Performance of Network Coding in Transport Networks with Traffic Protection

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Abstract

Increasing traffic demands in the transport networks as well as declining revenues per bits require an increased transport efficiency. The concept of network coding has shown to increase the network throughput in capacity limited networks compared to traditional routing solutions. We show in this paper that applying network coding to certain reference transport networks with traffic protection reduces the required transport resources thus improves the network efficiency. Besides investigating the achievable resource savings we elaborate constrains and limiting factors for the performance and application of network coding in transport networks with a 1+1 path protection.

1 Introduction

Traffic demand forecasts show a growth rate of the traffic in the transport networks of roughly 50%-100% per year [1], [2]. Besides the traditional internet data traffic also new services and applications, which require significant transport resources, like television transmission over the internet as well as video on demand distribution are becoming more and more frequent in the transport network. Therefore transport providers have to increase the throughput through their networks, either by implementing more transport capacity or via more efficient network utilization.

Recent investigations have shown that the concept of network coding [3], [4] is a potential strategy to increase the network throughput in transport capacity limited networks. Compared to traditional transport networks where bits are treated as independent units, which can either be processed and thus forwarded at a network node or dropped, 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, e.g. by linear coding with XORing bits from independent data stream [5], can lead to a reduction of the required transport resources, especially in multicast network scenarios. However it has been shown that also for some unicast traffic scenarios, e.g. with certain traffic protection schemes, network coding can increase the transport efficiency. One of these scenarios is the 1+1 path protection where data is transported in parallel on two edge disjoint paths between a source and a sink node. Therefore in case of a link failure in one transport path the sink node still receives the full data from the other transport path without any interruption of the transported service. However this protection mechanism is also the one which requires with traditional routing at least a doubling of transport capacity between the source and the sink node.

Investigations about the efficiency of network coding are often done in artificial networks therefore currently little is known about the performance of network coding in realistic network topologies with realistic traffic demands. Therefore in order to elaborate some constraints for using network coding in current realistic transport networks we investigate in this paper the performance of network coding when it is applied to transport networks with a 1+1 path protection scheme. Besides evaluating the theoretical benefits we also consider realistic traffic demands and different network topologies.

The paper is structured as follows. In section 2 we provide an introduction into the basic concept of network coding and derive an upper bound for the achievable capacity savings in a 1+1 transport path protection scenario. Additionally we elaborate some constraints when applying network coding to the transport network. In section 3 we present simulation results for 1+1 path protection scenarios considering different traffic routing mechanisms with realistic network traffic demands and topologies based on German and European reference networks. Derived from simulation results we elaborate limiting parameters and constraints for an efficient application of network coding to current transport networks. Concluded is the paper in section 4 with a summary of the presented results.

2 Network Coding

2.1 Network Coding Principle

The idea of network coding was presented for the first time by Ahlswede et al. [6] as a method to increase the information flow between network elements in a multicast environment by allowing intermediate relay nodes to encode bits from different independent sources. It was shown that contrary to traditional IP multicast routing and switching network coding can achieve a network wide optimal throughput equivalent to the network multicast capacity.

Let $G = (V, E, C)$ be a network graph with V representing the network vertices $V = \{v_1,\ldots,v_N)$ and E the network edges $E = \{e_{1i},\ldots,e_{jN}\}$. Each edge $e_{ij}=e(i,j)$ represents a loss less directed point-to-point link between two network vertices v_i and v_j. Additionally each edge $e_{ij}\in E$ a non negative transmission capacity $c_{ij}=c(i,j)$ $c_{ij}\in C$ is assigned representing the maximum achievable data rate on the edge e_{ij}. Therefore $C(E) = \{c_{1i},\ldots,c_{jN}\}$ represents a set of the transport capacities for a given set of network edges. While the graph G models the network connectivity and link capacities an actual data transmission from a source node $s\in V$ to a set of receiver nodes $R\in V$, $R = \{r_i,..,r_j\}$ can be described via a sub graph $G_k = (V_k, E_k, d_k) \subsetneq G$. $V_k = \{s,v_i,\ldots, r_j\}$ represents the nodes and E_k the edges which are traversed in the data transport. The required data rates on the traversed edge, which are equal or below the link capacity, can be expressed via $0\leq d_k \leq c(e_{ij})$ $\forall$ $e_{ij} \in E_k$ In the following examples we assume that each link has unit capacity.

