Reliable Communications with Network Coding in Narrowband Powerline Channel

Josu Bilbao, Aitor Calvo and Igor Armendariz
Communications Department
IK4-Ikerlan
Mondragon, 20500 Spain
Email: jbilbao@ikerlan.es

Pedro M. Crespo
Electronics and Communications Dept.
IK4-Ceit and
tecnun University of Navarra
San Sebastian, 20018 Spain
Email: pcrestpo@ceit.es

Muriel Médard
MIT
Research Lab. of Electronics
77 Massachusetts Avenue
Cambridge MA 02478 USA
Email: medard@MIT.EDU

Abstract—Due to its wide availability narrowband powerline networks provide an interesting no-new-wires communication channel. Nevertheless, as powerline was not designed for data communication, its electrical characteristics make it a harsh environment for data transmission and prevents the deployment of services with high reliability requirements. This paper presents 3 main outcomes: (i) The characterization of the transmission error correlation among different nodes in a narrowband powerline network, which acts in favor of the cooperative schemes. (ii) Based on the conclusions obtained from real measurements campaign, we propose a new OSI-Layer2 scheme based on Network Coding to achieve reliable communications in narrowband powerline. (iii) We demonstrate the benefits of the proposed scheme validating its real implementation in an embedded system, and comparing the achieved performance improvement with different legacy ARQ schemes.

Keywords—ARQ; implementation; narrowband; network coding; noise model; OPNET; powerline; PLC; reliable communications.

I. INTRODUCTION

Narrowband powerline networks provide an interesting communications alternative for scenarios where a communications infrastructure deployment is costly or architecturally difficult, and there is an electrical power distribution wiring available.

The main purpose of the powerline network is power distribution. Its wide availability in any scenario with power supply requirements has generated an increasing interest in the use of this media as a no-new-wires communication channel. However, its electrical characteristics and the quality of the used physical medium makes this network a harsh environment for data communications [1], [2]. Therefore, designing robust and reliable transmission schemes for powerline communications networks is a challenge for the research community, and it is the main goal of this paper.

Due to the several effects as the capacitive coupling between different lines and the unstructured deployment of the transmission lines, powerline channel becomes a medium more similar to wireless than to wired ones. Hence, as data transmission over powerline networks shares several similarities with wireless communication [3], the schemes designed for wireless environments can be potentially applied in powerline communication networks (PLC). An example in the line of recent works is the use of wireless relaying techniques in PLC networks as is the case of the proposal of using cooperative coding with Reed Solomon (RS) and Hamming codes [4], or the proposal of using FEC mechanisms based on bit repetition and voting on reception to mitigate impulsive noise effects [5]. Unlike classical schemes that use a coding-decoding chain, the scheme proposed in present paper allows networked nodes to encode the frames previously coded by the source node, and cooperate with the information distribution improvement until it is finally decoded at destination node.

The main purpose of present work is to provide an OSI-Layer2 mechanism in order to improve reliability in the narrowband powerline C-Band (132.5 kHz) as defined by CENELEC EN-50065 standard [6]. This standard defines the frequency bands, signal levels and medium access techniques to be used, and has been widely adopted by both in-home and industrial scenarios [2].

The design of communication protocols able to provide reliability in narrowband powerline must consider the peculiarities of the error pattern nature in the narrowband powerline channel. To that end, the authors have made important experimentation efforts as well as measurement campaigns [2].

In the previous literature, several schemes for the powerline channel have been proposed based on cooperation [3], [4], and relay-aided amplify-and-forward communications [7]. However, to the best of our knowledge, this is the first work proposing the use of Network Coding (NC) in narrowband powerline.

A selection of interesting and promising research areas in the design of protocols for industrial wireless communications is discussed in [8], and NC is glimpsed as a future research field to full-fill the required QoS constraints. Given the communication problem similarities in both channels and the mentioned harshness level of the powerline channel, NC postulates as an interesting research field. Here we propose an OSI-Layer2 mechanism (link layer) based on NC, which improves the behavior and reliability of the communications in narrowband powerline harsh environments due to a cooperative scheme among nodes.

