

Reliable data communication link implementation via cellular LTE services for static or moving ground equipment control

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Abstract— Well-Developed data transmission services of the cellular mobile network (3G and LTE) facilitate cheap and lightweight wireless data communication solution for portable or moving ground equipment's wireless control channel implementation. However, the quality of cellular networks data transfer service is too low to be used in critical data transfer in remote control applications. Two independent cellular data transfer services are used to overcome this problem in our implementation. The solution may improve network throughput and/or availability and provides fail-safe operation depending on the selected congestion control scheduler. The solution is implemented in Linux and can be used for different kinds of data transfer via TCP protocol, both for static or moving remote control equipment.

Keywords—Mobile communication; Fault tolerant control; Land mobile radio equipment; 3G mobile communication; 4G mobile communication

I. INTRODUCTION

To date, both 3G DC-HSPA+ and LTE cellular data transfer services are well developed. These services promise high throughput and low latencies for the data transfer. This provides a cheaper solution for implementing a wireless control data channel for both portable and moving ground equipment. Unfortunately, the goal of 3G and LTE technologies is high data transfer speed by the cost of reliability of data transmission. 3rd generation (3G), as well as 3rd generation LTE (3G LTE or LTE) and 4th generation LTE (LTE-A or 4G) standards, are defined by the Third Generation Partnership Project (3GPP). Beginning with 3GPP Release 5, Hybrid Automatic Repeat Request (HARQ) is implemented at the base station (called NodeB), as well Adaptive Modulation and Coding schemes (AMC) are used in the downlink channel, called High-Speed Downlink Packet Access (HSDPA). The AMC and HARQ were later also implemented on an uplink channel, called a High-Speed Uplink Packet Access (HSUPA), in accordance with the 3GPP Release 6. The system that integrates HSDPA and HSUPA is called HSPA. This is a well-known, so-called "3G service". From now on, AMC and

HARQ (implemented at the base station) are mandatory for all future technologies such as: HSPA + (with MIMO and high order modulation in the downlink, referred to as the 3.5G network specified in 3GPP Release 7), DC-HSPA+ (with MIMO in the downlink and uplink, as well as Dual Carrier (DC) on the downlink and uplink, referred to as the 3.99G network specified in 3GPP Release 8), 3G-LTE (same as 3G DC-HSPA+, but with a more spectrum-efficient OFDMA instead of WCDMA (hence, it requires eNodeB instead of the existing NodeB), called LTE, and it is also defined in 3GPP Release 8) and LTE-A (LTE technology that supports carrier aggregation (CA)), called 4G, specified in 3GPP Release 10 and higher).

Since all the above-mentioned technologies use the same principles of AMC and HARQ, they can be discussed simultaneously. The use of AMC helps to get the highest possible data rate in particular conditions of a radio channel. Each modulation and coding scheme provides certain data rate and keeps Block Error Rate (BLER) low if the signal quality is satisfactory for the selected modulation and coding scheme. However, if the Signal to Interference Ratio (SINR) decreases below a certain modulation and coding scheme limit, the BLER increases significantly. The User Equipment (UE) continuously sends Channel Quality Indicator (CQI) reports based on SINR and BLER measurements to the base station (NodeB in 3G or eNodeB in LTE) to request modulation and coding scheme. Since the goal of mobile cellular data services is the highest possible data rate, AMC selects a scheme to operate with 10% BLER [1]. Further, the lost blocks are retransmitted by the HARQ mechanism. This adds jitter because the transmission time interval (TTI) is 2 ms, and if the network is not used by multiple users, the retransmission can be performed after a minimum of 2 ms (it should be noted that the available field studies indicate that each retransmission adds at least 10 ms to the Round Trip Time (RTT) [2]). To minimize the retransmission time for the downlink, starting from 3GPP release 5, the HARQ mechanism is implemented in the NodeB (in the eNodeB in the case of LTE) instead of the Radio Network Controller (RNC). The UE also have its own HARQ

for the uplink channel. Because a regular TCP connection also has its own retransmission mechanism (which is based on its packets ACKnowledgement), all TCP packets are immediately acknowledged by HARQ to prevent parallel retransmissions (via HARQ and TCP socket). Unfortunately, the HARQ mechanism theoretically ensures the correct delivery of only 99.9% of packets [1].