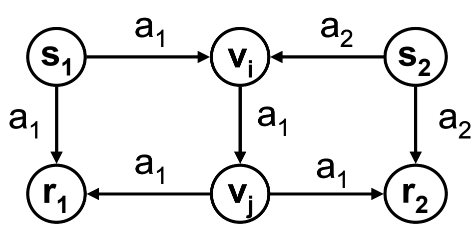

Figure 1 Multicast Transmissions without Network Coding

Figure 1 shows a non network coding example graph with six network vertices and seven edges. In this example multicast scenario with two sources s_1 and s_2, which both want to transmit unit capacity requiring information symbols a_1 and a_2 to the receiver nodes r_1 and r_2, both sub graphs G_1 and G_2 share a common network edge e(i,j). The information rate achievable at the receivers r_1 and r_2 is limited in the non network coding scenarios by the capacity of the bottleneck link e(i,j). In traditional routing and switching networks node v_i can either forward symbol a_1 or symbol a_2 at one time step. Therefore the average achievable information rate per receiver node is 1.5 symbols per time step.

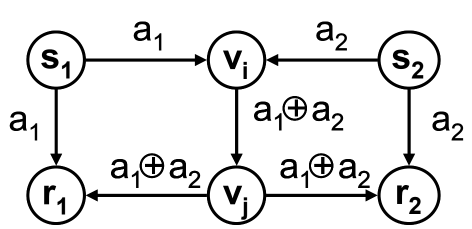

Figure 2 Multicast Transmissions with Network Coding

If we instead allow the intermediate node v_i to encode the symbols received from source one and source two based on a certain coding rule the information rate per user can be increased to two symbols per time step, which corresponds to the multicast capacity of this network. In Figure 2 it is shown that node v_i combines symbol a_1 and a_2 into one output symbol. Both receiver nodes r_1 and r_2 can reconstruct the original information symbols from the encoded symbol, by knowing the encoding rule, with the help of the other received uncoded symbol. Therefore both terminal nodes receive two symbols per time step and the average symbol rate has reached to the networks multicast capacity. It has been shown that a linear coding operation, e.g. XORing the information symbols, is sufficient for achieving the multicast capacity in such a network [5]. Therefore a possible implementation of the actual data encoding mechanism in a network element is rather simple.

Instead of increasing the information rate between network nodes network coding can also be interpreted as a method to reduce the amount of required transport resources. From the scenario presented in Figure 2 we can see that an information rate of two symbols per receiver node per time step can also be achieved with traditional routing and switching however this would require a doubling of the edge capacity of the bottleneck link e(i,j) between node v_i and v_j. Additionally network coding provides the benefit of reducing the amount of transported data in the network and thus decreases the probability for congestion and losses events [8].

