Experimental field trials of a utility AMR power line communication system analyzing channel effects and error correction methods.

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Abstract— **This paper analyses the effects of noise in a real Automated Meter Reading (AMR) environment where Power Line Communication (PLC) is used for meter reading. The aim is to give an analysis of periodic noise properties through its effect on a B-FSK based PLC system and to compare different error correction techniques under different constraints of attenuation and noise produced by the real loads installed in the network. Tests have been carried out using two different channel frequencies in the CENELEC A band taking into account frequency dependence of the line.**

Keywords— **Power Line Communication, Measurements and Channel Characterization, Forward Error Correction, Automatic Meter Reading.**

I. INTRODUCTION

The electric distribution line is a three level network. The first level is the High Voltage (HV) line, an aerial tri-phase high voltage, which connects the HV stations and the production plants through long distances. The second level, the Medium Voltage (MV) network connects the HV stations to the MV/LV transform stations through medium length lines. Finally, the LV network is the last distribution level, it has a radial structure and connects the MV/LV transform stations to the end users (both single and tri-phase).

The existing experience in the Automated Meter Reading (AMR) field shows that PLC narrow band technology is able to cover large areas or long distances ensuring the proper system performance [1]. This work studies the results of extensive experimental field trials carried out in a typical LV power line network used as a communication channel to exchange metering information, assuming a data concentrator on the MV/LV station acting as a Master in the communication with the Electricity meters, the slaves, placed at the end points of the distribution network.

In [2], [3] the fundamental properties of the Low Voltage Power Distribution Grid were analysed. Moreover the different sources of noise which affect the communication were presented. However a comprehensive statistic on synchronous noise was not given. In this paper, within the framework of a B-FSK modulation scheme we examine the effect of noise on the communication and we give an analysis of its periodic properties and effects. Furthermore the error correction capability of different codes is investigated under different constraints of attenuation and noise produced by the real loads installed in the network. In particular, the performance of four B-FSK detectors is tested: they are an uncoded system and two forward error correction (FEC) systems using respectively a binary block code of fixed length [5] and a convolutional code [6] with or without interleaving [7].

The paper is organized as follows: in Section II, the simulated field is presented together with a description of the different test's typologies, while in Section III the noise analysis is developed and the effect of different coding strategies and of frequency diversity studied. Conclusions are given in Section IV.

II. TEST BENCH DESCRIPTION

A. *Simulated Field*

The environment selected for test running and data collection is a dedicated infrastructure that ENEL built up some years ago at CESI Labs, near Milan, with the aim to validate his "Telegestore" system that indubitably is still today the worldwide biggest AMR solution in use for mass volume electricity customers.

Such simulated field is composed of real networks supplying real loads, according with the topology reported in Figure 1. In total, about 800 dummy customers, equipped with ENEL AMR meters (650 single-phase and 180 poly-phase), are supplied by feeding a spread of loads as usually happens in normal houses (e.g. PC, TV, Lamps, white goods, fans and so on). The load rate exercised over this installation is spanning from 50% to 70% and the noise level here originated, in ENEL experience is quite severe.

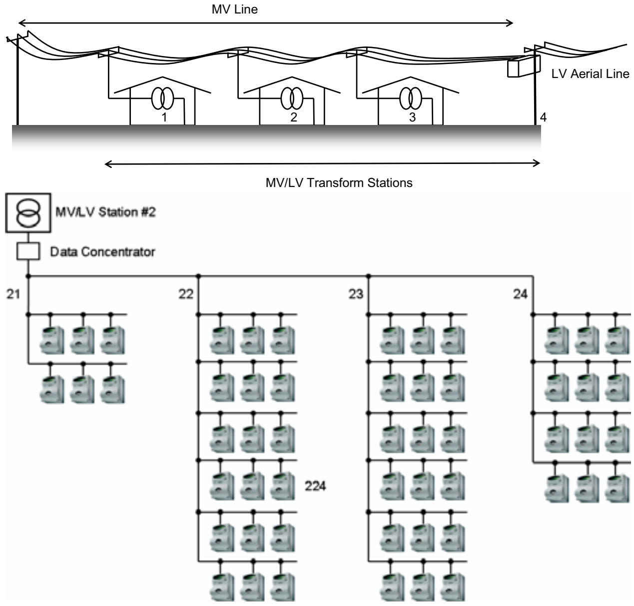

Figure 1 MV/LV transform station sub-network.

