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A Study on the Application of Rateless Coding in Non-Cellular MIMO Systems for Machine-Type Communication

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Abstract: For industrial applications, communication requirements are considerably different than in most other domains. Whereas in office environments and the consumer market networks are designed towards the maximum throughput, in Industry 4.0 scenarios, traffic inflicts real-time requirements, demands particular high reliability and low latency. Industrial applications of the past as well as in most current production facilities are interconnected via cable. Wireless communication in this surrounding is still a big challenge, due to the mentioned communication demands. The high demands on reliability and latency require adaptations both to the MAC layer and to the baseband signal processing of the radio system being used. Of particular importance here is the error protection coding of the radio system, the investigation of which is the subject of the given work. This needs to achieve particularly high reliability but also must not consume too much computation time, while introducing only a reasonable amount of redundancy. In order to strive for this goal, this paper examines the utilization of Fountain codes (which belong to the family of rateless codes) with very short packets (in the order of less than 100 bytes). Investigated is the impact in terms of packet error rate. It is numerically shown that the joint erasure- and error-correction coding outperforms the sole usage of either one coding scheme. Interestingly, this is true in the presence of a Rayleigh channel but also in the presence of an AWGN channel. Finally, the performance of such a method is compared to that of space time block coding.

Keywords: Communication systems, Coding schemes, MIMO, Reliable Communication, Industrial Radio

1. INTRODUCTION

The widespread application of the achievements of information technology within industrial production facilities has long since become reality. The trend towards more complex industrial communication technology has not only become apparent since the German "Industry 4.0" initiative, which provides more complex production scenarios and is accompanied by a more complex need for machine communication. In connection with the more complex production scenarios, there is also a paradigm shift for the communication systems used. Conventionally, systems were designed for the highest possible throughput of best-effort data traffic, but regarding industrial applications requirements are changing into the direction of machine-type data traffic, which is associated with high reliability requirements and short latency times, but not necessarily with a high data rate. The high demands on reliability and latency of an industrial radio system require adaptations both to the MAC layer [Karrenbauer et al. (2018b)] and to the baseband signal processing of the radio system being used. It is necessary to make the best possible use of available diversity. Therefore, in the following we assume a MIMO system, whereby the degrees of freedom of the system include, in principle, the MIMO configuration of the system and the design of the error correction. The latter one has to, on the one hand, ensure fulfilment of the reliability requirements; on the other hand, due to the strict latency requirements, it must not require too much computing effort. On the contrary: Due to the fre-

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quently required real-time capability of the radio system, the coding must be completed in a deterministic amount of time. Fountain codes are known in the literature for their low computational cost as well as a better performance in terms of packet error rate than traditional channel coding methods in erasure channels. It is well known that the advantages of rateless codes are especially evident in channels with severe multipath properties. In previous work, this has been investigated with a view to maximum throughput, i.e. for very large packet sizes. In contrast, this paper focuses on the application of rateless coding in industrial environments and thus in connection with very short packets (i.e. 64 bytes for scope of this paper). It is investigated to what extent the use of rateless coding in this context gives advantages in terms of packet error rate. Therefore, computer simulations are performed and the results are presented. The remainder of this paper is structured as follows. In the next section, an overview of the related work is given. In section 3, a numerical evaluation of the reliability improvements w.r.t. the packet error rate in the context of rateless coding, is performed. A conclusion is drawn in section 4.

2. RELATED WORK

The following is intended to give a brief overview of the related work to be found in the literature.

2.1 Industrial Use Cases and their Requirements

Industrial applications and their requirements for industrial wireless communication systems have already been investigated in the literature. In this context, the work within the German research framework "Reliable Wireless Communication in Industry" (German acronym: ZDKI) should be mentioned in particular. Within the HiFlecs project, corresponding applications were compiled and their requirements combined into three so-called requirement profiles [Bockelmann et al. (2017)]. From all projects within the ZDKI program, corresponding requirements were collected and scientifically evaluated by an accompanying research project. The corresponding report has been published and is available online [Rauchhaupt et al. (2016)]. In addition, a white paper is available, which provides an overview of the application of radio systems in industrial environments and in which the requirements of the relevant applications are summarized [Aktas et al. (2017)]. In this report, a very high reliability (Packet Error Rate $\leq 10^{-9}$) and a low latency (order of magnitude: 1 ms) are expected for discrete manufacturing applications. The expected packet size is in the range of 20 to 50 bytes. This use case represents the most challenging one from a communication technology point of view and is therefore assumed in the following to be a reference use case without limiting the generality.