2.2 Network Coding in Non Multicast Scenarios

In the today's optical transport networks the application of network coding seems to be less beneficial as there is only a very limited amount of multicast traffic. However there still exist unicast scenarios where network coding can improve the transport efficiency with respect to the amount of required transport resources. One of these scenarios is the application of resilience and traffic protection in the transport network. In this paper we examine the case of a 1+1 path protection scenario. This means a transport path between a sender node s and a receiver node r, which we again describe as a sub graph of the network graph $G_k = (V_k, E_k, C_k) \subsetneq G$ is protected by an additional edge disjoint end to end connection. In a 1+1 path protection scenario we have two paths between a sources s and a sink node r. Therefore we get two sub graphs $G_{k1} = (V_{k1}, E_{k1}, d_{k1})$ with $V_{k1} = \{s,v_i,\ldots,r\}$ and $G_{k2} = (V_{k2}, E_{k2}, d_{k2})$ with $V_{k2} = \{s,v_j,\ldots,r\}$, which have an empty edge intersection set $E_{k1}\cap E_{k2} = \{\}$. Consequently the terminal node r will receive the information symbols transmitted from source s from two disjoint edges. and in case of a link error in one transport path the terminal node still receives data from the protection path and thus no data is lost. The benefit from using network coding in such a network scenario is shown exemplary in Figure 3.

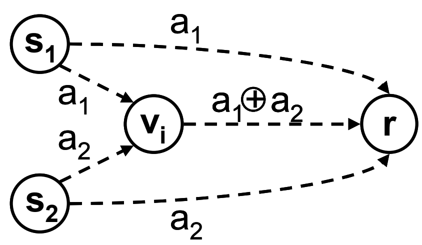

Figure 3 1+1 Path Protection with Network Coding

We assume a simple scenario with two sender nodes s_1 and s_2 which both want to transmit 1+1 path protected data to a receiver node r. Both senders therefore use two edge disjoint paths, here shown as direct paths between the corresponding senders and the receiver and protection paths traversing the intermediate relay node v_i. Between the paths intersection node v_i and the terminal node r the information symbols from both sources can be encoded with each other. It can be seen that in case of a single link error the terminal node r still receives enough information to obtain the information symbols from both sources. Either both information symbols a_1 and a_2 are directly received or node r can reconstruct the missing information symbol from the encoded symbol $a_1 \oplus a_2$ and the non affected symbol.

By using network coding the amount of required transport resources on the path between node v_i and r can be reduced in this scenario by one symbol per time step while still providing a protection against a link failure with instantaneous failure recovery. In the above presented scenario network coding therefore saves 1/6 of the total required network bandwidth compared to the 1+1 path protection scenario with traditional routing and switching. In principle bandwidth resource savings by introducing network coding in the transport network can be achieved if edges of sub graphs from independent source nodes s1 and s2 intersect. While the set of edges of the individual sub graphs for each source node e.g. E_{11} and E_{12} for sender node s_1 and E_{21} and E_{22} for the sender node s_2 have to be disjoint $E_{11} \cap E_{12} = \{\}$ and $E_{21} \cap E_{22} = \{\}$ the intersection set has to be non empty $(E_{11} \cup E_{12}) \cap (E_{21} \cup E_{22}) \neq \{\}$. However at the decoding node the information symbols have to arrive from N+1 disjoint edges in order to allow a successful decoding in case of a single link failure. Therefore in a scenario with two sources three edge disjoint inputs are are required which can be expressed as either $E_{11} \cap E_{12} \cap E_{21} = \{\}$ and $E_{11} \cap E_{12} \cap E_{22} \neq \{\}$ or $E_{11} \cap E_{12} \cap E_{21} \neq \{\}$ and $E_{11} \cap E_{12} \cap E_{22} = \{\}$. In the following we define D(E) to represent a set of data rates $D=\{d_1,..d_N\}$ of the traffic flows 1 to N traversing the edges in E. The required resources in the network coding scenario can be calculated by the cardinality of the edge intersection set, in this scenario $|(E_{11} \cup E_{12}) \cap (E_{21} \cup E_{22})|$ times the maximum of the required data rates $\max(D((E_{11} \cup E_{12}) \cap (E_{21} \cup E_{22})))$ of the sub graphs on the intersected edges. The maximum of the data rates is required as all other flows can be encoded into the maximum data rate flow in one time step. The resource savings can be calculated by subtracting the required resources with network coding from the resource requirements without network coding. The network coding gain, which we define here as the ratio of transport resources saved compared to the network wide required resources in a non network coding solution, is in above presented example network with two sources and one sink node 1/6. This represents the maximum achievable coding gain for this scenario. In the following we assume N sender network nodes s_1 to s_N, which want to transmit information symbols to a receiver node r. In order to achieve a 1+1 path protection we assume that each transmitting node has a sub graph G_{k1} $k=\{1\ldots N\}$ as direct link to the receiver as well as a protection path G_{k2} traversing node v_i. Consequently all protection sub graph G_{k2} intersect at the network edge between node v_i and r. The resulting abstract network topology is shown in Figure 4.

