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Practical Approach to IP Scheduled Throughput Measurements in Dual Connectivity Systems

Arkadiusz Zięba, Martin Kollar, Krzysztof Tatarczyk, and Jarosław Sadowski

***Abstract*—IP scheduled throughput defined according to 3GPP TS 36.314 reflects user throughput regardless of traffic characteristics, and therefore has become one of the most important indicators for monitoring Quality of Service (QoS) of the end user in Evolved Universal Terrestrial Radio Access Network (E-UTRAN). However, networks built on a distributed architecture make the above definition impossible to be applied directly due to the implementation challenges. This paper gives an overview of the classical Long Term Evolution (LTE) architecture as opposed to Dual Connectivity (DC) topology and focuses on a novel method of solving the calculation issue with the IP scheduled throughput measurement in edge computing environment. Experimental results show a good agreement with the real end user perception.**

***Keywords*—IP Scheduled Throughput, distributed system; edge computing; cloud; Long Term Evolution (LTE); Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Carrier Aggregation (CA); UE Throughput; Key Performance Indicator (KPI); Quality of Experience (QoE); Quality of Service (QoS)**

I. INTRODUCTION

THE demand for high data traffic is evolving exponentially with the new area of services introduced by modern technologies. 8K quality video, personal television via YouTube, movie services like Amazon Prime or Netflix, live streams, next gen video games on smartphones, and all other similar services coming from the entertainment industry are increasing this demand. With the endless development of new features and applications for the end-user, the whole network industry must produce a solution for such a request. This resulted in different Access Networks (AN), such as Long Term Evolution Advanced (LTE-A), Long Term Evolution Advanced Pro (LTE-A Pro), to provide new revolutionary features and to deliver higher multi-Gbps peak data rates [1, 2, 3, 13].

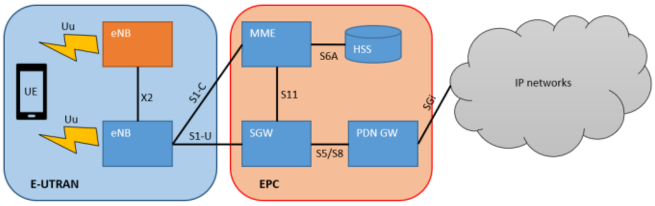

Fig. 1. LTE's basic system architecture [3]

LTE architecture consists of Radio Access Network (RAN), also known as E-UTRAN, Evolved Packet Core (EPC) and a User Equipment (UE), where RAN communicates with the core based on S1-C and S1-U interfaces [3]. The communication between two different base stations (BTS), which are known as evolved NodeB (eNB), happens over X2 interface inside RAN, as shown in Fig. 1.

Only the E-UTRAN part is discussed for the purpose of this research paper. In LTE system, an eNB is a network element responsible for radio communication and it is typically located in the coverage area of the served network. It translates the information received from the core using a specific protocol, i.e., Internet Protocol (IP) layer to another protocol, i.e., Medium Access Control (MAC). As radio transmission differs from a standard transmission which uses IP in fixed networks, the eNB must perform a translation between different layers [3].

The layer stack shown in Fig. 2 directly indicates what types of layers are used inside an eNB. For the downlink (DL) transmission, the IP traffic received by the eNB is translated firstly from the transport layer (GTP-U) into Packet Data Convergence Protocol (PDCP) layer, which is responsible for integrity, ciphering and header compression. The Radio Link Control (RLC) layer performs segmentation, concatenation, and error correction. The Medium Access Control (MAC) layer provides mapping between logical and transport channels and creates Transport Blocks (TBs). At the end, this information is sent over Physical (PHY) layer by the antenna [3].

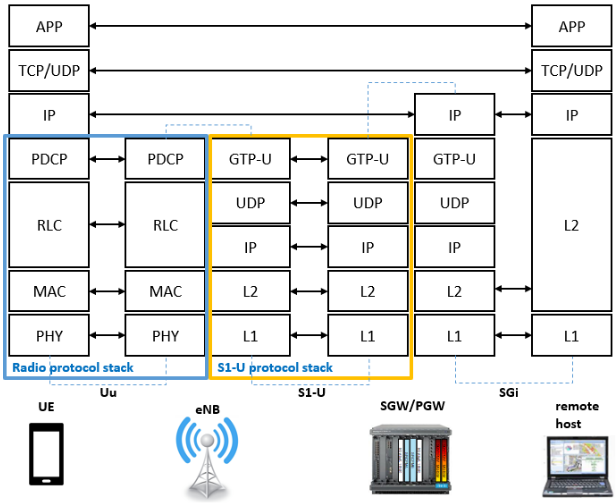

Fig. 2. E-UTRAN layer stack for S1-U [3]

As the amount of data traffic on mobile networks continues to grow, network operators are trying to meet the demands by adopting Dual Connectivity (DC) technology. A User

Arkadiusz Zięba, Martin Kollar and Krzysztof Tatarczyk are with Nokia Solutions & Networks, Poland (e-mail: arkadiusz.zieba@nokia.com, martin.kollar@nokia.com, krzysztof.tatarczyk@nokia.com).

Jarosław Sadowski is with Gdansk University of Technology, Poland (e-mail: jarsadow1@pg.edu.pl).

Equipment (UE) in DC configuration can be connected at the same time to two eNBs: a Master eNB (MeNB) and a Secondary eNB (SeNB). In case the MeNB and SeNB operate Secondary eNB (SeNB). In case the MeNB and SeNB operate on different frequencies, the concept may seem similar to Carrier Aggregation (CA) concept [1, 2, 3].

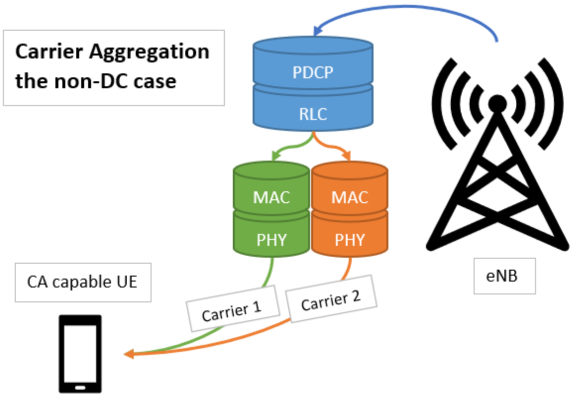

Fig. 3. Classical CA functionality [3]

Fig. 3 presents classical CA functionality, also described as non-DC, where different LTE cells are physically located in the same eNB. This eNB controls the whole protocol stack and is aware of the scheduling process in these different cells. The DL packets are sent to the eNB where the data split happens at the RLC layer. Packets are either fully directed to the Primary Cell (PCell) or, after the split, to PCell and Secondary Cells (SCells). Since the cells are within the same BTS, the eNB knows the exact outcome of the transmission process over the radio. With such information, the eNB can determine whether the whole PDCP Service Data Unit (SDU) packet was successfully transmitted or not. If not, then the retransmission process over the lower layers is triggered until all scheduled packets in the buffer of PDCP layer are sent successfully.