2.2 Error Correction Coding in Wireless Systems

The possibility of enabling use cases such as the already mentioned reference use case of discrete manufacturing with the use of wireless communication systems has been investigated in various places in the literature. In particular, it was found that a high degree of diversity must be exploited to achieve the reliability requirements. These include spatial diversity (i.e. the exploitation of signal transmission over several spatial streams [Tarokh et al. (1999)]), frequency diversity (using multi-carrier waveforms and/or spread spectrum techniques [Karrenbauer et al. (2017)][Karrenbauer et al. (2018a)]) as well as the exploitation of time diversity by using suitable error protection coding methods. In the latter field, fountain codes have recently become the focus of scientific interest [Shokrollahi (2006)].

Fountain Coding Traditionally, retransmissions have been used to improve reliability and to overcome packet erasures. However, in the context of industrial use cases, which are generally associated with hard real-time requirements, it is not appropriate to repeat a lost package. Rather, in the event of packet loss, the latest (sensor) data would be sent. Often high latency requirements do not allow a second transmission. Packet losses, so-called erasures, are therefore reduced by using a suitable erasure coding. The aim is to recover k data symbols from n transmission symbols at the receiver. The code rate r is therefore given as $r = n/k$. In the case of fountain codes, it is highly probable that the data symbols can be obtained by decoding k transmit symbols. It is irrelevant which k symbols were received from the n transmit symbols. Fountain codes belong to the class of erasure codes and possess specific properties. The authors in [Shokrollahi (2006)] state the properties of an ideal fountain code as follows:

(1) Using the fountain encoder, a sender should be able to generate as many code symbols as required by a receiver.
(2) A receiver receiving any subset of the encoded symbols should be able to reconstruct the original data using a fountain decoder, regardless of which encoded symbols were received and regardless of whether the encoded symbols were generated by one or more transmitters.
(3) The computing time for encoding and decoding should be linear.

Due to these properties it is possible to generate any number of code words at any time and thus to select the code rate almost arbitrarily. Several implementations of Fountain coding schemes are known in the literature and we will briefly describe them in the following.

Tornado Codes Tornado Codes have been developed by Luby et al. [Luby et al. (1997)]. Tornado codes proved to be up to 10,000 times faster than known implementations for Reed-Solomon-Codes, which have been classical erasure codes. Inexpediently, Tornado codes are fixed-rate codes, i.e. the encoder can only generate a fixed amount of code words.

LT-Codes Luby-Transform Codes (LT Codes) have been designed by Luby [Luby (2002)]. LT-Codes have been the first coding schemes, which are rateless, i.e. the encoder is able to generate as many codewords as desired and the decoder is able to decode the information as long as a sufficient amount of coded symbols is received. Due to the random nature of selecting the input packets, there is always a non-zero probability that some input packets might never be selected for coding.

Raptor Codes Raptor codes (Rapid Tornado codes) are a special class of LT codes. To address the aforementioned problem of never selected input packets, a precoding is done before LT coding takes place. RaptorQ codes are the latest version of the Raptor codes [Watson and Shokrallahi (2011)]. This method has the particular advantage that it is a systematic code (in contrast to all other codes mentioned so far).

Joint Erasure- and Error-Correction Coding Fountain codes belong to the class of erasure codes and are therefore primarily suitable for correcting transmission errors in a packet erasure channel. In an erasure channel, each transmitted packet has a certain probability of packet loss. At the end of the erasure channel it either arrives intact or not at all. A common wireless channel, however, is characterized by the fact that individual erroneous symbols occur in a transmitted packet. For the application of erasure codes, the wireless channel must therefore first be transformed into an erasure channel using a suitable inner coding (e.g. cyclic redundancy check (CRC) codes). The authors in [Berger et al. (2008)] already investigated the optimization of erasure and error correction coding for wireless transmissions. To this purpose, the authors consider a two-step coding strategy:

(1) First, an error correction is performed per packet, which is capable of reconstructing incorrectly transmitted bits under certain circumstances, but in any case reliably detecting incorrect packets. This transforms the wireless channel into an erasure channel, which in turn is coupled with
(2) erasure coding (e.g. digital fountain codes) which works across multiple packets.