In particular, the Low Voltage network portion belonging to the transformer 2 was appointed for carrying out the trial so that suitable test nodes at variable distances in the range between 150 and 650 metres were identified.
As shown in Figure 1 under transformer station 2 there are 18 lines divided in 4 groups (from 21 to 24). Each line is divided in 3 three-phase sub-networks (Q1, Q2 and Q3)[1].

During the experimental activity several statistics were collected as well as substantive measurements both of the signal level and of the noise spectrum characteristics.

B. *Communication devices*

Channel performance has been evaluated using two ST7538 based boards. The ST7538 FSK transceiver is able to communicate at several rates (from 600 to 4800 baud) and carrier frequencies in CENELEC A band (six channels from 60 kHz to 86 kHz) for metering applications; CENELEC B and C band (110 kHz and 132.5 kHz) for Home Automation applications [4].

Following several studies and on-the-field measurement it's common knowledge [1] [3] that the CENELEC A band suffers from background noise decreasing with the frequency. Communication boards are provided with a two channel frequencies Power Line Interface, so tests have been performed at 72 kHz and 86 kHz giving interesting results on interferers frequency distribution.

In order to evaluate the effect of synchronous noise sources a Zero Crossing circuitry provided the synchronization between the transmitting unit and the Mains voltage (220VAC@50Hz), allowing an analysis on the results that highlighted some interesting properties.

All the transmission statistics, test conditions and received data have been collected through an ad-hoc software, this approach allowed an intensive post processing session and will be used also for future analysis on possible solutions.

C. *Tests description*

Automatic Meter Reading communication can be divided in three communication cases: Data Concentrator (later mentioned as concentrator) to Single Phase Electricity Meter (later mentioned as meter), meter to concentrator and meter to meter.

The first case functionally happens when the concentrator asks for data to the meters, the second case regards the meter answer and the third is a special case where the meter is used as a repeater station to reach nodes not directly reachable by the concentrator.

These three cases differ substantially in the noise and in the attenuation they have to face; this is due to the fact that main noise and low impedance source are home appliances near to the meter node.

Our tests have been divided into nine sessions: four concerning the meter to meter communication, three the meter to concentrator communication and two the concentrator to meter communication.

Sessions differ in the meter station position in the network: this implies different connected loads and distribution line lengths. Each session is composed of a number of tests variable from 8 to 32 for a total of 144 tests.

Furthermore, to cover a wide range of possible communication solutions, we have varied tests modulation parameters like the channel frequency (72 or 86 kHz), the baud rate (1200 or 2400 baud) and the employed error correction method: an un-coded system, a block coded system and two convolutional code based systems with or without interleaving.

Each test consists in the transmission of a frame the format of which is sketched in Figure 2. After a preamble, a four bytes Unique Word, which permits, at the receiver side, frame detection and synchronization even under very noisy environments, is transmitted. After the Header, a 40 byte payload protected with cyclic Frame Check Sequence (FCS) for error detection and, in case, with the Forward Error Correction (FEC) methods above mentioned is sent. More details about the frame format can be found in Table 1.

Figure 2 Message Format

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[1] In Figure 6 of Section III the line 224 is depicted with its three sub-networks.

Table 1. Frame Length with different Coding Techniques

Frame section	Frame section length (bytes)			
	Not Coded	*Block Code*	*Convolutional Code*	*Convolutional Code plus Interleaver*
Preamble[(1)]	5	5	5	5
Unique Word[(1)]	4	4	4	4
Coding Mode[(1)]	1	1	1	1
Frame Header	5	10	10	10
Frame Header FCS	1	2	2	2
Payload	40	80	80	80
Payload FCS	2	4	4	4
Additional bytes due to Codec	0	0	2[(2)]	9[(3)]
Total Frame length	**58**	**106**	**108**	**115**

(1) = Un-coded bytes

(2) = 1 Byte is used to empty the Convolutional Shift Register encoder (giving 2 coded bytes).

(3) = 1 Byte is used to empty the Convolutional Shift Register encoder (2 coded bytes), 7 Bytes are used to fill the interleaver.

