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Innovative Two-path Data Transmission Scheme Proposal

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[1]***Abstract*—In this paper an innovative transmission scheme is proposed that improves resilience of data transmission over two, or generally more, separate channels. Within the solving of the wireless communication project we discovered a problem with optimal communication over independent transmission channels. This article presents a new transmission scheme as a solution to this problem. Our scheme uses techniques from the network coding field that manipulate the data within packets. Using this approach, and with the new internal logic at the decoder part, we obtained a lower end-to-end error rate compared to common path diversity schemes such as load balance or backup. These schemes were implemented, to verify our assumptions, as well as the proposed scheme, in the discrete network simulation framework OMNeT++ and mutually compared. Results of these simulations proved profitability of the proposed scheme.**

Index Terms—**Data transmission scheme, network coding, path diversity, error correction.**

I. INTRODUCTION

During the work on a project that addresses the problem of data transmission over multiple transmission channels, with an emphasis on the wireless environment [1], we came across the problem of how to optimally use these channels in terms of robustness of communication. We decided to look at path diversity methods more carefully and we optimized the transmission scheme. This paper presents a new technique of data transmission over two separate transmission channels. Robustness of the proposed scheme proved to be better compared to common path diversity methods. Our transmission scheme, called Combiner, uses distinct packet combination in the second channel. Due to this, and with the packet buffer at the destination part of the scheme, it is possible to recover more lost packets without retransmissions compared to the path diversity backup scheme.

Our approach has a similar basis as network coding theory, which was firstly introduced by Ahlswede *et al.* [2]. It brings the idea not only to move packets to different communication paths, but also to modify the content of packets. Other works dealing with similar subject are usually separable by the Open Systems Interconnection (OSI) model layers. Common way to improve the communication performance in the physical layer is the MIMO technology (Multiple-Input Multiple-Output), i.e. the use of multiple antennas at the receiver and transmitter [3]. Other optimization techniques in the physical layer area for wireless networks are for example dynamic subcarrier assignment and adaptive power allocation [4], or interference cancelation [5]. Optimization on the link layer is typically based on some kind of adaptability in order to adjust the protocol parameters to the actual network conditions [6], scheduling [7], or different back off mechanisms [8]. Many projects work with adding functionality between the OSI layers – cross-layer design, such as COPE [9]. COPE architecture improves throughput by implementing a new sub-layer between the link and network layers. This sub-layer identifies coding opportunities and benefits from them by forwarding multiple packets in a single transmission. Projects working on the network layer cover new routing methods, such as dispersity routing. Unlike conventional directory routing procedures, which route a message along a particular path between the source and destination, this routing mechanism sub-divides the message and disperses it through the maze of paths comprising the network [10]. Our work is fully transparent for the communicating systems and is independent of the transmission technology. The proposed scheme is an end-to-end (rather than point-to-point) correction system, which brings the possibility to overcome network nodes in the transmission path.

The paper is organized as follows. In Section II, we describe the principle of the proposed transmission scheme and its three stages. In Section III, we analyse abilities of the scheme and we obtain initial channel error probabilities. Simulation results and comparison of the proposed scheme with common path diversity methods are presented in Section IV.

II. PROPOSED TRANSMISSION SCHEME

Our goal is to improve resilience of data transmission in the system that uses two separate transmission channels. Our approach is in the involvement of the network coding

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principle, i.e. to affect packet data parts. The proposed scheme, called Combiner, uses bitwise exclusive disjunction (XOR) for the manipulation of data within packets from different data channels. Optimization of throughput or resilience, in systems with path diversity in use, has its reflection in MIMO methods of spatial diversity and multiplexing. The proposed data handling system as a part of the Combiner, on the contrary, is intended to be universal and independent of the physical layer.

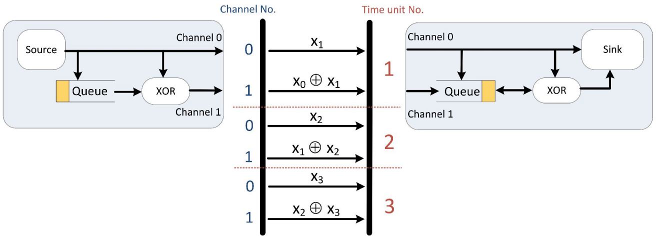

Fig. 1. Combiner transmission scheme.