Due to the mandatory joint use of erasure and error correction coding, the question arises as to the ideal operating point of the two coders with regard to their code rate. According to the authors, in difficult channel environments with Rayleigh fading, increased erasure coding redundancy proved to be advantageous, while in the case of a Nakagami-m channel with less significant fading characteristics, increased inner coding redundancy proved to be advantageous. We will revisit this in the following using computer simulations of the complete base-band signal processing chain and using a typical industrial numerology.

2.3 Space-Time Block Coding

Space-time block coding (STBC) is a coding technique used in MIMO communication systems. The idea is to transmit copies of a data stream over multiple antennas to improve the reliability of the data transfer. Alamouti et al. presented the first STBC technique for a system with two transmit antennas in [Alamouti (1998)]. This approach has later on been extended to higher orders of transmit antennas. Tarokh et al. presented a set of orthogonal STBCs [Tarokh et al. (1999)], which has been widely used in the literature since then. The authors also showed that it is not possible to have a STBC with code rate 1 for STBCs with a order higher than two.

3. NUMERICAL EVALUATION

In this paper, we assume a MIMO system. We investigate the following questions with the help of computer simulations:

(1) Assuming a fixed budget for the amount of redundancy information: Under which circumstances is the performance of joint erasure and error correction coding better than the sole usage of either one coding scheme regarding an industrial use case with limited packet length?
(2) Does a rateless encoder bring advantages in the context of a Rayleigh channel?
(3) How is the improvement by rateless coding compared to classical space time block coding to be evaluated?

It is expected that the performance of the joint erasure and error correction coding scheme will depend on the SNR of course, as well as on the channel model. For this reason, we evaluated the Packet Error Rate (PER) of the system as a function of the SNR, while using an AWGN as well as a block-static, packet independent and frequency-flat Rayleigh channel model. It is expected that the rateless coding outperforms the conventional approach in the case of multipath fading, i.e. when utilizing the Rayleigh channel model.

3.1 Setup

We simulated a setup according to the Figure 1. This simulation was done in Python 2.7 [Van Rossum and Drake Jr (1995)] using the following packages and libraries:

- We used Numpy [Oliphant (2006)], which is a package used for scientific computing with Python.
- The library “libraptorq” [Fulchir (2019)] in conjunction with the corresponding Python bindings [Kazantsev (2018)] provides a RaptorQ encoder and decoder in accordance with RFC 6330 [Minder et al. (2011)] and was used in this simulation.
- The library “bchlib” [Kent (2019)] is used for BCH encoding and decoding.

The components of the signal processing chain and their parameterization will be described in the following. The key parameters are as well summarized in Table 1.

Table 1. Simulation Setup

Parameter	**Value**
Packet length	64 bytes
Modulation	BPSK
FEC code rate (BCH)	1, 0.5, 0.25
RaptorQ code rate	0.25, 0.5, 1
RaptorQ symbol size	4 bytes
Channel model	AWGN, Rayleigh
OFDM FFT size	64
OFDM active subcarriers	52
OFDM CP length	16
Antenna configuration	4x4 MIMO

- Data Source: We use a simple vector data source, which generates balanced bit vectors of size 64 bytes.