The rest of the paper is organized as follows: Section II describes the harsh nature of the narrowband powerline channel. Section III describes the algebraic fundamentals over which the
proposed communication scheme is based on, as well as the state of the art and related previous work on the use of NC to provide reliable communications in lossy networks. Section IV describes the conclusions obtained from the experimentation and the analysis of the bit error correlation between different locations of the powerline network, and details the proposed communication scheme. Section V demonstrates the virtual model validation versus real implementation and describes the results of the comparative benchmark among ARQ legacy schemes and the proposed one, highlighting the obtained benefits for flows with hard reliability requirements.

II. HARSH SCENARIOS

A. Error sequence $e[t]$ in narrowband PLC

The design of the scheme and the benchmark of the behavior achieved by the new proposed communication mechanism requires the knowledge of the nature of the channel and the error pattern in real scenarios.

In contrast to other communication channels, the powerline channel cannot be modeled as an additive Gaussian noise (AWGN). Multipath effects due to impedance mismatch, attenuation and noise factors severely degrade communications, with noise being the main source of errors in PLC [9].

Despite the different types of noise considered in [1], the experimental measurements carried out by the authors of the present paper detailed in [2] ratify that the narrowband interferences and the periodic impulsive noise synchronous to the mains frequency (50/60 Hz) are the main predominant disturbance in the frequency band under study.

In this work, the errors produced by the powerline network are characterized by obtaining binary error sequences $e[t] = \{e_i : i = 1, 2, \ldots\}$, so that the overall received binary sequence $y[t]$ can be computed as $y[t] = x[t] \oplus e[t]$, where $x[t]$ denotes the transmitted binary sequence. This error characterization is based on the previous work presented by the authors in [2], where a fast and precise technique for bit error sequence characterization of a point-to-point narrowband powerline channel at a bit abstraction level (above OSI-Layer1) was presented. This approach will facilitate the comparison of new narrowband powerline protocols over realistic scenarios. Taking into account that the present paper proposes a cooperative model among networked nodes, it is important to know the correlation degree of the losses in narrowband PLC. To that end, the method proposed in [2] was modified to allow necessary synchronization for a parallel multichannel sampling (see section IV) and observe the behavior of the error sequence in different locations simultaneously.

The extensive measurement campaign helped the authors to detect a self-similar structure in the narrowband powerline channel bit-level error sequence $e[t]$, which shows a long-range dependence of the error sequence in the range of 10 ms up to tens of seconds with a heavy-tailed nature of the real error pattern distribution. This self-similar structure shows the conservation of the statistical parameters of the error sequence over different time integration scales, reflecting both noise, switch on/off and plug/unplug effects among others.

The error sequence variance evolution over varying observation time scales (variance-time plot), decays quickly before 10 ms time scales but is maintained with slow decay until several seconds time-scale integration, (with a measured Hurst Parameter $H \approx 0.77$ from experiments in [2] for narrowband powerline channel).

The realistic bit-error model derived from [2] is used to obtain simulation results and benchmarking with varying harshness level in discrete event simulator OPNET to compare results obtained with the proposed method faced with ARQ (Automatic Repeat Request) schemes. This paper validates obtained results with real measurements in scenario detailed in Fig. 2.

Channel characterization has a strong dependence on the number and nature of the elements plugged and/or switched on, affecting directly to the noise pattern. Therefore the benchmark study takes into account the varying conditions of the channel harshness (from low-harshness to harsh scenarios).

III. RELIABLE COMMUNICATIONS WITH NC

A. Network Coding and reliable communications

The emergence of the new Information Theory field known as Network Coding has originated a new approach with mechanisms enabling new achievable limits for the communication channel. Since the seminal work from one of the co-authors of the present paper [10], many new schemes have been proposed in bibliography based on RLNC (Random Linear Network Coding) to improve the reliability of communications in lossy networks with intra-flow NC schemes, as is the case of [11]. The introductory survey in [12] points out several other examples that propose NC to improve the communications reliability.

