        numReceivedMessages = 0;
        numErroneousMessages = 0;
        WATCH(numReceivedMessages);
        WATCH(numErroneousMessages);

        if( par("sendMsgOnInit").boolValue() == true) {
            // We schedule an initial auto-message. When it arrives, we will send
// the first network message
            EV << "Creating INITSELFMSG\n";
            cMessage * msg = new cMessage("InitialSelfMessage", INITSELFMSG);
            scheduleAt(simTime()+ 1.0,msg );
        }
        radio = getModuleFromPar<inet::physicallayer::IRadio>(par("radioModule"), this);
    }
    else if (stage == INITSTAGE_PHYSICAL_ENVIRONMENT) {

        inicializarPosicionRadio();
    }
    else if (stage == INITSTAGE_LINK_LAYER) {

        radio->setRadioMode(inet::physicallayer::IRadio::RADIO_MODE_TRANSCEIVER);


        cModule *submoduloMAC = this ->getParentModule() ->  getParentModule() ->
        getSubmodule("mac");
        PLCMAC *claseMAC = (PLCMAC*) submoduloMAC;
        soyRF = (bool) claseMAC -> getIsOutGateRF();

        if (soyRF){
            string imagen_nodo = "misc/signal_departure";
            // Nico - lo he cambiado para hacer todas las actualizaciones desde PLCMACSN
            //changeNodeImage(imagen_nodo);
        }

    }
}
```

```
void RfPhysicalInterface::handleMessage(cMessage *msg){
    EV << "Some message was received\n";

    if (msg->isSelfMessage()){
        handleSelfMessage(msg);
    }
    else{

        // We add to the counter of received messages
        numReceivedMessages++;


        checkArrivalGate(msg); // To determine if the message is from upper layers or radio
        //forwardMessage(msg);
    }
}

/**
            Describes the treatment of all self messages
*/
void RfPhysicalInterface::handleSelfMessage(cMessage *msg){

    switch (msg->getKind()){
        case INITSELFMSG:

            // This is our cue to send the first real message to the network
            EV << "Received the initialization self message\n";
            cancelAndDelete(msg);


            // Calling the following function to start with the network messages
            sendInitialNetworkMessage();

            break;

        default:
            throw cRuntimeError("Unknown self message: kind=%d", msg->getKind());
    }

}

/**
    When a node receives the initialization self message (INITSELFMSG) it creates and sends
an initial network message.
*/
```

```
void RfPhysicalInterface::sendInitialNetworkMessage(){


    if( par("standaloneRFNetwork").boolValue() == true) {
        // Utilizado cuando probamos RfCommuncation de manera individual
        EV << "We are now about to create the initial network message";

        long packetByteLength = long(par("packetByteLength"));
        auto data =  makeShared<ByteCountChunk>(B(packetByteLength));

        Packet *packet = new Packet("RFPHYPacket", data);   // I create a packet with the
        "data" defined above
        packet->addTagIfAbsent<MacAddressReq>()->setDestAddress(MacAddress::BROADCAST_ADDRESS);
        packet->addTagIfAbsent<PacketProtocolTag>()->setProtocol(&Protocol::ieee8021ae);

        EV << "Creating packet with a length of " << packetByteLength << " bytes\n";

        send(packet, "rfgateout");
    }

}


/**
    For not self messages, we check if they are from upper layers or network
*/
void RfPhysicalInterface::checkArrivalGate(cMessage *msg){

    if (msg->getArrivalGate() == gate("upperLayerIn"))
        processMsgFromUpperLayer(msg);
    else // Viene de Ieee802154NarrowbandInterface
        processMsgFromNetwork(msg);
}


void RfPhysicalInterface::processMsgFromUpperLayer(cMessage *msg){

    EV << "Message received from upper layer at RfPhysicalInterface\n";


    cPacket *omnetPacket = (cPacket * )msg;
    MACMsg *macFrame= (MACMsg *) omnetPacket;