D. Effect of heavy loads on transmitter units

The use of a non-dedicated line, like the electric distribution network, for data transmission involves some drawbacks which are common to other communication lines, mainly signal attenuation and high noise level at the receiver. Moreover the connection of loads to the mains alters the network impedance with heavy consequences both at the transmitter and at the receiver side.

A low impedance load connected close to the receiver reduces the amount of signal power received resulting in a higher line attenuation.

In an ideal system, with virtually infinite power capability, a heavy load close to the transmitter shouldn't affect the communication, so it could be neglected since the transmitter can act as a voltage controlled signal source. Nevertheless, in the real world, the transmitter power capability is finite so, if the line impedance at its side becomes lower than a certain value $|Z_0|$, the transmitter acts as a current controlled signal source and the output voltage decreases with the line impedance.

The data concentrator is usually placed on the MV/LV transform station at several hundreds of metres far from end users, and thus is not affected by low impedance effects. Meters, on the other side, are connected to the end user wiring and, thus, can experience such heavy loads.

III. RESULTS ANALYSIS

A. Noise analysis

The noise over the electrical network can be catalogued following different criteria. In this paper we focus on two characteristics: regularity and sources of noise.

Regularity. We'll divide noise effects between those that are synchronous with the mains 50Hz wave, later on referred as "synchronous noise", and those that are either non-periodic or not synchronous with the mains wave and we'll refer to it as "asynchronous noise".

Sources. We'll analyze the effect of noise generated on the same phase and sub-network where the communication takes place and we'll measure the effect of contiguous sub-network and contiguous phases noise.

B. Asynchronous noise

As described in [3] there are mainly two types of asynchronous noise namely background noise and impulsive asynchronous noise. In [3] background colored Gaussian noise is analyzed and a mathematical model of its power spectral density is given while a study of asynchronous impulsive noise is only sketched. In order to characterize this kind of noise we tried to analyze the burst errors seen at the receiver side, focusing on two characteristics:

- The length of the burst.
- The distance between two consecutive bursts.

The modulation used in these tests, a binary FSK, is strongly affected from error polarization when the interferer is not centered in the communication channel giving an equivalent asymmetric binary channel. To take into account this effect we evaluated as a burst an error sequence with no more than 8 consecutive correctly received bits.

Unfortunately we couldn't collect enough data to have a reliable statistic, since the majority of tests evidenced the presence of strong synchronous noise sources.

C. Synchronous noise

Synchronous noise is generated by devices having impulsive power absorption synchronous with 50Hz voltage peaks (e.g. SMPS, lamp ballast, PFC and so on); its effects have been studied in order to define two characteristics:

- Burst repetition frequency.
- Burst error length.

To analyze the synchronous noise effects we collected the error distribution compared to the 50Hz mains AC phase (i.e. number of errors related to their distance from the mains AC voltage zero crossing). We took into account not only the transmission phase, always the S phase, but also the other two phases, the so called R and T phases.

As shown in Figure 3 and Figure 4 we can have, generally, two cases:

1. Only one phase produces noise, in this case the burst repetition frequency is 100Hz, i.e. a minimum burst distance of 10ms (see Figure 3).
2. The noise affecting the communication is generated over more than one phase, in this case the minimum burst distance is 3.3ms (see Figure 4).

It's our opinion, in fact, that the behavior seen in Figure 4 is due to the effect of loads in different phases (in this case the phase S, the communication phase, and the phase R).

To analyze the burst length through its effects on the communication, we extrapolated from the collected data the cumulative probability distribution (CPD) of the burst length at different BER conditions, results are depicted in Figure 5.

As shown in Figure 5 the burst error length is proportional to the BER, and thus to the SNR, so it's important to know at which SNR the system should work to extrapolate the longest burst the system should correct. For instance at a BER = 10^{-3} the duration of more than 80% of bursts is less than 2 ms.

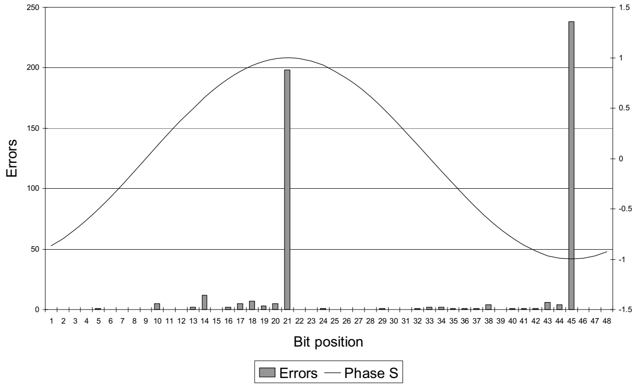

Figure 3 Errors distribution due to noise synchronous with one phase.