Generalizing the outgoing linearly combined packet generation statement in [11], it can be considered that the transmission is defined by a system of equations known as the “Transmission Matrix” ($G_t$). Lets consider $P_{in}$, as the $i$-th original information packet. We can consider $G_t$ compounded of a bucket of $K$ incoming information packets multiplied by ($\xi_i(k)$) randomly chosen coefficients in the Galois Field ($GF = 2^8$), being $K$ the “Generation Size” ($G_{size}$) or the number of packets involved in the linear packet combinations. The following linear system of equation defines the generation of the linearly combined outgoing packets $P_{out}$.

$$
\begin{pmatrix}
P_{e1} \\
P_{e2} \\
P_{e3} \\
\vdots \\
P_{ek}
\end{pmatrix}
= 
\begin{pmatrix}
\xi_1(e_1) & \xi_2(e_1) & \cdots & \xi_K(e_1) \\
\xi_1(e_2) & \xi_2(e_2) & \cdots & \xi_K(e_2) \\
\xi_1(e_3) & \xi_2(e_3) & \cdots & \xi_K(e_3) \\
\vdots & \vdots & \ddots & \vdots \\
\xi_1(e_K) & \xi_2(e_K) & \cdots & \xi_K(e_K)
\end{pmatrix}
\begin{pmatrix}
P_{i1} \\
P_{i2} \\
P_{i3} \\
\vdots \\
P_{ik}
\end{pmatrix}
$$

A receiver node $R_{ex}$ requires the reception of only any $K$ linearly independent packets, to be able to solve the equation system and decode the original information. Hence, if any node overhears the information, although it is partially, can collaborate generating linear combinations of the information packets previously heard and contribute to complete the information in the receiver node.

Unlike mechanisms in [4] and [5], the use of NC does not require to decode the information by the cooperative nodes,
but these can re-encode the received frames and cooperate to complete the information in destination, where receiver nodes will be able to decode. This process entails a huge simplicity in the relay (or cooperation) process, besides providing a node be able to cooperate even if it does not receive whole information.

B. Proposed scheme: GalaReS

Present paper proposes a decentralized inter-node and intra-flow NC collaborative scheme known as GalaReS, which is based on a HelpRequest–HelpResponse mechanism in order to improve the reliability of the narrowband PLC. The proposed scheme has been designed to fit in the OSI-Layer2 in order to provide a reliable communication layer over the narrowband powerline MAC standardized by CENELEC. Nevertheless main concepts and principles can be adapted to be used in every OSI layer above.

IV. NC in narrowband PLC

A. Uncorrelated losses in CENELEC narrowband powerline

**Theorem:** The maximum rank that can be achieved by a given receiver thanks to the use of NC is delimited by the information distributed to the network as a whole, so that:

$$ p[k] = \left( G_{size} \right)_k \cdot P_{netEquiv}^{-k} \cdot (1 - P_{netEquiv})^k $$

(2)

Where $p[k]$ is the probability that a receiver reaches $k$ degrees of freedom of the transmitted equation system after the collaboration process, $G_{size}$ the generation size or number of packets used in the linear combination process and $P_{netEquiv}$ the probability that none of the nodes in the network hears the transmission of a given packet. The mean value of the achievable degrees of information is therefore:

$$ E[doj] = \sum_{k=0}^{G_{size}} k \cdot p[k] $$

(3)

**Proof:** In order to calculate the probability of correctly receiving the packets by the network as a whole, we will use the Set theory to estimate the expression of $q_{netEquiv}$, and $(P_{netEquiv} = 1 - q_{netEquiv})$. For this, we consider the sample space of packets received by the whole network set $(Q_{netEquiv})$ as the union of the $Q_i$ sample spaces received by the different $n$ receiver nodes $R_{i=1,...,n}$, so that:

$$ \mathbb{P}\left( \bigcup_{i=1}^{n} Q_i \right) = \sum_{i=1}^{n} \mathbb{P}(Q_i) - \sum_{1 \leq i < j \leq n} \mathbb{P}(Q_i \cap Q_j) + \sum_{1 \leq i < j < k \leq n} \mathbb{P}(Q_i \cap Q_j \cap Q_k) - \cdots + (-1)^{n+1}\mathbb{P}(Q_1 \cdots Q_n) $$

(4)

Let's consider that the probability of losing a packet is independent from the rest of the packets of the same generation. As the packet loss probability varies slowly, it can be considered stationary for the whole generation ($G_{size}$) [2].