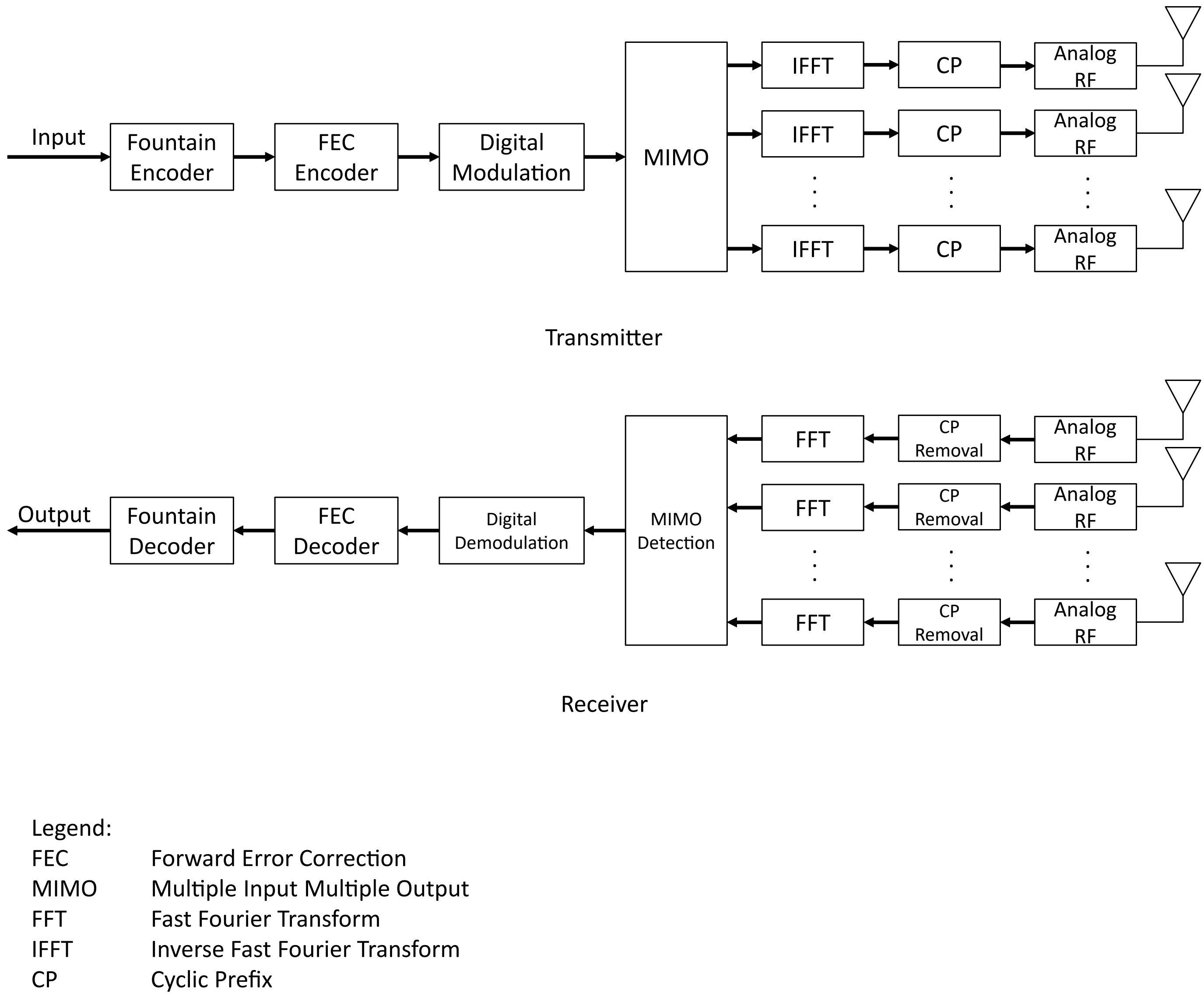

Fig. 1. Considered MIMO Transceiver

- RaptorQ Coding: For the scope of this paper, we use a RaptorQ encoder with a symbol size of 4 bytes.
- BCH Coding: As the inner coding layer, a (127, 36) BCH code is used in the case of the inner code rate $r_i = 0.25$ and a (63, 36) BCH code is used in the case $r_i = 0.5$. The BCH code's payload size is adaped to the RaptorQ symbol size using expurgation, i.e. every RaptorQ code symbol is coded using exactly one BCH code word. This ensures that a possibly undecodable BCH code word will only affect exactly one RaptorQ symbol.
- Digital Modulation: Since we are aiming towards applications with high reliability requirements, we chose to utilize the most robust digital modulation method w.r.t. BER/SNR for the scope of this paper, which is BPSK. It might be interesting to investigate higher modulation orders and their performance as well as their impact on the optimal operating point in the future.
- OFDM-Modulation: For the purpose of this paper, we chose a FFT size of 64, using 52 active subcarriers. The remaining subcarriers have been zero-padded at the borders of the FFT. The cyclic prefix length has been chosen to 16.
- Channel Model: In general, indoor industrial environments have a lot of reflecting objects such as metal walls, big machines as well as moving parts such as robot arms or rotating devices. This yields a variety of influences experienced by radiated waves during transmission over air. For this reason, in this paper, the AWGN channel as well as the Rayleigh channel are investigated.