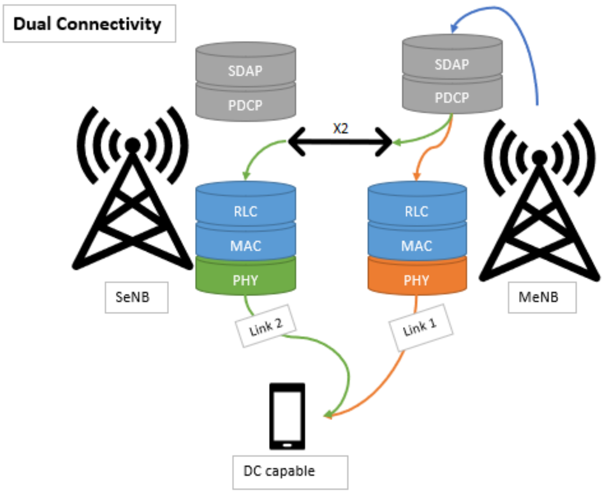

Fig. 4. The concept of DC based CA [3]

Fig. 4 shows the concept of DC based CA, where cells belong to different eNBs, connected via X2 interface. These different eNBs are not aware of the inside communication taking place in their neighbors. A similar concept may be used also for Multi-RAT Dual Connectivity (MR-DC), which uses the idea of CA happening between New Radio (NR) and LTE cells. The data exchange is done over the X2 link. The IP packets are sent to the Primary Master eNB (MeNB) where they are divided in the PDCP layer and, depending on the data distribution, directed to both PCell on the same MeNB and SCells on different Serving eNB (SeNB) via X2 interface. Although the PDCP SDU packet size is known by the primary MeNB, the BTS does not know whether the transmission process of lower layers on SeNB was successful for the given packet. A simple feedback mechanism would resolve this potential issue. It would, however, overburden the X2 interface and the primary MeNB with a substantial number of messages. Thus, the overall performance of the primary MeNB would be endangered [1, 2, 3].

In general, the DC concept allows a group of network nodes to co-operate but appear as one for the end-user to maximize the connection's throughput capability. However, such nodes are not typically aware of the processes happening over their counterparts. The DC logic is especially useful when the resources in the network are not utilized highly enough or when non-DC solution experiences a bottleneck for which a form of load balancing is needed. Furthermore, it is also useful when network nodes are not in the same area [4].

To summarize, both non-DC and DC solutions have their advantages and disadvantages. Firstly, the non-DC system can manage resources over different layers more fluently and can monitor the results of procedures taking place throughout multiple components, as the full stack protocol is under the supervision of a given network node. On the other hand, supervising over different layers overburdens the performance and may create an unnecessary delay in communication. In case of the DC system, the same supervision is not possible because the crucial decisions on bandwidth resource allocation are left to the network node which is physically transmitting a part of the packet. This means that the network node can react in a more efficient manner based on the current channel quality needs as the lower layers are in the same place with the antenna, thus the crucial decisions can be made faster, and the user experience is improved [4].

This paper gives an overview on the IP scheduled throughput definition from E-UTRAN 3GPP TS 36.314. Moreover, it describes issues connected with its implementation that led to the lack of proper solutions for the DC architecture, the resulting negative impact on performance measurement aggregation, especially in terms of end-user throughput, and finally it discusses the practical methods of solving these difficulties.

The paper has the following structure. Section II provides some basic information concerning the current 3GPP specification of IP scheduled measurements for E-UTRAN system. Section III describes other research ideas for distributed network types based on DC in the performance measurement area. In Section IV, the new method presents how to accurately measure IP scheduled throughput in distributed systems and how to improve the current specification document (3GPP TS 36.314). In Section V, the experimental results are presented. Finally, in Section VI, the authors show advantages of the new method, draw conclusions, and give certain recommendations.

II. IP SCHEDULED THROUGHPUT FORMULA DISCUSSION

If end users often experience low quality during the use of a service, they might change the wireless subscription provider, which shall result in loss of income for the network operator. Therefore, from a business point of view, it is essential to have high integrity of services. Throughput is one of the most important integrity measurements for Non-Guaranteed Bit Rate (Non-GBR) services. On the one side, the 3GPP TS 32.451 defines the measurement from the volume perspective on IP level (i.e., the volume part in throughput measurement shall be IP volume). On the other side, the measurement shall be defined so that the impact of burstiness of the incoming data flow is excluded (i.e., time when the eNB does not have anything to transmit shall not be included in any calculations, see T_Idle in Fig. 5 below) [7, 10].

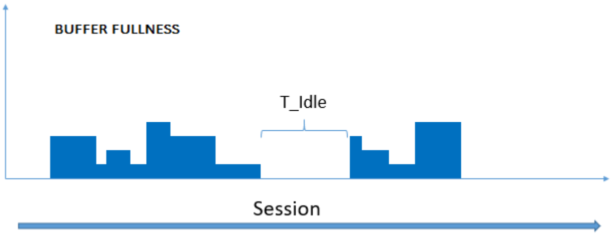

Fig. 5. Principle of the burst measuring in a session with idle time exclusion [7]

The corresponding throughput measurement is then defined in 3GPP TS 36.314 as "IP Scheduled Throughput". Fig. 6 shows example of a concept of the DL IP Scheduled Throughput calculation per one data burst.

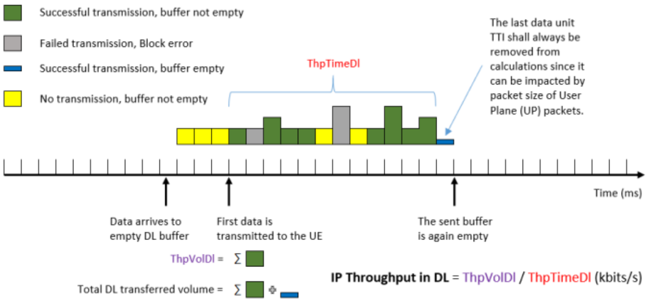

Fig. 6. Principle of IP scheduled throughput measurement in DL [7]

ThpVolDl represents the IP volume successfully transmitted to the UE and ThpTimeDl represents the burst duration. It shall be noted that further investigation within the 3GPP SA5 group resulted in defining the dedicated measurement of the IP latency within 3GPP TS 32.450. It represents the average initial latency of each new burst from the point in time when new data of the burst arrived to the empty eNB buffer until the first part was transmitted via air interface to the UE. Therefore, the initial latency of each new burst is not counted within the ThpTimeDl. The last Transmission Time Intervals (TTIs) emptying the eNB buffer (including bursts that last a single TTI) are also excluded. The reason behind is that such TTIs may not have enough user data to fill in the whole TTI. This may lead to addition of padding volume at MAC layer or to a more robust coding, which in fact is not needed and thus, may artificially impact the measured throughput [7, 8, 9].

