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Development of Functional Prototype of PDCP Sublayer in 5G NR

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***Abstract*—The 3GPP has initiated the development of a 5G NR (fifth generation New Radio) to meet the requirements of advanced technical solutions for highly mobile and connected society. 5G provides high-capacity mobile broadband service, massive connectivity among low energy devices with very low latency and ultra-high reliability. In India, the 5G mobile communication is yet be in operational stage. But the industry use cases that utilizes machine to machine communications with low latency and ultra-high reliability are gaining significance recently. 3GPP has released the 38- series technical specifications for the Radio Access of NR. In this paper, a functional prototype for the PDCP sublayer in the user plane protocol of 5G Radio Access Network is developed as per 3GPP TS38.323 v 15.2.0 specifications. A system model with complete flow of PDCP functionality is designed and presented with execution results.**

***Index Terms*—5G NR, PDCP, Radio Access Network, Data Plane, User Plane.**

I. 5G NR

Fifth Generation New Radio (5G NR) is a unified and more capable wireless communication network. Beyond interconnecting people, it also intelligently interconnects and control every devices, machines and objects virtually. 5G NR operates in high speed with high data rates, ultra-low latency and high reliability. It has the potential to empower the current cutting-edge technologies, Internet of Thongs (IoT), Artificial Intelligence (AI), Augmented Reality (AR) and many more. The key aspect of 5G is the fact that it operates on a higher frequency band of wireless spectrum i.e. above 24GHz, known as millimetre wave (mm wave). The three prime factors of 5G, massive capacity, high speed with low-latency and high reliability are defined as the three distinctive 5G use cases defined as enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable and low-latency communication (URLLC) [1,2] (Figure 1).

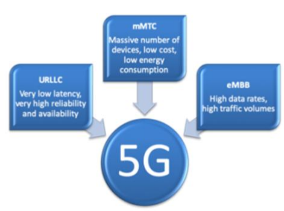

Figure 1 5G Use cases

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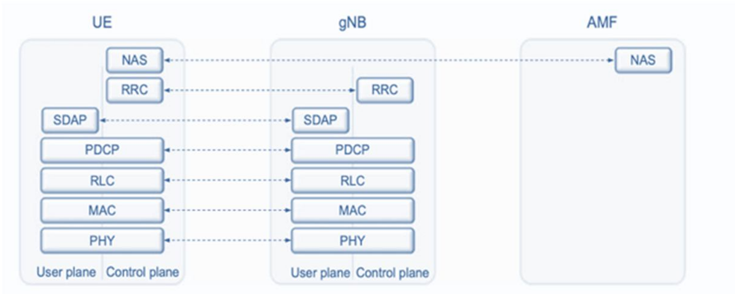


Figure 2 RAN protocol Architecture of PDCP Sublayer

A. 5G CN and RAN

3GPP is developing 5G core network (5GCN) to connect with 5G radio access technology, the Radio Access Network (RAN) architecture. The RAN is responsible for all radio-related functionality like scheduling, radio-resource handling, retransmission protocols, coding, and various multi-antenna schemes. The 5G core network is responsible for functions like authentication, charging functionality, and setup of end-to-end connections. Both 5GCN and RAN makes 5G a complete network.

B. PDCP sublayer in RAN

Packet Data Convergence Protocol (PDCP) sublayer exists in User Equipment (UE) & gNodeB (gNB) in both user plane and control of RAN Protocol Architecture. The RAN architecture for user plane and control plane between UE, gNB and Access and Mobility Management Function (AMF) is shown in Figure 2. The AMF is in charge of control signalling between the core network and the device, security for user data, idle-state mobility, and authentication.

Packet Data Convergence Protocol act as an interface between the User Equipment (UE) and the internal firmware of the UE. PDCP sublayer is the uppermost layer of the radio protocol stack of 5G New Radio. The functionality of PDCP is stated in 3GPP TS 36.323 for LTE and TS 38.323 for NR [3,4]. The PDCP receives services from its lower layer, Radio Link Control (RLC) and provides services to its upper layers Radio Resource Control (RRC) in case of control plane and to Service Data Adaptation Protocol (SDAP) in user plane. SDAP is responsible for mapping QoS bearers to radio bearers according to their quality-of-service requirements.

