5G Wireless Communication for Autonomous Excavation

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Abstract

The applicability of wireless 5G network to the information communication needs of autonomous excavations is studied. An autonomous excavator developed by the University of Oulu is used for the experiments in a 5G test network at the Linnanmaa Campus of the University of Oulu. In the experiments, remote and autonomous control methods were used for test drives, in which the operation working was observed and measured. As a reference system, 4G wireless network was used. Remote control worked well in 4G and 5G. In 4G, delay of 1,7 s was observed from joysticks to camera view, while in 5G, the delay was 799 ms. The 5G network delay of 15 ms improvement was measured. Camera and image processing were still the primary reason for delays, approximately about 784 ms. In the 5G test, some jerking movements and steering crashes in autonomous steering were observed. In current 5G networks, uplink speeds are a limiting factor, which requires further attention on future 5G networks and standardization to be better applicable for industry use scenarios.

Latency of the connectivity is an important performance characteristic, even more than throughput. 5G can bring some benefits to autonomous excavation, especially more capacity for real-time information utilization.

Keywords – Wireless network; Autonomous excavator; 5G

1 Introduction

1.1 Background

5G is the 5th generation of wireless mobile networks, a significant evolution of today's 4G LTE networks. 5G has been designed to meet the very large growth in data and connectivity of today's modern society, the Internet of Things (IoT) with numerous connected devices, and tomorrow's innovations [1].

On a general level, there are at least three common expectations for the use of the 5G network [2]:

- massive machine to machine communications (i.e., IoT connecting billions of devices without human intervention at a scale not seen before
- ultra-reliable low latency communications
- enhanced mobile broadband (faster data speeds and greater capacity).

Lukau (2014) pointed out that there are many difficult solutions, tasks, challenges, and requirements that need to be faced and successfully resolved in order to heft the mobile telecommunication technology to the next 5G level. [2]

Excavator is one of the most used earth-moving machines with the most hours of use on construction sites. Excavators typically have a lot of different booms, tools, additional equipment, and other systems included or connected to the basic machine frame. The working tasks are quite versatile and challenging to be automated. Most typical infra construction tasks are earthwork cutting and loading. In Finland, based on several interviews with the industrial key players, master class human operators are rare (about 1/15).

Vernersson et. al (2013) have evaluated that in road construction sites and quarries, there are clear improvement potentials with the introduction of wireless communication technologies especially for safety improvements and productivity optimization. In quarries, they suggested that a productivity increase of up to 30% can be achieved assuming a reliable wireless connectivity to minimize waste in the production. They also saw a clear potential in accident avoidance using wireless communication-based warning systems. [3]

Rylander (2021) has studied and experimented wireless short-range Communication Performance in a Quarry Environment with also a focus on earth moving operations. Rylander [4] points out that there is a clear potential in optimizing site throughput by better coordinating machine movements. Such an optimization requires a site control system with wireless communication to control the speed of each machine. Machines can travel at a more energy-efficient speed with lower fuel consumption instead of moving at maximum speed and then waiting at the destination. The research included the wireless short-range technologies ZigBee, 802.11g, and 802.11p using frequencies of 868 MHz, 2.4 GHz, and 5.9 GHz. In the study, 802.11p reached a range of 1767 meters in Line-of-Sight (LOS) conditions. The 802.11g performed well at the quarry top but gave a poor result in the quarry pit where it lost the most packets out of all standards. The 802.11g delivered an unstable communication in the pit and was sensitive to Non-Line-of-Sight (NLOS) areas and obstacles, and was unable to benefit from reflecting surfaces. The ZigBee RF provided the best results (only two data packet losses were observed, the maximum range of operation was 1753 m) and seemed to be unaffected by NLOS. In his study, Rylander [4] also evaluated the potentiality of fully automated machines and machine fleets and concluded that continuous activity measurements and feedback loops are required in the control process.

In Finland, infra construction machines with automatic machine control systems have been tested and used using commercial operator networks, 3G and 4G wireless networks, and/or using different Wifi network solutions. So far, we have not yet found any experiments with autonomous work machinery in 5G network. It is clear that the higher the level of automation the control of mobile machines are developed, the more speed, capacity, and reliability are required for the wireless data transmission required by the control. [6][7]

1.2 Aim

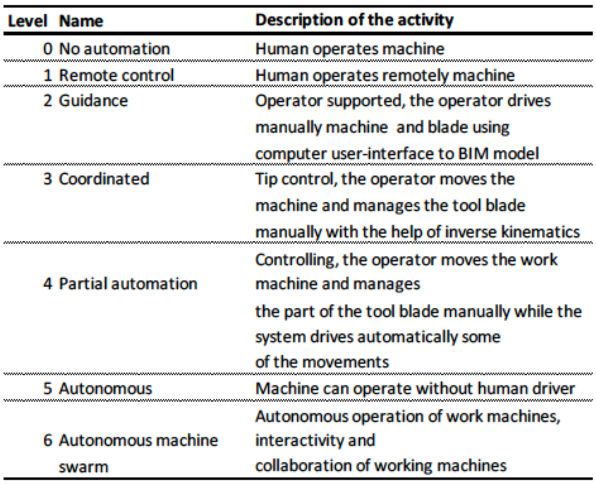
The aim of the research was to study and experiment the applicability of the wireless 5G test network to the information transfer demands of autonomous excavation work process.

