RP-232425

A Simple, PHY-Aware, MAC-Layer Outer-Coding Scheme for Reliable, Single-TTI Communication

Source: Indian Institute of Science, Bengaluru

3GPP TSG RAN #101 Plenary Meeting

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Agenda Item: 8A.2.15 Other RAN1/RAN2/RAN3 led topics

Abstract

A simple, packet-level outer-coding scheme, that can reliably transmit data within a single TTI and that operates at the MAC layer is presented. The setting is one in which strict latency requirements make it desirable to convey information within a single TTI, and where there exist two or more independent Datalink paths between transmitter and receiver.

Under the scheme, each code block within the transport block is a packet, and coding takes place across the code blocks transmitted across the independent data paths. Additionally, at the receiver end, the physical layer passes on all correctly-decoded code blocks to the MAC layer, even if the entire transport block has not been completely decoded.

Where latency requirements permit, HARQ retransmission can be used to further increase reliability. It is shown that the scheme significantly outperforms PDCP duplication.

Motivation

Reliable, low-latency communication is key to enabling applications such as

- V2X
- XR
- IIoT
- UAV
- Telesurgery

Existing techniques have their limitations and drawbacks:

- PHY-Layer FEC
  (cannot recover from packet erasures)
- HARQ
  (introduces undesirable latency)
- RLC-ARQ
  (introduces undesirable latency)
- PDCP Duplication
  (inefficient form of coding)

- A simple coding scheme that overcomes some of these limitations is presented here...

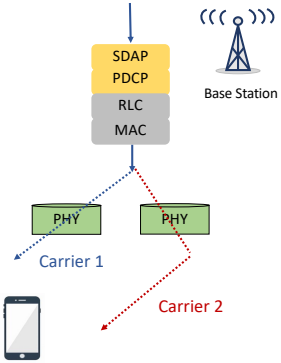
Outer Coding Can Be Helpful in Multiple-Datalink-Path Settings

- Outer Coding also called Network Coding, is a form of Packet-Level FEC
- That can be used to improve
  - reliability as well as
  - latency

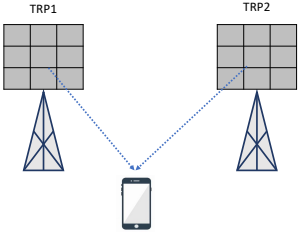
  by reducing or eliminating the need for HARQ or RLC-ARQ retransmissions
- Introducing an additional coding scheme at the packet level can potentially lead to a loss in spectral efficiency
- In settings where there are multiple Datalink paths between transmitter and receiver, PDCP duplication is currently employed to increase reliability
- *Such settings provide an opportunity to introduce outer coding without loss in spectral efficiency*
- We present a simple outer-coding scheme that addresses this setting and that significantly outperforms PDCP-layer duplication

Settings Where Two or More Datalink Paths Might be Available

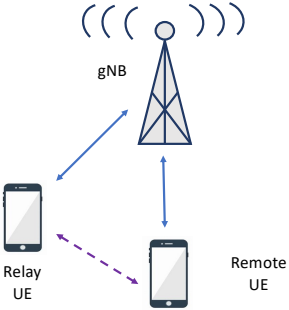
Carrier Aggregation (CA)



Multiple Transmission and Reception Point (mTRP)



UE Aggregation

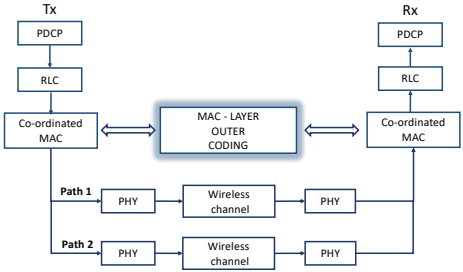


A Simple, PHY-Aware, MAC-Layer Outer-Coding Scheme for Reliable, Single-TTI Communication