RLC is responsible for segmentation and retransmission handling. The RLC provides services to the PDCP in the form of RLC channels. There is one RLC entity per RLC channel (and hence per radio bearer) configured for a device. Medium-Access Control (MAC) handles multiplexing of logical channels, hybrid-ARQ retransmissions, and scheduling and scheduling-related functions. The scheduling functionality is located in the gNB for both uplink and downlink. The MAC provides services to the RLC in the form of logical channels. Physical Layer (PHY) handles coding/decoding, modulation/demodulation, multi-antenna mapping, and other typical physical-layer functions. The physical layer offers services to the MAC layer in the form of transport channels.

In this paper, a functional prototype of PDCP sublayer is developed and presented as per 3GPP ETSI TS 38.323 Release 15 standard [4]. All the functionalities of PDCP sublayer for user plane is implemented and shown with the execution results. The remaining sections of this paper are organised as follows: Section 2 explains the structural and functional aspects of the PDCP sublayer. Section 3 elaborates the working system model of the functional prototype. Section 4 is presented with the simulation and execution results of the developed model. Section 5 concludes the paper with future work.

II. PDCP

A. Structure and Functionality of PDCP Sublayer

An instance of a PDCP sublayer based on radio interface protocol architecture is shown in Figure 3. The PDCP sublayer is utilized by Radio Bearers (RBs) mapped for the Dedicated Control Channel (DCCH) and Dedicated Traffic channel (DTCH). Each RB is associated with one PDCP entity. Each PDCP entity is associated with one, two, or four RLC entities depending on the RB characteristic (e.g. unidirectional/bidirectional or split/non-split) or RLC mode.

The PDCP sublayer consists of several PDCP entities. One or more PDCP entities can be defined for a UE. Every single PDCP entity carries data of a single radio bearer. The functionalities done by PDCP sublayer is

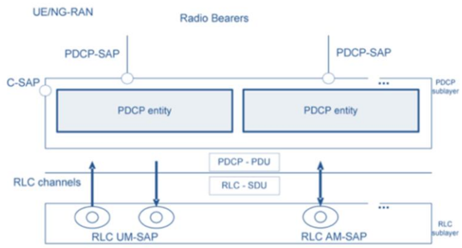


Figure 3 PDCP Structural View

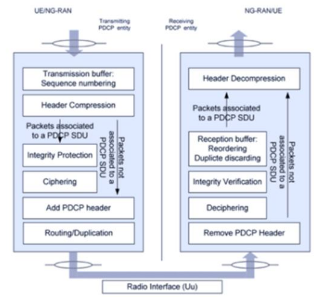


Figure 4 PDCP Functional View

shown in the Figure 4. Every data block received from the upper layer is numbered with Sequence Number (SN). The sequence numbering procedure helps in in-order deliver, retransmission and duplicate removal. The sequence numbers are also used to combine the multiple chunks of data block into an original big chunk.

The PDCP then performs the IP header compression to reduce the number of bits to transmit over the radio interface. The header-compression mechanism is based on robust header compression (ROHC) framework [5], a set of standardized header-compression algorithms also used for several other mobile-communication technologies. PDCP is also responsible for ciphering to protect against eavesdropping and, for the control plane, integrity protection to ensure that control messages originate from the correct source. At the receiver side, the PDCP performs the corresponding deciphering and decompression operations.

B. User Plane

The user plane of PDCP sublayer transmits and receives either Data PDU or Control PDU is depicted in Figure 5. The Data PDU is classified as Signalling Radio Bearer (SRB) and Data Radio Bearer (DRB). SRB carries signalling messages like Radio Resource Control (RRC) or Non-Access Stratum (NAS).

SRB is further classified as SRB-0, SRB-1 SRB-2 and SRB-3. SRB-0 and SRB-3 is for RRC messages using Common Control Channel (CCCH), and Dedicated Control Channel (DCCH) logical channels respectively. SRB-1 and SRB-2 is for RRC and NAS using DCCH logical channel [6]. For all the SRBs the integrity check and ciphering are optional. The packet format of SRB Data PDU is shown in Figure 6.

