

Article

Centralized SDR-Based Performance Analytics Platform for Interoperable Smart Grid Communications with Renewable Energy Sources

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Abstract

Smart grids with renewable energy sources require communication platforms that can evaluate heterogeneous links before field deployment. This article presents a centralized software-defined radio (SDR)-based performance analytics platform for physical/MAC-layer assessment of RF900, G3-PLC, GPRS CS2–CS3, hybrid PLC–GPRS, and renewable-event communication profiles. The platform combines a controlled UPS SDR/USRP experimental-simulation reference with reproducible packet-level simulations using traffic generation, channel impairment abstractions, CRC-based integrity verification, and centralized metrics: latency, bit error rate (BER), packet error rate (PER), useful throughput, and offered channel load. The revised evaluation uses a 120 s window, 3444 packets per baseline scenario, and 30 independent random seeds. The RF900 AWGN baseline achieved 36.58 ± 0.01 ms mean latency, 1.78×10^{-4} BER, 0.175 ± 0.003 PER, and 24.23 kbps useful throughput. Hybrid PLC–GPRS reduced PER to 0.025 ± 0.001 , while the renewable-event hybrid profile achieved 89.33 ± 0.13 ms and 0.028 ± 0.001 PER. This study provides a reproducible pre-deployment analytics framework, not full utility field validation or application-layer interoperability certification.

Keywords: software-defined radio; smart grid communications; G3-PLC; IEC 61850; IEC 62056; IEEE 2030; interoperability; performance analytics; BER; PER; packet-level simulation

1. Introduction

The increasing penetration of renewable sources, such as solar and wind energy, is driving the transition toward smarter, more flexible, and more digitalized electrical grids [1]. These grids require communication and control infrastructures capable of ensuring stability, operational efficiency, and interoperability among heterogeneous systems [2,3].

The conceptual framework proposed by the National Institute of Standards and Technology (NIST) in the smart grid interoperability framework SP 1108r4 defines interoperability as an essential component for integrating distributed resources, metering devices, supervisory systems, and communication technologies within the electrical system [4]. IEEE 2030 complements this perspective by organizing smart grid interoperability across power-system, communication-technology, and information-technology views [5]. In this work, interoperability is understood as the ability of different devices, systems, and organizations to exchange information effectively, securely, and semantically consistently [6,7].



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International standards such as IEC 61850 and IEC 62056-1-0:2014 provide reference models for communication and data modeling in substations, distribution networks, metering systems, and automation systems, facilitating compatibility among equipment from different manufacturers [8–10]. Narrowband PLC references such as ITU-T G.9903 support G3-PLC communication through PHY and data-link-layer mechanisms for low-voltage and medium-voltage grid environments [11]. In the Ecuadorian context, previous work at Universidad Politécnica Salesiana (UPS) evaluated wireless sensor networks for smart-home services using physical- and data-link-layer parameters such as frequency band, frame size, transmission power, receiver sensitivity, coverage, energy use, and channel utilization, highlighting the need for comparative communication performance analysis across heterogeneous technologies [1].

The deployment of wireless technologies in the electrical grid introduces additional challenges related to latency, reliability, spectrum congestion, and cybersecurity [12,13]. Although ultra-low-latency communications, 5G networks, and distributed control have reduced response times, flexible and reconfigurable platforms are still required to adapt protocols, bands, and topologies without replacing physical equipment [14].

Software-defined radios respond to this need by allowing communication parameters to be modified through software. This feature facilitates the evaluation of transmission schemes, modulations, and protocols within the same experimental environment [15]. Lascano [12] implemented at UPS a system based on NI-USRP-2920/2921 devices (National Instruments Corp., Austin, TX, USA), demonstrating that it is possible to model communication links for smart electricity metering and obtain metrics such as latency, BER, and PER.

Complementarily, recent studies integrate SDR, performance analytics, and IoT to build centralized monitoring platforms capable of improving operational efficiency in grids with high renewable penetration [16,17]. These solutions combine standardized data flows, distributed storage, and performance analysis to correlate communication parameters with electrical indicators, such as frequency stability, energy efficiency, and response times.

Based on this background, this work proposes a centralized SDR platform with performance analytics for preliminary evaluation of smart grid communication links. The proposal combines a controlled SDR/USRP experimental-simulation reference developed at UPS with reproducible packet-level simulations focused on physical- and MAC-layer communication performance. The study does not claim full-scale field deployment validation or complete application-layer interoperability certification; instead, NI-USRP2920/USRP2921 parameters are used to support the experimental feasibility of the SDR chain and to define practical scenario boundaries for the extended simulations.

The core novelty of the work is the integration of four functions that are usually treated separately in single-function SDR testbeds: (i) reconfigurable SDR-based link emulation; (ii) technology-dependent communication profiles for RF900, PLC, GPRS, and hybrid PLC–GPRS links; (iii) centralized packet-level analytics using latency, BER, PER, useful throughput, and offered channel load; and (iv) traffic differentiation for periodic smart-meter reporting and renewable-node event reporting. Traditional SDR testbeds commonly validate one modulation, frequency band, or transmitter–receiver chain. In contrast, the proposed platform uses the SDR abstraction as a unified analytics layer for comparing several smart grid communication profiles under the same packet generation, integrity verification, and performance evaluation procedure.

The specific contributions of the article are: (i) the design of a centralized SDR architecture to integrate meters, concentrators, and renewable monitoring nodes under a reconfigurable communication layer; (ii) the documentation of a controlled SDR/USRP experimental-simulation setup at UPS as the practical reference for frequency, modulation,

packet framing, sampling, and transport constraints; (iii) the implementation of reproducible physical/MAC-layer simulations for RF900, PLC, GPRS, and hybrid PLC–GPRS scenarios, including AWGN, RF multipath fading, PLC impulsive noise, and GPRS fading/outage effects; (iv) the incorporation of a performance analytics module based on latency, BER, PER, useful throughput, and offered channel load; and (v) the differentiation between periodic metering traffic and event-driven renewable-node traffic.

Accordingly, the manuscript focuses on the electronic communication layer that enables reliable and timely data exchange in smart grid environments rather than on energy-management optimization alone. Application-layer semantic validation, DLMS/COSEM object compliance, and full IEC 61850/IEC 62056 conformance testing are outside the scope of the present work and are identified as future extensions.

The article is organized as follows: Section 2 presents the state of the art on interoperability, communications, and SDR platforms; Section 3 describes the problem and the proposed solution; Section 4 presents the materials and methods, including the platform architecture, simulation parameters, and controlled SDR/USRP experimental-simulation setup at UPS; Section 5 reports the results; Section 6 discusses the findings and compares the proposal with related studies; Section 7 presents the limitations; and Section 8 presents the conclusions and future work.

2. State of the Art

Smart grid communication research has evolved from isolated metering links toward heterogeneous cyber–physical infrastructures that combine distributed generation, AMI, SCADA, IoT gateways, and wide-area monitoring. Recent surveys emphasize that communication technology selection must consider latency, bandwidth, reliability, cybersecurity, interoperability, and scalability instead of only nominal data rate [18,19]. This requirement is particularly relevant in grids with renewable energy sources, where intermittent generation increases the need for timely monitoring and coordinated control.

Interoperability remains one of the central barriers to large-scale smart grid deployment. According to the NIST framework [4], interoperability must be analyzed at technical, semantic, and organizational levels. Technical interoperability depends on compatible interfaces, link layers, and protocol stacks; semantic interoperability requires common data models and meaning; and organizational interoperability depends on coordinated procedures among utilities, operators, and technology providers. Standards such as IEC 61850, IEC 62056 (DLMS/COSEM), IEEE Std 2030-2011, and OPC UA contribute to this integration by defining reference models for substations, metering, distributed generation, and supervisory systems [5–8].

Power-line communication is widely used in smart metering because it exploits the existing electrical infrastructure and reduces additional deployment costs. Narrowband PLC technologies such as PRIME and G3-PLC are commonly associated with residential and low-voltage distribution networks, but their performance is affected by impedance variations, impulsive noise, branch topology, and electromagnetic interference from power electronic converters. Recent work on G3-PLC channels confirms that interference and frequency-selective attenuation can significantly affect the available capacity and link robustness [20]. Therefore, PLC links should be evaluated using packet-level indicators, not only theoretical data rates.