If we consider a scenario with a transmitter node $T$ and 2 receiver nodes ($A$ and $B$), we can study the following possible cases for the analysis of the information spread all over the network:

**Case a)** If the loss pattern of the different links can be considered as an independent process, the calculation of the probability that the whole network receives the information correctly can be expressed so that: $\mathbb{P}(Q_A \cup Q_B) = \mathbb{P}(Q_A) + \mathbb{P}(Q_B) - \mathbb{P}(Q_A \cap Q_B) = \mathbb{P}(Q_A) + \mathbb{P}(Q_B) - \min(\mathbb{P}(Q_A), \mathbb{P}(Q_B)) = \max(\mathbb{P}(Q_A), \mathbb{P}(Q_B)).$

**Case b)** If perfectly correlated losses are considered, we have that the sample space of the information received by the receiver nodes fulfills that $Q_i \subseteq Q_j$, and the value of $q_{netEquiv}$ can be calculated so that: $\mathbb{P}(Q_A \cup Q_B) = \mathbb{P}(Q_A) + \mathbb{P}(Q_B) - min(\mathbb{P}(Q_A), \mathbb{P}(Q_B))$.

Hence, depending on the losses correlation degree, a different upbound limit is reached for the probability of reconstructing the information in receiver nodes, being the case with uncorrelated losses the most favorable.

It can be deduced from the described expressions that the more population of nodes in the network, the more probable to complete the information due to cooperation among nodes. The following section proves that the losses in different locations of narrowband powerline are highly uncorrelated, and therefore it shows a great potential to employ NC techniques.

B. Loss correlation measurement field trials in powerline

The mutual information degree $MI(R_i, R_j)$ shared by the different receiver nodes $(R_{i=1,...,n})$ in the network, shows the measure in which different nodes have received the same information, or they have received the complementary one that allows to mend the original information through the cooperation among nodes. The correlation degree of the losses produced between different receiver nodes $R_i$, allows therefore the analysis of the potential degrees of freedom distributed all over the network, and the study of the upper-bound of the information that can be reconstructed even in case of an eventual transmitter node disconnection.

**Lemma:** The less mutual information between receiver nodes (more uncorrelated losses), the greater the potential benefit of the cooperation between nodes, taking into account that thanks to Network Coding, the nodes can rebuild the information distributed in the whole network by the transmitter.

**Remark:** The proposed cooperative protocol helps the receiver node(s) reach the degree of information achieved by the whole network $\bigcup_{i=1}^{n} R_{x,i}$ where $R_{x,i}$ represents the sample space of the received information by each $i$-th collaborative node $R_{x,i}$.

The measurement campaign and the numerical results have been carried out for a single-carrier FSK system used in multiple home automation and industrial applications in CENELEC C-Band. To analyze the error pattern $e[t]$ for each location a low cost embedded system with a 8 bit microcontroller (NEC78K0/KC2) has been used. It has an FSK modem (ST7538Q) which is used to oversample (x4) the
original pseudorandom pattern transmission @4800 bps as is described in [2]. In order to analyze the correlation of the losses between different locations, a Virtex-4 (XC4VFX20) FPGA development kit has been used. The FPGA is connected to each receiver node to sample the reception pins of the bridges in a simultaneous way, in order to analyze afterwards the degree of correlation of the errors.

It can be observed in Table I the results obtained from the process of characterization of different indoor low-voltage and 50 Hz narrowband powerline channels (see Fig. 2). It can be highlighted that, besides the varying harshness with errors due to a predominant impulsive noise synchronous to the mains (zero crossing), there is an important degree of uncorrelation between the losses observed in each receiver node. Column $A - B$ indicates the percentage of errors in $A$ which do not take place in $B$, and $A \setminus B$ shows the percentage of correlation of the losses or losses coincidental in both locations, observing values below 20% in most of the experiment sets.