III. IP SCHEDULED THROUGHPUT MEASUREMENT ISSUES IN DUAL CONNECTIVITY SYSTEMS

An example of a DC implementation in Nokia environment is shown in Fig. 7. It applies to CA where the SeNB may cover the SCell while the MeNB may cover the PCell.

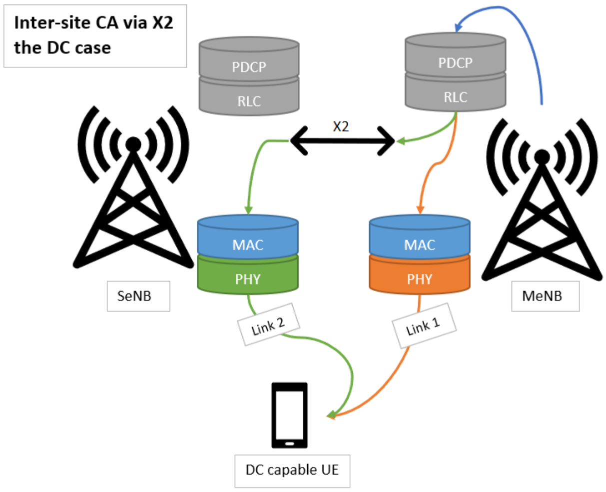

Fig. 7. The concept of DC based Inter-site CA via X2 [3, 4]

This solution may be beneficial in case there is a need to extend CA to some carriers provided by eNBs physically located in different places, the so-called inter-site CA. Compared to the concept of DC described in Section I, the split is on RLC Protocol Data Unit (PDU), instead of PDCP PDU level, which is typical for standard CA concept - named in the remaining part of the paper as intra-site CA. The IP scheduled throughput for DC system shall follow the same principles as summarized in Section II. However, due to layer stack separation, each scheduler makes decisions on its own. The PCell's PDCP layer is not aware of the transmission outcome for parts of PDCP SDUs that are sent as RLC PDUs to the SCell. The global buffer status covering both PCell and SCell is not known by the MeNB either [3, 4]. Fig 8. Shows an example of the global buffer status for DC inter-site CA system consisting of PCell MeNB and SCell SeNB.

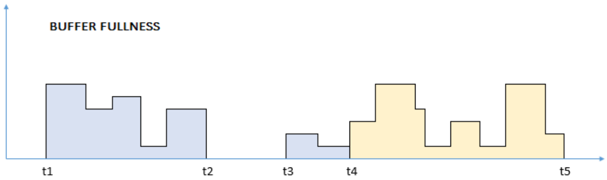

Fig. 8. Buffer fullness in case of inter-site CA system

In this example, although there is data in the buffer from the point in time t_1 till t_2 and then from t_3 till t_5, only the time intervals from t_1 to t_2 and from t_3 to t_4 are known by the PCell MeNB. Thus, applying the IP scheduled throughput method according to 3GPP TS 36.314, named in the remaining part of the paper as the classical method, would lead to incorrect results. In principle, the following options are possible to approach this issue. The first one with the ThpTimeDl, represented as the time interval with the data in the buffer time of the PCell MeNB (from t_1 to t_2 and from t_3 to t_4) and all transmitted PDCP SDU volume (also portions transmitted over the SCell SeNB). Using this method would lead to overestimated results because the time intervals related to data in the buffer of the SCell SeNB are excluded from consideration. The second one with the ThpTimeDl represented as time interval with the data in the buffer time from t_1 to t_5 and all transmitted PDCP SDU volume (also portions transmitted over the SCell SeNB). This would lead to underestimated results because the time interval from t_2 to t_3 is counted in addition. Other viable options, such as for example counting the time with data in the buffer only in the PCell MeNB and excluding from counting the portion of PDCP SDU volume that is transmitted over the SCell. None of these approaches lead to correct throughput monitoring [7].

Neither 3GPP nor the scientific area define the way to apply the IP scheduled throughput calculation principles in DC systems. To the best of the authors' knowledge, no scientific papers have been published on this topic so far. The remaining part of the paper focuses on evaluating the IP scheduled DL throughput measurement for DC inter-site CA system.

IV. NEW METHOD FOR IP SCHEDULED THROUGHPUT MEASUREMENT IN INTER-SITE CA AS DUAL CONNECTIVITY SYSTEM

As summarized in Section III, the knowledge of global buffer status covering both PCell and SCell is essential to apply the IP scheduled throughput calculation principles according to 3GPP TS 36.314 [7] in case of DC inter-site CA system. The obvious way to make the MeNB aware of the global buffer status is to transfer the necessary information from the SeNB to the MeNB. This would require establishing a dedicated message flow between MeNB and SeNB per each data package scheduled for processing at SeNB. Each message exchange information of the SCell buffer status needs to be reported, and once received by MeNB, stored temporarily in memory. MeNB needs to keep track of the local buffer status also storing it in memory. This is because the SeNB reports can be delayed, and hence the calculation of the global buffer status must be done as post-processing. The global buffer status is built out of the reported burst transmission timestamps, so the MeNB and SeNB need to be perfectly synchronized in terms of a system clock. Otherwise, the global buffer status, once constructed by MeNB out of the reported timestamps, would not reflect the data transmission correctly, leading directly to errors in the IP scheduled throughput calculation. In addition, MeNB would need to reserve enough memory to store both MeNB and SeNB timestamp reports, as well as the needed processing power to properly combine them. Such a procedure, although providing the data necessary to obtain IP scheduled throughput value, imposes unrealistic requirements to MeNB and SeNB. Thus, a simplified approach is required to make the IP scheduled throughput calculation feasible for DC systems. This new method is based on the following postulates:

Postulate I

Let's assume that the SCell buffer, physically located in the SeNB, is not empty at the time when RLC PDU data is sent to this SCell from the PCell. The exact point in time, when this transmission occurs and the data received in the SCell, is not relevant. From the end user perspective, the data is received as if it was sent via the PCell buffer of the MeNB.