Consider a transmission scheme in Fig. 1. The first channel is used only for sending newly transmitted packets. When a new packet is generated, its copy is saved to the queue and the original is sent through the channel 0. Channel 1 is designed as redundant; it is utilized by a combination of two consecutive packets. This combination is made by XOR operation. When a packet is lost in the channel 0, there is still a chance to recover this packet, with a packet from the channel 1 and its simple XOR operation with the appropriate packet from the queue at the destination node. Nevertheless, this is possible to do with a simple redundant channel without any operations with packets. Considering this, why use XOR operation? Because if the redundant channel also delivers a corrupted packet, or if the redundant channel fails, then in the simple network scheme, without the proposed transmission scheme, this packet is lost completely. On the contrary, with our system it is still possible to obtain this packet from the transmissions of the following packets.

The coder part of the Combiner is designed to be placed after the data source (generally at the edge of the sender). The decoder part should be just before the data sink as indicated in Fig. 1. The proposed system is independent of transmission technology, each of the channels can use various communication paths for packets, different number of network nodes for both channels is also possible.

The difference, which determines the number of packets the Combiner is able to reconstruct at a particular stage, is determined by the inside logic and also by the decoder queue length. With longer queue and more sophisticated logic the capability of packet reconstruction increases. The internal logic of codes is described in diagrams in Fig. 2 and Fig. 3.

The first decision point in Fig. 2 separates received packets to the innovative ones (transmitted through channel 0) and the redundant ones. Variables *errorInCurrent* and *errorInPrevious* refer to the situation whether error in packet happened or not. Variable *errorInOriginal* holds information if the packet from channel 0 is erroneous. The decision which of variants showed in Fig. 3 will be performed is based on variables *errorInCurrent* and *errorInPrevious*.

The queue lengths mentioned in the following sections are the shortest possible ones; therefore packets must arrive in the order in this case. In this article we use the terms *lost packet* or *packet error* as general terms for all situations when the received packet has any bit errors, including complete transmission channel failure.

Three variants of the Combiner, which differ in their packet correction capability, are described in the following sections. Combiner analysis and the comparison of its all three variants with common path diversity methods are described in Chapter III.

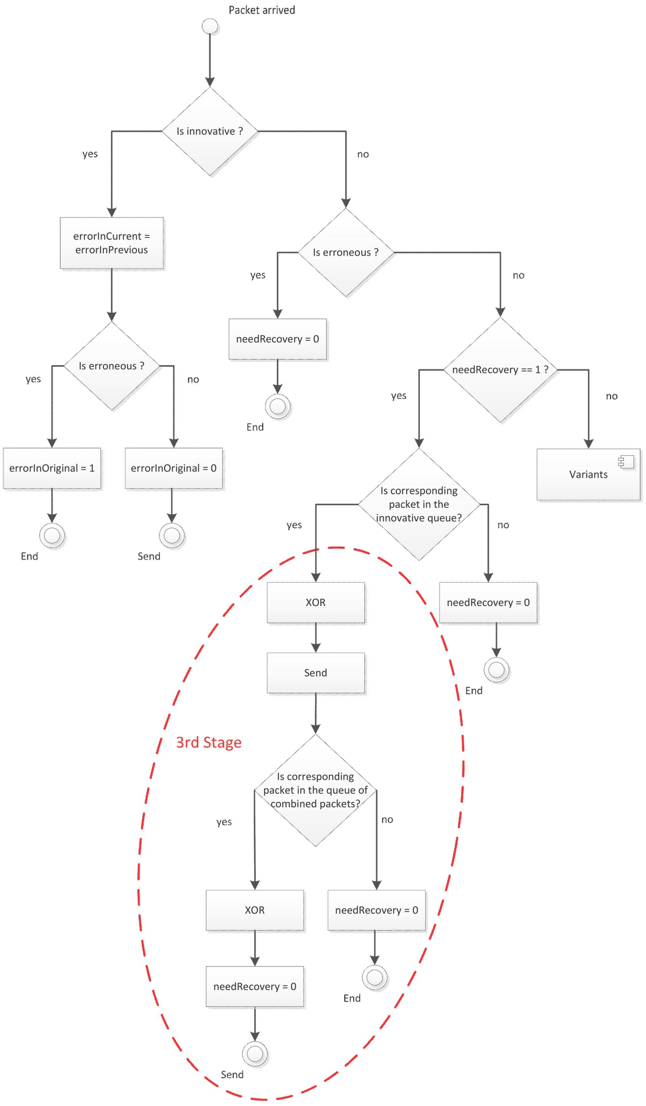

Fig. 2. Combiner internal logic diagram (first part).

A. 1st Stage

This stage of the Combiner scheme is able to reconstruct one lost innovative packet (that means the packet from the transmission channel 0) using the packet from the other channel. The queue at the decoder part has capacity for only one packet in this case. See Fig. 1 where the Combiner scheme is depicted. Every generated packet is sent through the channel 0 and its copy is XOR-ed with the previous packet, which was saved last time in the queue. This XOR-ed packet goes through channel 1 as redundant information. The copy of the generated packet is saved in the queue for the future combination with a newly generated packet.

