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Apilo, Olli; Pinola, Jarno; Ahola, Riikka; Kemppainen, Juhani; Happonen, Jukka

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Experimental evaluation of a traffic warning system based on accurate driver condition assessment and 5G connectivity

Olli Apilo and Jarno Pinola
VTT Technical Research Centre of Finland Ltd.
Oulu, Finland
{olli.apilo, jarno.pinola}@vtt.fi

Riikka Ahola, Juhani Kemppainen and Jukka Happonen
Polar Electro Oy
Kempele, Finland
{riikka.ahola, juhani.kemppainen, jukka.happonen}@polar.com

***Abstract*—Reliable detection and sharing of information about fatigued or otherwise impaired drivers can provide valuable extra information to improve cooperative road traffic safety services. With such information, connected manually driven or automated vehicles in the area can proactively take precautions and prepare for possible risks caused by a fatigued drivers. In order to provide accurate assessment of the driver condition and efficient distribution for the related warnings, the proposed human tachograph service concept combines ubiquitous wearables-based driver monitoring with 5G connectivity. The combination of the real-time driver biosignals measured while driving and the historical data related to driver's sleep and physical activity outside the vehicle enables the driver condition to be assessed more accurately than with currently used on-board systems. Based on the driver condition analysis, the 5G-based traffic warning system triggers warning messages towards other road users. The paper also presents the trial setup used to evaluate the performance of end-to-end service as well as the 5G network on top of which the service is deployed. Based on the results, the initial 5G deployments can already achieve clearly better average latency than LTE-based deployments but the reliability should yet be improved for road safety applications.**

***Index Terms*—5G, wearables, live network measurements, latency, reliability, cooperative road traffic safety systems**

I. INTRODUCTION

The advances in Vehicle-to-Everything (V2X) communications enable cooperative road safety services and applications where vehicles and other road users share information to improve their preparation to safety hazards [1], [2]. Cooperative collision avoidance is a particularly promising concept to avoid traffic accidents by predicting and reacting to potential collisions [3], [4]. This involves sharing the location, velocity, and acceleration of the road users. Prediction, detection and sharing information about fatigued or otherwise impaired drivers is seen as one of the potential improvements to road safety services such as cooperative collision avoidance [5].

Driver condition monitoring systems have high potential to improve road safety. Nearly 1 in 3 drivers say they have driven when they had a hard time keeping their eyes open during the past 30 days [6]. Fatigue has a huge impact on driving impairing the driver's ability to observe dangers, control the car and make wise and informed decisions. The willingness to take risks increases, but reaction time gets longer. For these reasons, falling asleep while driving is a major cause for road accidents. It has been estimated that one third of fatal accidents are due to fatigue. Usually when fatigued drivers start driving, they are already tired from their past activities, such as physically demanding work, long working hours, shift work, lack of sleep or possible sleep apnoea. Fatigue can be efficiently prevented by sleeping enough, avoiding too long work shifts, avoiding alcohol the night before, having active breaks, being physically active, eating regularly and having short daytime naps. By warning an impaired driver already in an early stage or even educating him to prevent fatigued state, accidents could be prevented. Wearables, such as smartwatches, can help drivers to track their lifestyle habits, including sleep and physical activity, and monitor their physiological status also during driving.

5G has great potential to be the common connectivity platform for cooperative road safety systems. As a commercial communication technology serving a large variety of user groups, it has two distinct benefits also when applied to V2X usage scenarios, i.e., availability and performance. A large and heterogeneous user base guarantees that the technology continues to evolve and up-to-date equipment is available for large scale deployments also in the future. Fig. 1 depicts the main building blocks for a cooperative driver monitoring and traffic warning system enabled by wearables and 5G networks. With the enhanced communication capabilities provided by 5G, a fatigue prevention guidance service based on the driver condition monitoring data collected with wearables as well as sharing of driver status information with other road users in the form of real-time warning messages can be realized on top of a single communication infrastructure.