When a new data burst begins, it is assumed that the first portion of the transmission happens in the PCell, and after that in the SCell(s). It means that the beginning of the transmission can be uniquely established in the PCell (no additional message exchange between the PCell and the SCell(s) is necessary).

Postulate II

The buffer status combines the PCell and the SCell(s) buffer statuses regardless of their physical location. Having data in the buffer means that PCell's buffer or/and at least one of the SCell(s)' buffers contain some data.

Postulate III

From the PCell MeNB perspective, the time which the given i-th RLC PDU spends in the buffer, denoted as $Total\_T_{RLC\,PDU_{i}\,Buffer}$, is equal to:

$$Total\_T_{RLC\,PDU_{i}\,Buffer} = T_{X2\_RLC\,PDU_{i}\,Buffer} + T_{RLC\,PDU_{i}\,Buffer} \tag{1}$$

The $T_{X2\_RLC\,PDU_{i}\,Buffer}$ is the time a given RLC PDU needs to travel from the PCell MeNB to the SCell SeNB via the X2 interface. The $T_{RLC\,PDU_{i}\,Buffer}$ is the time which the data related to i-th RLC PDU remains in the SCell SeNB buffer (excluding last TTI transmission), calculated as follows:

$$T_{RLC\,PDU_{i}\,Buffer} = \frac{RLC\,PDU\,Volume_{i}}{IP\,Scheduled\,Throughput\,SeNB} \tag{2}$$

The $RLC\,PDU\,Volume_{i}$ is the volume of i-th RLC PDU frame which is sent from the PCell MeNB to the SCell SeNB. The IP Scheduled Throughput SeNB is according to 3GPP TS 36.314, measured in the SeNB solely for RLC PDUs received from the MeNB.

Postulate IV

The average values of the X2 transmission time and the IP Scheduled Throughput SeNB shall be used in calculation of (1) and (2). These average values are sent from the SeNB to the MeNB via X2 interface per a configurable time interval (e.g., hundreds of ms), therefore the resulting X2 message exchange (as shown in Fig. 9) can be decreased to an acceptable level.

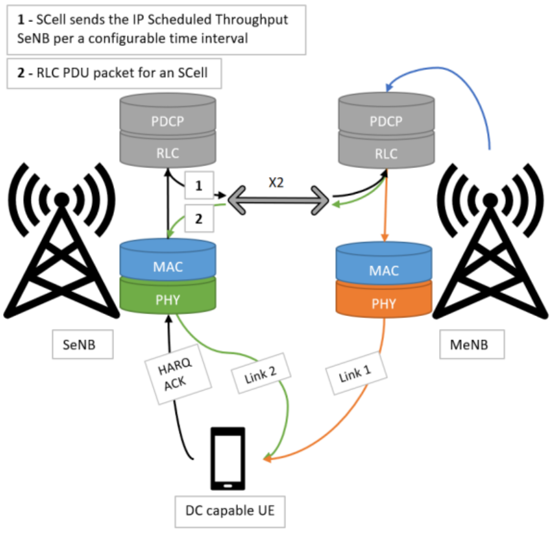

Fig. 9. Message exchange between MeNB and SeNB according to the new method

Fig. 10 shows an example of the case with a single CA UE and a single SCell located in SeNB. As per the postulate I, the PCell MeNB considers the SCell buffer as not empty at the point in time when RLC data is sent to this SCell (see graph #1 in Fig. 10). It does not matter when exactly in time the data is received in the SCell (see graph #2 in Fig. 10). The PCell MeNB considers the SCell buffer as empty at the point in time obtained from the timestamp using the (1). Graph #3 in Fig. 10 shows when the SCell buffer from PCell/UE perspective is empty or not empty. According to postulate II, the final graph #5 in Fig. 10 shows the transmission time from the PCell MeNB perspective obtained from buffer status check. The time is counted when there is data in the PCell and/or SCell buffer. The calculation is done using "OR function" for "graph #3 in Fig. 10" and "graph #4 in Fig. 10".

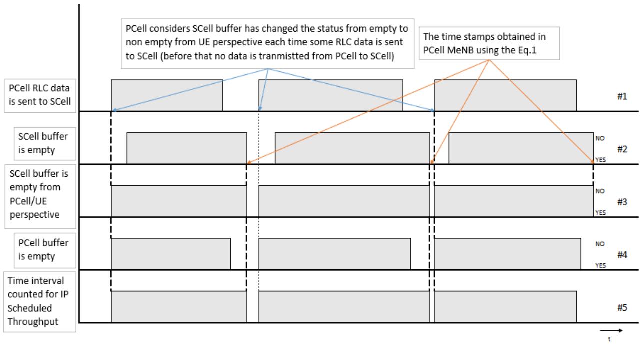

Fig. 10. The principle of the method in example

As presented, the proposed method reuses the principles of 3GPP TS 36.314 IP scheduled throughput measurement, and at the same time simplifies the necessary implementation complexity. Using the new method shall not impact the precision of the obtained throughput values because IP Scheduled Throughput SeNB per configurable time interval is perceived as an average similarly to per burst logic defined in 3GPP TS 36.314. The sampling periodicity does not change the precision of the averaged throughput itself. It only contributes to a delay when the information is passed from one node to the other [7].

V. TEST RESULTS FOR A DUAL CONNECTIVITY SYSTEM SCENARIO

To verify the correctness and precision of the proposed method, certain tests were executed. A DL throughput test design is shown in Fig. 11 based on a block diagram [11, 12, 13].

The given test setup consists of the following elements:

1) Qualcomm SDM845 UE supporting multiple CCs for CA and handling DL throughput tests.

2) Nokia MeNB representing PCell CC1 and SCell1 CC2 (described in more detail in each test type) for radio communication part.

3) Nokia SeNB representing SCell2 CC3 (described in more detail in each test type) for radio communication part.

4) Nokia Core components, such as MME, HSS, SGW and PGW for handling IP communication between client and server.

5) Nokia intranet for connectivity purposes between PGW and lab management area.

6) Data generator PC with an application based on iperf tool for active measurement of the maximum achievable bandwidth on IP networks [6].