At the decoder part, innovative packets from channel 0 are saved in the queue. In the case of packet error the packet from channel 1 is XOR-ed with the packet in the queue. If there is a corresponding packet, the lost packet is reconstructed.

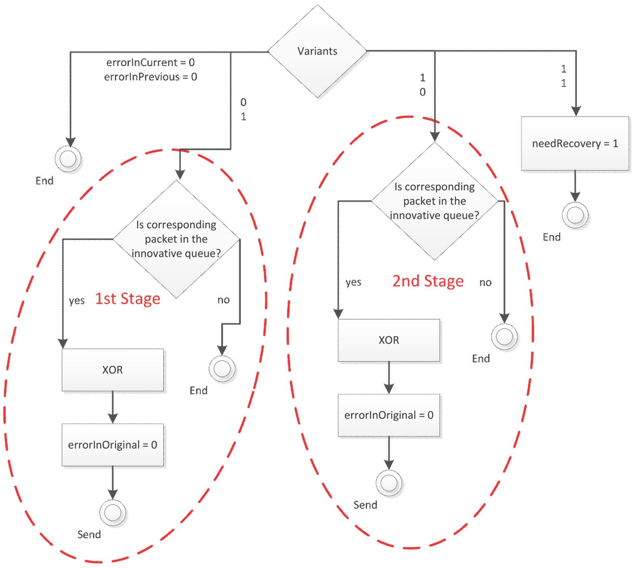

Fig. 3. Combiner internal logic diagram (second part).

This scheme brings no added benefit compared to the common scheme with full redundancy of packets in the second channel. Moreover, in the case that two or more consecutive original packets are lost, then the XOR-ed packets in channel 1 are useless, because it is impossible to decode them to the original form. We mention this only for completeness of the list of possibilities.

B. *2nd Stage*

This scheme is capable of reconstructing a lost innovative packet even in the situation when the corresponding redundant packet from channel 1 is also lost. This variant is more robust than a common parallel transmission scheme with the same added redundancy. The difference is in exploiting the properties of XOR-ed packets. Due to the fact that channel 1 transfers two consecutive packets XOR-ed into the single packet, it is possible to recover the innovative packet from the previous transmission with knowledge gained only from the current transmission. The necessary length of the queue is equal to one packet. For example, if the packet x_1 and also the packet $x_0 \oplus x_1$ are lost, then packet x_2 in XOR combination with the packet $x_1 \oplus x_2$ from the following transmission can recover the packet x_1, see the (1):

$$\begin{cases} x_1, x_0 \oplus x_1 \ldots lost, \\ x_2 \oplus (x_1 \oplus x_2) \Rightarrow x_1. \end{cases} \tag{1}$$

C. *3rd Stage*

The 3rd stage of the Combiner scheme is even more beneficial than the previous one while the same level of redundancy is preserved. This scheme is capable of the reconstruction of two lost innovative packets in a row even if the redundant packet for the first innovative packet is also lost. The principle of this scheme is in preserving information from the redundant channel 1 and appropriate exclusive-or coding application. For a complete packet reconstruction it is necessary to receive the redundant packet for the second lost innovative packet and the following pair of innovative and its corresponding redundant packet from channel 1. Therefore, the queue length must be at least equal to two; the third packet does not need to be stored as it is used for combining as soon as it arrives.

For instance (see Fig. 1) if packets x_1, $x_0 \oplus x_1$ and x_2 are lost, the following packets $x_1 \oplus x_2$ and x_3 are saved in the queue. When the packet $x_2 \oplus x_3$ arrives, it is possible to start the reconstruction of the lost innovative packets. From the exclusive-or combination of packets x_3 and its corresponding redundant packet $x_2 \oplus x_3$ the lost packet x_2 is obtained. The recovered packet is sent to its destination and its copy is used for the exclusive-or operation with the first packet from the queue ($x_1 \oplus x_2$). Therefore, the lost packet x_1 is also reconstructed. It is not necessary to recover the lost redundant packet $x_0 \oplus x_1$; only innovative packets provide information for the sink. The situation is explained in (2):

$$\begin{cases} x_1, x_0 \oplus x_1, x_2 \ldots lost, \\ x_3 \oplus (x_2 \oplus x_3) \Rightarrow x_2, \\ x_2 \oplus (x_1 \oplus x_2) \Rightarrow x_1. \end{cases} \tag{2}$$