    //Packet *packet = dynamic_cast<Packet*>(msg);

    switch( macFrame -> getHDR_HT() ){
```

```
    case 0: // This message has a specific MAC address
        EV << "This message has a specific MAC address";
      break;
    default:
        EV << "This message has generic MAC address\n";
        break;
}

// We will send this newly created INET packet
Packet *packet = new Packet("RFPHYPacket");


// How to add a tag to a packet
//auto RFMacMsgContent_object = packet->addTag<RFMacMsgContent>(); // add tag for dispatch
//RFMacMsgContent_object->setMensajeMac(macFrame); // set designated interface


// Si soy RF, marco el mensaje enviado como tal
if (soyRF){
    macFrame -> setHybridTransmitMode(1); // 1 indica que lo estoy enviando por RF
}


// We add the macFrame that comes from the upper layer
packet->addTag<RFMacMsgContent>()->setMensajeMac(macFrame);


// Because it is a generic MAC Address
packet->addTagIfAbsent<MacAddressReq>()->setDestAddress(MacAddress::BROADCAST_ADDRESS);
packet->addTagIfAbsent<PacketProtocolTag>()->setProtocol(&Protocol::ieee8021ae);



const auto& payload = makeShared<RFMessageChunk>();
//payload->setChunkLength(B(par("messageLength")));

// Vemos si podemos obtener el Byte len. del macFrame
auto tamanoBytes = macFrame -> getByteLength();
EV << "Tamaño de paquete de MacFrame: "<<  tamanoBytes  <<" B\n";


payload->setChunkLength(B(tamanoBytes));
payload->setMensajeMac(macFrame);
packet->insertAtBack(payload);

EV << "Sending new message\n";
```

```
    send(packet, "rfgateout");

}

void RfPhysicalInterface::processMsgFromNetwork(cMessage *msg){

    EV << "Message received from lower layer at RfPhysicalInterface\n";
    Packet *packet = dynamic_cast<Packet*>(msg);

    EV << "Simulating error for received message\n";
    bool hasBitError = simulateError(packet);


    if( par("standaloneRFNetwork").boolValue() == true) {
        // Utilizado cuando probamos RfCommuncation de manera individual

        if (hasBitError){
            // We add to the counter of erroneous messages
            numErroneousMessages++;
            packet->setBitError(true);
        }

        forwardMessage(packet);

    }else{

        // Utilizado para la integración hybrid

        const auto& payload = packet->peekData<RFMessageChunk>();
        MACMsg *macFrameRecibida= (MACMsg *) payload->getMensajeMac();
        EV_INFO << "packet content1: " << macFrameRecibida->getHDR_HT() << endl;

        EV << "Desencapsulación hecha\n";


        if(hasBitError){
            EV << "Error añadido al MACFrame\n";
            macFrameRecibida -> setBitError(true);
        }

        delete packet;

        send(macFrameRecibida->dup(), "upperLayerOut");

    }
}
```

```
// Esto solo está en uso para cuando corremos RfCommunication de manera aislada
void RfPhysicalInterface::forwardMessage(Packet *packet)
{

    bool hasBitError = packet->hasBitError();

    if (hasBitError){


        EV << "Packet has bit error. Deleting received message and creating a new one\n";
        delete packet;

        long packetByteLength = long(par("packetByteLength"));
        auto data =  makeShared<ByteCountChunk>(B(packetByteLength));

        Packet *packet = new Packet("RFPHYPacket_alt", data);   // I create a packet with the "data" defined above
        packet->addTagIfAbsent<MacAddressReq>()->setDestAddress
        (MacAddress::STP_MULTICAST_ADDRESS);
        packet->addTagIfAbsent<PacketProtocolTag>()->setProtocol(&Protocol::ieee8021ae);


        EV << "Sending new message\n";
        send(packet, "rfgateout");
    }else{

        EV << "Packet does not have bit error. Returning same message\n";