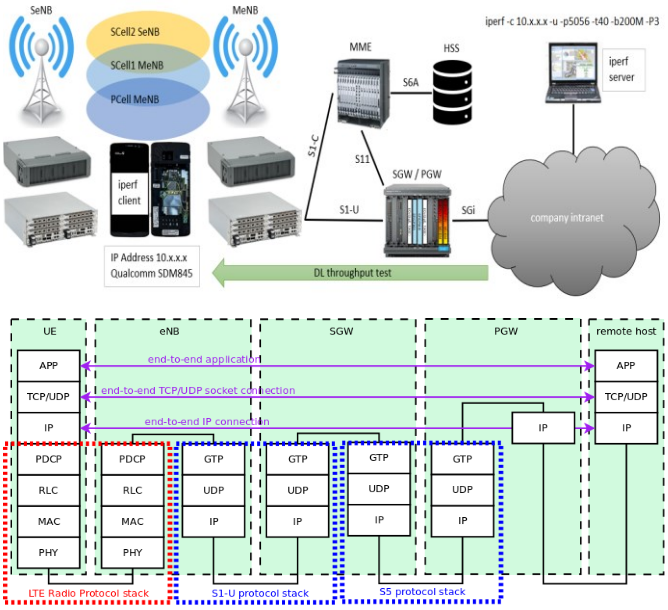

Fig. 11. Test design architecture

Two tests were done for User Datagram Protocol (UDP) traffic and two configurations. The intention of test A with configuration 1 was to measure the behavior of the classic method versus the new method for the inter-site CA (DC solution) with a single SCell SeNB during a long call time interval with usage of long data bursts and to compare the results with intra-site CA (non-DC solution). This shall prove the stability and precision of the new method for both DC and non-DC systems, regardless of the call duration.

In case of test B with configuration 2 the intention was to measure the behavior of the classic method versus the new method for inter-site CA (DC solution) with a multiple number of SCells, one local (intra-site) SCell MeNB and second remote (inter-site) SCell SeNB, during a short call time interval with usage of long data bursts and to compare the results with intra-site CA where both SCells are local (non-DC solution), i.e. SCells MeNB. This shall prove the precision of the new method for both DC and non-DC systems, regardless of the mixed SCell configuration types, where part of the packet is divided between PCell and corresponding SCells.

The above tests were needed to determine the usability scope of the new method in mixed radio environments (DC and non-DC). In such setups call duration may vary and different number of SCells can be used.

Two additional tests were done for Transmission Control Protocol (TCP) traffic. The intention of test C with configuration 3 was to measure the behavior of the classic method versus the new method for both intra-site CA (non-DC solution) and inter-site CA (DC solution) with two SCells on SeNB and short TCP data bursts.

In case of test D, the intention was to measure the precision of the new method. The classic method values were captured directly on the SCell (where the actual transmission is done by SCell scheduler), while the new method on the PCell (where periodical reports are provided from SCell to PCell for expected throughput).

Both tests were needed to determine whether the new method is applicable also for the transmissions where the demand on data per user is low. Moreover, the test D verified the precision of the new method for the same transmission measured on both network elements, where one uses direct implementation of 3GPP principles on IP scheduled throughput measurements [7,8] and the other uses the new method with Throughput reporting mechanism.

The framework how Throughput (ThpVolDl / ThpTimeDl) [Mbps] is calculated is based on counter measurement principles described in 3GPP specification [7,8]. Each burst sample defined by the volume of ThpVolDl and the time length ThpTimeDl are captured by a counter provider component responsible for PDCP level measurements. Subsequently, both internal counters containing the instantaneous values are sent from counter provider to counter collector, which shall perform the time aggregation over longer time interval from all received samples, for example 5, 10 or 15 minutes. The aggregated value of a single counter (ThpVolDl or ThpTimeDl) is reported at the end of measurement time interval to external data file.

QXDM Throughput [Mbps] is an averaged value from all samples measured at the application layer from UE perspective during the data transmission.

Test results do not depend on specific channel numbers, E-UTRA Absolute Radio Frequency Channel Number (E-ARFCN), and discrepancies between successive tests are the effect of the availability of selected equipment in a specific time period.

A. Test A - UDP Full Buffer Configuration 1

The setup configuration for test A is described in Table I. The iperf commands have been used for the given test to simulate full buffer UDP traffic type with 205 Mbps of throughput. The transmission time has been set to 642 and 652 seconds for intra and inter-site CA, respectively. Thus, the stability of the methods over longer time interval for a single transmission has been verified.

The purpose of this test was not to achieve maximum throughput capabilities but to provide high enough data flow for the SCell to be activated. Therefore, the SCell has been used periodically in the individual timeslots, depending on the PCell's scheduler decision for the distribution of data volume. This is the direct cause of the 31.11% value for the ratio of DL TTI Utilization / samples, where the samples are the time slots for which the test was captured.

MAC PDU Throughput has been shown to visualize the potential increase of the bit rate with the usage of CA functionality. It is worth to mention that the bit rate values for the lower layers are higher than for the PDCP layer due to addition of extra header, error-detecting mechanisms, or retransmission mechanisms.

The overall distribution of Modulation and Coding Scheme (MCS) in the PCell achieved in majority of cases the highest 28 value, which means radio conditions were the best possible. Similarly, for the SCell the MCS scored the highest possible value for almost 95% of all slots during the transmission.

Table I
Test Results For 2CC And 64QAM Mode Cells With UDP Traffic In LTE For Inter-Site Ca

		PCell	SCell
Iperf UDP Throughput	*[Mbps]*	205 (PCell+SCell)	
MAC PDU Throughput	*[Mbps]*	172.46	49.69
MCS = 28, CW1	*Ratio [%]*	99.95	94.48
MCS = 28, CW2	*Ratio [%]*	99.98	95.23
MCS = 27, CW1	*Ratio [%]*	0.05	1.05
MCS = 27, CW2	*Ratio [%]*	0.02	1.03
Other MCS CW1	*Ratio [%]*	0	4.47
Other MCS CW2	*Ratio [%]*	0	3.74
E-ARFCN	*[#]*	66600	1100
DL TTI Util / samples	*Ratio [%]*	99.66	31.11
Avg PRBs used	*[#]*	88.66	82.41
Max PRB per TTI	*[#]*	100	100
DL BW	*[MHz]*	20	20
Modulation	-	256QAM	256QAM
MIMO layers	*[#]*	2	2

The average MCS value (derived as an arithmetic average from all slot samples) for PCell was captured at 28 for both codeword1 (CW1) and codeword2 (CW2), and for SCell at 27.72 for CW1 and 27.82 for CW2.

Average Physical Resource Blocks (PRBs) used values were calculated when the resources were scheduled per TTI in a given cell. This means whenever the SCell was not used by CA algorithm then the value was excluded from calculation. Nevertheless, this proves that the demand for data transmission was lower than the radio resource capability of CA configuration sets, as the average PRB used was below the maximum capability.