III. ANALYSIS

The transmission scheme depicted in Fig. 1 can be described using the probability P_r. The probability P_r indicates that all the original packets (innovative) arrived to their destination without an error. Let *n* denote the number of original packets, and p_0, p_1 denote the probability of packet loss in channel 0 and channel 1, respectively; then

$$P_r = \left[(1-p_0)(1-p_1) + p_0(1-p_1) + p_1(1-p_0)\right]^n. \tag{3}$$

In the simulation the same error probabilities for both channels $p_0 = p_1 = 0.058987$ were used. This number comes from the widely used IEEE 802.11g standard [11], especially from the 16-QAM modulation with coding rate 1/2 (bitrate 24 Mbps). Since we did not want to be focused on specific technologies with a particular correction code, we assume that if an error occurs in a single bit during transmission then the entire packet is treated as erroneous. The bit error rate depends on the bit-to-symbol mapping; for SNR >> 1 (Signal-to-noise ratio) and Gray-coded assignment it is possible to assume that each symbol error causes only one bit error [12]; then the probability of a bit error per carrier is

$$P_{bc} \approx \frac{4}{b}\left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3b}{M-1}\frac{E_b}{N_0}}\right), \tag{4}$$

where

$$Q(x) = \frac{1}{2} erfc\left(\frac{x}{\sqrt{2}}\right). \tag{5}$$

Since the carriers are independent, the overall bit error rate is the same as the per-carrier error rate

$$BER \approx P_b = P_{bc}, \tag{6}$$

where P_{bc} – probability of bit error per carrier, P_b – probability of bit error, E_b – energy per bit, b – number of bits per symbol, N_0 – noise power spectral density [W/Hz], M – number of symbols in the modulation constellation, $Q(x)$ – Gaussian error function.

This work operates with packets; therefore, it is good to mention the relationship between bit error rate and packet error rate for a packet with the length of P_L

$$PER = 1 - (1 - BER)^{P_L}. \tag{7}$$

For the evaluation of the newly proposed schemes it is beneficial to compare them with traditional path diversity methods such as load balance and backup. The load balance method with a uniformly distributed load relies on the assumption that if there are two parallel data streams and each of them transmits half of the input data, then, owing to a lower bitrate for a single data channel, higher resistance using more robust modulation will be achieved. Therefore, if we have set error probabilities by calculation based on the 16-QAM modulation in systems with the entire input data rate in both channels, then in the load balance system channels it is necessary to use modulation which provides half bitrate. In accordance with the standard IEEE 802.11g it is the QPSK (Quadrature Phase Shift Keying) modulation with 1/2 coding rate (bitrate 12 Mbps) that after calculation gave us error probabilities $p_0 = p_1 = 0.0007827$ for both channels. Overall throughput will be the same as in the system with the second channel used as a redundant one.

The backup method with data mirroring takes advantage of the situation that two parallel channels transmit the completely the same data. It is necessary to have a less robust modulation, compared to the previous method, which is capable of transmitting data with the same overall throughput. Therefore, error probabilities for both channels will be set on the same level as in the newly proposed method (see Table I). Due to the parallel transmission of data, high durability of this scheme and low error rate are preserved despite higher error rate per channel compared to the load balance caused by the less resilient modulation technique. The resulting transmission speed is the same for all cases.

TABLE I. INITIAL CHANNEL ERROR PROBABILITIES.

Scheme Name	**Load Balance**	**Back up**	**1st Stage**	**2nd Stage**	**3rd Stage**
Channel 0	0.0007827	0.058987			
Channel 1	0.0007827	0.058987			
Modulation	QPSK	16-QAM			

Delay of end-to-end packet delivery varies for different types of schemes. If we compare common path diversity schemes with the 1st stage of Combiner scheme, they have the same delay. For the 2nd stage, in case of error, the delay of packet delivery corresponds to the size of one packet. The 3rd stage, depending on the number of errors in a row, has delay with a maximum size of two packets. This delay is caused by the reconstruction of lost packets from the newly arrived ones.

IV. SIMULATION RESULTS

All three stages of the Combiner were implemented in C++ code in cooperation with the simulation framework OMNeT++ [13]. This discrete network simulator allowed us to verify our assumptions with high precision because of easy possibility of the generation of a large number of packets for many simulation runs. At the same time, the question about random generation, which is never really random in a simulation environment, is satisfied due to pseudo-random number generator Mersenne Twister used in OMNeT++ [13]. This high-quality generator, developed by Matsumoto and Nishimura, has the period of $2^{19937} - 1$ and 623-dimensional equidistribution property, is sufficient for our purposes. More information about the Mersenne Twister can be found in [14].