Wireless and cellular technologies complement PLC in locations where the electrical channel is noisy, discontinuous, or difficult to access. RF900 links provide relatively low latency and suitable coverage for neighborhood aggregation, while cellular technologies such as GPRS remain useful for low-rate rural telemetry due to their wide coverage and existing infrastructure. However, cellular links generally introduce higher latency and

higher channel occupancy than local RF links. For this reason, hybrid communication architectures that combine PLC, RF, or cellular fallback are increasingly considered for AMI and smart grid deployments, because they improve availability and resilience under variable channel conditions [21,22].

Software-defined radio is a suitable tool for studying these heterogeneous communication profiles because it allows carrier frequency, modulation, filtering, transmission power, and signal processing to be reconfigured through software. Unlike fixed-function transceivers, SDR platforms make it possible to test several physical-layer configurations without replacing hardware. Previous SDR studies have addressed reconfigurable gateways, cognitive radio testbeds, and energy-information transmission over wireless channels [16,23–25]. However, fewer works combine SDR reconfigurability with a unified analytics layer for comparing PLC, RF900, GPRS, and hybrid smart grid links under the same performance metrics.

Based on this gap, the present work focuses on a reproducible SDR-based simulation framework that links communication performance analytics with interoperability assessment. The contribution differs from purely physical-layer SDR implementations because it evaluates latency, BER, PER, useful throughput, and offered channel load as common indicators for heterogeneous smart grid communication technologies. This approach makes it possible to compare communication profiles before field deployment and to identify where reliability mechanisms such as FEC, ARQ, adaptive modulation, packet-size optimization, or dynamic link selection are required.

3. Problem Description and Proposed Solution

3.1. Problem Description

The implementation of smart grids in Latin America, and particularly in Ecuador, faces technical limitations associated with the lack of interoperability among devices from different manufacturers and the absence of flexible platforms to validate emerging technologies [1,2].

UPS studies show that meters and concentrators marketed in the country, from brands such as Landis + Gyr, Itron, Elster, Echelon, and GE, use different communication media and protocol stacks, including PLC-PRIME, RF, ZigBee, GSM/GPRS, DLMS/COSEM, and other manufacturer-specific implementations [3]. In this study, that heterogeneity is addressed only at the physical and MAC layers through common packet-level indicators. Semantic data-model interoperability, DLMS/COSEM object validation, and full IEC 61850/IEC 62056 compliance testing are not evaluated in the present simulation.

This technological heterogeneity generates four communication-layer problems that motivate the proposed platform. First, concentrators and meters do not always share equivalent link capacity, delay, error behavior, or medium-access overhead. Second, conventional testbeds depend on costly physical equipment, such as USRP radios, PLC modems, and cellular gateways, which restricts early evaluation of multiple scenarios and topologies. Third, many studies evaluate electrical parameters or isolated communication metrics without using a common set of indicators to compare alternative links. Fourth, SCADA, HES, and AMI systems often lack analytical modules that quantify latency, packet integrity, useful throughput, and channel occupancy before deployment.

Consequently, the scope of the platform is deliberately limited to physical/MAC-layer communication evaluation. IEC and DLMS/COSEM standards are used as background motivation and traffic-profile references, but the platform does not certify application-layer interoperability or standard conformance.

In addition, the increasing penetration of intermittent renewable sources increases grid variability and demands a reliable, secure, and adaptable communication infrastructure to coordinate distributed nodes in real time [17,26,27]. In this context, hardware-only

methods are insufficient to evaluate interoperability and resilience scenarios. A solution is required that combines configuration flexibility, low experimental cost, physical/MAC-layer parameter plausibility, and comprehensive performance analysis capability.

3.2. Proposed Solution

To overcome the identified limitations, it is proposed to design a centralized SDR platform with performance analytics that enables the simulation, evaluation, and preliminary comparison of physical/MAC-layer communication among smart meters, renewable monitoring nodes, concentrators, and control systems.

The solution consists of a modular packet-level simulation environment, based on software-defined radio principles, that emulates the behavior of concentrators and PLC, RF, and GPRS links without requiring specialized hardware during the simulation stage. Additionally, configuration parameters from a real USRP testbed are incorporated as boundary references for feasible SDR implementation conditions.

3.2.1. Technical Approach

The platform allows essential communication parameters to be configured by software, such as carrier frequency, modulation type, power, symbol rate, packet size, internal delay, packet-level overhead, and traffic-profile parameters [16]. Thus, representative communication behavior associated with equipment such as Landis + Gyr E450-PRIME, Itron OpenWay, Elster, Echelon, and GE can be compared in a single physical/MAC-layer simulation environment without claiming application-layer conformance certification.

The model is organized into three hierarchical levels: (a) local or HAN level, where virtual meters, sensors, and renewable monitoring nodes generate packet-level consumption, production, and operating-status reports; (b) neighborhood or NAN level, where simulated concentrators aggregate and retransmit information through PLC, RF, or cellular links; and (c) central or WAN level, where an analytics server calculates metrics and validates packet integrity using indicators motivated by NIST SP 1108r4 interoperability principles.

3.2.2. Performance Analytics

The system incorporates an analytics module to evaluate latency, BER, PER, offered channel load, and useful throughput. These variables are relevant because smart grid interoperability frameworks recognize that reliable, timely, and standardized information exchange depends directly on the performance of the communication layer.

The platform makes it possible to quantify the impact of delays, losses, and errors on the availability and timeliness of operational data. Therefore, performance analysis is not limited to describing link quality; rather, it serves as a basis for comparing physical/MAC-layer communication compatibility and packet-level reliability among heterogeneous devices.

3.2.3. Expected Benefits

The expected benefits are fourfold: flexibility to adapt technologies, frequencies, and modulations without physical changes; scalability to integrate new concentrators and packet-level traffic profiles; cost reduction during simulation and preliminary validation; and communication analytics motivated by NIST SP 1108r4, IEC 62056, IEC 61850, and IEEE 2030, without performing application-layer conformance certification.

In summary, the proposed solution establishes an experimental and analytical basis for evaluating the interoperability and efficiency of smart grids and can serve as a reference for future implementations of SDR platforms in Latin American electrical systems.

4. Materials and Methods

The development of the platform was aimed at building a centralized, flexible, and modular SDR-based experimental-simulation environment capable of representing the operation of a smart grid from data generation at local nodes to processing at the central level. The implementation combines a controlled UPS SDR/USRP reference setup with reproducible packet-level simulations, supported by accompanying Python 3.12 source code and CSV output files for verification and reuse.

The architecture was structured into three functional levels consistent with the NIST and IEC reference models: the local level (HAN), where electrical data are generated; the neighborhood level (NAN), where concentrators aggregate and process information; and the central level (WAN), where system analytics are performed. Figures 1 and 2 show the integration among heterogeneous devices, communication technologies, the SDR layer, and the performance analytics module.

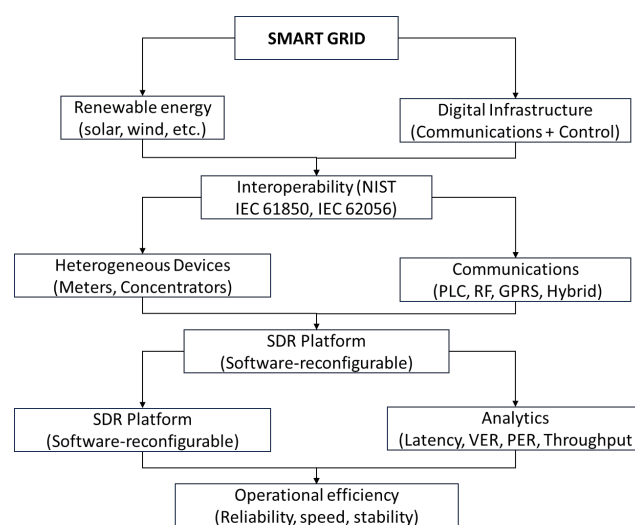


Figure 1. Conceptual map of the centralized SDR platform for smart grids. Colored blocks distinguish the functional layers and system components; arrows indicate communication and data-flow directions between components.