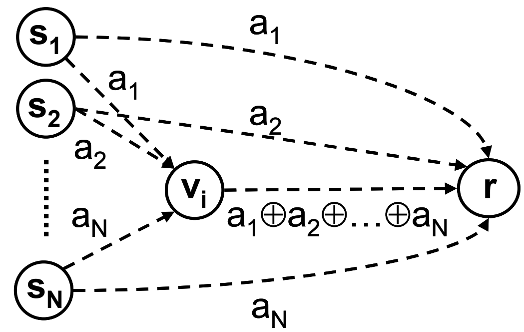

Figure 4 1+1 Path Protection with Network Coding and N sources

The receiver node r must receive the N information symbols plus the coded information symbol from N+1 independent inputs otherwise a decoding of all information symbols, in a link error case on any of the direct paths, is not possible. If we calculate the network resource requirements for a traditional routed 1+1 path protection in the example network shown in Figure 4 we can see that for N sources of which we assume each source s_t wants to transmits a symbols a_t $t=\{1\ldots N\}$ to node r per time step with unity bandwidth requirements, a total of 3*N network transport bandwidth is required. If we allow the network node v_i to conduct coding operations on the received information symbols the total network bandwidth resource requirements can be reduced to 2*N+1. Therefore the network coding can be calculated as shown in Equation 1.

$$\frac{3*N-(2*N+1)}{3*N}=\frac{N-1}{3*N}\xrightarrow{N>>1}\frac{1}{3} \qquad (1)$$

For a large number N of network sources and assuming all information symbols require the same amount of transport bandwidth the network coding gain converges in the presented generalized scenario to an upper bound of 1/3, meaning that 1/3 less network bandwidth is required compared to the uncoded traditional routed 1+1 path protection solution. This result represents an upper bound for the achievable coding gain in a 1+1 path protection scenario with N disjoint source nodes. It can be seen from Figure 4 that in principle the 1+1 path protection is converted by the encoding of the information symbols into a N:1 protection where N transport path are protected with one protection path. The protection path carries the encoded information from all other path thus allows an instantaneous data recovery in a single link failure scenario [9], [10].

2.3 Constraints and Challenges to Determine the Optimum Network Coding Solution

As can be seen from the mathematical presentation above a major constraint for applying network coding in a transport network is the network node degree. The network node degree determines the number of disjoint edges which are attached to a network node. As stated earlier a network coding solution is only possible if the decoding node r receives the uncoded information symbols of the N sources as well as the encoded information symbol from at least N+1 disjoint network edges. Therefore the possibility of achieving a coding gain is a direct function of the network node degree. Terminal nodes with a degree smaller than three can in principle not receive any encoded information in order to be able to successfully reconstruct all information symbols in case of a link error. Besides the network node degree the control plane for finding a network coding solution also plays an import role for the efficiency of a network coding solution. At first the control plane has to identify which network flows can in principle be encoded with each other and secondly an optimal coding strategy has to be defined. The network wide bandwidth resource optimizing flow coding strategy has to consider the amount of different traffic flows which can be encoded with each others at a network node as well as the length of the transport path the encoded flow is traversing in the network. E.g. it can be more optimal for minimizing the required network wide transport resources to encode only two flows at a network node which share two network edges instead of encoding multiple flows, which share only one common edge.