Table II below shows test results which have been performed with 2CC configuration for 1 UE in LTE system with UDP traffic type. The tests were performed separately for Intra-site CA and Inter-site CA, using both the classic and the new method. The actual user experience throughput is verified via QXDM log monitoring tool on UE side (“QXDM Throughput”), while the methods are verified via counter reporting mechanism at the end of measurement time interval (calculations are performed internally in MeNB for “Throughput”).

As it can be seen in Table II, the relative error of the throughput measured by the new method for DC and non-DC system scenarios is 0.024 % and 0.16 %, respectively. In case of

TABLE II
Test Results for 2CC and 64QAM Mode Cells With UDP Traffic in LTE

	Non-DC / Intra-site CA	DC / Inter-site CA	
	New method	Classic method	New method
ThpVolDl [Mbit]	131125	46496	133134
ThpTimeDl [ms]	642134	290498	652430
Throughput [Mbps]	204.20	160.06	204.06
QXDM Throughput [Mbps]	204.15	204.26	
Relative Error [%]	0.024	-21.6	-0.16

Throughput [Mbps] = (ThpVolDl/ThpTimeDl)
Relative Error [%] = (100(Throughput -QXDM Throughput) / QXDM Throughput)*

the classic method for inter-site scenario, the relative error in the measured throughput is -21.6 %. From Table II it follows that the time returned by the classic method (ThpTimeDl) is equal to 290498ms, which is less than half of the time (44.5%) of the new method. For the ThpVolDl the difference is even greater as the classic method counted 46496 Mbit, which is one-third (34,9%) of the new method. The differences come from the fact how the burst is perceived due to division between PCell MeNB and SCell SeNB over X2, as not only the last TTIs emptying the buffer are excluded but also packets directed partly to PCell MeNB and the supplementing carrier. This results in counting less PDCP data volume sent only over PCell MeNB in total. Such values prove that there is a limitation in the classic method in case of DC system, which is solved with accurate results by the new method. In addition, the new method meets the expectations for both non-DC and DC systems and demonstrates its usability also in mixed environments.

Limit of the classic method is tied to the fact that SCell SeNB traffic is not counted at all and PCell MeNB traffic is understated due to the division between MeNB and SeNB.

B. Test B - UDP Full Buffer Configuration 2

The setup configurations for test B are described in Table III and Table IV. The first site setup for Intra-site CA is built with cells on the same eNB1 in FDD technology with band combination 3A-3A-1A. The second site setup for Inter-site CA is built with PCell and SCell2 on MeNB in FDD technology, and SCell1 on SeNB in TDD technology with uplink/downlink configuration 2 and special subframe configuration 7. The following band combination is used: 3A-1A-40A.

TABLE III
TEST RESULTS FOR 3CC AND 256QAM MODE CELLS WITH UDP TRAFFIC IN LTE FOR INTRA-SITE CA

		PCell	SCell1	SCell2
Iperf UDP Throughput	*[Mbps]*	600 (PCell+SCell1+SCell2)		
MAC PDU Throughput	*[Mbps]*	193.44	83.08	41.13
MCS = 28, CW1	*Ratio [%]*	99.97	0	0
MCS = 28, CW2	*Ratio [%]*	99.98	0	0
MCS = 27, CW1	*Ratio [%]*	0.02	89.92	79.82
MCS = 27, CW2	*Ratio [%]*	0.02	89.99	79.84
Other MCS CW1	*Ratio [%]*	28	26.87	26.58
Other MCS CW2	*Ratio [%]*	28	26.89	26.59
E-ARFCN	*[#]*	1350	1500	200
DL TTI Util / samples	*Ratio [%]*	99.89	99.75	99.55
Avg PRBs used	*[#]*	98.94	49.21	24.48
Max PRB per TTI	*[#]*	100	50	25
DL BW	*[MHz]*	20	10	5
Modulation	-	256QAM	256QAM	256QAM
MIMO layers	*[#]*	2	2	2

The iperf commands have been used for the given test to simulate full buffer UDP traffic type with 600 Mbps of throughput in total. The transmission time has been set to 40 seconds for both tests.

The purpose of this test was to achieve the maximum throughput capabilities. Thus, Iperf UDP Throughput target was set above the limit of the given configuration set. This is reflected in DL TTI Utilization / samples indicator in both Table III and IV, where the values are close to the maximum possible. In case of Inter-site CA configuration, the SCell1 value is close to 80% due to the usage of TDD technology with specific settings, where not all transmission slots are used for the downlink direction.

TABLE IV
TEST RESULTS FOR 3CC AND 256QAM MODE CELLS WITH UDP TRAFFIC IN LTE FOR INTER-SITE CA

		PCell	SCell1	SCell2
Iperf UDP Throughput	*[Mbps]*	600 (PCell+SCell1+SCell2)		
MAC PDU Throughput	*[Mbps]*	193.46	71.22	41.14
MCS = 28, CW1	*Ratio [%]*	99.87	99.76	0
MCS = 28, CW2	*Ratio [%]*	99.88	99.95	0
MCS = 27, CW1	*Ratio [%]*	0.12	0.08	79.97
MCS = 27, CW2	*Ratio [%]*	0.12	0.01	80
Other MCS CW1	*Ratio [%]*	0.01	0.16	20.03
Other MCS CW2	*Ratio [%]*	0	0.04	20
E-ARFCN	*[#]*	1350	38760	200
DL TTI Util / samples	*Ratio [%]*	99.95	79.62	99.79
Avg PRBs used	*[#]*	98.94	48.22	24.47
Max PRB per TTI	*[#]*	100	50	25
DL BW	*[MHz]*	20	10	5
Modulation	-	256QAM	256QAM	256QAM
MIMO layers	*[#]*	2	2	2

The overall distribution of MCS in the PCell achieved in majority of cases the highest 28 value, which means radio conditions were the best possible. Similarly, in Inter-site CA case for the SCell1 the MCS scored the highest possible value for almost all slots during the transmission. Though, for the SCell2 the MCS distribution had the 80% of values at 27, while 20% of the rest was between 1 and 26 value. This suggests that SCell2 has experienced worse radio conditions during the test than the other two cells and could not achieve the peak throughput. For Intra-site CA configuration, the SCell2 has experienced radio conditions on the same level as for Inter-site. Though, the SCell1 the radio conditions were slightly worse, achieving MCS 27 for 90% of time, comparing to Inter-site SCell1 99.9%. The average MCS value for Inter-site PCell and SCell1 was captured at 28 for both CW1 and CW2, and for SCell2 at 26.59 for CW1 and 26.60 for CW2. For Intra-site PCell has taken the values of 28, while SCell1 26.87 and 26.89 for CW1 and CW2, and SCell2 26.59 for both codewords.

