Network Coding in Passive Optical Networks

Martin Belzner(1), Herbert Haunstein(2)

(1) Chair of Information Transmission, Friedrich-Alexander University of Erlangen-Nuremberg, Cauerstr. 7, D-91058 Erlangen, Germany, belzner@LNT.de

(2) Alcatel-Lucent Deutschland AG, Thurn-und-Taxis-Str. 10, D-90411 Nuremberg, Germany,

Abstract *The application of network coding in passive optical networks is shown to provide benefits in intra-PON communication scenarios with respect to reducing the packet loss ratio and queuing delay in case of congestion.*

Introduction

In standard Passive Optical Networks like Ethernet-PON (E-PON) or Gigabit-PON (G-PON) the available downstream data rate per attached user is often limited as all users have to share a common transport resource. Due to the broadcast nature in the system design for the downstream direction information transmitted on the optical medium intended for a certain Optical Network Unit (ONU) reduced the remaining available resources for all other ONUs in the same PON environment. Especially applications, which require intra-PON data exchange, e.g. voice or video communication services between ONUs reduce the efficiency of the network as information symbols dedicated for a certain sink ONU are also always additionally transmitted back to the source ONU.

Recent investigations have shown that the concept of *network coding* promises to be a powerful data transport strategy compared to traditional data routing in order to increase the network throughput in transport capacity limited networks. In contrast to traditional transport networks, where information bits are processed as independent entities, which can either be forwarded or dropped at a network node, the concept of network coding means a shift in this transport philosophy by allowing a network node to jointly process bits from independent traffic streams. This joint data processing can lead to a reduction of the required transport capacity especially in multicast network scenarios. This paper demonstrates the benefits of using network coding with respect to the achievable packet loss ratios and end-to-end packet delay in an intra PON communication scenario with additional interfering downstream traffic.

Network coding principle

The idea of network coding was presented for the first time by Ahlswede et al. as a method to increase the information flow between network elements in a multicast environment[1]. It was shown that contradicitory to traditional IP multicast routing and switching network coding can achieve a network wide optimal throughput equivalent to the network multicast capacity[2]. One of the basic principles of network coding is that it allows to encode information symbols via predefined coding operations e.g. XORing bits, from independent data stream. As a consequence the required transport resources are reduced however at the cost of additional network controlling effort. A side effect of the coding operation is that in case of congestion the average queue length is also reduced as several information symbols in the queue can be encoded into a common output information symbol.

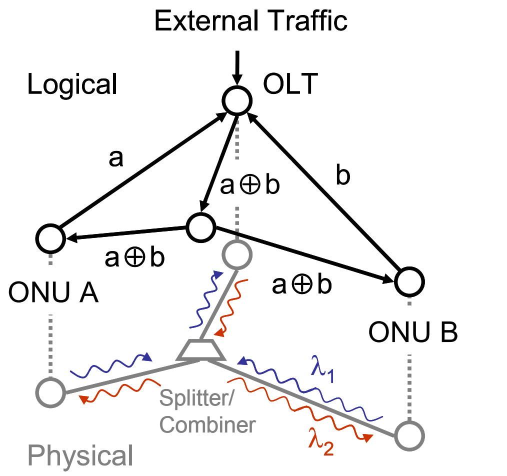

Fig. 1: Network Coding in a PON environment

Fig. 1 shows an exemplary PON network. We assume that ONU A transmitts a contineous stream of information symbol “a” dedicated for ONU B as well as ONU B a stream of symbol “b” dedicated for ONU A upstream towards the OLT. Assuming no transmission delay as well as that each logical connection posseses unit capacity and each symbol requires unit data rate the OLT can only forward either symbol “a” or symbol “b” downstream in one time step. Therefore in a contineous transmission case the average achievable information symbol rate per time step at each ONU is 0.5. If we allow the OLT node to jointly code the symbols received from ONU A and ONU B based on a certain coding rule, in this case e.g. XOR operations on the bits, the information rate per user can be increased to one symbol per time step, which corresponds to the multicast capacity of this network. Each terminal ONU can decode the received encoded information symbol via the knowledge of its own transmitted symbol. The gain in the achievable information rate comes at the expense of a required data buffering of the transmitted symbols at the ONUs. Through the process of encoding the information symbols at the OLT an inherent communication overhear security[3] between the participating ONUs is realized as only these

ONUs can sucessfully decode the received symbols by uniquely knowing their upstream transmitted data. This is especially helpful in multicast and broadcast environments like PONs where the ONUs receive all downstream transmitted data.