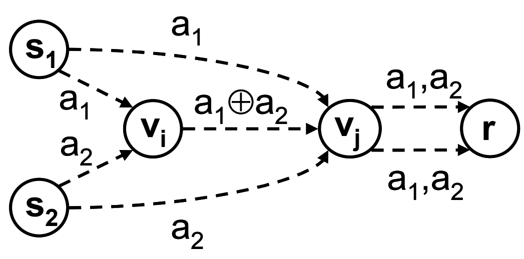

Figure 5 1+1 Path Protection with Network Coding and intermediate decoding node

A further problem in finding a coding solution can be seen from Figure 5. While from the receiver node's r perspective a network coding solution for flows dedicated for it seems not be possible, as node r posses only two disjoint input network edges an intermediate coding on the path towards node r can nevertheless still be possible. In the presented scenario network node v_j receives all flows from source s_1 and s_2 before forwarding them to the corresponding receiver node r. Additionally the node receives the flows from sufficient edge disjoint inputs thus that a network coding on the transport path between nodes v_i and v_j is possible. However in the given scenario in order to preserve the protection functionality the network node v_j has to decode and forward the uncoded information symbols a_1 and a_2 instead of just forwarding the encoded information $a_1 \oplus a_2$ to node r. Therefore the intermediate network node v_j must know that terminal node r receives the information symbol flows a and b only from it and therefore only from two disjoint edges in this scenario. It can be seen that for determine an optimum solution either an omniscient control plan is required or an appropriate signaling protocol has to be defined. The requirements and constraints, e.g. signaling overhead, for such a control plane shall not be discussed in this paper and are still an open issue for further research. Therefore we assume in the following sections an omniscient control plan which allows as a network wide optimization of the data encoding for a given set of routed traffic flows..

3 Network Coding in Realistic Network Topologies

In the following section we examine the actual achievable resources saving by using network coding and 1+1 path protection in hypothetical but realistic traffic and network topology scenarios. As reference networks we use two German reference networks (called "Germany17" and "Germany50") as well as a Pan-European network. ("Europe28") [11]. While the network topologies are based on hypothetical assumptions in order to present realistic network scenarios the assumed traffic demands are calculated based on population models, which reflect the regional population density and economical performance. The corresponding network topologies are shown in the Figures 6a-c. In the examined scenario all flows are routed corresponding to the selected routing algorithm between the sources and receivers nodes whereas the protection paths are always routed edge disjoint to the original transport

Table 1 Network Parameters for the Reference Networks

	Germany 17	Europe 28	Germany 50
Number of Nodes	17	28	50
Avg. Node Degree	3.06	2.93	3.56
Nodes with Degree>2	59%	68%	74%
Avg. Distance (hops)	2.71	3.57	3.89