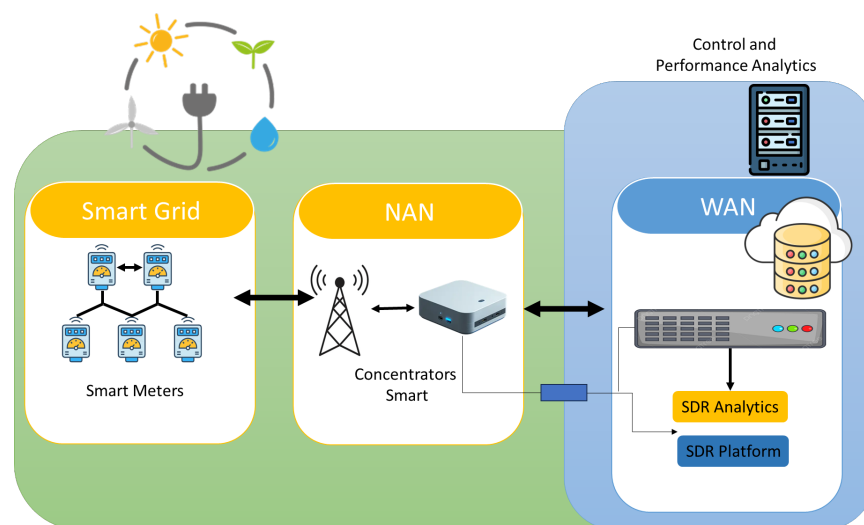


Figure 2. General architecture of the SDR platform integrated into a smart grid.

The general extended-simulation configuration was defined through a set of global parameters that control the number of meters, total simulation time, packet size, modulation, traffic generation, channel error behavior, and link-dependent delay. These parameters are

grouped into a configuration structure to facilitate scenario modification and reproducibility. Table 1 summarizes the values used in the common packet-level model.

Table 1. Main simulation parameters used in the revised reproducible evaluation.

Parameter	Symbol/Variable	Value	Description
Number of nodes	cfg.Nnodes	20	Virtual smart meters and renewable monitoring nodes in the baseline case.
Simulation time	cfg.simTime_s	120 s	Total duration of each independent simulation run.
Independent runs	cfg.seeds	30	Seeds 1001–1030 were used to calculate mean values and 95% confidence intervals.
Transmitted packets	cfg.Npackets	3444	Number of generated packets per baseline scenario, preserving the original offered traffic rate of 28.7 packet/s.
Payload size	cfg.payloadBits	1024 bits	Useful metering or renewable-node information.
Header and CRC size	cfg.headerBits	64 bits	Identifier, timestamp, addressing, and integrity field.
Total frame size	cfg.packetBits	1088 bits	Payload plus header and CRC field.
Traffic model	—	Periodic plus event-driven classes	AMI metering packets are periodic; DER packets can include event-driven alarms.
Randomization	rng	Fixed seeds	Ensures repeatability of packet loss, jitter, and bit-error generation.
Integrity verification	CRC	Enabled	Lost packets or packets with residual bit errors are classified as invalid.
Latency statistic	—	Valid packets only	Mean and p95 latency are calculated over correctly received packets; lost/invalid packets contribute to PER.

For reproducibility, each simulated packet follows the same processing sequence. First, the local node generates a timestamped payload containing electrical variables and operating status. Second, the concentrator adds an internal processing delay, MAC overhead, and link-dependent jitter. Third, the SDR chain maps the binary frame into symbols, transmits it through the selected channel model, and demodulates the received sequence. Finally, the central node verifies packet integrity and computes the metrics. Latency is calculated as the difference between packet generation and successful reception timestamps; BER is obtained from the ratio between erroneous bits and transmitted bits; PER is calculated as the ratio between invalid or lost packets and transmitted packets; useful throughput is computed from correctly received payload bits over the simulation time; and offered channel load is estimated from the occupied transmission time with respect to the nominal available channel time.

The metering and renewable generation nodes were modeled as packet generators with differentiated traffic behavior. Smart meters generate periodic fixed-size reports. Renewable generation nodes, such as photovoltaic and small wind monitoring nodes, generate the same periodic monitoring packets and additional event-driven messages when power ramps, voltage deviations, frequency deviations, or operating-status changes occur. This distinction is necessary because renewable-rich grids do not produce only periodic metering traffic; they also require event reporting during fast generation variability. Table 2 summarizes the modeled traffic classes.

Table 2. Architecture- and standard-aware traffic classes used in the simulation. The standards are represented as packet-level classes only; semantic object validation, protocol-stack certification, and conformance testing are outside the scope of this model.

Traffic Profile	Layer	Standard/Reference	Payload	Reporting Behavior	Modeled Use
AMI periodic metering	HAN/NAN	IEC 62056 DLMS/COSEM reference class	1024 bits	periodic	meter reading and billing telemetry
G3-PLC smart metering	HAN/NAN	ITU-T G.9903/PRIME- like PLC PHY-DLL assumptions	1024 bits	periodic	urban PLC metering over LV/MV grid
IEC 61850 MMS-like monitoring	NAN/WAN	IEC 61850 supervisory data reference class	1536 bits	periodic/ request-response	DER or substation supervision; no semantic confor- mance testing
Renewable event reporting	NAN/WAN	NIST/IEEE 2030 interoperability data-flow perspective	512 bits	event-driven with priority	power ramp, voltage/frequency alarm, status change
Backup telemetry	WAN	cellular GPRS CS2–CS3 abstraction	1024 bits	periodic or fallback	rural telemetry and backup path

Smart concentrators were implemented as intermediate blocks that receive packets from multiple meters, aggregate them, introduce processing delays, and limit traffic according to their capacity. To represent real heterogeneity, manufacturer profiles were parameterized considering processing capacity, base rate, and delay interval. Table 3 presents the profiles used.

Table 3. Concentrator profiles.

Brand	Link	Internal Delay	Capacity	Base Rate
Landis + Gyr	PLC/Ethernet	20 ms	250 pkt/s	200 kbps
Itron	RF900/Cellular	15 ms	300 pkt/s	300 kbps
Elster	Cellular/RF/C	30 ms	220 pkt/s	150 kbps
Echelon	PLC/IP	25 ms	260 pkt/s	250 kbps
GE	RF/PLC	18 ms	280 pkt/s	220 kbps

Transmission between levels was represented through a digital SDR chain. This chain includes modulation, propagation through a channel with noise and variable delays, demodulation, and data reconstruction. In the controlled UPS setup, this SDR chain is supported by USRP-based experimental references; in the extended scenarios, the same chain is represented through packet-level models so that RF900, PLC, GPRS, and hybrid communication profiles can be compared under a common analytics procedure.

To evaluate performance, the study includes a baseline RF900 AWGN scenario and four non-ideal communication profiles: RF900 with multipath fading, PLC with impulsive noise, GPRS with slow fading/outage, and hybrid PLC–GPRS with fallback. Each scenario represents a different communication condition in terms of latency, bandwidth, robustness, overhead, and deployment context. The RF900 AWGN case is maintained as the baseline scenario linked to the Itron concentrator and the SDR/USRP reference configuration, while the PLC, GPRS, and hybrid profiles are evaluated with technology-specific

impairment models. Table 4 summarizes the communication parameters used for the comparative scenarios.

The RF900 AWGN baseline uses the conventional 16-QAM over AWGN chain as a reference for model verification. The RF900 fading case multiplies the useful signal by a Rayleigh-distributed fading coefficient before demodulation and therefore represents multipath degradation rather than an ideal static link. The PLC profile uses a Bernoulli–Gaussian impulsive noise term superimposed on the background noise; this is consistent with the fact that narrowband PLC channels are affected by impulsive noise, narrowband interference, and group delay effects. The GPRS profile uses a slow-fading/outage abstraction to represent variable cellular access conditions. The hybrid PLC–GPRS profile first evaluates the PLC packet and then applies GPRS fallback for a subset of packets affected by PLC degradation.

