Potential of Routing with Network Coding in PLC Networks

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Abstract

The application of Network Coding (NC) has long time remained not feasible due to the high demand on the computation performance. With the recently developed C++ Kodo library and increasing performance of DSPs it becomes feasible and challenging. NC can improve ARQ and routing increasing throughput and decreasing latency. In this contribution, the potential of Extremely Opportunistic Routing (ExOR) in PLC is investigated. It's shown that ExOR becomes feasible in real applications only when using NC. The simulation results advocate the positive potential gain of ExOR+NC performance over any conventional routing protocol.

Index Terms

Network Coding, ExOR, routing, ns-3, ARQ

I. Introduction

CONSIDER a routing problem between a single source (v_0) and a single destination (v_n) in a directed network graph $\mathcal{G}$ consisting of nodes V ($v_0, v_n \in V$) and edges E. with a communication channel on the cut between Logical Link layer (LLC) and MAC layer (not physical channel). Considering specifics of PLC medium and existing PLC technologies, this is a discrete noiseless erasure non-degraded broadcast relay multiple-access channel with TDM.

Using a conventional single-path routing protocol a chain of relays ($v_1,\ v_2, ..v_{n-1} \in Y,\ Y \subset V$) is selected, which forward data from v_0 to v_n. Usually, only $v_i \in Y$ and v_0 are eligible to send data. The nodes $v_j \in V \setminus (Y \cup v_0 \cup v_n)$ drop all received packets. With Extremely Opportunistic Routing (ExOR) any received packet by $v \in V$ is potentially useful. ExOR differs to other routing protocols by a highly dynamic selection of the relays. It is not possible to make a static selection of relaying nodes because the selection is done upon the fact of the packet reception and the packet erasures are random. If several nodes receive the same packet the node with less path cost to v_n forwards it, which increases throughput in comparison to other routing protocols. Still, ExOR creates heavy communication overhead, which makes it infeasible for application in real networks without further modifications. The communication includes signaling the packet reception by each node and exchange/updating of the path cost values.

This disadvantage can be substantially reduced when using the Network Coding (NC). There are multiple merges of ExOR and NC already known like MORE, MIXIT, COPE, etc. These protocols create much less communication overhead and are successfully used in wireless networks.

The key idea lies in recoding of the received packets at each node before relaying. Linear Network Coding performs linear operations on received packets in a finite field. With Random Linear NC (RLNC) no coordination for coding vector selection is required, i.e. each node can recode fully autonomously. With NC ExOR does not need to signal the packet reception by each node. This is a major benefit created by NC to ExOR with considered channel and communication scenario. Instead, a probabilistic relay selection is used. If the packet losses can be described with a stationary process and the loss ratios can be calculated for each edge $e \in E$ each node can guess how many packets were received by each node. Basing on this guess each node can almost autonomously select itself for relaying.

In fact, it is more common to name a relay node here as a helper. The helper node does not only relay the incoming data but mixes it (recoding) and adds the coding redundancy with a rateless code if needed.

Despite of being successful in wireless networks the benefits from ExOR are still not obvious for certain network scenarios. In this contribution, we investigate the potential of ExOR with NC in access PLC networks. For this purpose we do not implement a routing protocol itself. Instead the potential of ExOR with NC is estimated with an upper bound of gain over any conventional routing protocol. The results are achieved by means of simulation.

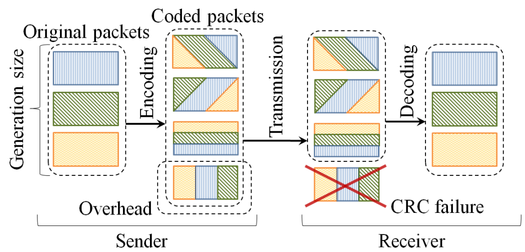


Fig. 1: Data transmission with NC [3]