Communications reliability and latency are essential key performance indicators (KPIs) in any warning system. For Vehicle-to-Infrastructure (V2I) and Vehicle-to-Pedestrian (V2P) road safety applications, the latency should be below 100 ms while for Vehicle-to-Vehicle (V2V) collision avoidance applications, the latency should be below 20 ms [7]. In case

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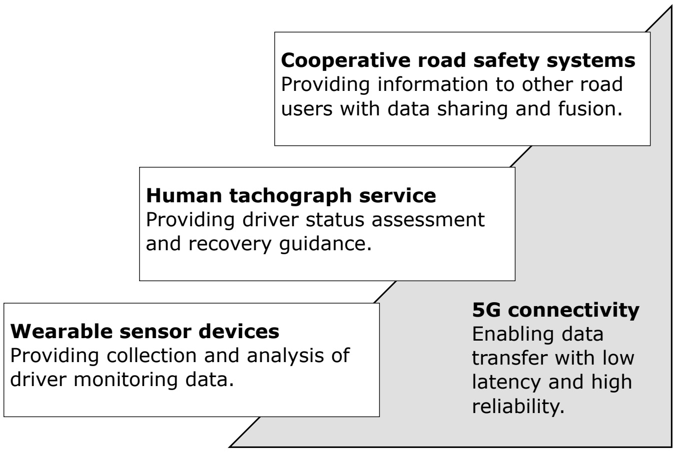

Fig. 1. Building blocks for a cooperative traffic warning system based on wearables and 5G connectivity.

of cooperative collision avoidance with automated driving, the requirements are even more stringent with 10 ms latency with a reliability of 99.99 % [8]. The reliability in communication systems is defined as the number of sent data units for the given protocol layer successfully delivered to the destination within the time constraint required by the targeted service, divided by the total number of sent data units [9]. Thus by definition, the measurement of end-to-end latency is needed for evaluating the reliability.

The V2X connectivity can be implemented using the Dedicated Short Range Communications (DSRC) via the IEEE 802.11p or the emerging IEEE 802.11bd radio access technologies [10]. However as these approaches require deployment of dedicated infrastructure for V2I communications, there has been growing interest in taking Cellular-V2X (C-V2X) into use via the existing LTE or emerging 5G networks [10]. In particular also the sub-1GHz frequencies are now being allocated for 5G [11], which enables nationwide 5G coverage along the main roads. The currently deployed Rel-15 5G networks already achieve better throughput and latency than the LTE networks. In the near future, several features greatly enhancing the C-V2X capabilities are introduced to the 5G standards and networks. These include ultra-reliable low-latency communication (URLLC) improvements and new sidelink design supporting V2V unicast, multicast, and broadcast [12].

In this paper, we introduce a novel human tachograph concept, which utilises driver's biosignals and provides guidance to prevent fatigue and improve wellbeing. Unlike most of the existing driver fatigue detection systems, the human tachograph tracks both live biosignals as well as sleep and physical activity in long-term. The information from the tachograph application can also be shared with other drivers and vehicles. For this purpose, we evaluate the feasibility of a 5G-based traffic warning system, which triggers warning messages towards other road users and road traffic safety systems based on the human tachograph driver condition analysis. The performance is measured in a live 5G network in terms of communication latency and reliability.

Previous studies on wearable driver monitoring systems have focused on detection of drowsiness or sleepiness based on vehicular or physiological signals measured while driving [13], [14]. In a study on truck drivers' motivation to use wearable devices to support their wellbeing, the drivers saw that wearables could motivate them to take more responsibility of their health and wellbeing, and prevent future health problems [15]. However, combining the driver's long-term fitness and sleep information with the real-time wearable-based monitoring data has not been proposed earlier.

At the time of writing, there are only a few publicly available measurement results reported from live 5G networks [16]–[18]. The experimental results on 5G one-way latency or end-to-end reliability have so far been largely missing from the scientific literature most likely because their accurate measurement can be difficult and time-consuming. Measuring one-way latency requires that the measurement end points are accurately synchronized to the same timing reference, while any higher reliability levels require measurements over a very large number of packets. Recently, a method for estimating the reliability of live networks that can greatly reduce the time for measurements was presented in [19].