Table 4. Communication scenarios and simulation parameters.

Scenario	Reference Profile	Nominal Rate	Base Delay	Jitter	MAC Overhead	Deployment Use
RF900 AWGN	Itron RF900/16-QAM	300 kbps	15 ms	6 ms	18%	Urban and suburban aggregation baseline.
RF900 fading	Itron RF900/16-QAM	300 kbps	15 ms	8 ms	20%	Wireless aggregation under multipath fading.
PLC	PRIME/G3-PLC narrowband	128.6 kbps	20 ms	20 ms	30%	Residential and urban metering over existing power lines.
GPRS	Cellular CS2–CS3 telemetry	53.6 kbps	150 ms	120 ms	35%	Rural low-rate telemetry and wide-area monitoring.
Hybrid	PLC primary with GPRS fallback	128.6 kbps	30 ms	35 ms	28%	Mixed deployments with link fallback and heterogeneous coverage.

The packet generation process was identical in the scenarios used for the main comparison. Link-dependent jitter was generated with a log-normal distribution to avoid negative delays and to reproduce asymmetric delay behavior. The arithmetic mean and shape factor of each jitter distribution are reported in Table 5. Bit errors were generated using a binomial process with the scenario residual BER. Packet losses represent collisions, deep fades, electrical noise bursts, or cellular access failures. A packet was accepted only when it was not lost and passed CRC-based integrity verification. Therefore, the PER reported in the results includes both residual bit-error effects and link-level packet loss.

Table 5. Stochastic impairment parameters used for the revised simulations.

Scenario	Jitter Mean	Jitter Shape σ	Residual BER	Packet-Loss Probability	Impairment Interpretation
RF900 AWGN	2.3 ms	0.35	1.78×10^{-4}	0.000	Effective 16-QAM link after non-ideal receiver abstraction.
RF900 fading	2.0 ms	0.45	1.95×10^{-4}	0.005	Rayleigh multipath and shadowing abstraction.
G3-PLC	2.8 ms	0.55	3.00×10^{-5}	0.030	Bernoulli–Gaussian impulsive noise and background noise.
GPRS CS2–CS3	70.0 ms	0.60	2.00×10^{-5}	0.060	Slow fading, access delay, and outage abstraction.
Hybrid PLC–GPRS	10.0 ms	0.55	8.00×10^{-6}	0.016	PLC primary link with probabilistic GPRS fallback.
Renewable-event hybrid	12.0 ms	0.62	9.00×10^{-6}	0.018	Hybrid fallback with DER event bursts and priority marking.

The central level integrates an analytics module that calculates metrics such as end-to-end latency, BER, PER, effective throughput, and offered channel load in real time. These metrics make it possible to quantify the quality of service of the communication network and evaluate its impact on the operational efficiency of the electrical system. Table 6 details the indicators used.

Table 6. Performance metrics.

Metric	Symbol	Unit	Meaning
Mean latency	Lat_mean	ms	End-to-end delay for correctly received packets.
95th-percentile latency	Lat_p95	ms	95th-percentile delay for correctly received packets.
Bit error rate	BER	—	Proportion of received bits with errors.
Packet error rate	PER	—	Proportion of lost or invalid packets.
Useful throughput	—	kbps	Correctly received payload bits divided by simulation time.
Offered channel load	ρ	%	Offered traffic relative to nominal channel capacity; values above 100% indicate saturation demand, not physical utilization.

4.1. Link Between Analytics, Operational Efficiency, and Interoperability

Performance analytics is used as a bridge between the communications layer and electrical operation. In a smart grid with renewable sources, the availability of timely data makes it possible to coordinate distributed generation, detect congestion, estimate link quality, and select appropriate communication technologies before physical deployment. Therefore, the metrics are not interpreted in isolation, but rather as indicators that support operational, scalability, and interoperability decisions. Table 7 summarizes the relationship between communication metrics, operational efficiency, and interoperability.

Table 7. Relationship between communication metrics, operational efficiency, and interoperability.

Metric	Impact on Operational Efficiency	Impact on Interoperability
Latency	Determines the timeliness of monitoring, alarms, and coordination of renewable resources.	Enables verification of whether different links meet common temporal exchange requirements.
BER	Evaluates the physical quality of the link and helps select modulation, SNR, and frequency.	Facilitates comparison of heterogeneous technologies under a common reliability indicator.
PER	Measures packet integrity and the continuity of operational data.	Identifies the need for FEC, ARQ, or more robust communication profiles among manufacturers.
Useful throughput	Estimates the effective capacity to transport measurements, alarms, and generation states.	Enables dimensioning of the integration of new meters, concentrators, and renewable nodes.
Offered channel load	Indicates congestion, growth margin, and scaling capacity.	Enables comparison of PLC, RF900, GPRS, and hybrid links under a uniform quantitative basis.

The present study does not use a composite index as a current decision criterion because assigning universal weights to latency, BER, PER, throughput, and offered load would depend on the application class. For this reason, the analysis reports the individual metrics directly. A future operational performance and interoperability index may be defined after full utility field validation, application-specific weight selection, and sensitivity analysis.

The operational flow of the system is executed iteratively during the simulation period. In each cycle, local nodes generate packets, concentrators aggregate and retransmit them, the SDR chain simulates transmission through the channel, and the central level receives the information to update performance metrics.

Basic logical security mechanisms were also incorporated, such as node authentication and data integrity verification. Complete cryptographic algorithms were not implemented in this stage; therefore, the security analysis is limited to the qualitative impact of authentication and integrity checking on latency and channel use. Future versions should include encryption, key management, replay protection, and cybersecurity traffic profiles.

Figure 3 shows the SDR processing chain and the flow of the performance analytics module.

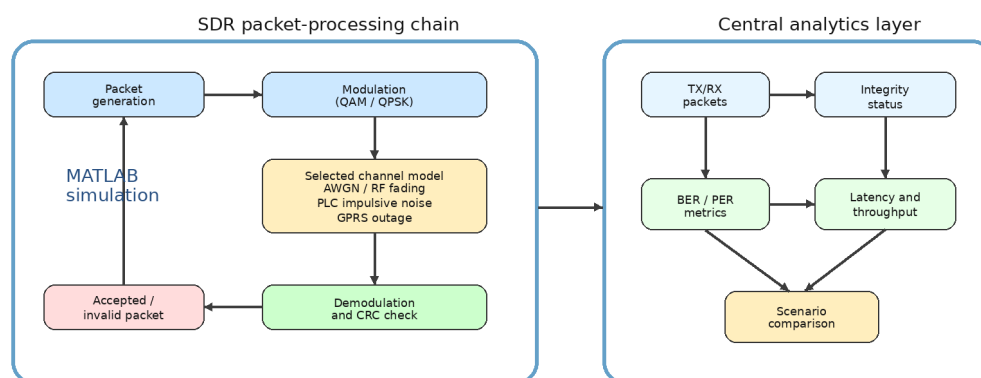


Figure 3. SDR processing chain and flow of the performance analytics module.

4.2. Simulation Algorithm of the SDR Platform

The SDR processing chain and performance analytics flow are shown in Figure 3. The operation of the SDR platform is described by the simulation algorithm in Figure 4. Initially, parameters such as the number of meters, SNR, modulation, transmission rate, packet size, and concentrator profile are defined. Then, during the simulation, each meter generates packets that are sent to the corresponding concentrator.

For each transmitted packet, the SDR processing chain is executed, including conversion to bits, digital modulation, transmission through the selected impairment model, demodulation, and integrity verification. Next, it is determined whether the received packet is valid or contains errors. Finally, latency, BER, PER, useful throughput, and offered-load metrics are calculated.

4.3. Controlled SDR/USRP Experimental-Simulation Setup at UPS

A controlled SDR/USRP experimental-simulation setup was implemented at Universidad Politécnica Salesiana (UPS), Block H, to verify the practical feasibility of the SDR communication chain and to define realistic implementation boundaries for the extended packet-level scenarios. The experimental chain uses NI-USRP-2920/2921 virtual instruments and VERT2450 antennas (National Instruments Corporation, Austin, TX, USA), radio links at 915 MHz and 5 GHz, QPSK modulation, 40-byte payload writes, and host connection through Gigabit Ethernet. Table 8 summarizes the most relevant configuration parameters used as experimental references.