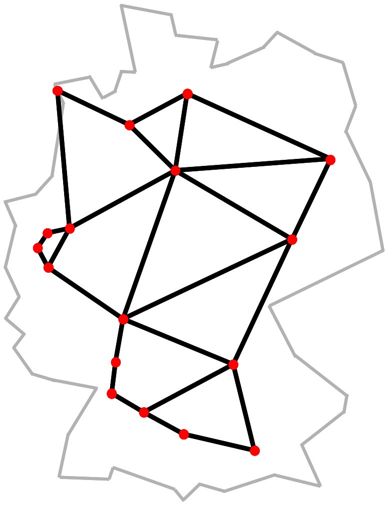

Figure 6a German Transport Network with 17 nodes

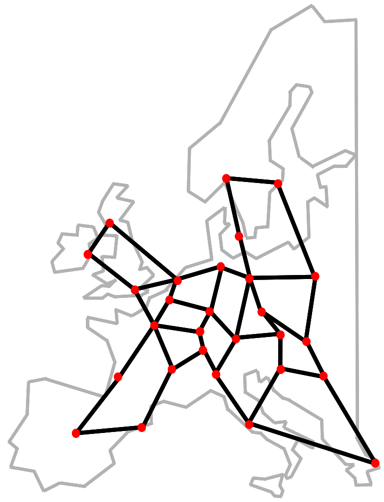

Figure 6b European Transport Network with 28 nodes

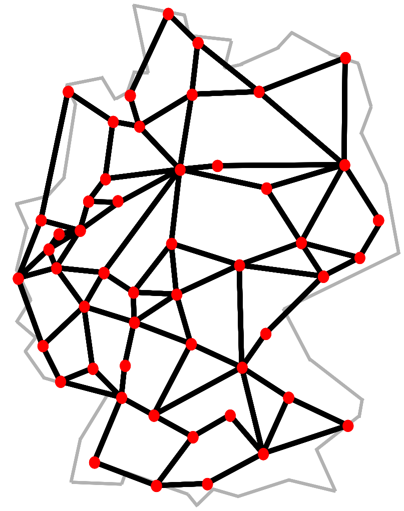

Figure 6c German Transport Network with 50 nodes

paths in order to assure the failure protection in case of a single link error.

Some important parameters for evaluating the performance of network coding in the transport networks are the shown in Table 1. The node degree represents as explained previously the number of possible edge disjoint inputs into a network node. As presented in Figure 5 only network nodes with a node degree larger than two can contribute to resource savings with network coding as they can receive the uncoded information symbols as well as the encoded information symbol in 1+1 path protection scenarios from sufficient edge disjoint inputs. Consequently a larger node degree provides a larger probability for finding a network coding solution as more flows can arrive from independent edges thus be potential encoded at a shared transport path towards the node. The distance between two nodes represents the number of traverse intermediate nodes for a data transport. A larger distance increases the number of traversed network nodes thus increases the probability of intersecting with other flows. Additionally a larger distance also increases the probability that in case of a network coding solution more edges are shared between the encoded flows thus additionally transport bandwidth can be saved.

From Table 1 we can see that the “Germany50” reference network provides the largest average node degree as well as the largest average distance between two network nodes. Therefore we expect that the largest network coding gain can be achieved there. A detailed evaluation of the achievable transport bandwidth resource savings in 1+1 path protection scenarios as well as a discussion about the constraints and limiting factors is presented in the following sections.

3.1 Influence of Different Traffic Routing Protocols

A major factor for the achieving resource savings is the traffic distribution protocol. As explained earlier only an omniscient control plane can find an optimal network wide encoding rule and thus determine the optimal traffic flow routing. Therefore we expect sub-optimal solutions for currently used standard traffic routing protocols. In the following we compare two simple flow distribution algorithms with respect to the achievable network coding gain.

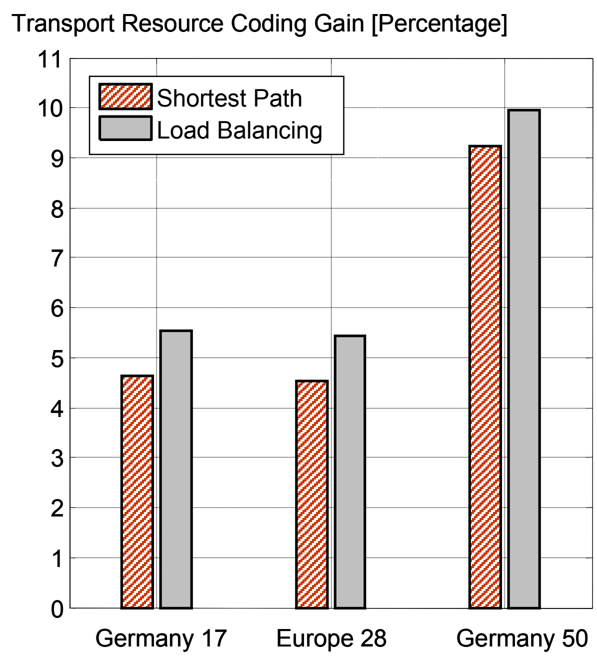

Figure 7 Resource Gain from Network Coding for Different Traffic Flow Routing Algorithms