3.2 Results

In figure 2, the performance of the erasure and error correction coding w.r.t. the packet error rate in the presence of an AWGN channel has been depicted. As one would expect, the error correction coding outperforms the RaptorQ coding in this case. However, in our considered use case with rather short package length, the combination of these two approaches yields an interesting result. Keeping

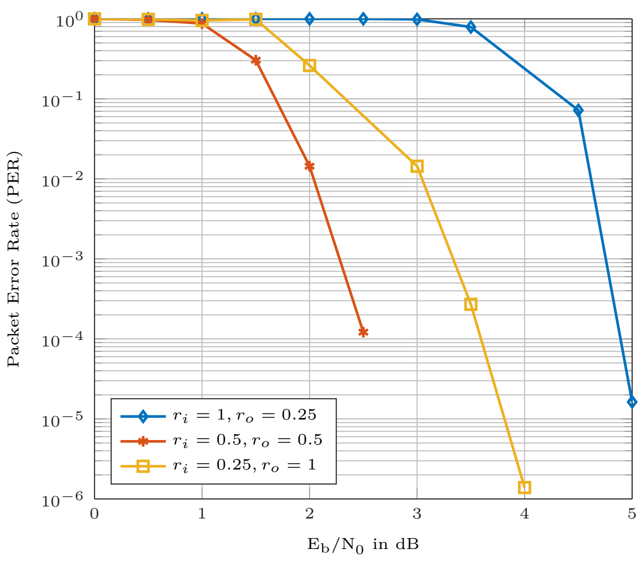

Fig. 2. PER vs. E_b/N_0 for different values of r_i and r_o in an AWGN channel

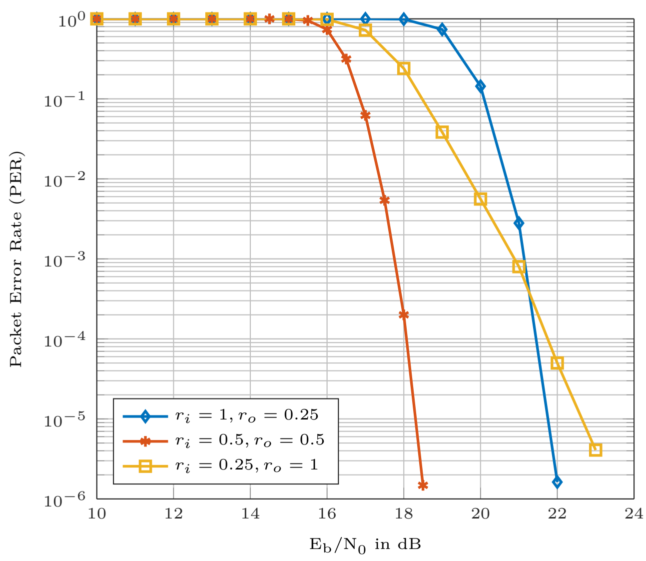

Fig. 3. PER vs. E_b/N_0 for different values of r_i and r_o in a Rayleigh channel

the overall amount of redundancy constant, joint erasure and error correction coding outperforms the sole error correction coding with a gain in the normalized signal-to-noise-ratio (SNR) E_b/N_0 of approximately 1 dB.

In the presence of a Rayleigh channel, the picture is slightly different, which is depicted in figure 3. First of all we can see that the RaptorQ coding curve becomes steeper than the curve of BCH inner coding. In other words, with improving SNR, the correction performance of RaptorQ increases significantly faster than that of the BCH code. As a result, from a certain value for the SNR (approximately 21 dB in our case), the initial disadvantage of RaptorQ encoding vis-à-vis BCH encoding is overcompensated. Furthermore, joint erasure and error correction coding shows again a better performance w.r.t. to the packet error rate and achieves a gain of approximately 3 dB when compared with the sole RaptorQ encoding. It should also be noted that the packet error curve in this case follows the RaptorQ behaviour rather than that of the BCH code.

In the context of reliability studies in MIMO systems, the consideration of space-time block coding is almost mandatory. For this reason, a further simulation compared the performance of space-time block coding with the performance of rateless coding in a Rayleigh channel. In the case of the space-time block code, an orthogonal code according to [Tarokh et al. (1999)] with code rate $r = 0.5$ defined by the following coding matrix was applied:

$$C_{4,1/2} = \begin{bmatrix} c_1 & c_2 & c_3 & c_4 \\ -c_2 & c_1 & -c_4 & c_3 \\ -c_3 & c_4 & c_1 & -c_2 \\ -c_4 & -c_3 & c_2 & c_1 \\ c_1^* & c_2^* & c_3^* & c_4^* \\ -c_2^* & c_1^* & -c_4^* & c_3^* \\ -c_3^* & c_4^* & c_1^* & -c_2^* \\ -c_4^* & -c_3^* & c_2^* & c_1^* \end{bmatrix}$$