The UPS experimental-simulation setup supports the feasibility of the SDR transmitter–receiver chain and provides practical limits for frequency selection, modulation capability, packet size, sampling rate, and Ethernet transport. These measurements are used as controlled implementation references for the SDR layer. They are not interpreted as full utility field measurements and are not used to calibrate PLC, GPRS, or hybrid channel impairments directly; those impairments remain extended packet-level abstractions. Therefore, the study combines controlled SDR experimentation at UPS with reproducible simulations, while full hardware-calibrated RF/PLC/cellular field validation is reserved for future work.

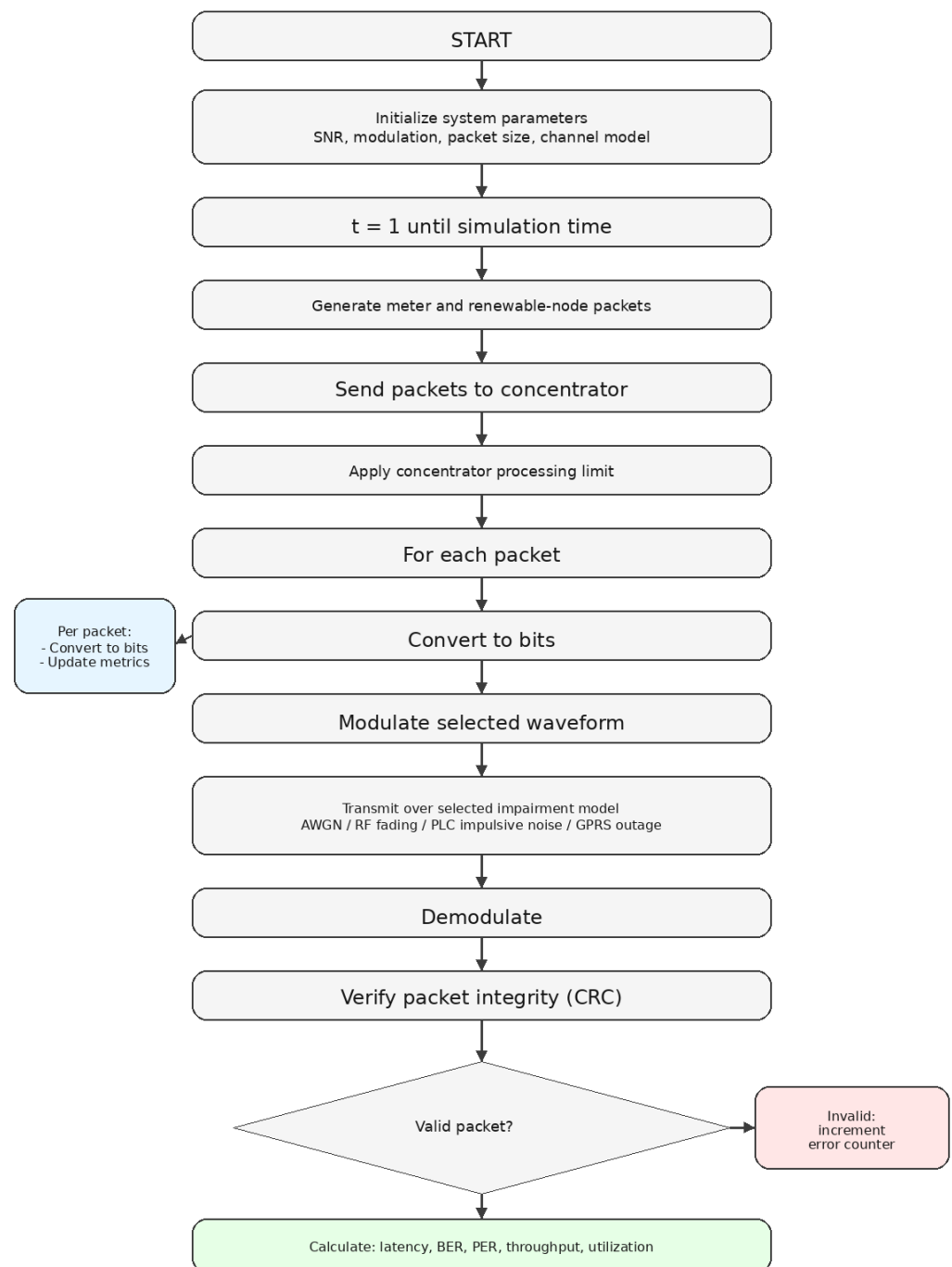


Figure 4. Flowchart of the simulation algorithm of the SDR platform.

Table 8. Controlled SDR/USRP experimental-simulation parameters used at UPS as implementation references.

Parameter	Value or Description
Test site	Block H of Universidad Politécnica Salesiana, Quito, Ecuador.
Host computers	One Dell computer (Dell Technologies Inc., Round Rock, TX, USA) for transmission and one Lenovo computer (Lenovo (Beijing) Ltd., Beijing, China) for reception, connected by Gigabit Ethernet.
SDR platforms	USRP2920 and USRP2921 (National Instruments Corp., Austin, TX, USA).
Antennas	Four VERT2450 antennas (National Instruments Corp., Austin, TX, USA).
Selected RF ports	TX1 on the transmitter and RX1 on the receiver.
Transmission frequencies	915 MHz and 5 GHz, depending on the scenario.
Reference physical modulation	QPSK.
I/Q sampling rate	400 kS/s reported for the receiver configuration.
Output power range	0–15 dBm, depending on the selected frequency.
Packet payload	40 byte writes, equivalent to 320 bits per payload unit.
Supported MTU	1500 bytes on USRP2920/USRP2921 through 1 Gigabit Ethernet.
Reference total	573 data units transmitted in the controlled SDR experimental-simulation series; the complete series contains 576 records, with three edge samples excluded during preprocessing.
Ambient temperature	20 °C during the experiments.

5. Results

The results are reported in two complementary levels: a controlled UPS SDR/USRP experimental-simulation reference that supports the feasibility of the SDR chain, and extended reproducible packet-level simulations that compare heterogeneous smart grid communication profiles. The revised simulation evaluation addresses the main reproducibility and robustness limitations of the preliminary 20 s simulation. Each communication profile was simulated for 120 s, preserving the same offered packet rate used in the original model. Consequently, each baseline scenario generated 3444 packets instead of 574 packets. In addition, 30 independent seeds, from 1001 to 1030, were executed for each scenario. The values reported in this section correspond to the mean of those independent runs, and the uncertainty terms correspond to 95% confidence intervals. Latency statistics were calculated only over correctly received packets, while lost or corrupted packets were included in PER.

The evaluated profiles were selected according to the HAN/NAN/WAN architecture used in smart grid communication planning. RF900 represents low-latency neighborhood aggregation; G3-PLC represents narrowband PLC metering over the electrical infrastructure; GPRS CS2–CS3 represents low-rate wide-area telemetry; hybrid PLC–GPRS represents a fallback architecture for heterogeneous deployments; and the renewable-event hybrid profile represents DER monitoring with periodic and event-driven traffic.

For the node-density analysis, packet rejection is modeled as the combination of channel errors, independent losses, and a simplified congestion/drop term. The total PER is expressed as

$$PER_{total} = 1 - (1 - PER_{channel})(1 - P_{loss})(1 - P_{cong}), \quad (1)$$

where $PER_{channel}$ is obtained from bit-level corruption, P_{loss} represents independent technology-dependent losses, and P_{cong} represents offered-load-induced drops. The congestion term is activated only when the offered load ρ approaches the nominal channel capacity:

$$P_{cong} = \begin{cases} 0, & \rho \leq 0.85, \\ \min(0.95, 1 - e^{-0.75(\rho-0.85)}), & \rho > 0.85. \end{cases} \quad (2)$$

This term does not replace a full discrete-event MAC simulator. It is included to avoid treating scalability as independent of node density and to represent the expected packet discard produced by contention, queue buildup, or concentrator saturation when the offered load exceeds the available communication capacity.