It can be concluded that the existing data transmission services of the cellular mobile network provide high data rates for the user by the cost of the increased jitter (each repetition of the block adds at least 10 ms) and increased the number of lost packets (stationary UE packet loss is 0.1% typically). The situation is exacerbated by the fact that all TCP packets are automatically confirmed by HARQ mechanisms, so the TCP retransmission mechanism cannot retransmit packets lost in the cellular network radio interface. It should be noted that the performance of cellular network services can be affected by multi-user activity (for example, in [3], the loss of packets of some networks was up to 42% due to the base station terrestrial backhaul overload). In addition, the quality of mobile user service is degraded as soon as the UE starts to move (for example, [4], [5]) mainly due to fast radio signal quality fluctuations (local shading, unpredictable multipath propagation, and interference from other UEs and base stations). All the above makes the data transmission services of the cellular mobile network unsuitable for critical data transmission in the control channels of ground equipment.

Parallel redundancy can be used to improve the service quality of data transmission services of a mobile cellular network. In such a solution, each data/control packet is sent in parallel by two cellular data transfer services simultaneously. For example, the solution described in [6] uses a Parallel Redundant Protocol (PRP). Such a solution reduces latency and jitter, and significantly improves network availability, while the data rate will be equal to the lowest data rate. However, the implementation of such a solution is impractical, since PRP requires two data transmission channels, and both receiving and transmitting parties must be equipped with two network adapters with different real IP addresses.

The solution described in this document is also based on the use of two cellular network data transfer services. The use of the two services helps improve network availability and can also improve RTT and the maximum possible data rate, depending on the applied parameters of the congestion control scheduler. The implemented solution is flexible for network topology and allows simultaneous protection of transmitting or transmitting and receiving parties. In our setup, it was decided to protect only part of the cellular data transmission, since 100 Mbit Ethernet BER should not be more than $1e-10$ (defined in IEEE Std 802.3 [7]) compared to the BER $1e-4$ cellular data service [1] (or even more if the service is overloaded [3]).

II. THE EXPERIMENTAL SETUP

A. Hardware and Software

In the experimental setup, two computers are used: one acts as a wireless remote-controlled equipment, and the second - as a wired remote-control terminal.

The laptop is used to implement remote-controlled equipment. It runs the 64-bit Gentoo Linux operating system (based on stable kernel version 4.9) and is equipped with two cellular data transfer USB dongles Huawei 3372h. The Huawei 3372h USB dongle supports 2G (EDGE), 3G (Cat 24, DC-HSPA+ with a maximum data rate of 42.20 Mbps in the downlink and 5.76 Mbps in the uplink) and LTE (LTE Cat 4, 3G LTE with a maximum data rate of 150 Mbps in the downlink and 50 Mbps in the uplink). It operates in HiLink mode (CdcEthernet). In this mode, the device operates as a NAT server, emulates a virtual network card (NDIS) on the local computer, and the local IP address of the computer is assigned by the DHCP server of dongle. The use of HiLink mode facilitates user-friendly configuration, since Linux NetworkManager supports its operation by default. During all subsequent experiments, the dongles were equipped with randomly purchased different cellular operators SIM cards, and the modes of operation were locked at LTE mode. The simultaneous use of two dongles is provided by the implementation of Multipath TCP version 0.94 [8] in the Gentoo kernel.

Multipath TCP allows to use more than one network interface for a single TCP data flow. Multipath TCP provides TCP data subflows, creating regular TCP connections over available network interfaces. To maintain the integrity of each subflow and prevent it from being blocked by network equipment, each TCP subflow is started with a 0 packets sequence number, so the transmission of the subflow is completely transparent to the network. Further, the original data is restored in the receiving side using the sequence number of the data that is transmitted in the MPTCP subdivision of the TCP packet header. This means that the receiving party must also be compatible with Multipath TCP. Therefore, Multipath TCP always sends the MP_CAPABLE flag during a three-way handshake (initial creation of a TCP subflow) and waits for MP_CAPABLE confirmation. If the use of Multipath TCP is not confirmed by the receiver, Multipath TCP will use only one TCP flow. This makes it capable of operating with both MPTCP and conventional TCP receiving parties. For those interested, more detailed information about the operating principle of Multipath TCP can be found in [9].