Overview

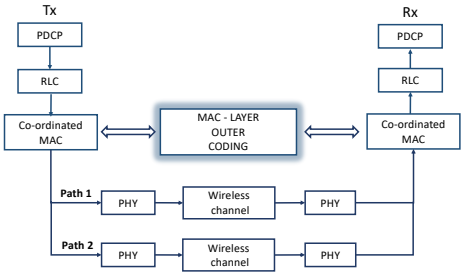
- **Setting:**
  - Where tight latency requirements make it desirable to transmit a Data Block $\mathcal{D}$ over a single TTI
  - Where there are two or more independent Datalink paths between transmitter and receiver

- **Coding Scheme:**
  - Coding takes place at the MAC layer
  - Data block $\mathcal{D}$ is mapped to a transport block
  - $\mathcal{D}$ is fragmented by MAC layer into packets
  - Each packet corresponds to an LDPC code block
  - Outer coding using a Reed-Solomon (RS) code is carried out across the LDPC code blocks transmitted across the data paths



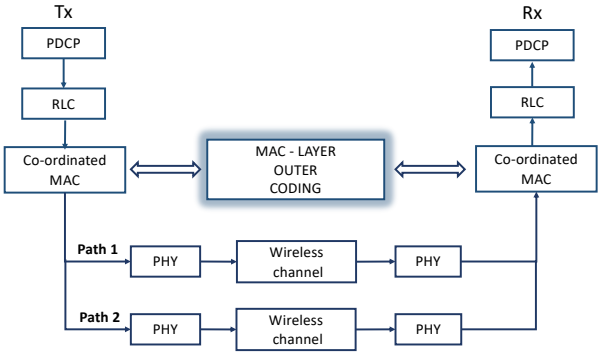
Overview

- **PHY-Awareness:** PHY layer passes on all correctly-decoded code blocks to the MAC layer, even if the entire transport block has not been completely decoded
- **HARQ retransmission:** Where latency requirements permit, one or more HARQ retransmissions can be used to further increase reliability
- **PDCP duplication:** Scheme significantly outperforms PDCP duplication



Operation

- The PHY-Aware, MAC-Layer Outer Coding Scheme for the downlink data channel operates as follows...



Transmitter Operation

- RLC layer indicates need to transmit data block $\mathcal{D}$ of size M bytes, over a single TTI, to MAC layer

$\Downarrow$

- MAC layer assigns transport block to $\mathcal{D}$

$\Downarrow$

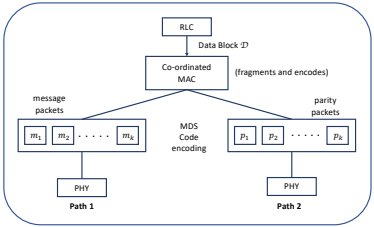
- fragments $\mathcal{D}$ into k equal-size LDPC code "message" blocks

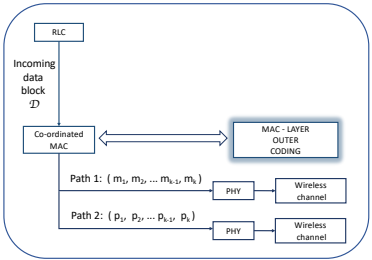
$\Downarrow$

- employs $[2k, k]$ Reed-Solomon code to create an additional k "parity" LDPC code blocks

$\Downarrow$

- passes distinct set of k fragments to each PHY for LDPC encoding





Receiver Operation

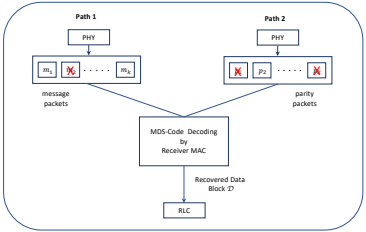
- each PHY layer at the receiver end, passes on decoded LDPC code blocks to the MAC layer even in instances where the entire transport block has not been decoded