The rest of the paper is organized as follows: The human tachograph concept is presented in Section II. An example of a 5G-based road safety system utilizing the human tachograph data is introduced in Section III. The measurement setup to evaluate the communications reliability and latency of a such system is described in Section IV. The results from the measurement campaign are presented in Section V. Finally, the conclusions are drawn in Section VI.

II. Human tachograph for professional drivers

A tachograph is an EU regulated device to record driving times, breaks and rest periods of professional drivers. It is mandatory to have a tachograph in large commercial vehicles to guarantee that professional drivers have enough rest between driving to prevent fatigue, ensure minimum working conditions standards and guarantee road safety. However, the tachograph is not based on the actual physiological status of the driver. Human tachograph is a wellness solution concept based on 24/7 unobtrusive monitoring of the (professional) driver with wearables. Consumer wearables are cheap and can be worn unobtrusively, which provides potential to user satisfaction; it is easier for end-users to accept and commit to use them. Being wearable, there is no need to install additional sensors to the vehicles so integration is easy.

Working upon the current tachograph solution, human tachograph utilises driver's biosignals and provides guidance to prevent fatigue and improve wellbeing. It is tracking both live biosignals as well as sleep and physical activity in long-term, and based on the combined analysis, the human tachograph adjusts the proposed break times and fatigue management tips. The information from the application could also be shared with other drivers and vehicles. After all, a more accurate assessment of driver's condition is important not only for the driver himself, but also to the other road users.

Professional driving requires good overall health. Having a healthy lifestyle may however be challenging with the working conditions professional drivers typically face, including shift work, long and irregular working hours and changing work environment. As such, the role of sleep in recovery is especially important due to long working hours. It might also be challenging to eat healthy and be physically active on a regular basis. Studies have shown that being overweight, smoking and being inactive is common among professional drivers. Daytime sleepiness and inadequate night sleep are also common together with mental and physical stress [20]. Sleep deficiency also affects general health, for example increases the risk for being overweight. Consequently, health promotion for professional drivers is needed to guarantee enough labour force in the future. In this context, human tachograph could be a valuable tool to assist transport/automotive companies or occupational healthcare.

Wearables-based driver condition monitoring can provide useful data also for the active safety systems utilised in cars and other vehicles, such as trucks and engines. However, this information will be especially useful for future connected automated vehicles where accident prevention can be aided by sharing information between vehicles and other systems. If the monitoring data, typically restricted to the current state of the driver, is extended to include the potential risk factors identified from the driver's history data (e.g. sleep deprivation, high stress, etc.), more proactive measures can be taken to improve the safety of driver, passengers and other road users. Wearables, when coupled with high-performance connectivity and service platforms, can furthermore provide driver condition monitoring capabilities to vehicles which do not have an on-board system installed or function as part of network-assisted warning and safety systems.

Data privacy is an important issue in the concepts including data sharing. Warnings containing information on the impaired driving status of one should be anonymized and sent only when there is enough traffic to guarantee anonymity. The warning system logic should be such that warnings are sent sparsely to keep them effective for other road users.

III. 5G-BASED ROAD SAFETY SYSTEM

For the rest of the paper, it is assumed that the human tachograph introduced in Section II is combined with a road safety system that sends warnings to road users when extra caution is needed. The communications architecture for the system is shown in Fig. 2. The wearable device responsible for the real-time driver biosignal monitoring is connected to the driver's phone or vehicle's cellular connectivity unit via a Bluetooth Low Energy (BLE) link. The cellular communications is based on the 5G non-standalone (NSA) architecture where we assume that Evolved Packet Core (EPC) is deployed close to the base station in order to avoid additional delays. In addition, the edge processing capability is deployed on a virtual machine in the same server rack as EPC to minimize any delays outside the radio access network.