Figure 4 illustrates results from simulations of three Combiner stages also in comparison with two simple path diversity methods – load balance and backup. It is clearly visible that the 3rd stage has the lowest probability of failure, also the 2nd stage is still superior to the other systems. This result is even more interesting because of the fact that the load balance system had an error probability set to 75.36 times lower value for each of channels compared to other simulated systems. The simulation results are listed in Table II.

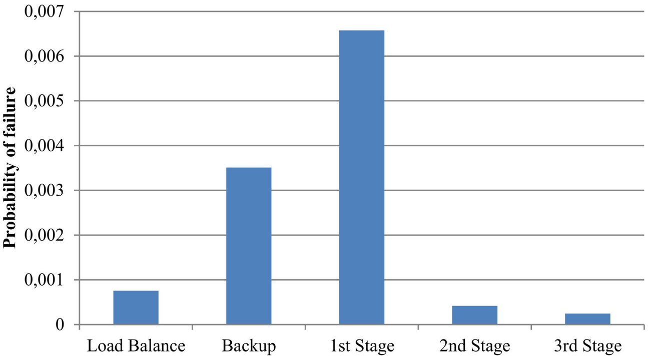

Fig. 4. Simulation results.

The 1st stage of the Combiner has worse results than the backup system; this is an expected result, because recovery capability of the 1st stage is limited by the possibility of the reconstruction of only one single packet from the channel 0 and, moreover, the reconstruction is dependent on the correct arrival of the appropriate packet in previous transmission (if the packet order is preserved).

TABLE II. SIMULATION RESULTS.

Scheme Name	**Load Balance**	**Backup**	**1st Stage**	**2nd Stage**	**3rd Stage**
Probability of Failure	7.57e-4	3.51e-3	6.57e-3	4.17e-4	2.47e-4
Confidence Interval	8.47e-7	8.05e-7	1.60e-6	6.10e-7	4.10e-7

Table III shows the improvement of newly proposed schemes compared to backup scheme in terms of end-to-end error rate. The comparison is made with the backup scheme because it also uses two channels for transmission and its error rates are set to the same value (see Table 1). The 1st stage of the Combiner is obviously worse than the backup system because the ratio of error rates is less than one. Reasons for the worse results are mentioned above. Already, the Combiner 2nd stage shows its benefit against the backup system while the 3rd stage has the best results with the fourteen times lower probability of packet loss compared to the common backup system.

TABLE III. IMPROVEMENT OF THE PROPOSED SCHEMES.

Comparison of Schemes	Improvement Ratio
Backup to 1st Stage	0.53
Backup to 2nd Stage	8.39
Backup to 3rd Stage	14.21

Table IV demonstrates benefits of the newly proposed schemes in comparison among the proposed stages of the Combiner and also with usual diversity methods. Values in the *Improvement Ratio* column represent how many times the second mentioned method is more beneficial compared to the first one. The load balance system showed that it is very robust for transmission over two separate channels with its better results than backup or 1st stage; nevertheless, the 2nd and 3rd stage of the Combiner proved to be even more robust.

TABLE IV. COMPARISON OF SCHEMES.

Comparison of Schemes	Improvement Ratio
1st Stage to 2nd Stage	15.73
1st Stage to 3rd Stage	26.65
2nd Stage to 3rd Stage	1.69
Load Balance to 3rd Stage	3.07
Backup to 3rd Stage	14.22

V. CONCLUSIONS

This paper presented a new scheme of data transmission with the ability to improve the resilience of end-to-end data communication over two separate transmission channels. The proposed transmission scheme reveals a potential packet reconstruction without retransmission. Our scheme, called Combiner, has up to fourteen times lower overall packet error rate compared to common path diversity transmission schemes because of the new internal logic described in the paper. The proposed scheme is independent of the transmission technology; however, we plan to implement this scheme in the project for optimization of wireless communication over multiple transmission channels.

Combiner involves a network coding technique manipulating the data inside the packet data part. Specifically, the bitwise exclusive disjunction is used for a combination of packets and the decoder part of the scheme has an internal logic that uses possible combinations of incoming packets for restoration of lost packets. Combiner scheme logic is proposed in three different stages that differ in the maximum resulting delay. The maximum delay is, in the worst case, only two packets. Results were verified by a simulation in a discrete simulation framework OMNeT++.

In the future work we intend to focus on the deployment of our scheme in specific real-time services such as a Voice over IP, M2M communication or for the rapidly developing field of Smart Grids [15]–[17] and examine its impact on them. Implementation of the Combiner into the physical device is also planned in the near future.

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