        //Packet *packet = dynamic_cast<Packet*>(msg);
        packet->addTagIfAbsent<MacAddressReq>()
        ->setDestAddress(MacAddress::STP_MULTICAST_ADDRESS);
        packet->addTagIfAbsent<PacketProtocolTag>()->setProtocol(&Protocol::ieee8021ae);

        EV << "Sending same message again\n";
        send(packet, "rfgateout");
    }

}

/**
 * Simulates whether message has error or not by looking at
 * the corresponding BER curve. Returns true if there is an error.
 *
 * @param msg the message for which the error is simulated
 */
bool RfPhysicalInterface::simulateError(Packet *packet){

    bool errorInMsg;
```

```
    float SNR = computeSNR(packet);
    EV<< "SNR calculado: " << SNR << endl;

    float BERleida = obtainBERforSNR(SNR);
    EV << "Ber leida: " << BERleida << endl;


    if (dblrand() < 1.0 - pow(1.0 - BERleida, (double) packet->getBitLength())){
        errorInMsg = true;
        EV << "Error en el mensaje RF recibido\n";
    }else{
        EV << "No error en el mensaje RF recibido\n";
        errorInMsg = false;

    }


    return errorInMsg;
}

/**
 * Calculates the SNR of the received message by looking at
 * Px and noise power.
 *
 * @param msg the message for which SNR is calculated
 */
float RfPhysicalInterface::computeSNR(Packet *packet)
{

    auto signalPowerInd = packet-> getTag<SignalPowerInd>();
    auto rxPower = signalPowerInd->getPower().get();


    EV<< "RX power= " << rxPower << "W" << endl;

    float rxPowerdB = 10 * log10(rxPower);
    EV<< "RX power= " << rxPowerdB << "dBW" << endl;


    // We compute background noise level

    // The background noise level in dB is obtained from wireless model
    cModule *ruidoFondo;
    if (par("standaloneRFNetwork")){
        // En caso de ser standalone no hay que mirar tan arriba para encontrar el radioMedium
```

```
        ruidoFondo = getParentModule() -> getParentModule() -> getSubmodule("radioMedium") ->
        getSubmodule("backgroundNoise");
    }else{
        // En caso de NO ser standalone
        ruidoFondo = getParentModule() -> getParentModule() -> getParentModule()
-> getSubmodule("radioMedium") -> getSubmodule("backgroundNoise");
    }


    double backgroundNoisePowerdBm = ruidoFondo -> par("power");

    double backgroundNoisePowerdB = backgroundNoisePowerdBm - 30; // We transform to dB
    EV<< "Noise power= " << backgroundNoisePowerdB << "dBW" << endl;


    float SNR = rxPowerdB - backgroundNoisePowerdB;

    return SNR;
}



/**
 * Returns a BER value for a specific SNR
 * The BER curve is specified in the .ini file
 * If the SNR value is not a point in the SNR/BER curve,
 * the corresponding BER is obteined by interpolation
 *
 * @param msg the message for which the BER is obtained
 */
float RfPhysicalInterface::obtainBERforSNR(float SNR_mensaje)
{

    // We will now interpolate the message's SNR between to valid points in the curve.
// The points in the curve are separated .25


    float SNR_limite_superior = obtenerSNRValidaSuperior(SNR_mensaje);


    float SNR_limite_inferior = SNR_limite_superior - 0.25;

    float BER_leida_superior = leerBERforSNRfromFile(SNR_limite_superior);
    float BER_leida_inferior = leerBERforSNRfromFile(SNR_limite_inferior);

    float BER_interpolada = BER_leida_inferior + (SNR_mensaje - SNR_limite_inferior) *
(BER_leida_superior - BER_leida_inferior) / (SNR_limite_superior - SNR_limite_inferior);
```