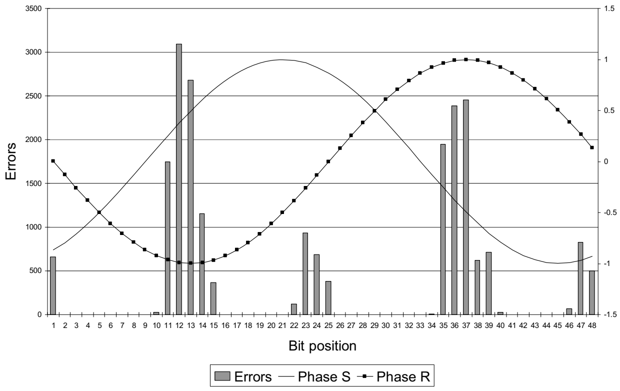

Figure 4 Errors distribution due to noise synchronous with more than one phase.

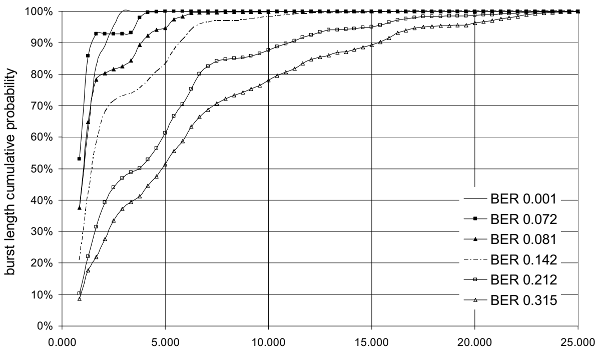

Figure 5 Burst length cumulative probability distribution at different BER conditions.

D. *Noise sources*

The noise at each PLC node can be seen as composed of noises coming from several source lines:

- Noise generated on meter sub-network.
- Noise generated in contiguous sub networks in the communication phase
- Noise generated in phases other than the one used to communicate.

The noise spectrum at the node 224Q3 phase S (Figure 6) due to the contribution of the entire network is shown in Figure 7. A narrow band interferer with frequency of 28 kHz (due to a lamp ballast) and its harmonic components are visible as well as a 40 kHz narrow band noise (due to a Switched Mode Power Supply). In Figure 8 the noise spectrum at the same node due to the external sub networks 224Q1 and 224Q2 is shown (in our case users on 224Q3 S, R and T phases were disconnected and the nearest sub network is 200 m far). Finally, in Figure 9 the noise spectrum at the same node, the 224Q3 phase S, due to the contribution of 224Q3 R and T phases only is depicted. While the effect of external sub-networks noise is not so easy to detect, the effect of noise coming from the other phases (R and T in our case) can be seen in Figure 4 where the majority of errors is due to noise generated in a phase other than the one where communication takes place.

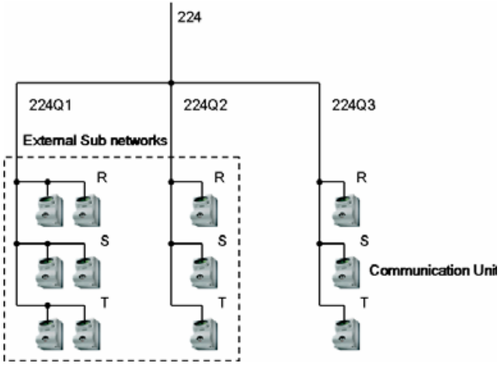

Figure 6 Subnetwork 224 scheme.