In the case of the rateless code, a RaptorQ code has been used. In this case spatial multiplexing has been assumed, allowing a fourfold data rate, so that a code

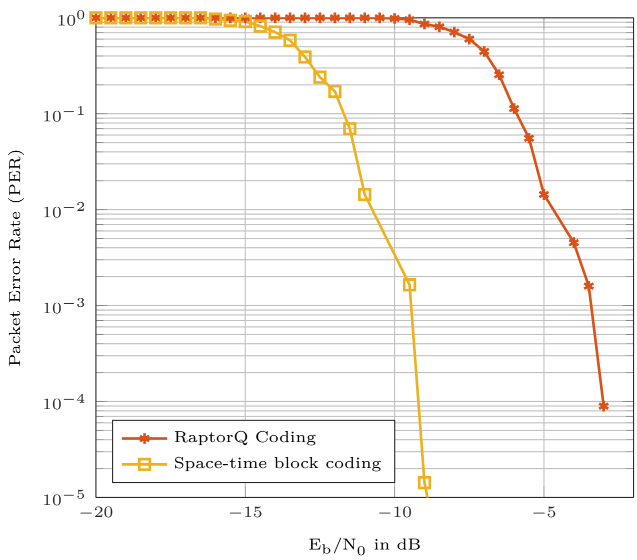

Fig. 4. PER vs. E_b/N_0 for RaptorQ coding in comparison to Space-time block coding assuming full CSI

rate of $r_0 = 1/8$ has been assumed. The result is shown in Figure 4 and 5. As we can see in Figure 4, with full channel information available at the receiver, space-time block coding outperforms RaptorQ coding. The gain in terms of SNR is approximately 5 dB. Also in the case of no CSI available at the receiver, Space-time block coding outperforms RaptorQ Coding, as depicted in Figure 5. However, space-time block coding allows a very limited adjustment of the code rate, whereas rateless coding can generate any amount of redundancy information at any time. In the case of rateless coding, a system can therefore be adapted very quickly and steplessly to the channel status and the required data rate. If this advantage is not required by the application, space-time block coding would be preferable.

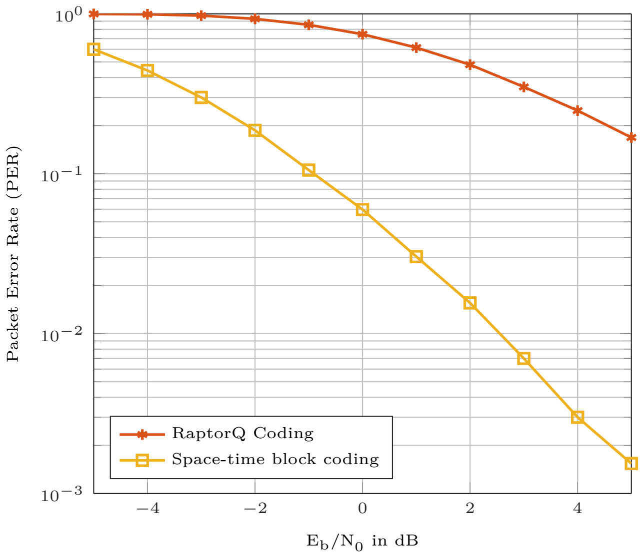

Fig. 5. PER vs. E_b/N_0 for RaptorQ coding in comparison to Space-time block coding assuming no CSI

4. CONCLUSION

In this paper, the joint erasures and error-correction coding in a wireless system with rather short packet length has been investigated for AWGN as well as Rayleigh channels. As a result, we are able to answer the questions raised in section 3 as follows:

(1) It has been numerically shown that the joint erasure- and error-correction coding outperforms the sole usage of either one coding scheme in AWGN as well as Rayleigh channels.
(2) As it is expected, the joint erasure- and error correction coding brings advantages in the presence of a Rayleigh channel. Interestingly, this is also the case in the presence af an AWGN channel.
(3) Even though, when compared to space-time block coding, the latter one proofs to be the more effective solution, the advantage of rateless coding comes with its flexibility. The use of rateless coding allows the amount of redundancy information to be arbitrarily selected at any time, so that system performance can be very flexibly adapted to channel properties and application requirements. This feature is expected to be a crucial one in industrial communication, since the requirements of industrial applications in terms of data rate, latency and reliability are diverse and the wireless channel is expected to be time-variant in nature.

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