Average PRBs used values were calculated when the resources were scheduled per TTI in a given cell. This means whenever the SCell was not used by CA algorithm then the value was excluded from calculation. Nevertheless, this proves that during the transmission the radio resources were fully utilized as the average PRB used is close to the maximum value.

Table V below shows test results which have been performed with 3CC configuration for 1 UE in LTE system with UDP traffic type. The tests were performed separately for Intra-site CA and Inter-site CA, using both the classic and the new method. The actual user experience throughput is verified via QXDM log monitoring tool on UE side (“QXDM Throughput” in the Table V), while the methods are verified via counter reporting mechanism at the end of measurement time interval (calculations are performed internally in MeNB for “Throughput”).

TABLE V
Test Results for 3CC and 256QAM Mode Cells With UDP Traffic in LTE

	Non-DC / Intra-site CA		DC / Inter-site CA	
	Classic method	New method	Classic method	New method
ThpVolDl [Mbit]	12791	12889	6558	12244
ThpTimeDl [ms]	40440	40752	39986	40290
Throughput [Mbps]	316.32	316.29	164.01	303.91
QXDM Throughput [Mbps]	317.32		304.97	
Relative Error [%]	-0.315	-0.324	-46.22	-0.326

As it can be seen in Table V, the relative error of the throughput measured by the new method for DC and non-DC system scenarios is -0.326 % and -0.324 %, respectively. In case of the classic method for the intra-site scenario the relative error in the measured throughput is -0.315 %, while for inter-site scenario -46.22 %. From Table V it follows that the time returned by the classic method (ThpTimeDl) is equal to 39986 ms, which is close to the new method (99.2%) and the throughput's length time. This is because the buffer fullness is not counted globally for the given transmission, but only data in the buffer of the PCell is counted. However, for the ThpVolDl the difference is considerable as the classic method counted only 6558 Mbit, which is only more than half (53.56%) of the new method. The differences come from the fact how the burst is perceived due to division between PCell MeNB and SCell1 SeNB over X2, as not only the last TTIs emptying the buffer are excluded but also packets directed partly to PCell MeNB and the supplementing carrier. This results in counting less PDCP data volume sent only over PCell MeNB in total. Such values prove that there is a limitation in the classic method in case of DC system, which is solved with accurate results by the new method. In addition, the new method meets the expectations for both non-DC and DC systems and demonstrates its usability also in mixed environments.

Limit of the classic method is proven to be similar as in Test A for which the SCell SeNB traffic is not counted at all. Furthermore, the significance of the new method increases with the usage of higher number of CCs.

C. *Test C - TCP short burst Configuration*

The setup configuration for test C is described in Table VI and VII. The TCP small data bursts intend to mimic end-user experience when web-browsing is the main service. The traffic has been simulated for small TCP data bursts of 25 MB each with a waiting timer of 10s between the bursts.

The purpose of this test was to achieve throughput high enough for the SCell(s) to be activated. Therefore, both SCells have been used periodically in the individual timeslots, depending on the PCell's scheduler decision for the data volume distribution. This is the direct cause of the 10.53% and 28.51% value for the ratio of DL TTI Utilization / samples, where the samples are the time slots for which the test has been captured.

TABLE VI
Test results for 3CC and 256QAM mode cells with TCP small bursts (25MB each) every 10 seconds traffic in LTE for Inter-site CA

		PCell	SCell1	SCell2
MCS = 28, CW1	*Ratio [%]*	85.99	88.66	89.96
MCS = 28, CW2	*Ratio [%]*	95.78	89.74	91.03
MCS = 27, CW1	*Ratio [%]*	2.83	7.54	7.03
MCS = 27, CW2	*Ratio [%]*	3.12	7.61	7.4
Other MCS CW1	*Ratio [%]*	11.18	3.8	3.01
Other MCS CW2	*Ratio [%]*	1.1	2.65	1.57
E-ARFCN	*[#]*	1100	66600	67000
DL TTI Util / samples	*Ratio [%]*	89.8	10.53	28.51
Avg PRBs used	*[#]*	85.77	90.23	92.99
Max PRB per TTI	*[#]*	100	100	100
DL BW	*[MHz]*	20	20	20
Modulation	-	256QAM	256QAM	256QAM
MIMO layers	*[#]*	2	2	2

TABLE VII
Test results for 3CC and 256QAM mode cells with TCP small bursts (25MB each) every 10 seconds traffic in LTE for Intra-site CA

		PCell	SCell1	SCell2
MCS = 28, CW1	*Ratio [%]*	89.44	91.71	91.58
MCS = 28, CW2	*Ratio [%]*	95.23	91.95	91.63
MCS = 27, CW1	*Ratio [%]*	3.36	6.94	6.61
MCS = 27, CW2	*Ratio [%]*	3.56	6.93	6.92
Other MCS CW1	*Ratio [%]*	7.2	1.35	1.81
Other MCS CW2	*Ratio [%]*	1.21	1.12	1.45
E-ARFCN	*[#]*	66600	1100	67000
DL TTI Util / samples	*Ratio [%]*	92.44	12.36	29.75
Avg PRBs used	*[#]*	90.53	95.07	96.12
Max PRB per TTI	*[#]*	100	100	100
DL BW	*[MHz]*	20	20	20
Modulation	-	256QAM	256QAM	256QAM
MIMO layers	*[#]*	2	2	2

The overall distribution of MCS in the PCell and SCells, reaching values of 28 or 27, proved that radio conditions were sufficient to achieve high throughput.

Average PRB values were calculated when the resources were scheduled per TTI in a given cell. This means that whenever the SCell was not used by CA algorithm then the value was excluded from the calculation. While for both SCells the values are closer to maximum PRB per TTI, for the PCell there is still space for additional scheduling for different users without degrading the transmission performance for the test C.

The reason MAC PDU and QXDM Throughput has been excluded from the Tables VI, VII and VIII comparing to previous tests, is because the external software does not know the buffer status on PDCP level, thus it is not able to properly calculate the time component. This is the opposite situation to the full buffer UDP test, where the continuous stream of data was used to precisely recognize the time component.

Another point is that the TCP protocol starts the transmission from low data volume, below the RAN's handling capability, constantly increasing the volume of data with each consecutive time slot. This means that the first TTI when the data is being scheduled is uses only a small portion of throughput capability. Furthermore, TCP increases the time from which the end user perceives the connection as established. These facts prevent the correct calculation of the end user perceived bit rate while using QXDM.