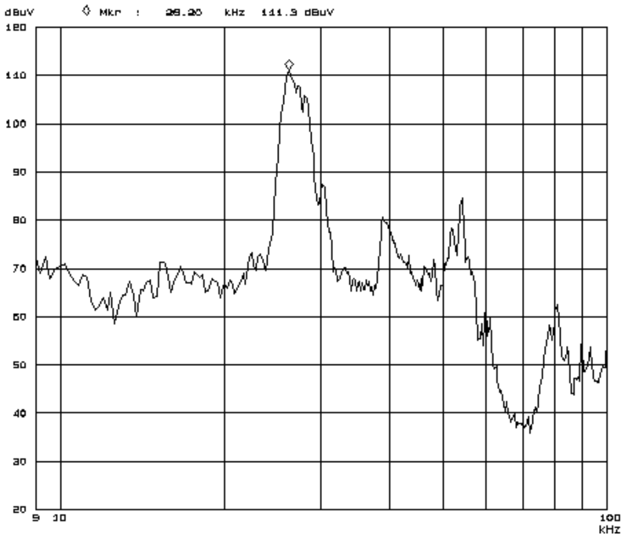

Figure 7 Noise spectrum measured at the node 224Q3-S generated on the same phase.

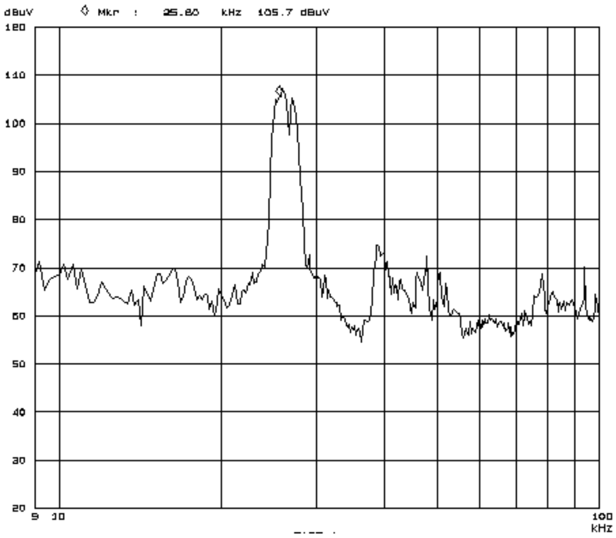

Figure 8 Noise spectrum measured at the node 224Q3-S generated on the external sub-networks.

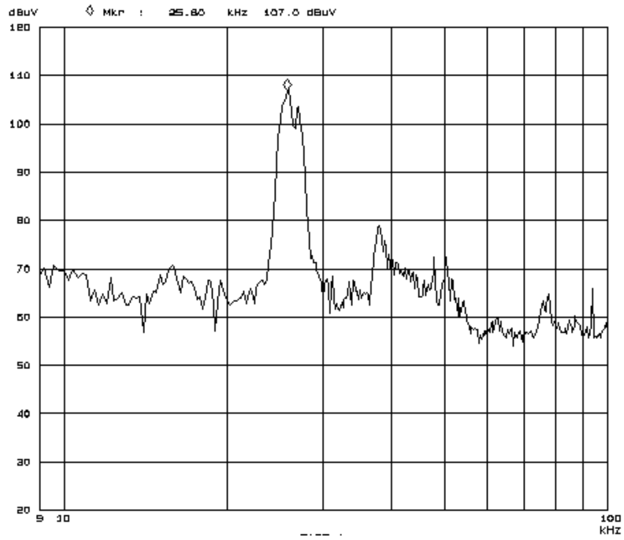

Figure 9 Noise spectrum measured at the node 224Q3-S generated on the other phases of the same sub-network.

E. *Coding gain*

The analysis on coding techniques performance has been done taking results from all the sessions grouped by coding method.

The complete comparison between coding techniques used in our tests is reported in Figure 10.

The block code here employed is a cyclic burst correcting code, described in [5], which can correct up to 3 consecutive errors. Its drawback is the impossibility to correct two or more isolated errors affecting a codeword. As Figure 5 shows, these types of errors are likely to occur due to the extended burst duration. Nevertheless, the block code offers a gain with respect to the un-coded system of about 2.5 dB.

The convolutional code is a rate ½, free distance maximizing, constraint length 5 convolutional code [6] decoded with hard Viterbi algorithm. It yields a further gain of 1.5 dB with respect to the block code. A soft decoding algorithm should give a higher gain.