<table>
<thead>
<tr>
<th>Set1</th>
<th>Transmitter</th>
<th>$R_{x1}$</th>
<th>$R_{x2}$</th>
<th>$A - B$ [%]</th>
<th>$B - A$ [%]</th>
<th>$A \setminus B$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set1</td>
<td>Backstg-1(1)</td>
<td>FrontR(O)</td>
<td>FrontR(O)</td>
<td>55.06</td>
<td>60.42</td>
<td>4.52</td>
</tr>
<tr>
<td>Set2</td>
<td>Backstg-1(1)</td>
<td>FrontR(O)</td>
<td>FrontR(O)</td>
<td>51.86</td>
<td>32.94</td>
<td>17.85</td>
</tr>
<tr>
<td>Set3</td>
<td>Backstg-2(2)</td>
<td>FrontR(O)</td>
<td>FrontR(O)</td>
<td>60.09</td>
<td>47.40</td>
<td>2.25</td>
</tr>
<tr>
<td>Set4</td>
<td>Backstg-3(3)</td>
<td>FrontR(O)</td>
<td>FrontR(O)</td>
<td>60.09</td>
<td>41.32</td>
<td>18.57</td>
</tr>
<tr>
<td>Set5</td>
<td>BelowSink(4)</td>
<td>FrontR(O)</td>
<td>FrontR(O)</td>
<td>58.48</td>
<td>42.89</td>
<td>18.51</td>
</tr>
<tr>
<td>Set6</td>
<td>Hall(10)</td>
<td>Hall(10)</td>
<td>FrontR(O)</td>
<td>58.47</td>
<td>53.85</td>
<td>7.68</td>
</tr>
<tr>
<td>Set7</td>
<td>Desk(8)</td>
<td>FrontR(O)</td>
<td>FrontR(O)</td>
<td>55.52</td>
<td>42.83</td>
<td>8.85</td>
</tr>
<tr>
<td>Set8</td>
<td>FrontR(6)</td>
<td>FrontR(6)</td>
<td>FrontR(6)</td>
<td>62.85</td>
<td>57.14</td>
<td>0.80</td>
</tr>
</tbody>
</table>

![Fig. 1. Error ($e(t)$) sample space correlation graphical view.](image1)

![Fig. 2. Embedded system Lab. floor plan and node (1-10) location.](image2)

**TABLE I. ERROR MEASUREMENTS IN EMBEDDED SYSTEM LAB.**

Fig. 3. GalaReS OSI-Layer structure.

**C. Inter-node NC cooperative scheme**

Thanks to the cooperative mechanism, the probability that a node can complete the information, even if the transmitter ($Tx$) node fails, is reduced to the fact that the whole network receives the information and can rebuild it in the different receiver nodes using cooperative mechanisms. Therefore, given the highly uncorrelated errors observed, the use of cooperation based on NC mechanisms approach is remarkably useful, since the collaboration scheme can reach the upbeat limit of the information overhead by the whole network.

The proposed mechanism is based on the GalaReS sublayer (see Fig. 3), which receives the packets with the information to be transmitted from the upper OSI layer. Depending on the value of $G_{size}$, which could be variable, the transmission matrix $(G_t)$ is composed combining the packets with randomly selected coefficients to create linearly independent combinations. The combined packets are then transmitted (broadcasted) to the network. The GalaReS scheme allows the concatenation of up to a number $w$ of simultaneous generations creating a Sliding Window. It should be stressed that in order to minimize the information packet overhead, random coefficients can be picked up from a Vandermonde type matrix in the source node. The resume of the transmitter process state machine is shown in Fig. 4 (with $w = 1$ for representation simplicity).

If the receiver process obtains a new linearly independent packet, the rank of the received information matrix is increased in destination and received packet is included in the decoding matrix, or discarded otherwise. Depending on the adaptive timeout explained in [12], or if the receiver node detects that it does not receive the complete generation after the sliding window advance in transmission, so that $rank(R_{x1}) < G_{size}$, the receiver process transmits a HelpRequest packet asking for help to the rest of the potential cooperative nodes. See Fig. 6 for details on the state machine.

As soon as a cooperative (or relay) node receives the help query, if it has complementary information, it will respond with a HelpResponse packet compound of a linear combination of the packets it has overheard with the aim of increasing the rank of the receiver node. The relay node can send as many HelpResponse packets as degrees of freedom can provide to the final receiver. The relay process state machine is summarized in Fig. 5, and a example of GalaReS behavior is depicted in Fig. 8.