Table VIII below shows test results which have been performed with 3CC configuration for 1 UE in LTE system with TCP traffic type with small bursts. The tests were performed separately for Intra-site CA and Inter-site CA, using both the classical and the new method. The methods are verified via counter reporting mechanism at the end of measurement time interval (calculations are performed internally in MeNB for Throughput).

TABLE VIII
TEST RESULTS FOR 3CC AND 256QAM MODE CELLS WITH TCP SMALL BURSTS (25MB EACH) EVERY 10 SECONDS TRAFFIC IN LTE

	Non-DC / Intra-site CA		DC / Inter-site CA	
	Classic method	New method	Classic method	New method
ThpVolDl [Mbit]	6060	6154	4095	5881
ThpTimeDl [ms]	24050	25473	24014	24077
Throughput [Mbps]	251.97	241.59	170.53	244.27
Relative error classic method [%]	100*(170.53 - 251.97) / 251.97 = -32.32			
Relative error new method [%]	100*(244.27 - 241.59) / 241.59 = 1.11			

Throughput [Mbps] = (ThpVolDl/ThpTimeDl)
Relative Error classic/new method [%] = (100(DC Throughput - Non-DC Throughput) / Non-DC Throughput)*

The Relative error measured by the new method is 1.11%, while for the classical method -32.32%. The result is especially significant in case of DC system, where the factor of data distribution between PCell and SCell is simply excluded from counting in case of the classical method.

D. *Test D - accuracy of the method from node perspective*

Test D represents a comparison of throughput for the same transmission from two different network node perspectives. The first network node, which is based on the classical method principles, measures the throughput where the actual transmission happens. The second network node, which is based on the new method principles, measures the throughput with the help of the new reporting mechanism from the cell which controls the scheduling. This means that the second node is the PCell on MeNB, while the first node is the SCell on SeNB.

The measurements are based on simulation test performed internally using Nokia software, divided into 1h reporting intervals. The traffic model is built based on both small and large TCP data bursts.

The motivation of Test D is to show the precision of the new method comparing to the classical one, which is shown in Fig.12 and Fig.13. The relative error is calculated as:

$$100 \times \frac{IP\ Throughput_{new} - IP\ Throughput_{classical}}{IP\ Throughput_{classical}} \qquad (3)$$

where $IP\ Throughput_{new}$ and $IP\ Throughput_{classical}$ are the IP Scheduled Throughput figures obtained using the classical and the new method, respectively.

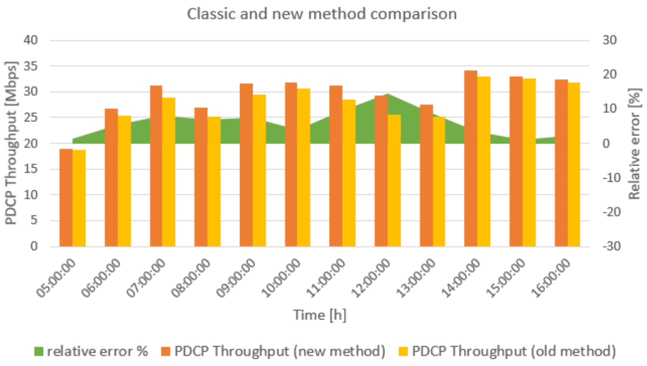

Fig. 12. The classical and the new method comparison for the same transmission measured from node perspectives.

Fig. 12 describes the Throughput distribution over time, while Fig. 13 shows the normal distribution function for the relative error. The average value of the relative error was estimated at 6.03%. Majority of the samples for the relative error values do not exceed 10%.

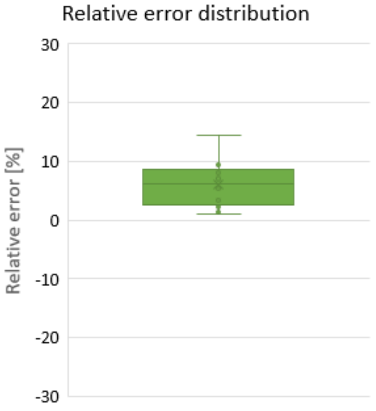

Fig. 13. Relative error distribution for Test D.

The difference between the classical and the new method comes from the fact that the IP Scheduled Throughput SeNB, used to approximate transmission time in SeNB, is calculated out of historic data. The value used to obtain the current SCell transmission time comes from previous transmissions and might not directly correspond to the actual radio conditions at the SCell. This fact manifests itself especially in case of degrading radio conditions in SeNB, which leads to overestimation of IP Scheduled Throughput. Similarly, when radio conditions at SCell improve, the resulting IP Scheduled Throughput is underestimated. In the presented Test D, which was performed in the controlled environment, the biggest value of the relative error is 14.47%. It is still much lower than the relative error stemming from neglecting the SCell traffic, demonstrated in Test C as 32.32%. There are plenty of options to improve quality of the reported IP Scheduled Throughput SeNB, for example by using specific filtering mechanism to properly equalize the extreme values. The future tests should be continued to study how the reporting mechanism of IP Scheduled Throughput SeNB can be improved.

The presented data shows that the new method, based on IP Scheduled Throughput SeNB, yields much lower relative error than the alternative approaches, in particular the one where SCell traffic is totally not considered. The presented solution comes with moderate implementation cost, which is not dependent on transmission volume. For the new method, the total number of IP Scheduled Throughput SeNB reports stays the same regardless of the increasing data demand from particular end-user.

CONCLUSION

This paper has proved the following advantages of the new method:

1) proper counting of traffic in non-DC, DC, and mixed systems,

2) accurate aggregation of results over the whole network in a centralized monitoring tool,

3) minimal exchange of additional messages between MeNB and SeNB over X2 interface.

4) moderate implementation cost, which is not dependent on transmission volume.

This work has evaluated the performance of the new method for counting IP throughput KPIs in DC systems, such as Inter-site CA in LTE, and has shown the results which resemble the end user experience. The paper has studied the difference between the definition of throughput measurement in 3GPP TS 36.314 and the new method proposed by the authors of this article and evaluated within a lab environment. The analysis has been done from an independent perspective, complementing the one provided by 3GPP and emphasizing the role of DC system towards the new throughput measurement principles.

Future work shall focus on thorough verification of reporting mechanism, especially examining its reaction to changing radio conditions. Also studying 5G and its cloud architecture, where currently there is no possibility to measure IP scheduled throughput from end-user perspective. Other work for 3GPP TS 38.314 specification may be anticipated.

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