Figure 5 shows the communication topology used in the RF900 scenario.

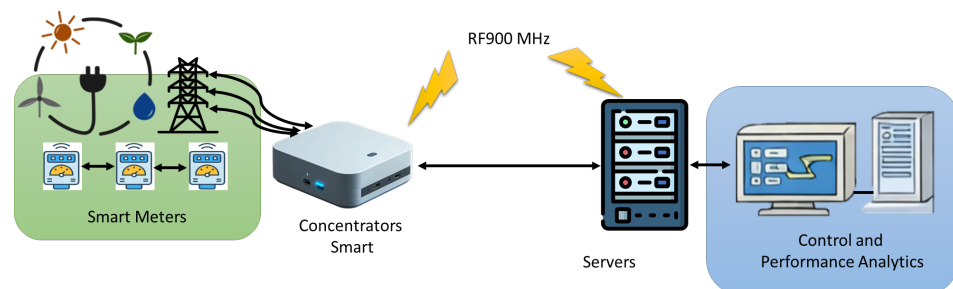


Figure 5. Communication topology in the RF900 scenario.

5.1. Physical-Layer Verification for the RF900 Baseline

The simulated RF900 BER was compared with the theoretical BER of square 16-QAM in an AWGN channel. For Gray-coded 16-QAM, the approximate bit error probability is

$$P_b \approx \frac{4}{\log_2 M} \left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3 \log_2 M}{M-1} \frac{E_b}{N_0}}\right), \quad M = 16. \quad (3)$$

The corresponding packet error probability for a 1088-bit frame is estimated as

$$PER_{th} = 1 - (1 - P_b)^{1088}. \quad (4)$$

If the 18 dB value is interpreted as an ideal E_b/N_0 , the theoretical BER is approximately 4.52×10^{-13} and the theoretical PER is 4.92×10^{-10} . This ideal reference is useful for checking the analytical expression, but it does not represent the complete packet-level behavior considered in the experimental-simulation framework. In the present model, 18 dB is treated as a nominal gross link condition. The residual degradation produced by implementation losses, synchronization uncertainty, receiver imperfections, finite packet detection, and unmodeled RF effects is represented through an equivalent effective E_b/N_0 of 11.84 dB. This effective value is not introduced as an independent field calibration or as an additional performance claim; it is a conservative equivalent-link abstraction used to reproduce the residual impairment level imposed in the baseline packet simulation. Under this effective condition, the theoretical BER is 1.78×10^{-4} , and the expected PER is 0.176, which is consistent with the multi-seed RF900 AWGN PER of 0.175 ± 0.003 .

Table 9 compares the theoretical and simulated BER/PER values for the RF900 16-QAM baseline.

Table 9. Theoretical and simulated BER/PER verification for the RF900 16-QAM baseline.

Case	BER	PER	Interpretation
Ideal 16-QAM AWGN at $E_b/N_0 = 18$ dB	4.52×10^{-13}	4.92×10^{-10}	Ideal physical-layer reference.
Effective condition, $E_b/N_0 = 11.84$ dB	1.78×10^{-4}	0.176	Equivalent residual-impairment condition used for packet-level verification.
RF900 multi-seed simulation	1.78×10^{-4}	0.175 ± 0.003	Packet simulation result with CRC-based discard.

5.2. End-to-End Latency, Packet Integrity, and Throughput

Tables 10–12 present the revised quantitative comparison. RF900 AWGN maintained the lowest end-to-end delay, with 36.58 ± 0.01 ms mean latency and 38.12 ± 0.02 ms p95 latency. RF900 fading preserved low delay but degraded reliability because multipath conditions increased PER to 0.195 ± 0.002 . G3-PLC achieved 53.81 ± 0.01 ms mean latency and 0.062 ± 0.002 PER, which is suitable for non-time-critical AMI metering. GPRS CS2–CS3 presented the highest delay, with 282.54 ± 0.31 ms mean latency and 369.23 ± 1.29 ms p95 latency, and its offered channel load reached 78.65%, indicating limited scalability at the selected offered load. Hybrid PLC–GPRS obtained the best packet-level reliability, with 0.025 ± 0.001 PER and 28.66 kbps useful throughput. The renewable-event hybrid case remained close to the hybrid case, with 0.028 ± 0.001 PER, showing that the framework can represent event-driven DER packets while maintaining a clear distinction from application-layer conformance testing.

Table 10. Mean packet-count comparison using 120 s simulations and 30 independent seeds. Because values are averages over independent runs, correct and invalid packet counts are reported with one decimal place.

Scenario	Tx Packets	Mean Correct Packets	Mean Invalid Packets
RF900 AWGN	3444	2839.7	604.3
RF900 fading	3444	2771.2	672.8
G3-PLC	3444	3231.9	212.1
GPRS CS2–CS3	3444	3166.8	277.2
Hybrid PLC–GPRS	3444	3358.8	85.2
Renewable event hybrid	3444	3348.0	96.0

Table 11. Revised packet-integrity comparison using 120 s simulations and 30 independent seeds. Values after $\pm$ indicate 95% confidence intervals.

Scenario	BER	PER
RF900 AWGN	1.78×10^{-4}	0.175 ± 0.003
RF900 fading	1.96×10^{-4}	0.195 ± 0.002
G3-PLC	3.02×10^{-5}	0.062 ± 0.002
GPRS CS2–CS3	2.02×10^{-5}	0.080 ± 0.002
Hybrid PLC–GPRS	8.18×10^{-6}	0.025 ± 0.001
Renewable event hybrid	9.14×10^{-6}	0.028 ± 0.001

Table 12 reports the revised latency, throughput, and offered-load comparison across the simulated communication profiles.

Figure 6 shows the mean end-to-end latency and the 95% confidence intervals for the revised simulations.

Useful throughput remained lower than the nominal physical rate because the configured traffic model generated an offered payload load of 29.39 kbps. Therefore, the gap between nominal rate and useful throughput is mainly caused by the intentionally low offered payload load, MAC/header/CRC occupation time, and CRC-based packet discard,

not by RF900 physical-layer saturation. Table 13 decomposes this effect. For example, the RF900 AWGN link has a 300 kbps nominal physical rate, but the traffic generator injects only 29.39 kbps of useful payload. After frame overhead and the 18% MAC occupation factor are included, the equivalent occupied channel rate is 36.84 kbps, corresponding to 12.28% of the available channel time. CRC/PER discards reduce the delivered payload by 5.16 kbps, resulting in 24.23 kbps of useful throughput. Thus, the main bottleneck in the RF900 baseline is not physical-rate saturation but the combination of low metering offered load and packet discard. GPRS is different: its equivalent occupied rate reaches 42.16 kbps over a 53.6 kbps channel, or 78.65% offered load, making it the least scalable profile under the selected traffic demand.

Table 12. Revised latency, throughput, and offered-load comparison using 120 s simulations and 30 independent seeds. Values after $\pm$ indicate 95% confidence intervals.