The 4 bits of first byte of PDU are reserved and their default value is 0. The SRB Data PDU has 12-bit Sequence number (SN) and followed by data of variable length. The MAC-I bytes are padded with 0 bits as there is no integrity check for SRB data PDU.

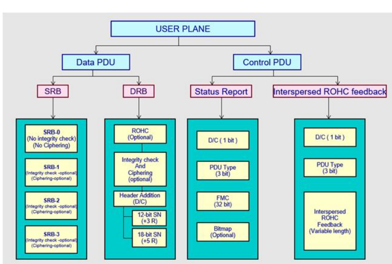


Figure 5 User Plane Classification in PDC

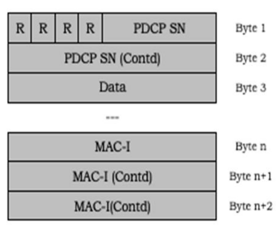


Figure 6 PDCP Data PDU for SRBs

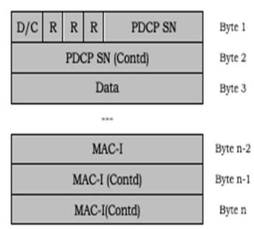


Figure 7 PDCP Data PDU- 12 bits PDCP SN

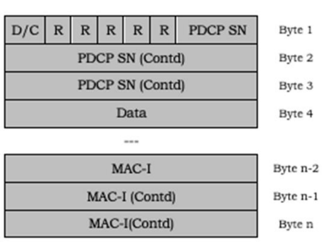


Figure 8 PDCP Data PDU - 12 bits PDCP SN

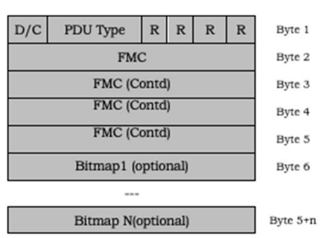


Figure 9 PDCP Control PDU PDCP status report

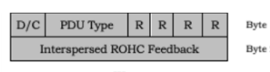


Figure 10 PDCP Control PDU format Interspersed ROHC Feedback

The IV bits of first byte of PDU are reserved and their default value is 0. The SRB Data PDU has 12-bit Sequence number (SN) and followed by data of variable length. The MAC-I bytes are padded with 0 bits as there is no integrity check for SRB data PDU.

The DRB PDU has two packet structure as shown in Figures 7 and 8, one with 12-bit Sequence number and 18-bit Sequence number. In 12-bit SN format, the first byte consists of 3-bit R field and 3-bit PDU type field. In 18-bit SN format, there are 5-bits for R field. In both the PDU format, the foremost bit (D/C) is used to classify whether the DRB is a Data (1) or Control (0) PDU. For DRB control PDU, the type of the control, status report or interspersed ROHC feedback is determined by the 3-bit values 000 and 001 respectively.

The packet format of control PDU is shown in Figures 9 and 10. The Control PDU carries status report for Acknowledged Mode (AM) DRBs and interspersed ROHC feedback for both AM and UM DRBs. The receiving entity acknowledges the transmitter using the status report control PDU. The 32-bit First Missing Count (FMC) indicates the value of the first missing PDCP SDU within the reordering window. The variable length Bitmap fields indicates the missing SDUs with a ’0’ in Nth bit position. The correctly received SDUs are indicated with a ‘1’ in the respective Nth bit position.

III. System Model

In this work, the PDCP system model is designed as per specification stated in 3GPP ETSI TS 38.323 Release 15 standard [6]. The system implements the functionality of the PDCP sublayer as two separate modules, transmitting and receiving. The transmitting module (Tx) implements the functions of the transmitting PDCP entity and the receiving module (Rx) implements the functions of the receiving PDCP entity as stated in the structure and functionality of PDCP sublayer. The detailed description of each module is stated below:

A. Transmission (Tx) Module

When upper layers request a PDCP entity establishment for a radio bearer, the UE shall: (i) establish or re-establish a PDCP entity for the radio bearer, (ii) transmit the data and (iii) release the PDCP entity for the radio bearer. The type of the radio bearer may be SRB or DRB. The PDCP entity accepts SDU from upper layer and builds a PDCP PDU to be delivered to the lower layers. The entire process flow of Tx module is depicted in the Figure 11 below.