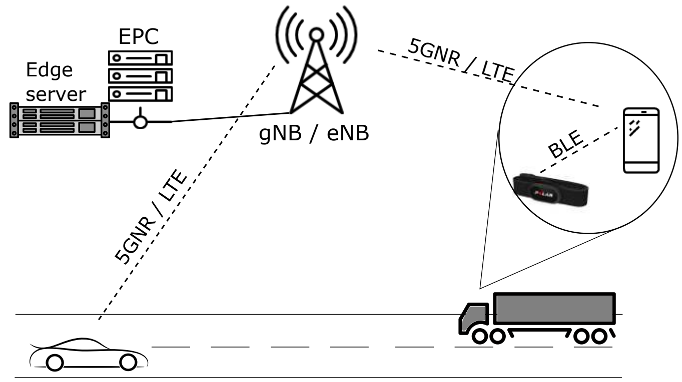

Fig. 2. Communications architecture for the 5G-based road safety system.

A key system design choice in this approach is who makes the decision when a warning message has to be sent to other road users. In a distributed architecture, the human tachograph processing is performed at the driver's phone or vehicle's on-board processing unit. In this option, the user equipment (UE) can independently decide to trigger a warning message, which can be delivered to other road users either via direct V2V links or through the cellular uplink (UL) to the edge processing unit, which distributes the warning message to the area. The latter option has the benefit that also the road users not having C-V2X capability can be reached.

From the cellular network point of view, the distributed architecture is preferable because the warning messages are small and uncommon resulting in low network load. However, the distributed architecture requires that each individual human tachograph operates reliably to prevent, e.g., the flooding of warning messages. In practice, it may be easier to deploy a secure warning system based on the centralized architecture in which the human tachograph processing is located at the edge server. The network load is clearly increased especially if all the raw measurements from the wearables are forwarded to edge processing. However, the amount of load can be reduced by pre-processing at the UEs. The distribution of downlink (DL) warning messages is similar in both architecture options and can be based on multicasting or unicasting.

If the communication network is able to provide the required service quality for the centralized architecture, an additional benefit of this approach is the more straightforward integration towards other road safety systems. As the processing of the collected wearable sensor data is performed in the network, both the raw and analysed driver status information is available for further utilization in the same network location. For example, in the 5G-HEART project [21], the centralized architecture is investigated from both performance and business perspectives, in order to find the best deployment strategies for the human tachograph service and the potential synergies with the variety of other vertical use cases trialled in the project.

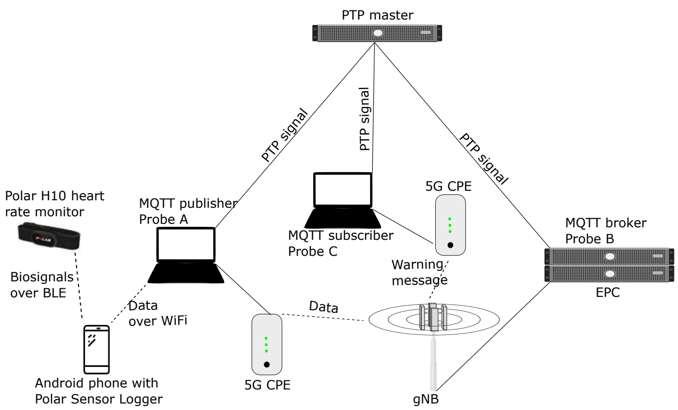

Fig. 3. Laboratory setup for the reliability measurements.

IV. Measurement setup

As discussed in Section I, evaluating the communications reliability in a live network requires accurate latency measurements between the sender and receiver. The users of a road safety system are mobile which makes the accurate synchronization between the measurement end points difficult. Unless dedicated Global Positioning System (GPS) hardware is used, the measurement application receives its clock synchronization data from the base station via Network Time Protocol (NTP), which has rather poor accuracy in the order of 10 ms [22]. In order to enable accurate one-way latency measurements, we have connected the measurement end points to a Precision Time Protocol (PTP) master via Ethernet connections.

The setup for the reliability measurements is shown in Fig. 3. Polar H10 heart rate sensor measures the biosignals and sends them over the BLE connection to an Android phone running the Polar Sensor Logger app [23]. In the case of the distributed architecture, the phone processes the biosignals together with the long-term sleep and activity information and, if required, triggers a warning message. In the centralized architecture, the phone just publishes all the biosignals to the Message Queuing Telemetry Transport (MQTT) broker. The Mosquitto MQTT broker is running in the same server rack as the EPC to avoid any extra delays. In the distributed architecture, the warning messages generated by the phone can be directly subscribed by other users while in the centralized architecture, the processing of the human tachograph data and warning message triggering is done at the network edge.