Simulation Setup

We have chossen an E-PON similar environment as simulation scenario with 16 attached ONUs and a line rate of 1Gbit/s in upstream and downstream direction. In the upstream direction a TDMA resource allocation mechanism is used with fixed time slot equally distributed over all ONUs repeating in a 2ms cycle. The network traffic comprises packets with a fixed size of 1.5KByte and exponentially distributed packet interarrival times. Each ONU is set to generatel traffic for the intra-PON communication equal to 5% of the available line rate. Assuming a maximum delay of 20ms in the communication between the ONUs a 1Mbit buffer is required at each side for a sucessful decoding of network coded packes. At the OLT we also assume a maximum queue size of 1Mbit. In the downstream direction the intra-PON traffic is intermingled with additional downstream traffic.

Impact on the system performance

Packets from the different ONUs arrive temporal disjoint at the OLT due to the TDMA mechanism. A gain by using network coding in an intra PON communication can therefore only be achieved in case of packet queuing and therefore temporal congestion at the OLT. As consequence only in scenarios with large additional downstream traffic the benefits of network coding can be fully realized. However congestion events contribute significantly to packet delay and packet loss. In case of congestion where packets of both communicating ONUs are present in the queue of the OLT an encoding into a common output packet reduces the required transport resources on the downstream link therefore in principle allows an oversubscription of the downstream link. The achievable oversubscription depends on the actual amount of intra PON traffic between the communicating ONUs and is upper

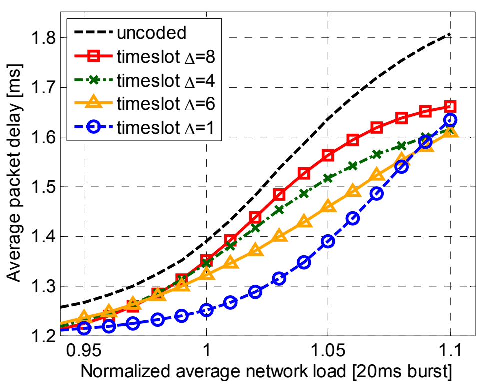

Fig. 2: Network coded intra-PON communication packet delay for different transmission timeslot distances

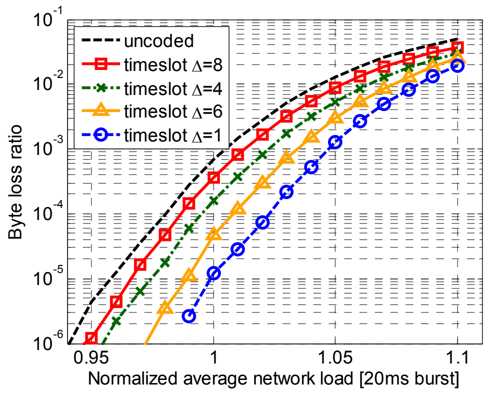

Fig. 3: Network coded intra-PON communication byte loss ratio for different transmission timeslot distances

bounded by the minimum of the individual flow data rates of the participating ONUs. Network coding additionally reduces the queuing delay. This is a result of the encoding process where later packets in the queue can be shifted to an earlier time slot which also leads to an overall reduced queue length. The simulated average end-to-end packet delay is plotted in Fig. 2. The normalized network load represents the sum of the intra-PON traffic and the additional downstream traffic divided by the available PON downstream line rate. It can be seen that the actual achievable delay reduction with respect to the network load is also depending on the temporal time slot distance between the communicating ONUs. The larger the scheduled temporal time slot distance between the ONUs is the more traffic load is required, and therefore longer congestion events, in order to achieve a noticeable delay reduction. Only if packets from both communicating ONUs are simultaneously present in the queue an encoding can be performed. The same effect can be observed examining the achievable byte loss ratio, plotted in Fig. 3. It can be seen that assuming a fixed byte loss ratio a higher traffic load can be accepted with network coding compared to the uncoded scenario. Especially in cases where temporal limited queue congestion occurs, network coding significantly reduces the resulting byte loss ratio. Equally to the queuing delay assigning subsequent timeslots to the ONUs for the intra-PON communication is more beneficial.

Conclusions

It has been shown by traffic simulation that network coding can reduce the end-to-end packet delay as well as the byte loss ratio in an intra-PON communication scenario (10% of the traffic) by minimizing the average queue length especially in case of congestion

References

1 R. Ahlswede et al., *IEEE* Trans. IT, **46**(4), (2000) pp. 1204-1216
2 M. Médard et al., Proc. OFC'09, OThO3 (2009).
3 C. Fragouli et al., *FTNET*, **2**(2) (2007) pp 135-269