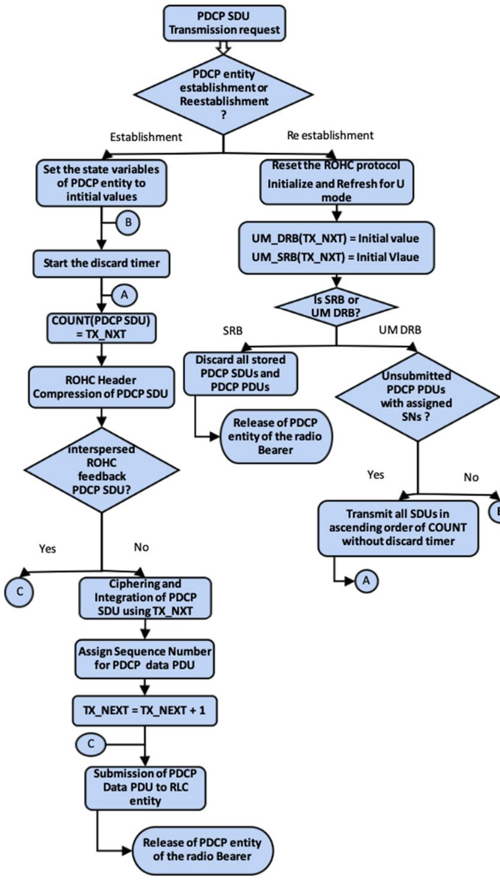
B. Receiver (Rx) Module

The work flow of the Rx module is shown in Figures 12. When upper layers request a PDCP entity establishment or re-establishment, the receiving PDCP entity will process the PDCP Data PDUs that are received from lower layers. The parameters used in Rx module is listed in Table 1. The receiving PDCP entity determines the COUNT value of the received PDCP Data PDU, based on the window size. The determined COUNT is stored as RCVD_COUNT, as a combination of PDCP HFN (Hyper Frame Number) and PDCP SN. After determining the RCVD_COUNT, the deciphering and integrity verification of the PDCP Data PDU is done. The integrity check on the receiving module is represented as X-MAC. On the success of the X-MAC, if the received PDCP PDUs are not duplicated, they are buffered for the upper layers. In case of duplicated PDCP PDUs, they are discarded. If integrity verification fails, the error message is indicated to the upper layers and the PDCP PDUs are discarded. The buffered PDCP PDUs are decided whether to wait for more PDCP PDUs or send them to upper layers based on t-reordering timer. When t-reordering timer expires, all the available PDUs are sent to upper layers in ascending order of the COUNT value.

C. PDCP Establishment

During the establishment procedure, the UE shall establish a PDCP entity for the radio bearer, set the state variables of the PDCP entity to initial values, and follow the procedures as in ETSI TS 138 323 V15.2.0 (5.1-5.6). The state variables and other parameters are listed in the Table 1. All state variables are non-negative integers, and take values from 0 to [232 – 1].

After the initialisation of state variables, the data transmission operation begins by starting the discard timer associated with corresponding PDCP SDU. A COUNT value corresponding to TX_NEXT is associated to this PDCP SDU. For all the packets, associated with each PDCP SDU, the ROHC header compression is applied based on the type of radio bearer. In case of SRB, header compression (ROHC) is not necessary. Though the header compression is stated as optional in the TS specification for DRBs, in this work, to reduce the traffic overload, header compression is applied for all PDCP SDU except the SDAP control PDU. By default, the SDAP header in all PDCP SDUs will not be compressed.



