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An efficient network coding scheme for reliable multicast power line communications

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ABSTRACT

Nowadays, Power Line Communication (PLC) technology is receiving a renewed attention for a wide class of innovative applications and services, mainly thanks to the advantage of using the existing electrical infrastructures, thus reducing the deployment costs. However, such electrical infrastructures have been originally conceived for power distribution and not for data. Hence, signal propagation is affected by more severe impairments than traditional media, such as impulsive noise and frequency selectivity. Furthermore, new emerging PLC applications need more efficient information delivery schemes that encompass both unicast and multicast mode. Towards this end, this paper deals with an efficient Network Coding (NC) based multicast reliable PLC scheme that makes use of (i) a decision direct impulsive noise mitigation approach and of (ii) a scheme based on multiple transmissions of a same symbols in the frequency domain. A suitable optimization procedure is also proposed here with the aim of improving the performance of the proposed scheme, under the constraint of a specified maximum data flow delivery failure probability. Finally, comparisons with alternative solutions are provided in order to highlight the significant advantages of the proposed scheme in terms of data flow delivery delay and overall transmission energy cost, under specific service constraints.

1. Introduction

Power Line Communication (PLC) technology is a promising approach to provide data transfer by exploiting an existing electrical infrastructure [1]. This opportunity strongly reduces the deployment costs that, in this case, are mainly due to the connection of the modem to the power grid. The modem modulates the signal using orthogonal frequency division multiplexing (OFDM) and sends it through the electrical wire, superimposed on the electrical signal. At the receiving end, a filter allows the recovery of the transmitted data. Thanks to its easy and cheap deployment PLC is considered a viable solution for several applications. Indeed, PLC systems support high bit rate services such as video transfer, internet access and gaming for domestic applications, as well as low bit rate services, such as telemetry or control signals, in industrial and smart grid applications [2,3].

Recently, PLCs have been largely investigated for communications in Smart Grid, in order to transmit control signals, diagnostic information or data measured by sensors [2,4]. In addition to this, a new trend for future PLC systems is that of providing multicast and broadcast services.

Towards this goal, an important issue that still needs to be carefully investigated is how to match the end-user Quality of Service (QoS) profiles (i.e., data flow delivery delay and reliability) with the communication channel quality. Despite recent proposals [3], limited attention has been paid to the problem of matching a QoS level on a Multicast Group (MG) basis, for example, the problem of delivering services with a target QoS profile to all the end-devices belonging to a same MG. Furthermore, it is important to consider that the delivery of multicast services in a reliable mode by resorting to acknowledge-based schemes may be complex, due to their implementation issues impairments [5]. As a consequence, the use of Network Coding (NC) seems to be a promising methodology to enable Point-to-Multipoint (PtM) communications and to match the implementation constraints (i.e., limiting or even avoiding the number of acknowledge messages) [6,7].

Recently, several works have discussed the effectiveness of NC schemes in PLC systems (NC-PLC) [7–11]. In particular, in [7], the NC approach is considered as a promising solution to fulfill specific QoS constraints, without requiring feedback messages in PLC systems. According to this research trend, we propose and validate here a novel NC scheme by carefully taking into account that the PLC medium is dominated by distance losses, impulsive interference and multipath propagation due to the wire discontinuities, thus causing frequency selectivity. In particular, Impulsive Noise (IN) is considered as one of the most detrimental effects,

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and several research activities have been carried out to counteract this impairment [12]. As a consequence, the performance of NC schemes could be enhanced if they were used jointly with suitable IN mitigation schemes.

Several mitigation techniques, including nulling and clipping [13], have been proposed, as well as more sophisticated methodologies [14–16]. This paper aims at extending previous results [7,14–16], by counteracting the negative effect of the PLC medium by means of a suitable IN mitigation scheme and proposing, at the same time, an optimized procedure for the data rate selection for the transmission of the NC data flow. In particular, we validate the good behavior of the proposed data rate Optimized NC (ONC) scheme with respect to a basic (i.e., not adopting the rate optimization) NC alternative [7], in terms of delivery delay and transmission energy cost of the whole data flow with a target decoding probability (i.e., specified QoS profiles) for all the end-devices of a given MG.

The proposed ONC scheme achieves the aforementioned goals by resorting to the use of (i) a suitable IN mitigation technique to counteract the negative impairments of the communication channel and of (ii) a multiple transmissions of the data symbols belonging to a same NC packet in the frequency domain. In particular, replicas of the data symbols of a same NC packet sent by the transmitter are coherently combined at each receiving end in order to increase the data reliability. It is straightforward to note that this method increases the data flow delivery delay and transmission energy cost. As a consequence, a suitable optimization procedure has to be defined in order to identify the best trade-off between data flow reception reliability and delivery delay/transmission energy cost constraints.