As flow distribution algorithms we have chosen a shortest path routing and a traffic load balancing algorithm. The shortest path routing minimizes the total network resource requirements while the load balancing algorithms minimizes the coefficient of variation of the network link loads by distributing the traffic more uniformly through the network. The resulting bandwidth resource savings by using network coding in the three reference networks compared to the non coded routing solutions can be seen in Figure 7. As expected the "Germany 50" scenario, which has the most network nodes with a degree greater than two as well as the largest average number of hops between to network nodes, allows to achieve the highest bandwidth resource savings. However the overall capacity savings are still single-digit. It can be seen that the shortest path routing provides less resource coding gain than the load balancing solution in a 1+1 path protection scenario. Shortest path routing minimizes the number of traversed network nodes and links and therefore decreases in the presented reference networks the probability of independent traffic flows intersecting at shared traffic edges. This however also decreases the probability of a network coding solution. The traffic load balancing algorithm distributes the traffic in the network in order to reduce the traffic load of otherwise heavily used network link. As consequence the average number of hops for a used transport path between two network nodes increases. The distribution increases the probability of independent traffic flows intersecting at network edges thus increases the probability for a possible network coding. Additionally the traffic distribution also provides a better utilization of the available network node degree, which again increases the probability for finding a network coding solution as independent traffic flows can arrive from more disjoint network edges at a network node.

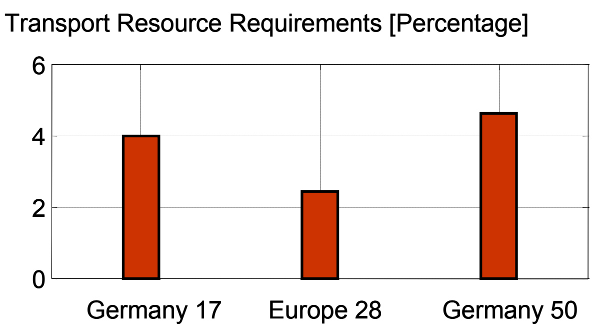

Figure 8 Resource Requirement Increase using Load Balancing compared to Shortest Path Routing

Note that the traffic distribution of the load balancing algorithm also leads to larger total network resource requirements compared to the shortest path routing, shown in Figure 8, therefore to some extend limits the larger resource coding gain. However compared to the capacity requirements for the uncoded shortest path solution in the presented scenario a load balancing mechanism with network coding still requires less overall transport bandwidth resources while at the same time offers similar resilience against single link failures and additionally provides a more uniform network wide link utilization.

3.2 Full Meshed Transport Networks

As seen in the previous simulation results the network node degree is one of the major performance limiting factors in realistic networks for achieving large bandwidth resource savings with network coding. Therefore we examine in this section the maximum possible coding gain for the three reference network scenarios if we allow an arbitrary meshing between the network nodes. In order to achieve the full network coding gain a network structure similar to one presented in Figure 4 with mutual edge disjoint direct connection from each source node to the receiver node as well as a non direct connections from all source nodes to the receiver intersecting at a common intermediate node is required. As shown in Eq. (1) the coding gain in such a scenario increases with the number of network nodes and converges to 1/3 for a large number of nodes. The required topology in such a scenario can be

Table 2 Network Parameters for Full Meshed Networks

	Germany 17	Europe 28	Germany 50
Avg. Node Degree Full Mesh	16	27	49
Avg. Distance (hops) Full Mesh	1	1	1

represented via a full meshed network. In a realistic environment this could be e.g. realized as a network with transparent optical paths between all network nodes. Again we compare the achievable savings for the two traffic flow routing algorithms shortest path and load balancing.
From the network parameters shown in Table 2 we expect the network coding gain to improve significantly, due to the increased average node degree.