The GalaReS layer works in 2 stratum. On the one hand, there is a generation “manager”, in charge of sending available packets to start new generations, declare the obsolete
ones, erase them, etc. Once a generation is acknowledged it will advance in the sliding window. On the other hand, each generation behaves independently from the others, and the packets and notifications that it receives are exclusively dedicated to it. This way, these 2 strata are isolated and make possible the management of the Sliding Window scheme.

D. MAC in CENELEC C-Band

The medium access for the C-Band of CENELEC standard comes defined by [6], and we have used the same MAC sublayer for every protocol analyzed in the benchmark in order to obtain a fair comparison (see Fig.3). The maximum time allowed for a continuous transmission is 1 s, and a node must detect an inactivity period of the bus and access the medium after a random waiting time between \( t_{mac} \approx 85-115 \) ms. After a transmission a node must wait at least 125 ms before trying to access the medium for a new transmission.

When choosing a suitable \( G_{size} \) it is important to consider the maximum time a node is able to transmit continuously by CENELEC. From the extensive number of experiments done during this research work, an optimum 25 Byte payload (see frame description in Fig. 7), and \( G_{size} = 8 \) have been selected as a trade-off solution for varying harshness environments.

V. REAL IMPLEMENTATION

Besides the virtual model, the proposed scheme has been implemented into a real embedded system compounded by the bridge module described in previous paragraphs as the phy layer (@4800 bps), and implementing the MAC layer [6] and the proposed NC scheme in a Cortex-M4 (STM32F407), both connected via serial port (see Fig. 3). It can be observed in Fig. 9 that the results reached in the virtual implementation (OPNET) are inside the 95% confidence interval of the results in real implementation. This validation improves the efficiency for further multiparametric studies with the virtual model.

A. Reliable unicast flow experimentation

Although the concept of reliability can be very general, we have selected the achievable maximum throughput \((\gamma_{max})\) and link-failure ratio as the criteria for the design and selection of the optimal protocol.

Results in Fig.10 show the comparison between the maximum achievable throughput in narrowband powerline for different schemes using single carrier FSK modem @4800 bps and varying BER \((0 \leq p \leq 0.005)\) in the transmitter to receiver channel. Measurements show that the proposed scheme outperforms legacy ARQ schemes (Stop-and-Wait, Go-Back-N with \( N = 8 \) packets and Selective Repeat with \( w = 8, 32 \) packets window).

It can be observed that GalaReS improves achieved \( \gamma_{max} \) even when there is no packet loss, due to the correct selection of the \( G_{size} \) and the generation based ACK scheme that optimizes the use of the CENELEC band. Go-Back-N degrades its performance while loss rate increases, while Stop-and-
maintained highly stable within introduced with a potential relay node, the throughput is with high BER. However, when the cooperative scheme is Wait and Selective Repeat decay slowly. It can be highlighted communications reliability in lossy powerline links.

This fact opens an interesting framework for mechanisms based on cooperative schemes in order to improve commun-

losses of different locations in narrowband powerline channel.

The present paper shows a high level of uncorrelation between the relay eliminates any packet loss.

and source coding, whereas the insertion of the cooperative study. Packet losses are reduced significantly with GalaReS indicates the number of packets definitely lost after the maximum improvements and benefits in the system behavior are described, detailing the achieved higher transmission rates, lower completion time and link-failures elimination under varying harshness scenarios.

VI. CONCLUSION

Thanks to the number of experiments carried out, the present paper shows a high level of uncorrelation between the losses of different locations in narrowband powerline channel. This fact opens an interesting framework for mechanisms based on cooperative schemes in order to improve communications reliability in lossy powerline links.

Present paper proposes an innovative scheme based on Network Coding as an OSI-Layer2 cooperative algorithm (GalaReS). Subsequently the validation of the scheme is demonstrated with the comparison of the results reached by the implementation in a low cost embedded system for both legacy ARQ schemes and the new proposed one based on NC. Finally, the observed important improvements and benefits in the system behavior are described, detailing the achieved higher transmission rates, lower completion time and link-failures elimination under varying harshness scenarios.

REFERENCES