Scenario	Mean Latency	P95 Latency	Throughput	Offered Load
RF900 AWGN	36.58 $\pm$ 0.01 ms	38.12 $\pm$ 0.02 ms	24.23 $\pm$ 0.08 kbps	12.28%
RF900 fading	36.35 $\pm$ 0.01 ms	38.14 $\pm$ 0.02 ms	23.65 $\pm$ 0.07 kbps	12.49%
G3-PLC	53.81 $\pm$ 0.01 ms	56.95 $\pm$ 0.04 ms	27.58 $\pm$ 0.05 kbps	31.57%
GPRS CS2–CS3	282.54 $\pm$ 0.31 ms	369.23 $\pm$ 1.29 ms	27.02 $\pm$ 0.05 kbps	78.65%
Hybrid PLC–GPRS	83.37 $\pm$ 0.12 ms	124.92 $\pm$ 0.16 ms	28.66 $\pm$ 0.02 kbps	31.08%
Renewable event hybrid	89.33 $\pm$ 0.13 ms	132.83 $\pm$ 0.24 ms	28.57 $\pm$ 0.03 kbps	32.05%

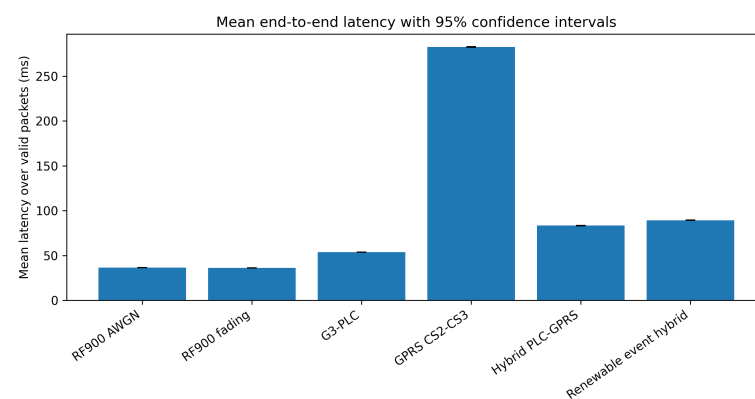


Figure 6. Mean end-to-end latency with 95% confidence intervals for the revised 120 s simulations.

Table 13 decomposes the throughput losses for the 20-node baseline.

Table 13. Throughput-loss decomposition for the 20-node baseline. The equivalent occupied rate corresponds to the nominal physical rate multiplied by the offered channel load. The CRC/PER discard term is the difference between generated payload load and delivered useful throughput.

Scenario	Nominal PHY Rate	Generated Payload Load	Frame/MAC Occupied Rate	CRC/PER Discard Loss	Useful Throughput	Primary Bottleneck
RF900 AWGN	300.0 kbps	29.39 kbps	36.84 kbps	5.16 kbps	24.23 kbps	Offered load and packet discard, not PHY saturation.
RF900 fading	300.0 kbps	29.39 kbps	37.47 kbps	5.74 kbps	23.65 kbps	Multipath-related packet discard.
G3-PLC	128.6 kbps	29.39 kbps	40.59 kbps	1.81 kbps	27.58 kbps	MAC occupation and PLC channel capacity.
GPRS CS2–CS3	53.6 kbps	29.39 kbps	42.16 kbps	2.37 kbps	27.02 kbps	High channel occupation and access delay.
Hybrid PLC–GPRS	128.6 kbps	29.39 kbps	39.98 kbps	0.73 kbps	28.66 kbps	Fallback management and MAC occupation.
Renewable-event hybrid	128.6 kbps	29.39 kbps	41.22 kbps	0.82 kbps	28.57 kbps	Event-burst occupation and fallback management.

5.3. Scalability and Node-Density Sensitivity

A complementary sensitivity analysis was carried out by scaling the number of nodes from 20 to 50, 100, and 200 while preserving the traffic rate per node. In this revised version, the PER model combines the channel impairment term with a density-related congestion/drop component that becomes active when the offered load approaches the nominal channel capacity. Consequently, PER remains governed by BER and independent packet losses at low load, but increases when MAC contention, queue growth, and concentrator buffer pressure are expected to appear. The offered channel load grows almost linearly with the number of nodes, and values above 100% indicate that the generated traffic demand exceeds the nominal channel capacity. Table 14 separates PER and offered-load values for selected node counts, while Figure 7 shows only the offered-load scaling trend. The former PER-sensitivity figure was removed because the tabulated PER values provide the necessary quantitative information without adding a redundant visual element.

Table 14. Node-density sensitivity of PER and offered channel load. Offered-load values above 100% indicate that generated traffic exceeds nominal channel capacity.

Scenario	PER 20	Load 20	PER 100	Load 100	PER 200	Load 200
RF900 AWGN	0.175	12.3%	0.177	61.4%	0.379	122.8%
RF900 fading	0.195	12.5%	0.196	62.5%	0.403	124.9%
G3-PLC	0.062	31.6%	0.457	157.8%	0.834	315.7%
GPRS CS2-CS3	0.080	78.6%	0.909	393.2%	0.954	786.5%
Hybrid PLC-GPRS	0.025	31.1%	0.425	155.4%	0.821	310.8%
Renewable-event hybrid	0.028	32.1%	0.448	160.3%	0.834	320.5%

Figure 7 shows the offered channel load under node-density scaling.

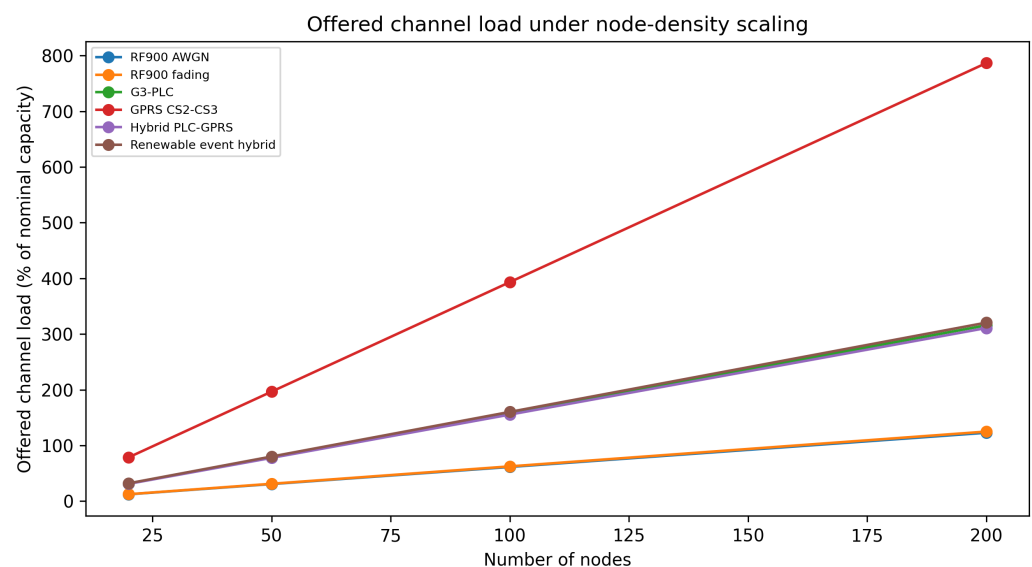


Figure 7. Offered channel load under node-density scaling. Values above 100% indicate that the generated traffic exceeds nominal channel capacity.

5.4. Interpretation of Scenario Suitability

The revised simulations support a more cautious and application-specific interpretation. RF900 is the lowest-latency option under the selected assumptions and offers the largest offered-load margin for NAN aggregation, but its packet reliability still requires coding, retransmission, diversity, or adaptive modulation under non-ideal RF conditions. G3-PLC is a suitable option for urban and residential AMI because it uses the existing electrical infrastructure and provides moderate latency and offered load. GPRS is useful for rural telemetry and backup paths, but its high delay and high offered load make it

unsuitable for time-sensitive control. Hybrid PLC–GPRS offers the strongest reliability by reducing permanent packet discard after PLC degradation, but it requires additional link-selection and management logic. The renewable-event hybrid case indicates that DER event reporting can be incorporated into the analytics framework, although IEC 61850 semantic mapping, DLMS/COSEM object validation, cybersecurity overhead, and SCADA/AMI integration remain future work.

5.5. Complementary Interpretation of USRP Equipment

The SDR/USRP values are not used to calibrate the simulated BER, PER, latency, or throughput. They are retained only to delimit feasible implementation conditions for future laboratory work. The 915 MHz USRP2920 reference is associated with longer line-of-sight coverage and longer channel occupation for the same payload, whereas the 5 GHz USRP2921 reference is associated with shorter coverage and lower occupation time. This comparison is qualitative in the present manuscript because the simulation profiles use technology-dependent packet abstractions rather than direct measurements from the USRP links.

Table 15 summarizes the qualitative role of the USRP reference parameters.

Table 15. Qualitative role of the USRP reference parameters in the simulation study.