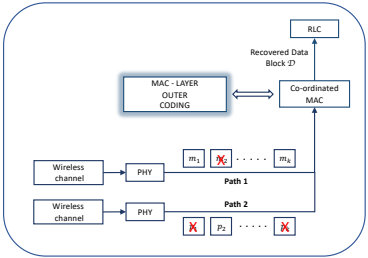
$$\Downarrow$$

- The coordinated MAC at the receiver end, receives all the correctly decoded code blocks that have been received over Path 1 and Path 2

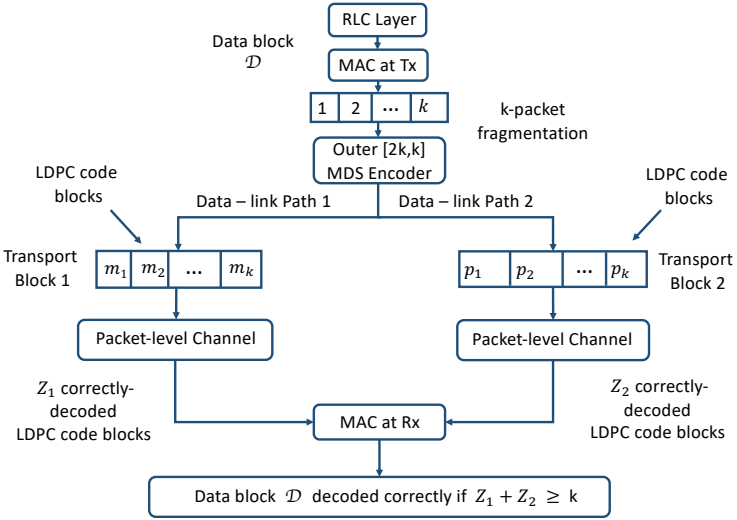
$$\Downarrow$$

- If the number of correctly-decoded code blocks across the two paths is $\geq k$, then the Coordinated MAC can decode

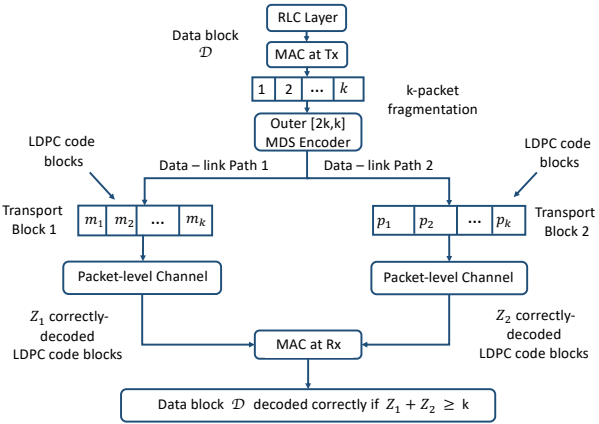




Consolidated Flowchart



Consolidated Flowchart (continued)



1. Flowchart shows encoding of data associated to a single TTI
2. Incoming data block $\mathcal{D}$ from RLC layer, is fragmented into k packets,
3. Each packet is the same size as an LDPC code block

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4. A $[2k, k]$ RS outer code is used to encode the k packets
5. The $2k$ packets are split into two disjoint sets and k packets are sent over each of the Datalink paths, Path 1 and Path 2

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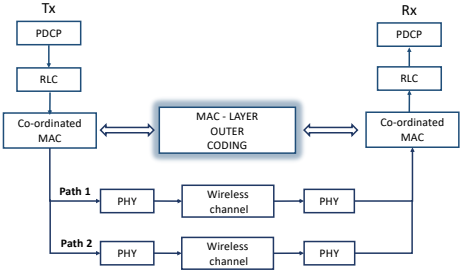
6. the PHY layers at Rx, pass on successfully decoded LDPC codewords (i.e., packets) to the MAC layer
7. The MAC layer can decode if a total of k successfully-decoded packets are received across the two paths