The latency measurements are done with Qosium Probes [24] that capture all the IP traffic from the pre-defined network interfaces. To have the same accurate timing reference at all measurement end points, the computers running the Qosium Probes are connected to the same PTP master via low-jitter Ethernet connections. Unlike PTP signalling, all the data to be measured, i.e. the biosignals or warning messages, are routed to the 5G network interfaces.

The measurements are performed in VTT's 5G Test Network [25] and the performance of 5G is compared to LTE. The 5G base station is operating in the NSA mode at band n78 with bandwidth of 60 MHz. The LTE base station is operating at LTE band 7 in the intra-carrier aggregation mode with 5+10 MHz bandwidth. The same 10 MHz LTE cell is also operating as the anchor cell for the 5G cell.

It is assumed that the warning messages have a structure similar to Cooperative Awareness Messages (CAMs) that carry the vehicle speed, acceleration, position, heading, and identifier [4] in the payload of 83 B. In the centralized architecture, Polar Sensor Logger publishes 1 heart rate, 2 electrocardiography and 6 accelerometer MQTT messages per second. In addition, it is assumed that the vehicle speed and position are also included to the heart rate reports. The total UL throughput per vehicle in the centralized architecture is approx. 50 kbps per driver. The DL warning message structure is the same in the both architecture options.

V. Measurement results

In order to gather enough latency statistics for the reliability evaluation in the distributed architecture, 100000 warning messages are published for each case with the message generation rate of 1 message per second. The two-way latency between the MQTT publisher and subscriber is recorded for each message. Additionally, the one-way UL latencies between the MQTT publisher and the broker (Probes A and B in Fig. 3) as well as the DL latencies between the MQTT broker and the subscriber (Probes B and C in Fig. 3) are recorded.

In the centralized architecture, there is no two-way latency for the warning messages as they are triggered at edge processing. However, the one-way DL latency is the same as in the distributed architecture and we also record the UL one-way latency statistics for Polar Sensor Logger biosignal reporting over 3 hours for each case. Unlike warning messages, biosignal reporting is not typically considered critical and thus the same level of reliability cannot be always guaranteed by network slicing or traffic prioritization. Thus, we also emulate the situation of the congested network by generating the full buffer UL traffic by another UE served by the same cell (or beam in the case of 5G) to see its effect on the biosignal reporting latency.

The cumulative distribution functions (cdfs) of the warning message latencies are shown in Fig. 4. It can be seen that the two-way latencies in the 5G are clearly better than in LTE. This is mostly due to the differences in the UL latencies while the DL latencies are typically only 1-2 ms shorter with 5G. It should also be mentioned that the measurements were repeated in the laboratory environment with different signal quality levels (reference signal received quality (RSRQ) varying between -3 and -9 dB) with no noticeable difference to the latency results. Thus, we can conclude that as the payload of the warning message is small, it is very robust to different channel conditions.

When we are interested about the reliability, the cdf of the latency should be presented in the logarithmic scale. This enables us to see at which time constraint a certain target reliability level can be reached. The reliability as a function of the time constraint for the warning messages is shown in

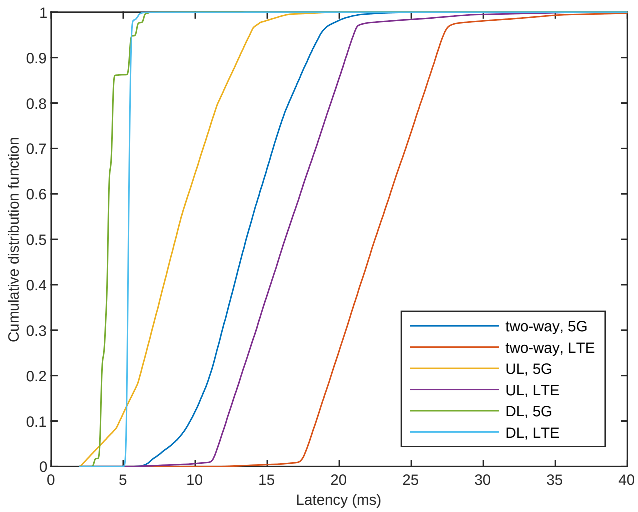

Fig. 4. The cdf of the warning message latency.