If the receiver is Multipath TCP capable, then the use of subflows depends on the selected congestion control Scheduler. There are three schedulers available starting from Multipath TCP version 0.92. If "Default" scheduler is used, then TCP packets are sent over the subflow with the lowest RTT. Further, when the subflow congestion window is full, it will start transmitting on the next subflow. This approach promises summarized bandwidth of both subflows [8]. If the "Redundant" scheduler is used, TCP packets are sent in parallel via both subflows simultaneously. This approach promises the lowest RTT [8], since the first arriving packet is processed by the receiver. The "Roundrobin" scheduler sends packets in cyclic mode and can work efficiently only with equal bandwidth links. This scheduler is not recommended by developers [8]. For those interested, additional information about the schedulers can be found in [10].

Since the receiving party must be Multipath TCP capable of operating in Multipath TCP mode, the wired remote-control

terminal was implemented in Raspberry PI 3B (RPI3) running Gentoo Linux. Since the trusted 4.9 kernel does not support RPI3, the 64-bit Gentoo 4.10 kernel was used. Here, to resolve conflict in `tcp_output.c` the string `void __pskb_trim_head(struct sk_buff *skb, int len)` was replaced by the `int __pskb_trim_head(struct sk_buff *skb, int len)`.

Hewlett Packard (HP) software for testing "netperf" was used in tests of the experimental setup. Netperf works in client-server mode and provides tests for unidirectional bandwidth and RTT. Since Multipath TCP only works with TCP packets, UDP tests were not performed. The experimental setup is presented in Table 1, and the Multipath TCP settings are shown in Table 2.

TABLE I. EXPERIMENTAL SETUP

	Wireless remote-controlled equipment	Wired remote control terminal
Hardware	Portable 64 bits computer	Raspberry PI 3B (RPI3)
Operating System	Gentoo Linux 64 bits Kernel 4.9 with MPTCP v.0.94 implementation	Gentoo Linux 64 bits Kernel 4.10 with MPTCP v.0.94 implementation
Network facilities	Two Huawei 3372h dongles, locked in LTE mode; different cellular operators SIM cards	Single wired Ethernet 100 Mbit
Testing sw	Netperf 2.7.0-r2 server	Netperf 2.7.0-r2 client

TABLE II. MULTIPATH TCP SETTINGS

Settings Option	Meaning
Default MPTCP Path-Manager	Full mesh
MPTCP advanced scheduler	Default, roundrobin or redundant
Default TCP congestion control	Linked Increase Algorithm (LIA)

B. Multipath TCP Lost Packets Delivery Aspects in the 3G/LTE Cellular Data Transfer Networks

In regular TCP connection, packets sequence numbers are ACKnowledged by the receiving party. In the absence of an ACK, the transmitter will resend lost data. Each Multipath TCP subflow is responsible for retransmitting lost packets based on a regular TCP retransmission mechanism. However, if the link of the subflow fails completely, then its data will not be delivered at all. Because Multipath TCP uses more than one subflow, it is possible to retransmit the lost packets thru the remaining subflow(s). However, mobile cellular network data transfer services (starting from 3GPP release 5) automatically acknowledges all packets before they are actually acknowledged by the receiving party and the HARQ mechanism is responsible for retransmission of data over the radio link. This means that if HARQ cannot deliver data, the sender will not be able to use absence of the ACK packet as a trigger for retransmitting data. As described in Section 1, a typical loss of data over a 3G or LTE network is 0.1% (1e-4).

To solve this problem, a Data Acknowledgement is implemented in the Multipath TCP [11]. It uses Data ACK to facilitate cumulative acknowledgment for the entire connection. Now, if Multipath TCP detects the absence of data ACK, the data will be retransmitted. The retransmission will be

performed in accordance with the selected congestion scheduler. The use of Data ACK makes Multipath TCP extremely suitable for trusted data transmission over mobile data services of a cellular network.

III. EXPERIMENTAL RESULTS

The benchmarking was done by running two netperf tests:

1. Stream (to measure the throughput of the connection in the uplink); the syntax of the command is: `netperf -P 0 -t TCP_STREAM -H dest.ip.addr - - o THROUGHPUT`
2. RR (to measure the Request/Response rate (how many TCP transactions per 1 byte can be made per second)); command syntax: `netperf -P 0 -t TCP_RR -H dest.ip.addr - - r 1,1 -o THROUGHPUT, MEAN_LATENCY, P99_LATENCY`

Statistical data for the average RTT, maximum RTT for 99% threshold of the probability, as well as 1 Byte TCP packet transactions per second rate is from the RR tests. Average throughput statistics are taken from the Stream tests. The duration of each test is 10 seconds, and each test is repeated 10 times (except for comparison in motion).