Additional Detail

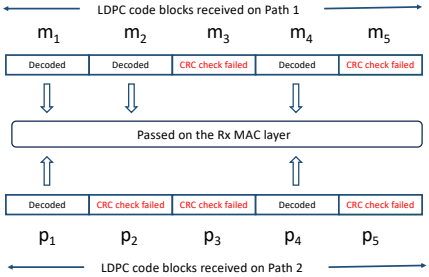
Explaining Use of LDPC Code Blocks as Packets at the Transmitter

- MAC layer maps incoming Data Block $\mathcal{D}$ to a Transport Block (TB)
- Based on size of the TB, the MAC layer can compute the size of each LDPC code block within the TB
- The MAC layer is thus able to fragment incoming data block $\mathcal{D}$ into packets where each packet is an LDPC code block



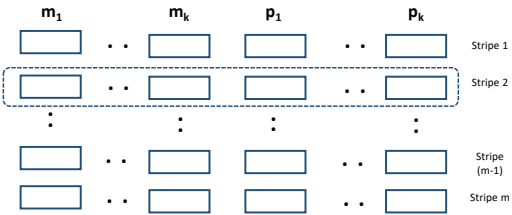
Explaining PHY-Awareness Need at the Receiver

- Since each LDPC code block is accompanied by a CRC, the Rx PHY is aware of which code blocks have been correctly decoded
- The Rx PHY can thus pass on the MAC layer at the receiver, all correctly-decoded code blocks,
- Even if all the code blocks within the transport block have not been correctly decoded
- These decoded LDPC code blocks can directly assist the MAC layer in decoding



Striping: From Scalar RS code $\rightarrow$ Packet-Level RS Code

- Striping is a simple means of using a scalar $[2k, k]$ RS code to construct an $[2k, k]$ packet-level RS code
- Each stripe (or row) in the figure is an RS code
- This simplifies encoding and decoding and enables adaptation to packet size
- Each symbol within a stripe can for example, be assumed to be a byte
- A byte-sized symbol alphabet will allow the construction of RS codes of length up to $2^8 = 256$

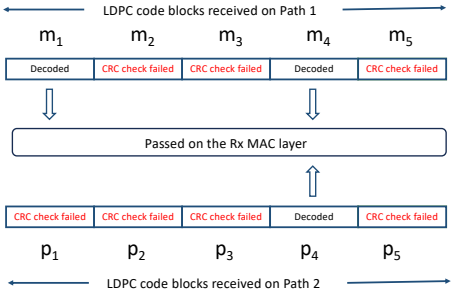


(each stripe (or row) is a [2k,k] scalar RS code)

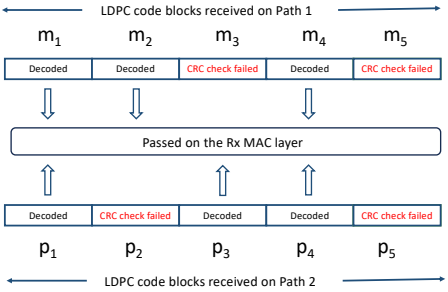
Choice of Block Code

1. While we have made use of RS codes in this document, any other Maximum Distance Separable (MDS) code can also be used and will be equally effective
2. In place of a $[2k, k]$ MDS code, we can also use any linear $[2k, k, d_{\min}]$ code having minimum Hamming distance $d_{\min}$
3. As an example, we could use a binary cyclic code
4. Such a code will require in general, the reception of $(2k - d_{\min} + 1)$ correctly-decoded code blocks at the receiver
5. MDS codes have the advantage of requiring the least number of correctly-decoded code blocks to recover the transmitted Data Block $\mathcal{D}$ as they have largest possible minimum value of $d_{\min} = k + 1$
6. Thus an RS code permits recovery of the Data Block $\mathcal{D}$ if any k code blocks are correctly recovered across the datalink paths