Platform	Reported Operating Feature	Use in This Manuscript
USRP2920 at 915 MHz	Longer line-of-sight range and higher occupation time for the reference payload.	Boundary reference for sub-GHz SDR feasibility; not used to calibrate BER, PER, latency, or throughput.
USRP2921 at 5 GHz	Shorter line-of-sight range and lower occupation time for the reference payload.	Boundary reference for higher-frequency SDR feasibility; not used to calibrate BER, PER, latency, or throughput.

6. Discussion and Comparison with Related Works

The revised version strengthens the methodological connection with communication standards and architectures without overstating compliance. NIST SP 1108r4 and IEEE 2030 are used as interoperability and architecture references; IEC 61850 and IEC 62056 are used as application-domain traffic references; and ITU-T G.9903/G3-PLC principles are used to justify the inclusion of narrowband PLC impairment behavior. The simulation remains at the physical/MAC layer, so the results should be interpreted as pre-deployment performance analytics rather than protocol conformance evidence.

The multi-scenario results clarify the role of each communication technology in the proposed SDR-based analytics platform. RF900 provides the lowest latency and the largest offered-load margin under the simulated assumptions, but its PER values of 0.175 in the AWGN baseline and 0.195 under multipath fading show that low delay alone is not sufficient for reliable smart grid communication. PLC with impulsive noise improves packet-level reliability under the selected metering load, but its performance depends on the electrical environment. GPRS provides wide-area coverage but introduces high latency and high channel occupancy. The hybrid PLC–GPRS profile obtains the lowest PER because the fallback mechanism reduces permanent packet loss, although it also increases management complexity.

These findings are consistent with recent smart grid communication surveys, which indicate that no single technology satisfies all use cases and that the communication profile must be selected according to monitoring, metering, control, or protection requirements [18,19]. They also agree with PLC studies reporting that electrical noise and power-electronics interference affect PLC channel capacity and reliability [20]. In addi-

tion, hybrid AMI research highlights that combining complementary links can improve availability and resilience compared with a single-medium deployment [21,22].

The comparison with SDR-related studies also shows the specific contribution of this work. Gavrilă et al. proposed a reconfigurable IoT gateway based on SDR, showing that SDR can support flexible gateway behavior for heterogeneous IoT environments [16]. You et al. developed a cognitive-radio-enabled smart grid testbed using SDR and real-time digital simulation, emphasizing the value of reconfigurable radio platforms in grid studies [23]. Gavrilă et al. also reported an SDR-based gateway for IoT and M2M applications, which reinforces the use of SDR as a flexible multi-interface communication platform [24]. Peñaherrera-Pulla et al. addressed the transmission and reconstruction of electrical load profiles using compression techniques and SDR wireless communication over a real channel [25]. These works demonstrate the flexibility of SDR, but they do not provide a unified smart grid analytics layer for comparing RF900, PLC, GPRS, hybrid fallback, and renewable-event traffic using the same packet-level metrics.

Table 16 compares this work with related studies.

Table 16. Comparison of related works based on communication technology, evaluation scope, and performance metrics.

Reference	Study Focus	Evaluation Scope	Metrics or Contribution
Gavrilă et al. [16]	Reconfigurable IoT gateway based on SDR.	IoT gateway architecture and SDR prototype.	Multi-interface gateway reconfigurability.
You et al. [23]	Cognitive-radio-enabled smart grid testbed.	SDR and real-time digital simulator.	Reconfigurable radio evaluation for smart grid scenarios.
Gavrilă et al. [24]	SDR-based gateway for IoT and M2M applications.	Embedded SDR gateway prototype.	Flexible gateway implementation for heterogeneous devices.
Peñaherrera-Pulla et al. [25]	Transmission of electrical load profiles.	SDR over a real wireless channel.	Signal reconstruction and energy-data transmission.
Saleem et al. [18]	Survey of smart grid communication technologies.	Communication requirements and architectures.	Classification of physical-layer technologies and challenges.
Aslam et al. [19]	Integrated modeling and simulation of control and communication systems.	Smart grid co-simulation and cyber–physical modeling.	Need for coupled communication and control analysis.
G3-PLC and hybrid PLC/RF studies [20–22]	PLC and hybrid PLC/RF behavior.	Narrowband PLC, RF, and hybrid AMI scenarios.	Impact of interference, availability, and link diversity.
This work	SDR-based smart grid performance analytics.	RF900, PLC impulsive noise, GPRS fading/outage, hybrid PLC–GPRS fallback, and renewable-event traffic simulations with USRP boundary references.	Latency, BER, PER, useful throughput, offered load, throughput decomposition, and physical-layer verification.

The differential contribution of this work is therefore the integration of SDR reconfigurability, controlled experimental-simulation references, packet-level communication analytics, and interoperability interpretation within a single framework. The platform is not presented as a complete utility field-deployment validation tool; rather, it is a reproducible engineering environment for preliminary technology comparison and for identifying the

robustness mechanisms needed before deployment. In particular, the PER results show that FEC, ARQ, interleaving, adaptive modulation, packet-size optimization, dynamic channel selection, and redundant links should be incorporated in future versions when the target application requires critical control or protection.

7. Limitations

The revised study improves methodological robustness by combining a controlled UPS SDR/USRP experimental-simulation reference with a longer simulation window, 30 independent seeds, explicit jitter distributions, residual BER values, packet-loss probabilities, a density-related congestion/drop component, and node-density sensitivity. Nevertheless, several limitations remain. First, the UPS SDR/USRP setup is a controlled academic experimental-simulation environment and should not be interpreted as a full-scale utility field deployment. Second, the PLC, RF, cellular, and hybrid impairments used in the extended comparison are stochastic abstractions and not measured channel traces from an operational utility network. Third, IEC 61850, IEC 62056/DLMS, IEEE 2030, and NIST references are represented through architecture and traffic classes only; no application-layer semantic object validation, protocol-stack conformance test, or interoperability certification is performed. Fourth, cybersecurity mechanisms are limited to logical authentication and CRC-based integrity verification; encryption, key management, replay protection, and intrusion-detection traffic are not included. Fifth, the congestion/drop term is a simplified offered-load abstraction and does not yet replace a full discrete-event implementation of CSMA/CA, ARQ, adaptive modulation, coding, queue management, or physical concentrator buffer dynamics. These aspects are required before the platform can be used for deployment certification or protection-grade communication design.

8. Conclusions

This work presented a controlled SDR-based experimental-simulation and performance analytics framework for preliminary evaluation of heterogeneous smart grid communication profiles. The revised manuscript corrected the main methodological weaknesses of the preliminary version by extending the simulation window from 20 s to 120 s, increasing the number of transmitted packets from 574 to 3444 per baseline scenario, executing 30 independent seeds, reporting 95% confidence intervals, specifying stochastic jitter and impairment parameters, and adding a node-density sensitivity analysis.

The RF900 AWGN profile achieved the lowest delay, with 36.58 ± 0.01 ms mean latency and 12.28% offered channel load, making it suitable for low-latency NAN aggregation when additional reliability mechanisms are available. The RF900 fading case confirmed that multipath degradation can increase packet loss even when latency remains low. G3-PLC achieved 53.81 ± 0.01 ms mean latency and 0.062 ± 0.002 PER, supporting its use for urban and residential AMI traffic over existing electrical infrastructure. GPRS CS2–CS3 achieved 282.54 ± 0.31 ms mean latency and 78.65% offered channel load, which limits its use to low-rate rural telemetry or backup links. Hybrid PLC–GPRS achieved the best packet-level reliability, with 0.025 ± 0.001 PER, while the renewable-event hybrid profile achieved 0.028 ± 0.001 PER and demonstrated that event-driven DER traffic can be represented within the same analytics framework.

The results support the use of centralized SDR-based analytics as a pre-deployment engineering tool for comparing latency, reliability, useful throughput, and channel occupation across RF, PLC, cellular, and hybrid profiles. The framework includes a controlled SDR/USRP experimental-simulation component at UPS, but it should not be interpreted as full utility field validation or application-layer conformance evidence. Future work will focus on hardware-calibrated multi-scenario SDR experiments, measured PLC and RF chan-

nel traces, adaptive modulation and coding, ARQ and queue management, cybersecurity overhead, IEC 61850/DLMS semantic validation, and integration with real AMI, SCADA, and renewable-generation equipment.

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