2 Materials and Methods

2.1 Autonomous Excavator

In the study, we used the autonomous excavator developed by the University of Oulu (Smart Excavator, Bobcat E85) [5], which is presented in Figure 1 as well as Figure 2 with omni antennas on the roof of the excavator. In Figure 3 is showed how VR glasses can be utilized to the remote control of the excavator. The control of the Smart Excavator is based on Open Infra Building Information Models (Open Infra BIM) that provide the needed information for machine control systems. Current types of automatic 3D machine control systems are presented in Table 1: (1) remote (human operates machine remotely), (2) guidance (human operates manually machine using computer user-interface to BIM model); (3) coordinated (human operates the machine and manages the tool blade manually with the help of inverse kinematics), (4) partial automation (human moves the machine and controls some of the blade movements while the system drives automatically the other movements), (4) teach-in (human operator drives a series of movements, which are recorded and can later be automatically repeated), and (5) autonomous (machine can operate without human operator).

Table 1. Levels of Automation for Infra Construction Machinery (University of Oulu).



Level	Name	Description of the activity
0	No automation	Human operates machine
1	Remote control	Human operates remotely machine
2	Guidance	Operator supported, the operator drives manually machine and blade using computer user-interface to BIM model
3	Coordinated	Tip control, the operator moves the machine and manages the tool blade manually with the help of inverse kinematics
4	Partial automation	Controlling, the operator moves the work machine and manages the part of the tool blade manually while the system drives automatically some of the movements
5	Autonomous	Machine can operate without human driver
6	Autonomous machine swarm	Autonomous operation of work machines, interactivity and collaboration of working machines

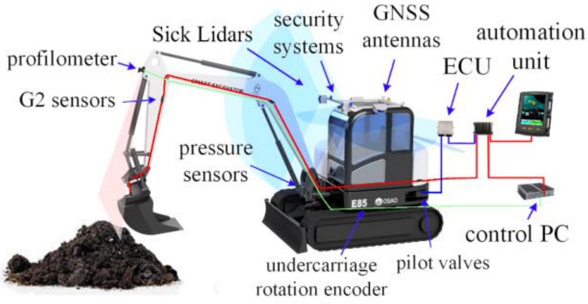


Figure 1. Smart Excavator of the University of Oulu – hardware, sensing, and control systems. [5]

Figure 2. Smart Excavator of the University of Oulu (top), Omni directional antenna on the top of the machine (below).

Figure 3. Remote control with VR glasses from the University of Oulu campus to the test site.

2.2 5G Test Network (5GTN) and equipment

5GTN is an R&D project with several partners in Finland [1]. The aim of 5GTN has been to provide access to the test network and related expertise to interested third parties. In the experiment, the used band was n78 (3500 MHz) with non-standalone (NSA) architecture for connecting excavator to the network. Modem integration to the Smart Excavator for 5GTN connection was developed as bachelor's thesis (Joona 2021). In the experiments, the 5G link was for connecting Smart Excavator, which was controlled from control cabin by wired (Figure 5).

The UE (User Equipment) used in the experiments was Vehicle Connectivity Unit (VCU) provided by Satel Oy. The UE is a robust machine connectivity unit designed to be used in heavy machinery. The modem supports theoretically DL 2.5 Gbps; UL 600 Mbps and LTE DL Cat 16/ UL Cat 18 speeds.

The test setup required the connectivity between the control PC and Lidar and Camera receivers in the cabin to be connected to the excavator internal network using L2 Ethernet. The solution to connect from the remote to the excavator over Ethernet was to establish an OpenVPN connection from the control cabin to Satel's VCU. The algorithms used were SHA256 for authentication and AES128-CBC for encryption. The OpenVPN connection was also established without encryption or authentication for performance comparison between non-encrypted, non-authenticated, and fully secured connectivity.