A. Stationary Remote-Controlled Equipment

The equipment with remote control is stationary. The radio channel performance indicator's averaged values are shown in Table 3. The experimental results are shown in Fig. 1. The results are combined in four groups: average RTT of 1 byte transfer (in milliseconds), maximum RTT with 99% threshold probability of 1 byte transfer (in milliseconds), number of 1 byte transfers per second, and finally – average uplink throughput (in megabits per second). Each group contains five columns: standalone operation of the eth1, standalone operation of the eth2, Multipath TCP operation over eth1 and eth2 with "default" congestion scheduler enabled, Multipath TCP operation over eth1 and eth2 with "RoundRobin" congestion scheduler enabled, and finally - Multipath TCP operation over eth1 and eth2 with "redundant" congestion scheduler enabled.

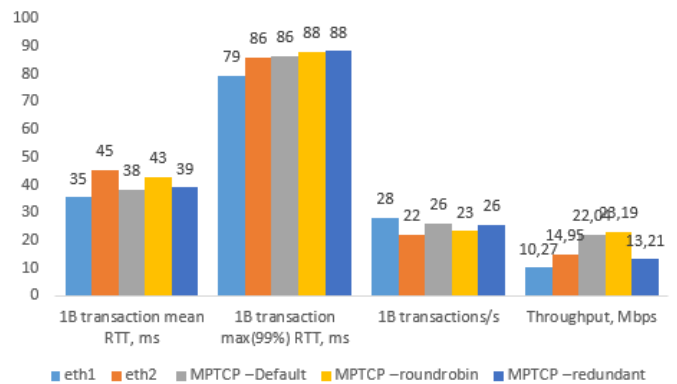


Fig. 1. Network performance results for the stationary remote equipment

TABLE III. CELLULARS NETWORKS PERFORMANCE INDICATORS

Dongle	RSSI, dBm	RSRP, dBm	RSRQ, dB	SINR, dB
eth1	-75	-107	-9	8
eth2	-75	-101	-9	-1

B. Effect of Subflow Fail on Network Performance

The next test is performed to check the Multipath TCP network response for eth2 failure. First, both eth1 and eth2 are operating, and then the SIM card is removed from the second dongle, called eth2. This keeps the eth2 interface "up", but it blocks any data transfer through the radio interface, which leads to failed TCP subflow. Further Multipath TCP congestion control is responsible for retransmission of failed data. The experimental results are shown in Fig. 2. The Fig. 2 layout is similar with Fig. 1. Please note that the standalone operations of eth1 and eth2 are shown here for comparison. The SIM card is not removed during testing standalone operation of the eth2.

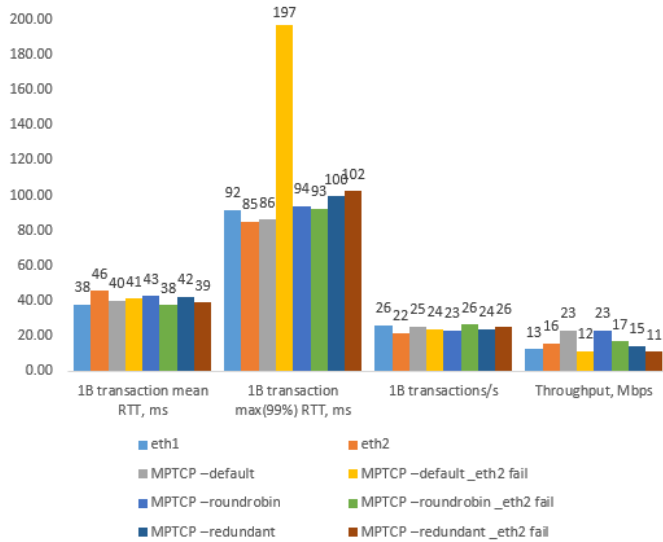


Fig. 2. Network performance results for the stationary remote equipment with and without failed eth2

Fig. 2 provides only statistical representation of two conditions: before and after failure of the TCP subflow through the eth2. The represented data is averaged. A more detailed representations of the effect of TCP subflow failure through eth2 with "default" congestion control scheduler are shown in Fig. 3 and Fig. 4. The TCP flow over eth2 fails between 6th and 7th measurements, that leads to significantly increased maximum RTT values during 30 sec period (each measurement duration is 10 sec).