Extensions of Outer Coding Scheme to Incorporate HARQ



(before HARQ retransmission)



(after HARQ retransmission)

1. Where latency requirements permit, one or more HARQ retransmissions can be employed to increase decodability
2. Since a HARQ retransmission can potentially lead to a larger number of decoded LDPC codewords as shown in example above

Settings Underlying the Plots

The next few slides present plots of Block Error Rate (BLER) versus SNR for various settings. By BLER, we mean the probability of incorrectly decoding a Transport Block (TB). The general setting is the following

- Two independent Datalink paths between transmitter and receiver, that share the same statistical channel model
- 275 resource blocks are available for the communication, corresponding to a total of 3300 sub-carriers
- 30KHz sub-carrier spacing for a total available bandwidth of 100 MHz
- Data block size of roughly 5KB
- The 3GPP Non-Line-of-Sight (NLOS) Tapped-Delay-Line (TDL-C) channel as implemented in MATLAB
- LDPC code having code rate 8/9
- 256-QAM symbol alphabet
- With interleaving between virtual and physical resource blocks switched on
- and Doppler shift set equal to zero

Detail on the Plots and an Acronym

- Each plot differs from the standard setting in that a single attribute is different, such as 16-QAM in place of 256-QAM or else, TDL-C channel replaced by TDL-E channel.

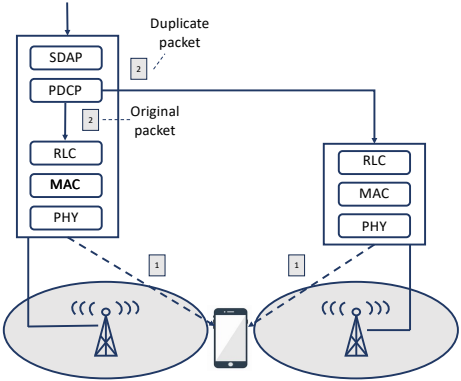
Plot 1	default parameters
Plot 2	5KB packet size replaced by 12 KB packet size
Plot 3	Interleaving turned off for the TDL-C channel
Plot 4	256-QAM replaced by 16-QAM
Plot 5	Doppler shift of 500 Hz introduced
Plot 6	TDL-C replaced by TDL-E
Plot 7	3 independent Datalink paths in place of 2

Acronym:

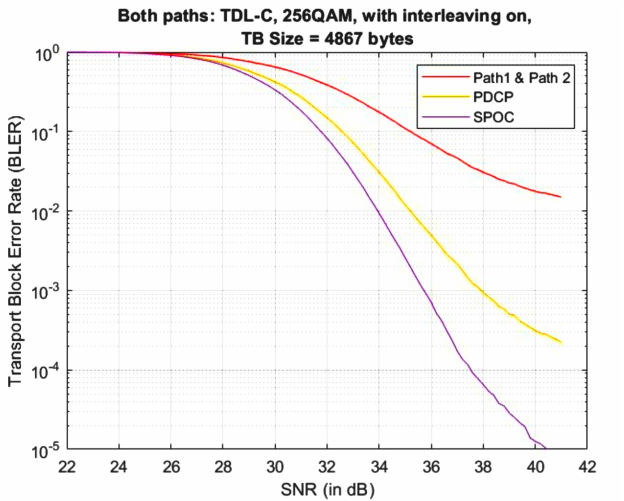
- In the plots, we have used the acronym **SPOC** to denote the **S**imple, **P**HY-Aware, MAC-Layer **O**uter-**C**oding Scheme

Note on Comparison with PDCP Duplication

- In the plots we make a comparison with "PDCP" duplication
- However, what we are really comparing against is duplication at the MAC layer
- PDCP duplication is expected to have worse performance since the duplication takes place at a higher layer and thus it cannot be guaranteed that packets corresponding to the same Data Block $\mathcal{D}$ will be transmitted in the same TTI on both data paths