II. RLNC BACKGROUND

Fig. 1 shows an example of intraflow NC without repeaters and for one generation. With the intraflow NC we code the packets from the same data flow (same source, destination and connection ID). For this purpose the original packets are grouped into generations. The coded packets are produced with linear operations in a finite field on the packets of each generation separatetly. Each coded packet, also referred to as a NC symbol, is a sum of products of original packets and certain scalars. A vector of scalars needed to create one NC symbol is also referred to as a coding vector [**?**]. With RLNC the coding vectors are selected randomly from the finite field. In fig. 1 we see an example with the generation size (G_s) 3. In practice the generation size depends on required quality of service and performance limits of hardware. It is possible to create more then G_s packets as a redundancy. It can help to recover the original data after losses during the transmission. If a node gets the coded packet belonging to the same generation from several nodes, it can put them to the same coding matrix. Before the transmission all packet in coding matrix are recoded. Each recoded packet hold a piece of information about each received packet.

III. SIMULATION MODEL

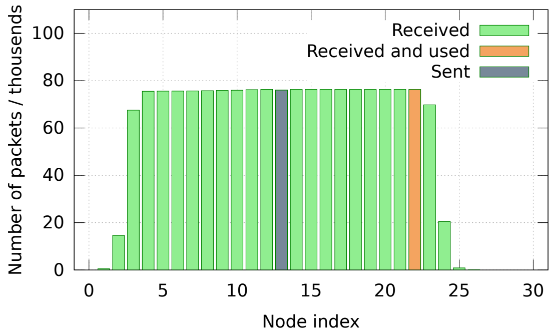
The simulation model is created in ns-3 environment. Physical (PHY) and Data Link Layer (DLL) specifications are implemented according to G.9960 and G.9961 [7], [8]. The channel is modeled using the ns-3 module described in [1]. It is a realistic channel model, which considers the signal reflections for calculation of the transfer function. The PLC signal is also deteriorated with colored noise [2] (best case scenario). The topology in our access network is a long line with equidistantly installed PLC modems. On the sample result shown in fig.1 the distance is 50 meters. So, the total distance between the source and the destination is 1450 meters. In fig.2 each point is obtained for different distances in range between 50 and 92 meters.

The PHY implementation allows to select the available in G.9960 modulations and FEC rates and uses the predefined envelope of the transmission PSD. Bit loading and FEC rate are selected adaptively basing on given channel transfer function and noise level (calculated by channel module).

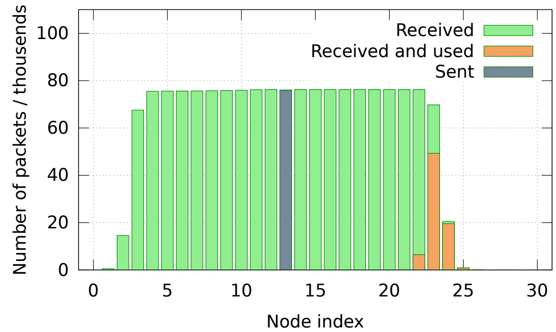
The DLL implementation is limited to ARQ, routing and MAC as defined in G.9961. The only modification is the backoff mechanism. The maximum contention window size given by G.9961 is too small for the selected scenario (G.hn was originally designed for in-home networks with a small number of nodes in one subnetwork). We calculate the contention window size as suggested in [6].

IV. SIMULATION RESULTS

In fig.1 one can see the simulation results for access PLC network topology (long line with 31 PLC modems placed at a distance of 50 meters between each other). At v_0 the data source in created, which constantly creates packets for v_{30}. This data is conveyed to v_{30} using the relay nodes v_{13} and v_{22} (conventional routing of G.9961). Each packet in ARQ buffer is indexed. The indexing is independent on each sender. In fig.1 the data received from only one sender is shown (v_{13}). Due to the broadcast nature of the PLC channel, multiple nodes receive the same data or a part of it. Twelve nodes to the right and twelve to the left of the sender receive same or partially same data. Using the original routing only the node v_{22} relays the received data (fig. 2a). But it's not the best strategy. In fig. 2b a group of helpers is shown, which could be used instead of a single relay. The node v_{25} locates the closest to the destination v_{30}. Due to the simplistic topology, it also has the lowest path cost to v_{30}. Therefore in accordance to ExOR, the node v_{25} should transfer all data it receives. The node v_{24} sends only that data, not received by v_{25} and so on. A potential gain achievable with ExOR+NC is obviously positive. It is analyzed with the help of the second figure.