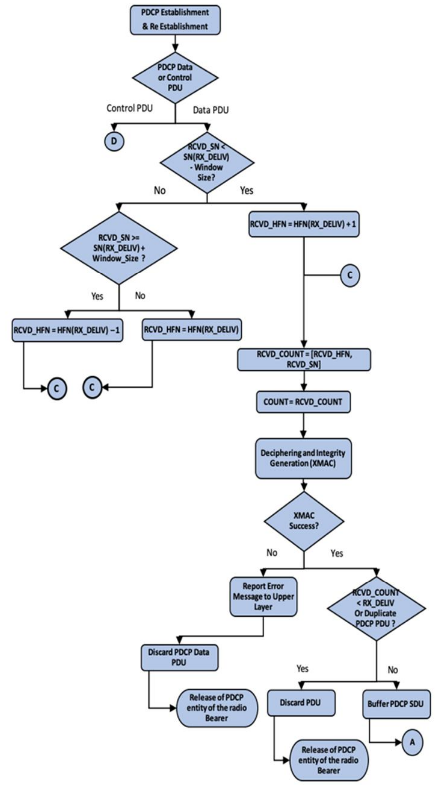


Figure 11 Transmission (Tx) Module of PDCP Entity

Figure 12 Receiving (Rx) Module (Part1) of PDCP Entit

Following header compression, integrity check is done by generating Message Authentication Code for Integrity (MAC-I) for all SRBs and DRBs expect SRB-0. The integrity protection algorithm and key to be used by the PDCP entity are configured by upper layers. The parameters required by PDCP which are provided by upper layers (TS38.331, 2018) are BEARER (defined as the radio bearer identifier) and KEY (KUPint).

The data unit that is ciphered is the data part of the PDCP Data PDU except the SDAP header and the SDAP Control PDU if included in the PDCP SDU, and the MAC-I. The ciphering is not applicable to PDCP Control PDUs. The ciphering function is activated by upper layers. When security is activated, the ciphering function shall be applied to all PDCP Data PDUs indicated by upper layers for the downlink and the uplink, respectively. The required inputs to the ciphering function include the COUNT value, and DIRECTION (direction of the transmission). The parameters required by PDCP which are provided by upper layers are BEARER (defined as the radio bearer identifier) and key.

In this work, 3 types of Ciphering/ Deciphering techniques are used: AES, Snow3G, ZUC

After integrity and ciphering, the Sequence number for the PDCP is set to TX_NEXT modulo 2[pdcp-SN-Size]. The encapsulated PDCP PDU is submitted to the lower layers for transmission.

D. PDCP Re-establishment

When upper layers request a PDCP entity re-establishment, the transmitting PDCP entity will reset the ROHC protocol and set the TX_NEXT of DRBs and SRBs to initial value. If the re-establishment request is for SRB, then all the previously buffered PDCP SDUs and PDCP PDUs are discarded. In case of unsubmitted DRBs with already assigned PDCP SNs, the PDCP SDUs received from the upper layers are processed with header compression, integrity and ciphering without restarting the discard timer.

TABLE I. PARAMETERS FOR TX AND RX MODULES

Module	Category	Name	Detail	Initial Value / Range
Tx	State Variable	TX_NEXT	COUNT value of the next PDCP SDU to be transmitted	0
	Parameter	SN	Sequence Numbers of PDCP Data PDUs	0 to $[2^{[pdcp\text{-}SN\text{-}Size] - 1}]$
	Timer	discardTimer	configured only for DRBs	configured by upper layers
Rx	State Variable	RX_NEXT	COUNT value of the next PDCP SDU expected to be received	0
		RX_DELIV	COUNT value of the first PDCP SDU waiting for deliver to the upper layers	0
		RX_REORD	COUNT value of PDCP Data PDU which triggers t-Reordering	Assigned by COUNT
	Constant	Window_Size	the size of the reordering window	$2^{[pdcp\text{-}SN\text{-}Size]} - 1$
	Timer	t-Reordering	used to detect loss of PDCP Data PDUs	Configured by upper layers

IV. SIMULATION

The above system model is simulated in compliance with 3GPPP specification for 5G NR using *c* language in Ubuntu operating system. Real time internet traffic data is used in the simulation. The internet traffic is captured using *pcap*, a packet capturing tool. The packets captured varies in size and they act as the PDCP SDUs from the SDAP layer. For Tx and Rx modules, the type of the radio bearer SRB / DRB is given as input. The mode of operation is chosen as unidirectional between the transmitting and receiving PDCP entity.