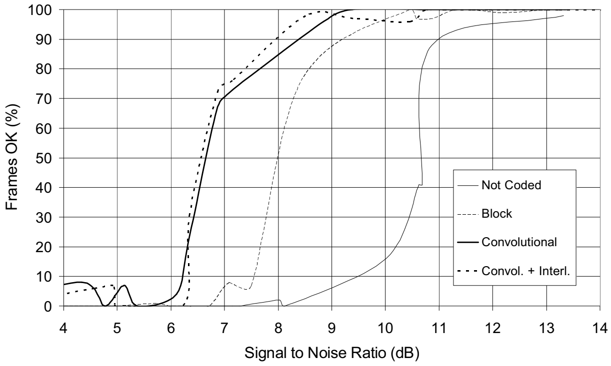

Figure 10 Different coding techniques performance comparison.

F. *Effect of interleaver introduction*

A classical solution to cope with a bursty channel consists in associating to the structure encoder-decoder the couple interleaver-de-interleaver [7]: the encoder output is sent to the interleaver; when reception takes place, the de-interleaver spreads the errors making more efficient the decoder work. The interleaver adopted in our experiments has the following characteristics:

i) Every burst which affects less than 9 bits results at the de-interleaver output in isolated errors separated by at least 6 bits

ii) Bursts with length greater than 8 bits result in errors separated by less than 6 bits

iii) A periodic sequence of isolated errors spaced by 8 bits results in a burst error.

In general the interleaver design should be a tradeoff among performance conditions like i), ii), iii), cost and protocol constraints.

In our specific case, if we fix our attention only on the noise synchronous with one phase, we note that we can easily derive the results summarized in Table 2.

The second column of Table 2 together with a careful examination of Figure 5 shows that performance improvements due to interleaving are possible only with a burst duration smaller than 2.5 ms. This could appear a success looking at the percentage of burst which satisfy this condition. In fact we must consider that noise can be synchronous with more than one phase (Figure 4), thus strongly penalizing the aforementioned improvements. Indeed a maximum gain of 0.5 dB is achieved with respect to the non interleaved convolutional code solution. Due to the irregular distribution of burst duration, we can conjecture that the increase of the baud rate, by enlarging the bit distance from two successive burst could amplify the interleaver gain.

Table 2

Baud Rate	Distance between two successive bursts
1200	12 bit
2400	24 bit

G. *Frequency diversity effects*

To analyze the effect of frequency and baud rate diversity on communication performance, the number of correctly received frames has been correlated to the channel and baud rate used for the tests.

Results have shown a strong effect of frequency diversity at the considered channel spacing of 14 kHz: 89% of the best communications (the ones with the greatest number of correctly received frames) took place on the 86 kHz channel, whilst the 72 kHz channel resulted the best one in 11% of the tests.

In 4 cases over 10, by changing the channel frequency, the percentage of received frames has increased of about 50% for the un-coded system up to 70% for the interleaved convolutional coded system. For instance for the un-coded system the percentage of correctly received frames has reached 54% by using the 86 kHz channel instead of the 72 kHz one where only 2% of frames were received.

IV. CONCLUSIONS

The analysis made on these field trial sessions gives us some interesting results that help to better understand the characteristics of the low voltage distribution network and will lead to an IC and protocol design tailored on this communication channel.

First of all we realized that meter to meter communication is by far the most difficult, whilst concentrator to meter is the best one. This can be explained with the loads and noise produced by home appliances that are closer to the meters; for this reason a communication protocol should try to maximize direct communication, using repeaters only for problematic situations.

Our analysis on synchronous noise effects shows the impact of all three phases on the communication and gives a method to estimate the length of noise bursts and the distance between them. This information is very useful to take the correct countermeasures against this kind of noise, for example an interleaving block with an appropriate length. As mentioned before, since the burst duration seems to be so irregular, we can conjecture that the increase of the baud rate, by enlarging the bit distance from two successive bursts, could amplify the interleaver gain.

Figure 10 shows that a proper error correction strategy can have a strong impact on single node reachability, allowing a reliable communication where an un-coded system is no more able to receive. In term of coding performance, the interleaved convolutional code solution would be the preferred choice. However, in our application, we must take into account even the system complexity: while, in fact, block decoding has a very low complexity, the Viterbi decoding algorithm is more expensive and may require an hardware implementation.

Finally the big change in communication performances found with frequency diversity, shows the great opportunity to fight against power line impairments and selective noise through a dual channel system, especially when the system is able to take advantage of coding gain.

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