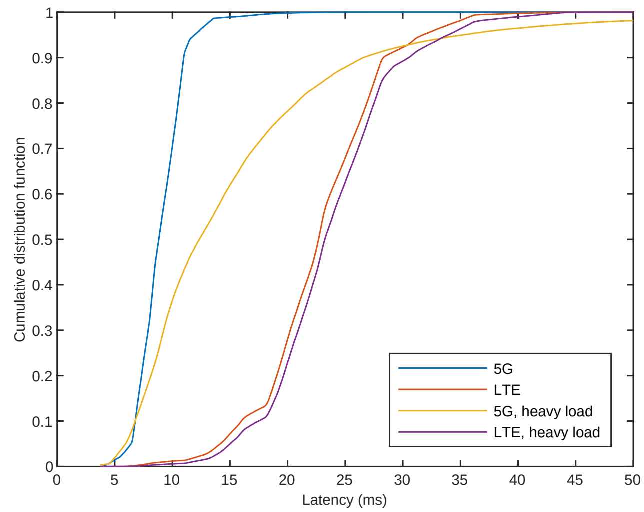

Fig. 6. The cdf of the biosignal reporting latency.

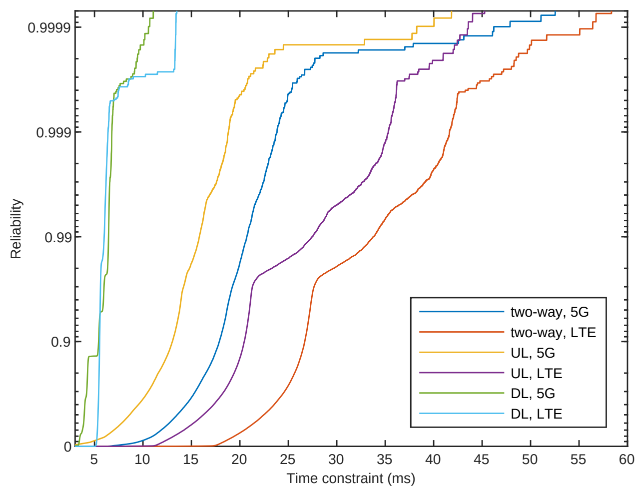

Fig. 5. The reliability of the warning messages as a function of time constraint.

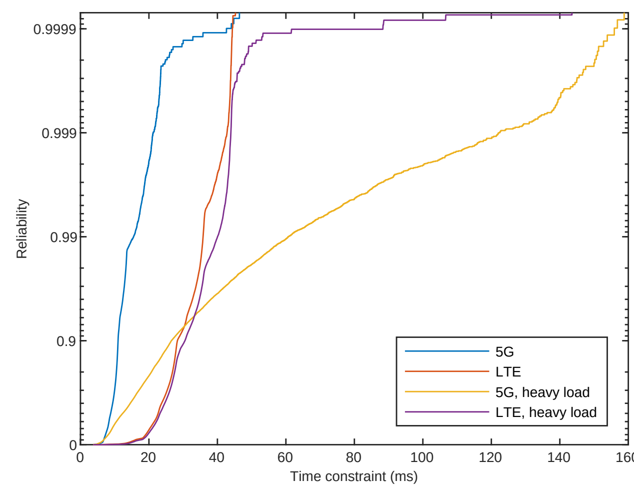

Fig. 7. The reliability of the biosignal reporting as a function of time constraint.

Fig. 5. Now the difference between the 5G and LTE is even more clear than in Fig. 4. This is mostly due to LTE UL latencies that can exceed 20 ms with quite high probability in case of retransmissions over the air interface.