The ROHC header compression / decompression is done on the IP header of the packets captured. The overhead for IPv4 and IPv6 packets is 40 and 60 bytes respectively. ROHC compresses the overhead of 40 or 60 bytes to approximately 1 or 3 bytes. The first set of compressed packets are larger in size than the consequently compressed packets due to the presence of redundant information. The consequent header compressed packets do not contain redundant information. Thus, they are comparatively smaller in size. For better compression, the packets are classified into streams before compressing. This classification takes advantage of inter-packet redundancy. Once a stream of packets is classified, *IP-only* compression profile is chosen.

The window size is set at half the size of the available sequence numbers. For both 12-bit and 18-bit sequence numbers, window size is 2048 and size of available sequence number is 4096.

For Ciphering and Deciphering, all the three AES, Snow3G and ZUC algorithms are used. The choice of the algorithm is given as input. For strong encryption, 128-bit key is used. Other parameters used in this simulation are shown in the Table 1. The execution results of the Tx and Rx modules are explained in this section.

A. DRB

The Figure 13 is the snapshot of a Tx and Rx module of PDCP Data PDU of type DRB. The left portion of the Figure 13 depicts the Tx module. In Tx module, a packet of size 40 bytes is considered as the PDCP SDU received from the SDAP layer. ROHC header compression is applied and the SDU size is reduced to 32bytes. The PDCP header encapsulation is done by assigning a 12-bit sequence numbers resulting to 34 bytes of PDCP PDU. For Ciphering, AES encryption is applied on the payload. 2 bytes of MAC-I is generated and added with the PDCP PDU. Totally, 38 bytes of PDCP Data PDU is submitted to the lower layers.

Figure 13 Tx and Rx of PDCP DRB with Snow 3G Encryption

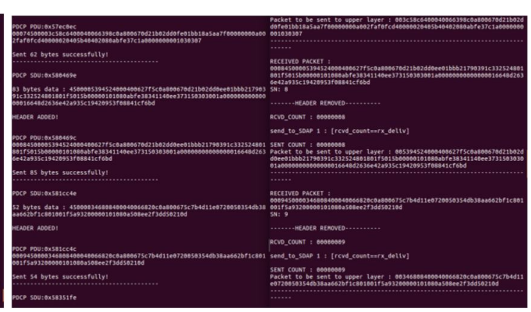


Figure 14 Tx and Rx module of PDCP SRB-0

The submitted PDCP PDU is assumed to be received at the Rx module. In the same figure 13, the right portion explains the Rx module. In the Rx module, 38 bytes of PDCP PDU is received and MAC-I is separated from it.

The payload portion of the PDU is deciphered with AES algorithm. X-MAC is generated and verified with MAC-I. On the success of integrity check, ROHC header decompression is done resulting to the original 40 bytes of PDCP SDU. The decompressed PDCP SDU is submitted to the upper layer. The Figures 15 and 16 are the snapshots of the PDCP Data PDU of type DRB for the encryption techniques ZUC and Snow 3G.

B. SRB

The snapshot of a Tx and Rx module of PDCP SDU of type SRB-0 is shown in Figure 14. In Tx module (left side of the snapshot) the signalling message in this SRB-0 is assumed to be an RRC Reestablishment Request. No ROHC header compression is done. The SRB0 SDU is encapsulated with PDCP header and sent to the lower layers. On the Rx module (right side of the snapshot), the PDCP PDU is received and decapsulated. As the SRB-0 is the signalling message, all the stored PDCP SDUs and DUs are discarded, leading to the fact that the storage buffer in the receiving entity is cleared.

V. CONCLUSION

The functional prototype presented in this paper executes the flow of both transmitting and receiving PDCP entities for the data plane SRBs and UM DRBs successfully. All the three ciphering techniques, AES, ZUC and Snow 3G are implemented with an option. Use of real time internet traffic as PDCP data PDUs matches with the dynamically varying sizes of 5G data communications. It strengthens the correctness and efficiency of the prototype developed.

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