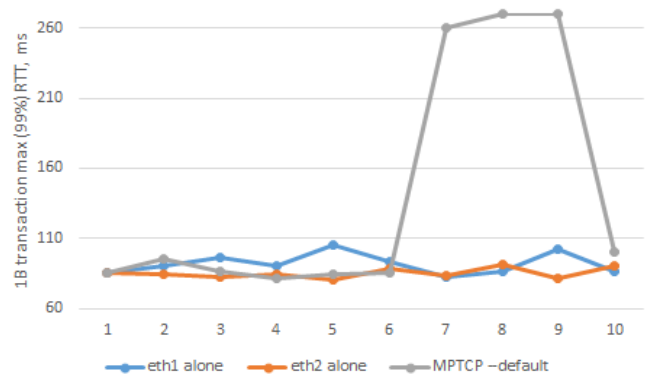


Fig. 3. Maximum RTT values for the stationary remote equipment with failed TCP subflow over eth2 after 6th measurement and "default" congestion scheduler applied

The "default" congestion scheduler allows to combine both uplink subflows. This leads to summarized uplink throughput if both TCP subflows are operational. Failure of the TCP subflow through eth2 leads to decreased uplink throughput down to remaining eth1 throughput.

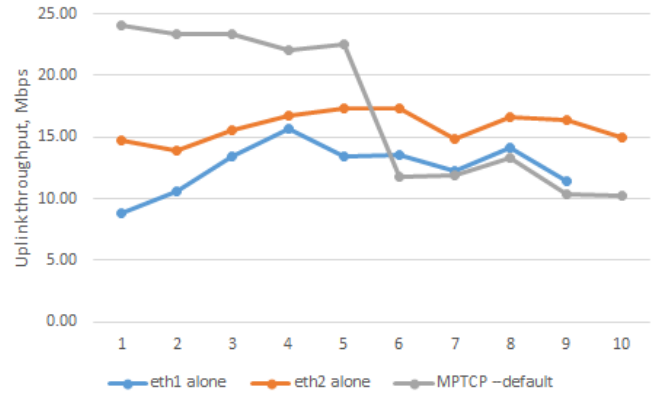


Fig. 4. Uplink throughput for the stationary remote equipment with failed TCP subflow over eth2 after 6th measurement and "default" congestion scheduler applied

Use of a "redundant" congestion control scheduler does not allows to summarize both TCP subflows throughput, but helps to avoid delays in packets delivery if one TCP subflow is failed. Both these effects are shown on Fig. 5 and Fig. 6. In this experiment, a TCP subflow failure through the eth2 occurs between 4th and 5th measurements.

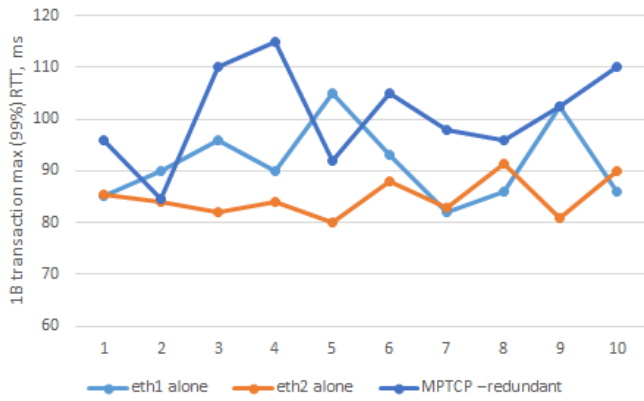


Fig. 5. Maximum RTT values for the stationary remote equipment with failed TCP subflow over eth2 after 4th measurement and “redundant” congestion scheduler applied

The “redundant” congestion scheduler allows to obtain the resulting throughput equal to the best throughput of two subflows (in this experiment it is throughput through the eth2). Failure of the TCP subflow through eth2 leads to decreased uplink throughput down to remaining eth1 throughput.