The latency and reliability of biosignal reporting are not so important in the centralized architecture because the human tachograph is likely to process the biosignals from a long period of time before triggering a warning message. However, it is interesting to see what level of reliability can be reached for biosignal reporting and if it's comparable to the reliability of UL warning messages in the distributed architecture. The results for the biosignal reporting latency and reliability are shown in Figs. 6 and 7, respectively. It can be seen from Figs. 6 and 4 that in 5G the UL latency is at the same level for both warning messages and biosignal reporting. There is also significantly lower latency for biosignal reporting in 5G than in LTE. However, if the mobile operator is not willing to prioritize the biosignal reporting over other traffic and there is high demand for other UL traffic (full buffer traffic from another UE, in our case), the latency and especially reliability performance in 5G degrade significantly. Interestingly, the degradation under heavy load in LTE is much less severe. This is most likely due to different scheduler implementations or their configurations. The performance degradation could be avoided by setting high priority Quality of Service (QoS) class for biosignal reporting.

The main numerical results from the measurements are given in Table I where the columns with percentages refer to percentiles, e.g. 99% refers to the 99th percentile of the latency. It can be concluded that on average 5G achieves below 20 ms two-way latency already with the Rel-15 equipment. Especially the DL reliability is already at the target level for cooperative collision avoidance for automated driving, i.e. 10 ms latency with a reliability of 99.99 %. In the UL side, there are still some reliability challenges to be solved. Even though the current Rel-15 based 5G networks offers clearly lower

TABLE I
MAIN LATENCY RESULTS IN MS.

	Average	**90%**	**99%**	**99.9%**	**99.99%**
Two-way, 5G	13.7	17.9	20.7	23.8	46.2
Two-way, LTE	22.7	26.7	33.8	41.6	56.4
UL, 5G	8.8	13.0	15.8	18.8	38.3
UL, LTE	16.4	20.5	27.5	35.3	43.6
DL, 5G	4.1	5.4	6.4	6.8	10.6
DL, LTE	5.4	5.5	6.0	6.4	13.4
Biosignal, 5G	9.0	11.0	15.5	21.2	42.6
Biosignal, LTE	22.8	28.3	35.8	42.8	44.4
Biosignal heavy load, 5G	15.6	26.6	60.7	122.5	155.9
Biosignal heavy load, LTE	23.7	30.5	40.1	44.0	88.4

average latencies than LTE, the reliability at the target level of 99.99 % is not that much better in 5G than in LTE. However, it is expected that with the emerging URLLC extension, the reliability in 5G should be clearly improved.

VI. CONCLUSIONS AND FURTHER WORK

In this paper, we introduce a novel human tachograph concept, which combines driver's biosignals and long-term sleep and physical activity information. The human tachograph provides guidance to prevent fatigue and improve wellbeing and estimates the driver condition more accurately than the currently used on-board systems. The driver condition analysis from the human tachograph can also be used by a variety of cooperative road safety services to warn other road users about driver's impaired capability to drive. This can potentially proactively reduce the risk of road accidents.

This paper also evaluates the performance of a 5G-based road safety system concept, which triggers warning messages towards the other road users based on the human tachograph driver condition analysis. We consider both the distributed architecture, where the human tachograph and warning message triggering are implemented in the UEs, and the centralized architecture where the human tachograph processing is located at the network edge. The performance is measured in a live 5G network in terms of communication latency and reliability. According to the measurement results, the average two-way latency well below 20 ms, which is a target for collision avoidance applications, can be achieved for warning messages in Rel-15 5G networks. The reliability in the 5G UL was not yet found to be at the level required by automated driving. However, the reliability is expected to improve considerably when the support for Rel-16 URLLC is available.

In order to get accurate latency measurements, the measurement end points were synchronized to the same PTP time reference in the laboratory environment via low-jitter Ethernet connections. As a further work, we aim to integrate such timing reference equipment to the measurement setup that would enable field measurements using moving vehicles in 5G networks with roadside coverage. Another interesting future direction would be to compare the performance to the DSRC and emerging 5G C-V2X systems.

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