```
    return BER_interpolada;
}

/**
 * Returns an SNR value that is defined in the SNR/BER curve.
 * This value is the closest higher point to the introduced SNR.
 *
 * @param SNR_a_redondear SNR to round up to the nearest valid point
 */
float RfPhysicalInterface::obtenerSNRValidaSuperior(float SNR_a_redondear)
{
    // We round upwards to required decimal precision (two positions) and multiply by
// 100 to get integers - necessary for roundUp()
    int SNR_int = (int)((SNR_a_redondear + 0.005) * 100);

    // Now we round to the closest "25". This is because SNR/BER pairs have been
// obtained to a precision of .25
    int SNR_redondeada_int = roundUp(SNR_int, 25);

    // Finally, we divide by 100 to get back to the true SNR value
    float SNR_redondeada_float = (float)SNR_redondeada_int / 100;


    // The returned value is a valid value of SNR (in intervals of .25) rounded
// upwards from the read value
    return SNR_redondeada_float;
}


/**
 * Simple rounding function that rounds a given integer to the
 * closest specified multiple.
 *
 * @param numToRound number to round
 * @param multiple the rounding will be done to a multiple of this parameter
 */
int RfPhysicalInterface::roundUp(int numToRound, int multiple)
{
    if (multiple == 0)

        return numToRound;

    int remainder = numToRound % multiple;
    if (remainder == 0)
        return numToRound;
```

```
    return numToRound + multiple - remainder;
}


/**
 * It loads the data from the SNR BER curve into a global
 * variable for later lookup
 *
 */
void RfPhysicalInterface::loadBERCurveFile(){
    //std::string filename = "../BERDATA/RSC_M_2.txt";
    std::string filename  = par("BERFilename");

    std::string auxComMode;
    std::string auxFEC;
    std::string auxModulation;

    std::string BER;
    std::string SNR;
    float fBER;
    float fSNR;

    std::ifstream file(filename);
    if (file.is_open())
    {

        getline(file, auxComMode);
        //std::cout << "Leo Communication Mode: " << auxComMode << std::endl;
        EV << "Leo Communication Mode: " << auxComMode << endl;

        getline(file, auxFEC);
        //std::cout << "Leo FEC: " << auxFEC << std::endl;
        EV << "Leo FEC: " << auxFEC << endl;

        getline(file, auxModulation);
        //std::cout << "Leo Modulation: " << auxModulation << std::endl;
        EV << "Leo Modulation: " << auxModulation << endl;

        while (std::getline(file, BER, '|'))
        {
            getline(file, SNR);
            //std::cout << "Leo BER: " << BER << " Leo SNR: " << SNR << std::endl;
            //EV  << "Leo BER: " << BER << " Leo SNR: " << SNR << endl;finish

            fSNR = std::stof(SNR);
            fBER = std::stof(BER);
```

```
            // Anadimos los datos a un map que relaciona SNR con BER
            snrBerMap[fSNR] = fBER;
        }

        //std::cout << "snrBerMap[5.50] is " << snrBerMap[5.50] << '\n' << std:endl;
        //EV << "snrBerMap[5.50] is " << snrBerMap[5.50] << '\n'<< endl;
    }
    else
    {
        //std::cout << "Error al abrir el archivo de datos de la curva BER" << std::endl;
        EV << "Error al abrir el archivo de datos de la curva BER\n"  << endl;
    }
    file.close();

}


/**
 * Looks up BER for given SNR value within the BER
 * curve specified in the .ini file
 *
 * @param SNR_a_leer SNR value to look ip in the BER curve values
 */
float RfPhysicalInterface::leerBERforSNRfromFile(float SNR_a_leer){

    float BER_leida = snrBerMap[SNR_a_leer];

    return BER_leida;
}



void RfPhysicalInterface::inicializarPosicionRadio(){

    //EV << "Mi parent display string es: "<< parentDispStr <<"\n";
    //  Ejemplo de display string de mi grandparent
    p=1033,290;i=misc/house;q=txQueue;i2=status/red