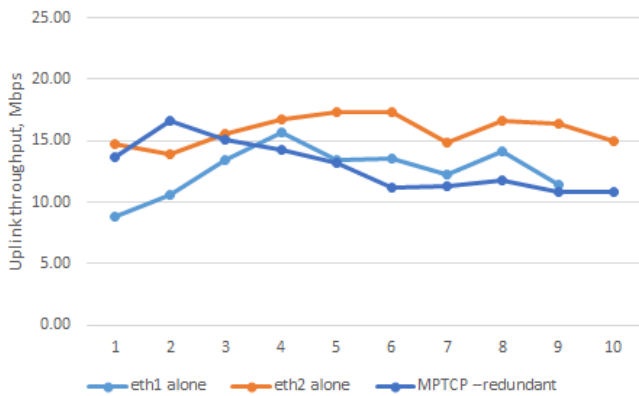


Fig. 6. Uplink throughput for the stationary remote equipment with failed TCP subflow over eth2 after 4th measurement and “redundant” congestion scheduler applied

C. Moving Remote-Controlled Equipment

One of the key features of cellular networks is the support of UE mobility. In the next benchmark the remote-controlled equipment is moved by car in the city. Since each test should be performed separately, testing was carried out sequentially, following the same path several times. The experimental results are shown in Fig. 7. In this experiment, average uplink throughput measurements were not performed due to limited amount of allowed data traffic.

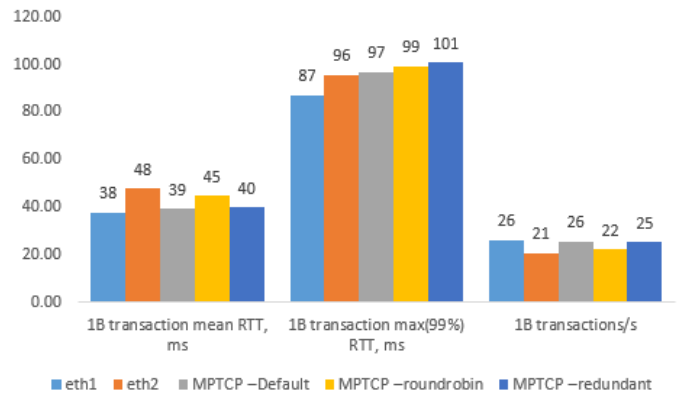


Fig. 7. Network performance results for the moving remote equipment

IV. CONCLUSION

The packet loss rate and the availability of 3G data services (HSPA + and higher) and LTE cellular network data transfer services are unacceptable for data transmission in the remote-control equipment control channel. Simultaneous use of two mobile cellular network data transfer services helps to overcome this problem. The resulting performance of a multi-path data network depends on the selected congestion control scheduler. The “Round-robin” scheduler is only suitable for networks with an equal cost, its use is not recommended by the developer, and this will not be discussed here.

TABLE IV. RESULTING NETWORK PERFORMANCE COMPARISON

Performance Parameter	Congestion Scheduler in use	
	Lowest-RTT-First (“default”)	Bufferblot Mitigation (“redundant”)
Resulting network average throughput	Effectively summarize both subflows throughputs	Almost equal to faster subflow throughput
Resulting network average RTT	Almost equal to the RTT of the subflow with the lowest RTT	Almost equal to the RTT of the subflow with the lowest RTT
Resulting network maximum RTT	Almost equal to the RTT of the subflow with the highest RTT	Almost equal to the RTT of the subflow with the highest RTT
Number of TCP transactions per second	Almost equal to the trans/s of the subflow with the highest trans/s rate	Almost equal to the trans/s of the subflow with the highest trans/s rate
Network response on the subflow failure	Two times larger RTT of non-delivered packets (scheduled to failed subflow) during first 30 seconds	RTT and Throughput momentarily becomes equal to the remaining subflow performance indicators

It can be concluded that the use of “default” congestion control scheduler allows to effectively summarize both subflows throughput. However, its usage can be recommended only if the goal is to obtain maximum data rate over wired networks with low data loss by itself, because lost (undelivered) packets leads to significantly increased maximum RTT due to resends. This makes “default” congestion control schedules unfitted for moving equipment due to cellular data transfer

services fluctuations and temporary interruptions. The “redundant” congestion control scheduler does not allow to summarize both subflows throughputs, but makes no increased RTT due to undelivered packets over partially or fully failed subflow. This makes “redundant” congestion control scheduler more suitable for portable or moving ground equipment’s wireless control channel implementation.

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This is a post-print of a paper published in Proceedings of the 2018 IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCon 2018) and is subject to IEEE copyright.

<https://doi.org/10.1109/RTUCon.2018.8659849>

Electronic ISBN: 978-1-5386-6903-7.

USB ISBN: 978-1-5386-6902-0.

Print on Demand (PoD) ISBN: 978-1-5386-6904-4.