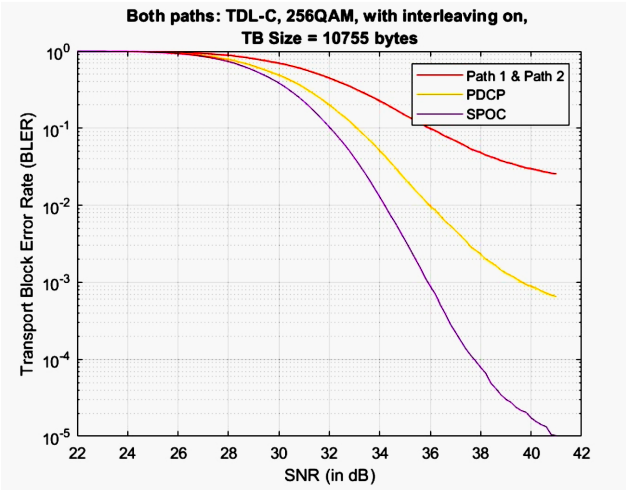
Plot 1 - Baseline Configuration



- 2 independent Datalink paths having identical statistics
- 3GPP channel model TDL-C
- VRB-PRB interleaving on
- Zero Doppler shift
- 256-QAM
- Transport block size of 4.867 KB
- $k = 5$ code blocks per TB
- Time duration: 2 OFDM symbols

- Improvement over PDCP duplication at 10^{-3} BLER point:
  - 2.2 dB SNR gain or
  - further BLER reduction by a factor of 14.45

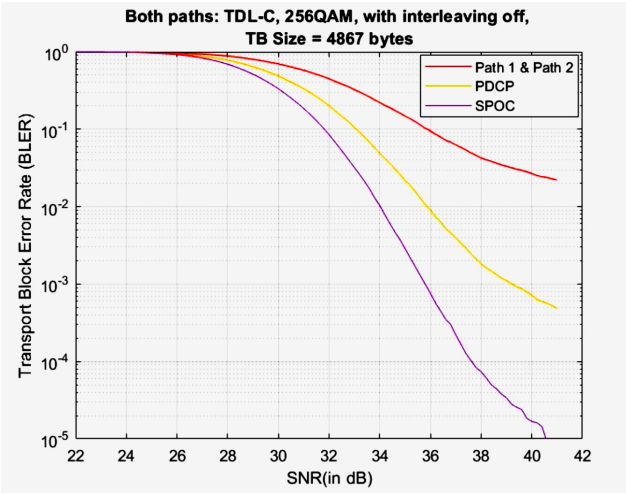
Plot 2 - Larger Packet Size



- 2 independent Datalink paths having identical statistics
- 3GPP channel model TDL-C
- VRB-PRB interleaving on
- Zero Doppler shift
- 256-QAM
- Transport block size of 10.755 KB
- $k = 11$ code blocks per TB
- Time duration: 4 OFDM symbols

- Improvement over PDCP duplication at 10^{-3} BLER point:
  - 3.5 dB SNR gain or
  - further BLER reduction by a factor of 47