    // Tengo que encontrar la verdadera posición en la que debería de estar este nodo.
    // Para eso voy a utilizar su MacAddress y los siguientes parámetros
    int nBranchesInt =  (cSimulation::getActiveSimulation())->getSystemModule()
    ->par("nBranches");
// Para decidir si es par o impar lo necesitamos como int

float nBranches = static_cast< float >(nBranchesInt);
// Lo cogemos como float para que miRama se calcule correctamente
```

```
int nhostsPerBranch =
(cSimulation::getActiveSimulation())->getSystemModule()->par("nHostsPerBranch");
    int busLengthInMetersInt = (cSimulation::getActiveSimulation())->getSystemModule()
    ->par("busLengthForRadios");
    float busLengthInMeters = static_cast< float >(busLengthInMetersInt);
    //float total_number_nodes = nBranches * nhostsPerBranch;

    // Comencemos...

    // Cogemos la dirección MAC de la capa mac (que ya ha sido inicialiada)
    // primer padre: WirelessNodeBasic     segundo padre: PLC_Hybrid_SN  que ya tiene un
    submódulo llamado mac
    cModule *submoduloMAC = this ->getParentModule() ->  getParentModule() ->
    getSubmodule("mac");
    PLCMAC *claseMAC = (PLCMAC*) submoduloMAC;
    int miMAC = (int) claseMAC -> getMACAddress();
    EV << "Mi MAC Address: " << miMAC << "\n";


    // En un principio pensaba que las MAC Address empezaban en 0 y todo el
    // codigo está pensado para ello. Por eso se hace este ajuste aquí:
    miMAC = miMAC -1;
    // El BN es un caso especial. Ver el final de este trozo de código (en la inicialización de
    posicion_x y posicion_y) para ver cómo se trata a este nodo


    // Esto lo hacemos para que el primer SN tenga de posición el "0". Esto nos servirá para
    colocarlo en la posición 0 de la primera rama
    float miPosicionEnVectorDeSN = miMAC -1;

    // Porque si no el bucle for que viene a continuación se vuelve loco
    if (miMAC == 0){
        miPosicionEnVectorDeSN++;
    }


    // Mi rama es la parte entera de dividir mi índice SN entre el número de ramas. Los SN se
    van colocando de manera ordenada "rellenando" estas Branches.
    //float miRamaFloat = miPosicionEnVectorDeSN/nBranches;
    //int miRama = (int)(miRamaFloat-0.01);

    int miRama;
    int miPosicionEnLaRama;
    int counter = 0;
    for(int i = 0; i < nBranches; i++){
        for(int j = 0; j<nhostsPerBranch; j++){
```

```
            if(counter==miPosicionEnVectorDeSN){
                miRama = i;
                miPosicionEnLaRama = j;
            }

            counter = counter +1;
        }
    }


// He asumido de aquí en adelante que la primera branch (la de más arriba) es la branch 0
    Mi posición en la rama es la parte decimal de dividir mi índice SN entre el número de
    ramas multiplicado por el número de objetos en una rama.

// Mi posición puede ir desde 0 (el primero de la rama) hasta nhostPerBranch -1
(el último de la rama). Mi posición X se obtiene dividiendo la longitud en "nhostsperBranch"
trozos y después multiplicando por mi posición en la rama (ajustado +1 para que la pos
empiece a distancia del BN)

    float miX = (busLengthInMeters/nhostsPerBranch) * (miPosicionEnLaRama + 1);

    // Ahora calculamos el Y de mi rama. Esta posición dependerá de dónde estes
    relativa al BN y depende de si las ramas son pares o no
    int yDelBaseNodeInt = par("posicionYdelBN");
    float yDelBaseNode = static_cast< float >(yDelBaseNodeInt);
    int verticalDistBetweenBusesInt = (cSimulation::getActiveSimulation())->getSystemModule()
->par("verticalDistanceBetweenBuses");
    float verticalDistBetweenBuses = static_cast< float >(verticalDistBetweenBusesInt);
    int indRama;
    float offsetMiRama;
    float yMiRama;