(a) Conventional routing: relay v_{22}



(b) NC+ExOR: group of helpers $v_{22}, v_{23}, v_{24}, v_{25}$

Fig. 2: Sender (current relay) - v_{13}, destination - v_{30}

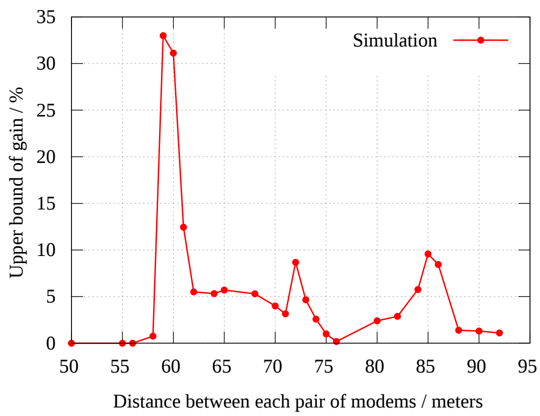


Fig. 3: Potential gain with NC

In fig.2 the topology is the long line as well. The number of nodes is 15. The first node (v_0) sends data to the last node (v_{14}) on the line. The nodes are positioned at an equal distance from each other. For each given distance we estimate the potential gain. The range of distances is selected is such way that the source needs exactly two hops (one repeater) to reach the destination. Such restriction was applied to ease the calculation of the potential gain. The gain calculation is clarifed in the following.

Let v_0 sends with data rate R_0 and repeating node v_i sends with R_i. Then the average data rate between v_0 and v_{14} is $R = R_0 \cdot R_i/(R_0 + R_i)$. If ExOR is used then a number of nodes $v_j \in V_H \subset V$ can help in communication. Each of them sends not all the the received data but as described above. Let v_0 send message M and each node v_j receives M_j^R part of this message and sends M_j^S part with the smaller or equal size then M_j^R with data rate R_j. Note that $\sum M_j^S = M$. Let $\xi_j = M_j^S/M$ is a part of M transmitted by v_j. Consider that v_0 and each v_j adds the coding redundancy on PHY layer. But since the communication channel on the cut between LLC and MAC is considered, the value ξ_j is not affected by PHY coding. Eventually the potential average data rate between v_0 and v_{14} with ExOR:

$$R' = 1/\left(1/R_0 + \sum \xi_j/R_j\right). \tag{1}$$

The potential gain of ExOR+NC over any conventional routing schemes is estimated as follows:

$$g = (R' - R)/R \cdot 100\%. \tag{2}$$

It's shown in fig.2. This is shown in fig.2. The values ξ_j were obtained by means of simulation. For this purpose the data was routed between v_0 and v_{14} using G.hn protocol as described above. In this process a detailed log of received segments of data on LLC layer was conducted. From this log it's possible to deduce, which nodes received which segments. Using this data the sizes of messages M_j^S in term of number of LLC segments were evaluated. But the simulation was not influenced by these values. They served solely to calculte R', which could have been achived if M_j^S values were used.

In practice it's not possible to calculate M_j^S values as accurate as in the simulation because it would create too much overhead. But using NC each node can guess them.

The peaks in fig.2 correspond to the change of the repeating node v_i. Note that with 50 meters distance the node v_i is one of the closest to v_{14}. The greater the disance is, the closer is v_i to the center of the line.

V. Conclusions

One could expect that each node in the network can contribute to data transmission when ExOR is used. In fact, for the access PLC scenario this is not true. Only a small group of receivers ($v_{22}, v_{23}, v_{24}, v_{25}$ in fig. 2b) will forward the data coming from one relay.

The potential gain much depends on the distance between nodes. The actual gain (comparing implemented routing protocols) will be smaller due to following factors: feedback overhead (this is not negligable even with NC), estimation error of the length of the messages M_j^S due to the stohastic nature of the channel.

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