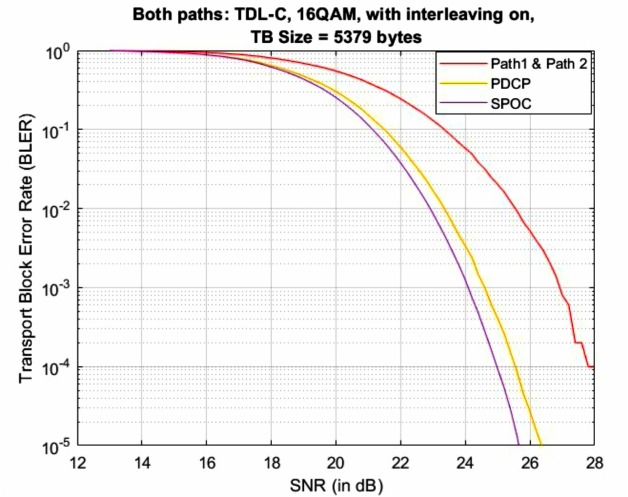
Plot 3 - With No VRB-PRB Interleaving



- 2 independent Datalink paths having identical statistics
- 3GPP channel model TDL-C
- VRB-PRB interleaving off
- Zero Doppler shift
- 256-QAM
- Transport block size of 4.867 KB
- $k = 5$ code blocks per TB
- Time duration: 2 OFDM symbols

- Improvement over PDCP duplication at 10^{-3} BLER point:
  - 3.6 dB SNR gain or
  - further BLER reduction by a factor of 36.28

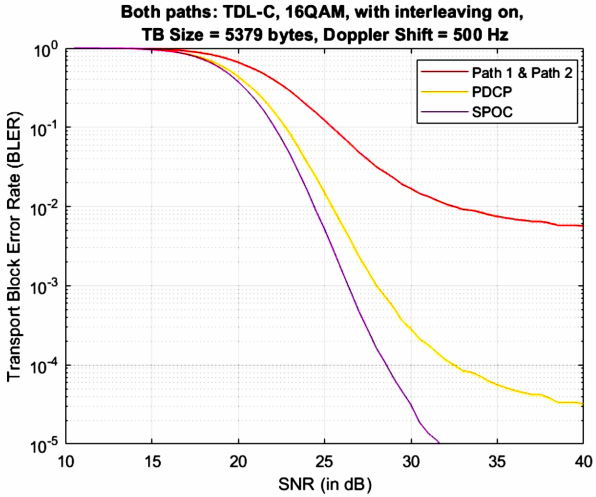
Plot 4 - 16-QAM Signal Constellation



- 2 independent Datalink paths having identical statistics
- 3GPP channel model TDL-C
- VRB-PRB interleaving on
- Zero Doppler shift
- 16-QAM
- Transport block size of 5.379 KB
- $k = 6$ code blocks per TB
- Time duration: 4 OFDM symbols

- Improvement over PDCP duplication at 10^{-3} BLER point:
  - 0.5 dB SNR gain or
  - further BLER reduction by a factor of 3.57

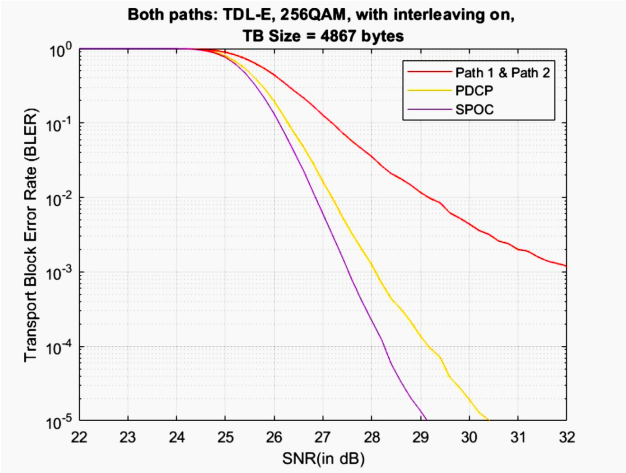
Plot 5 - With Doppler Shift of 500 Hz



- 2 independent Datalink paths having identical statistics
- 3GPP channel model TDL-C
- VRB-PRB interleaving on
- 500 Hz Doppler shift
- 256-QAM
- Transport block size of 5.379 KB
- $k = 5$ code blocks per TB
- Time duration: 2 OFDM symbols

- Improvement over PDCP duplication at 10^{-3} BLER point:
  - 1.6 dB at BLER of 10^{-3}
  - or further BLER reduction by a factor of 6.16