Summarizing, the main features of the proposed ONC multicast PLC system are:

- The transmitter sends out a data flow formed by K coded packets with each data symbol transmitted m times, with $m = 1, 2, 4, 8$, on m different subcarries;
- Coherent data symbol combining is performed at the receiver;
- Acknowledgment messages are not used.

In order to highlight the advantages of the proposed approach we provide a performance comparison with a basic NC multicast PLC scheme (i.e., for which $m = 1$ and each data symbol forming a coded packet is transmitted only once) and conventional and optimized NACKed alternatives. In particular, it is highlighted here by providing performance results and comparisons a significant improvement in terms of data flow delivery delay, overall transmission energy cost under the constraint of a specified failure probability of the data flow decoding for all the end-devices belonging to a same MG.

The paper is organized as follows; Section 2 outlines the system model assumed in our analysis. In particular, the Physical Layer (PHY) performance is derived here under the assumption of the use of a suitable IN mitigation scheme and transmission of multiple copies of each data symbol forming a NC packet in the frequency domain. Section 3 presents the proposal of an analytical optimization method to achieve the lowest data flow delivery delay, under proper constraints while the next Section 4 provides numerical results and comparisons. Finally, our conclusions are drawn in Section 5.

2. System model

We focus on the scenario shown in Fig. 1. Here, low-voltage (LV) power cables are employed to provide last-mile broadband communications, using PLC technology, to a set of end-devices in a controlled environment (e.g., smart buildings, factories, etc.) [17]. Base Stations (BSs) allow the connection of the PLC access networks with the backbone communication network. Usually, they are located in the same place of the transformer unit, connecting the LV supply networks with the medium voltage (MV) supply network. In particular, a BS has to convert the communication signals in formats suitable for the delivery through the backbone and the PLC access networks. We assume here that the M end-devices are connected to a BS by means of a PLC network with a *star* topology. Each end-device is equipped with a PLC modem, i.e., it is connected to a socket in the internal electrical network, in order to convert the incoming signal from the PLC network into a standard format that can be processed by the local device or distributed through a local network infrastructure to client devices within the same building. The end-devices of a MG are assumed in spatially separated sites and connected to the appropriate BS (see Fig. 1) through individual LV power cables with different lengths (maximum hundreds of meters), according to a star topology. Moreover, we have assumed that each device experiences an independent lossy channel characterized by a different Signal to Noise Ratio (SNR) value. In this scenario, it can be useful to have efficient and reliable multicast transmissions in order, for example, to send control information or update software to a (sub)set of the connected devices in a controlled environment. The transmission is affected by IN, multipath fading and frequency selectivity. Hence, at the PHY layer suitable countermeasures are adopted, while at the link layer a NC scheme is considered, as it is pointed out in the following Sections.

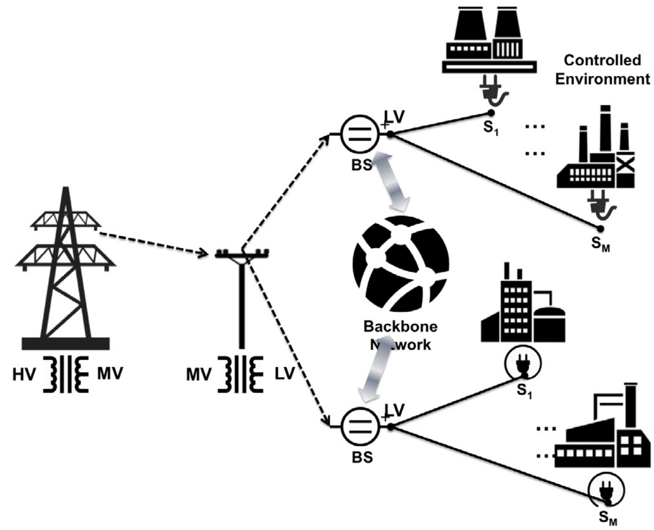

Fig. 1. Reference application scenario: Sets of end-devices belonging to specific MGs are connected to the appropriate BSs through LV power cables according to a star topology. The BSs, in their turn, provide connections of the PLC access networks with the backbone network.

We assume here that the BS sends out NC packets by transmitting m copies of each data symbol forming a NC packet on m different subcarriers. Moreover, the number of NC packets to be transmitted is optimally derived in order to allow a correct decoding of the data flow at all the end-device with a target decoding failure probability. We demonstrate the advantages of the proposed NC scheme by providing performance comparisons in terms of data flow delivery delay and overall energy transmission cost with different alternatives. The obtained results clearly indicate the proposed NC scheme as a suitable approach for implementing multicast services and applications over PLC systems.

2.1. PHY-Layer model

The transmitted PLC signal is assumed hereafter to be an OFDM signal with the PHY parameters described in Table 1, according to [18].