    // Según si las ramas son pares o no, se hace un cálculo de la Y distinto
    if (nBranchesInt%2 == 0){

        // Número par de ramas
        // miRama   índice_deseado
        //   0        2
        //   1        1
        //   2       -1
        //   3       -2

        if (miRama >= nBranchesInt/2){
// Primero convertimos al índice. Estos están por debajo del BN y serán negativos
            indRama = -miRama  + nBranchesInt/2 - 1;
// Después calculamos el offset respecto al BN
            offsetMiRama =  -( (verticalDistBetweenBuses/2) + (-indRama - 1) *
```

```
            verticalDistBetweenBuses);
        }
        else{

// Primero obtenemos el índice. Estos están por encima del BN
            indRama = nBranchesInt/2 - miRama;

            offsetMiRama = (verticalDistBetweenBuses/2) + (indRama - 1) *
            verticalDistBetweenBuses;
        }

        yMiRama = yDelBaseNode + offsetMiRama;
    }
    else{

        // Número impar de ramas
        // miRama   índice_deseado
        //   0        2
        //   1        1
        //   2        0
        //   3       -1
        //   4       -2
        if (miRama >  nBranchesInt/2){
            indRama = -miRama + nBranchesInt/2;
            offsetMiRama = verticalDistBetweenBuses * indRama;

        }
        else if(miRama < nBranchesInt/2){
            indRama = nBranchesInt/2 - miRama;
            offsetMiRama = verticalDistBetweenBuses * indRama;
        }
        else{
            yMiRama = 0; // Esta rama está a la misma altura que el BN. Es la rama "central"
            indRama = yMiRama;
        }
        offsetMiRama = verticalDistBetweenBuses * indRama;
        yMiRama = yDelBaseNode + offsetMiRama;
    }


    float posicion_x = miX;
    float posicion_y = yMiRama;

    // Si soy el BN, estoy en la posición (0, yDelBaseNode)
    if (miMAC == 0){
        posicion_x = 0;
        posicion_y = yDelBaseNode;
```

```
    }

    // Cojo un puntero al display string de mi padre, que es la que va a mirar luego la radio

    cDisplayString& parentDispStr  = getParentModule() -> getDisplayString();


    // Una vez encontrada, cambio sus argumentos de posición
    parentDispStr.setTagArg("p",0,posicion_x);
    parentDispStr.setTagArg("p",1,posicion_y);


    // Y muestro la posición en el string del abuelo
    cDisplayString& abueloDispStr  = getParentModule()-> getParentModule() ->
    getDisplayString();
    string  strBase = "x: " + to_string(round(posicion_x)) + " y: " +
    to_string(round(posicion_y));
    abueloDispStr.setTagArg("t",0, strBase.c_str() );


    // Actualizo mi puntero a los mismos valores que ha tocado la capa MAC
    //parentDispStr.parse(grandParentDispStr);
    EV << "Mi parent string actualizado es: "<< parentDispStr <<"\n";



}


void RfPhysicalInterface::changeNodeImage(string  strBase){

    cDisplayString& abueloDispStr  = getParentModule()-> getParentModule() ->
    getDisplayString();

    //string  strBase = "misc/helicopter";

    abueloDispStr.setTagArg("i",0, strBase.c_str() );
}


void RfPhysicalInterface::finish(){

    recordScalar("#ReceivedMessages", numReceivedMessages);
    recordScalar("#ErroneousMessages", numErroneousMessages);
}
```

B Data processing code

Python has been used to process the results generated by the OMNeT tool. The main functions of this code are represented in this appendix.