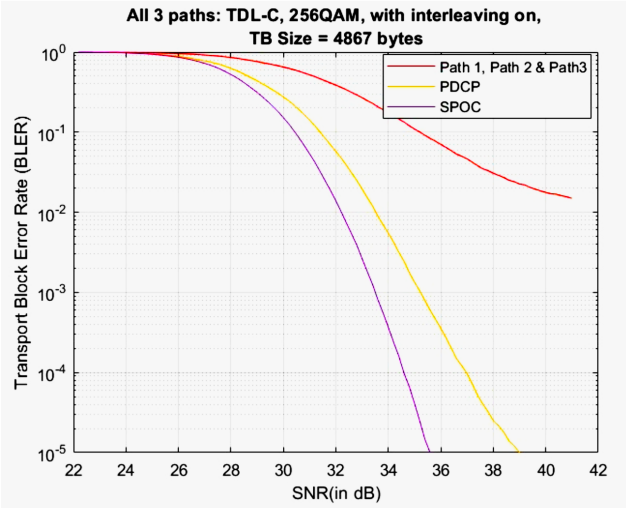
Plot 6 - With Line-of-Sight (LOS) TDL-E Channel



- 2 independent Datalink paths having identical statistics
- 3GPP channel model TDL-E
- VRB-PRB interleaving on
- Zero Doppler shift
- 256-QAM
- Transport block size of 4.867 KB
- $k = 5$ code blocks per TB
- Time duration: 2 OFDM symbols

- Improvement over PDCP duplication at 10^{-3} BLER point:
  - 0.5 dB SNR gain
  - further BLER reduction by a factor of 5.66

Plot 7 - With 3 Independent Datalink Paths



- 3 independent Datalink paths having identical statistics
- 3GPP channel model TDL-C
- VRB-PRB interleaving on
- Zero Doppler shift
- 256-QAM
- Transport block size of 4.867 KB
- $k = 5$ code blocks per TB
- Time duration: 2 OFDM symbols

- Improvement over PDCP duplication at 10^{-3} BLER point:
  - 1.7 dB SNR gain
  - further BLER reduction by a factor of 42.48

Partial Insight into the Performance Plots

- The relative improvement of SPOC over PDCP duplication, grows with increase in number of code blocks and this explains the improved performance of SPOC in Plot 2 (larger packet size)

- In general, SPOC will perform better in comparison to PDCP duplication whenever there is a significant variation in the probability with which individual code blocks are decoded incorrectly
  - As a result, switching off VRB-to-PRB interleaving (Plot 3) will tend to result in improved SPOC performance since in the absence of interleaving, there can be a wide variance in the channel frequency response encountered by different code blocks
  - For the same reason, SPOC performs better over NLOS channels since LOS channels (Plot 6) are close in behavior to that of an AWGN channel and in an AWGN channel, code blocks tend to have the same probability of being decoded incorrectly.

References

V2X:

- 3GPP TR 22.886: Study on enhancement of 3GPP Support for 5G V2X Services
- S. W. Kim et al., "Multivehicle Cooperative Driving Using Cooperative Perception: Design and Experimental Validation," in IEEE Transactions on Intelligent Transportation Systems, vol. 16, no. 2, pp. 663-680, April 2015.

XR:

- 3GPP TR 38.838: Study on XR (Extended Reality) Evaluations for NR

IIoT:

- 3GPP TS 22 104: Service requirements for cyber-physical control applications in vertical domains

PHY Layer Specs:

- 3GPP TS 38.211: Physical channels and modulation (pp. 95-97)
- 3GPP TS 38.214: Physical layer procedures for data

TDL-C and TDL-E References:

- 3GPP TR 38.901: Study on channel model for frequencies from 0.5 to 100 GHz

UE Aggregation:

1. ZTE, Sanechips, "RWS-230288: Views on user virtualization and collaboration in Rel-19", June 2023

Thanks!