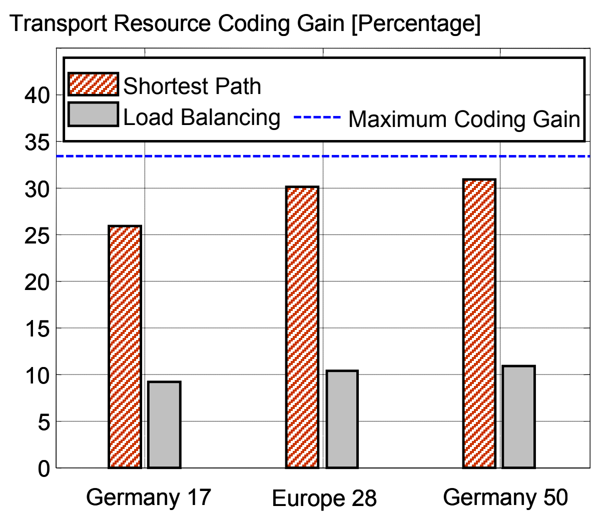

Figure 9 Resource Gain from Network Coding for Different Traffic Flow Routing Algorithms in Full Meshed Networks

In Figure 9 the relative resource savings compared to a non network coding data transmission for shortest path routing and load balancing in the three reference networks are plotted. It can be seen that shortest path routing outperforms the load balancing in this network topology in contrast to the results presented in Figure 7. Examining the shortest path routed traffic flows we can see that exactly the presented scenario shown in Figure 4 is realized. Each transmitting node has a direct path towards the receiver node as well as a protection path which is routed, due to the shortest path algorithms, for all source nodes over the same network node which has the lowest node ID. The difference between the theoretical achievable network coding gain and the actually measured one can be explained by the individual data rates of the transported traffic streams. As not all streams possess the same data rates, some larger flows can not be fully encoded with others so the full coding benefit can not be achieved with the given traffic demand distributions. The analysis of the shortest path routed full mesh networks presents an upper bound for the achievable resource savings by network coding with the given traffic demand matrices. Comparing the flow distribution for shortest path routing and load balancing it can be seen that for shortest path routing at each time step the information symbols of all traffic flows on the protection paths can be encoded with each other. The load balancing algorithm however achieves less resource savings due to traffic flows being more distributed therefore allowing less information symbols to be encoded with each other as not all flows intersect on a common network edge.

Additionally it shall be noted that a full network mesh would also required the least amount of total switching capacity compared to the previous presented network topologies. Therefore it is remarkably that network coding can in this switching resource optimized topology even more reduce the resource requirements in 1+1 path protection scenarios. However a fully meshed network scenario does not properly represent the current structure of the transport networks and as we have seen in the previous paragraphs in realist network topologies the network coding gain will be significantly lower.

4 Conclusion

In this paper we have introduced the concept of network coding and analyzed its performance when applied to transport networks with 1+1 path protection. We have shown that network coding can lead to transport resource savings however in current realistic transport networks the resource savings are limited. We have elaborated that the network node degree distribution, which is given by the network architecture and topology, as well as the traffic flow distribution, which is set by the corresponding routing algorithms, significantly influence the achievable resource coding gain. A higher node degree as well as an adequate routing method, adapted to the corresponding network topology, can increase the achievable resource savings. The theoretically achievable maximum coding gain of 1/3 can only be realized in large full meshed network with equally distributed traffic flow data rates. For minimizing the total network transport resources an optimum network coding solution together with an optimal traffic distribution and therefore a corresponding network control plane is required. The constraints, e.g. signaling overhead, of such a control plane have to be studied in future research. Finally the evaluation of network coding performance with larger amounts of multicast traffic in the transport networks is of further interest, since here better utilization and a larger network coding gain and thus transport resource savings, can be expected.

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