```
def sacarValoresDeVectoresDF(df, vector_name):


    ts_str = df[df['name'] == vector_name]['vectime'].values
    values_str = df[df['name'] == vector_name]['vecvalue'].values

    try:
        ts = [float(x) for x in ts_str[0].split(" ")]
        values = [float(x) for x in values_str[0].split(" ")]
    except IndexError:
        ts = [0]
        values = [0]


    return ts, values



def displayVectorTimeSeries(datos_escenarios, vector_name, title, yaxis, modo = "lines+markers"):

    lista_trazas = []
    #lista_ts = []
    #lista_valores = []
    #lista_nombres = []

    for escenario in datos_escenarios.keys():
        (ts,valores) = sacarValoresDeVectoresDF(datos_escenarios[escenario]['df'], vector_name)
        color = datos_escenarios[escenario]['color']
        #lista_ts.append(ts)
        #lista_valores.append(valores)
        #lista_nombres.append(datos_escenarios[escenario]['nombre'])
        traza =   go.Scatter(
                        x = ts,
                        y = valores,
                        name = datos_escenarios[escenario]['nombre'],
                        mode = modo,
                        line = dict(color = color),
                        )

        lista_trazas.append(traza)
```

```
    data = lista_trazas
    layout = go.Layout(title = title, xaxis_title = "Time in seconds", yaxis_title = yaxis, height = 500)

    fig = go.Figure(data = data, layout = layout)
    if save_images:
        titulo_guardado = title.split(" | ")[1] + "_" + title.split(" | ")[0]
        path = "./scenarioResultCollection_results/"+ titulo_guardado + ".png"
        fig.write_image(path)
    fig.show()



def tratarTTRAllMeters(df):
    ts_str = df[df['name'] == "DLMSCOSEMAppTTRAllMeters"]['vectime'].values
    values_str = df[df['name'] == "DLMSCOSEMAppTTRAllMeters"]['vecvalue'].values

    ts = [float(x) for x in ts_str[0].split(" ")]
    values = [float(x) for x in values_str[0].split(" ")]

    #ts_diferentes = ts[0::2][1:] # No devolvemos el primero porque es cuando se empieza a
    contar. Ahí aun no hay TTR
    ts_diferentes = ts[0::2] # AHora creo que sí que hay que devolverlo porque estaba todo
    corrido una a la izq
    ttr = [x - ts_diferentes[i - 1] for i, x in enumerate(ts_diferentes)][1:]

    return ts_diferentes, ttr # Devolvemos el ts del momento en el que acaba el TTR y cuánto
    tiempo ha estado leyendo (TTR)



def mostrarTTRAllMeters(datos_escenarios, title):
    lista_trazas = []
    for escenario in datos_escenarios.keys():
        (ts,valores) = tratarTTRAllMeters(datos_escenarios[escenario]['df'])
        color = datos_escenarios[escenario]['color']
        #lista_ts.append(ts)
        #lista_valores.append(valores)
        #lista_nombres.append(datos_escenarios[escenario]['nombre'])
        traza =   go.Scatter(
                        x = ts,
                        y = valores,
                        name = datos_escenarios[escenario]['nombre'],
                        line = dict(color = color),
                        mode = "lines + markers"
                        )
```

```
        lista_trazas.append(traza)



    data = lista_trazas
    layout = go.Layout(title = title, xaxis_title = "Time in seconds", yaxis_title = "TTR (s)", height = 500)

    fig = go.Figure(data = data, layout = layout)

    if save_images:

        titulo_guardado = title.split(" | ")[1] + "_" + title.split(" | ")[0]

        path = "./scenarioResultCollection_results/"+ titulo_guardado + ".png"
        fig.write_image(path)

    fig.show()



def mostrarTodasLasMetricas(grupo_escenarios, scenario_name):

    for metrica in dicc_metricas.keys():

        titulo = dicc_metricas[metrica][TITULO] + " | " + scenario_name
        eje_y =  dicc_metricas[metrica][EJE_Y]
        modo =   dicc_metricas[metrica][MODO]


        if metrica != "DLMSCOSEMAppTTRAllMeters":

            displayVectorTimeSeries(grupo_escenarios,metrica, titulo, eje_y, modo)
        else:
            # Esta métrica tiene un proceso especial
            mostrarTTRAllMeters(grupo_escenarios,titulo )
```

C Parameter values chosen for simulation

This appendix shows a compilation of the most important parameter values chosen for the simulations performed in this study. The first table represents the characterization of the two communication channels by providing the channel parameters established.

Class	Parameter	Value	Justification
RadioMedium	type	Ieee802154Narrowband	Used for 802.15.4 by INET
BackgroundNoise	type	Isotropic	Constant noise over time and frequency domains for simplest model
	power	-96.616 dBm	Default INET value
PathLoss	type of pathLoss	BreakpointPathLoss	Simple attenuation model with parameters defined in 802.15.4
	breakpointDistance	8 m	
	l01	40.2	Assumptions for coexistence scenarios
	alpha1	20	
	l02	58.5	detailed in 802.15.4 specifications
	alpha2	33	

The second table shows the specifications chosen to describe the RF PHY layer and the corresponding reference form the specifications.

Class	Parameter	Value	Justification
Radio	type	Ieee802154Narrowband	Used for 802.15.4 by INET
	centerFrequency	867 kHz	Hybrid specs. reference to 802.15.4
	bandwidth	200 kHz	Table 20.6 SUN FSK in 802.15.4
	power	3.6 dBm (2.29 mW)	Section 20.6.11 SUN FSK in 802.15.4
	sensitivity	-94.01 dBm	Section 19.6.7 SUN FSK in 802.15.4
	bitrate	100 kbps	Table 20.6 SUN FSK in 802.15.4
	headerLength	16 bits	Table 20.6 SUN FSK in 802.15.4

MAC layer parameters are specified in the third table. These are mostly timers that define the MAC layer's logical behaviour.

Class	Parameter	Value	Justification
MAC Layer	defaultALVTime (BN only)	120s	PRIME Hybrid specs. p.275
	ALVNumChances (BN)	5	PRIME Hybrid specs. p.270
	interPromotionTime (BN)	50s	PRIME Hybrid specs. p.178
	ALVOffset (SN only)	60s	PRIME Hybrid specs. p.340
	numDisconnBeforePRN (SN)	5	Own implementation

D Relationship with sustainable development goals

The current project can be linked with at least two of the seventeen Sustainable Development Goals. These milestones represent a blueprint established by the United Nations in 2015 with the objective of improving overall planet conditions. These goals are "an urgent call for action by all countries in a global partnership".

Particularly, it can be linked with goals number seven (Affordable Clean Energy) and eleven (Sustainable Cities and Communities). Out of the two goals, the project relates the most to the former one. In the following paragraphs, we shall explain how the work developed in this study relates to goal number seven of the sustainable development goals.

Goal number seven is expanded into "Ensure access to affordable, reliable, sustainable, and modern energy for all". This has several different verticals, including the provision of energy to people that do not have any access to it as of today. However, improving the efficiency rate and ensuring fair access to affordable energy is without a doubt an area where this project would fit.

Low voltage communications ensure that both energy producers and end consumers have more knowledge regarding consumer patterns. This enables better resource allocation and higher overall efficiency rates. Customers will be able to adjust their consumption patterns - albeit slowly and with low elasticity - to price signals. More importantly, they will also be able to choose a pricing scheme that better fits their needs. Producers on their part, will be able to perform a better allocation of resources and plan around the not always predictable renewable energy contributions whilst serving the end consumer in a satisfactory manner. This means that energy generation will be able to shift faster into higher proportions of renewable generation due to a deeper understanding of consumer patterns.

In conclusion, improvements in communication technologies deployed within the low voltage network will enable both energy consumers and producers to be more informed regarding their respective behaviours and lead to more effective resource allocation by all players in the market. This will lead to higher energy efficiency which is a crucial vertical of sustainable development goal number seven.