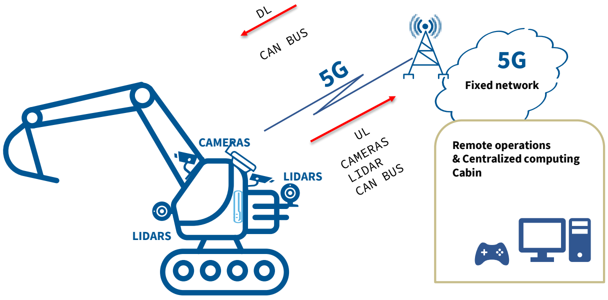


Figure 4. Network Schematics used in the 5G experiment (Satel Oy).

The quality of the application traffic from video streams, LiDARS, and CAN bus over the network connection was measured by Kaitotek's Qosium solution. Qosium is a passive and real-time network Quality of Service (QoS) measurement software. It measures QoS for the real ongoing application traffic over the network path of interest without creating any artificial test traffic to the network.

The measurement setup was a two-point measurement necessary for measuring QoS. We deployed a Qosium measurement agent on the remote controlling side in the end device. In the excavator, the measurement agent was running in an Ethernet bridge device through which all application traffic flows, being deployed right beyond the 5G router device.

2.3 Experiments

Real excavation work was not allowed at all in the Linnanmaa campus area. The excavator and the control booth were transported by truck to the campus. The excavator was operated on the 5G network (Fig 5) using two different automation methods, i.e., 1) remote control and 2) model-based autonomous control. Both automation methods were carried out from the nearby control booth. Plane excavating above the asphalt was selected for the model-based autonomous control. (Fig 6)

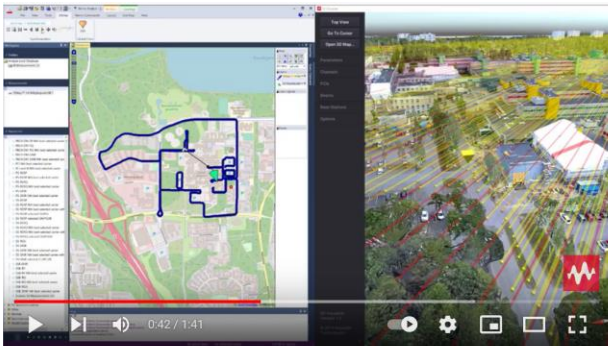


Figure 5. 5G Test Network at Linnanmaa Campus of University of Oulu.

During both control methods, lidar data and camera stream were transferred with the excavator control signals. Lidar data was sent by burst, and the camera stream was continuous. Data transfer rates and delays were measured with Kaitotek's Qosium and Wireshark software, and the results obtained from 4G (reference) and 5G networks were compared. Both control methods were also driven with and without encryption. The functionality of the automatic control was observed during the experiments.

Figure 6. Remote and Autonomous Control Operation.

The measurement solution used enabled us to see the performance of the 5G connection directly to the applications relevant to the remote control. The measurement solution only factors in the connectivity effect for the end-user experience. Thus, for example, video encoding and decoding latencies are not considered in the measurement results.

The statistics collected comprised QoS statistics, including delay, jitter, packet loss, and connection break. In addition, traffic and flow statistics showing, for example, bitrates, packet sizes, and packets per second were also measured. All statistics are one-way, meaning that the results are provided for the traffic originating from the control desk to the excavator and vice versa separately.

3 Results

Remote control worked well for both 4G and 5G connections. We measured, on average, 12 ms connection delays for the control signal traffic, with no significant difference between the access technologies. However, we observed a 1.7 s latency from joystick input to be shown on the camera view in 4G. In 5G, the latency was, on average, 799 ms. Thus, 5G performed much better in delays when there was more traffic over the network. The 5G network delay improvement of 15 ms was measured. Camera and image processing were still the primary reasons for latencies, approximately 799 ms – 15 ms = 784 ms.

The moving excavator cabin caused the 5G user plane of the employed Non-Standalone (NSA) 5G connection periodically to switch to a 4G network, as visible in Figure 7 (e.g., 5G RSRP values going to zero). Handover to 4G produced increased delays to the excavator control signals. This behavior was most likely due to the azimuth pattern of the used antenna. Using two or more antennas at different orientations could have prevented the observed effect.

In these experiment conditions, 5G throughput capacity measurements with the Iperf traffic generator resulted in only 24 Mbps and 75 Mbps for uplink and downlink, respectively, when no data encryption was used. With encryption, 17 Mbit/s (uplink) and 27 Mbit/s (downlink) were measured. The actual control signal + camera throughput averaged 3Mbit/s and with lidar data peeked to a maximum of 9 Mbit/s. Control signals delays median with and without encryption was about the same (30 ms with encryption and 28ms without). However, there was observed a significant difference with the automation method when using encryption with the loaded lidar data bursts. We observed some jerking movements and a steering crash in automatic steering, which ended up the safety person pressing an emergency stop. Available bandwidth for 4G anchor frequency was 10 MHz (on B7) and equivalent 5G allocation was 60 MHz.

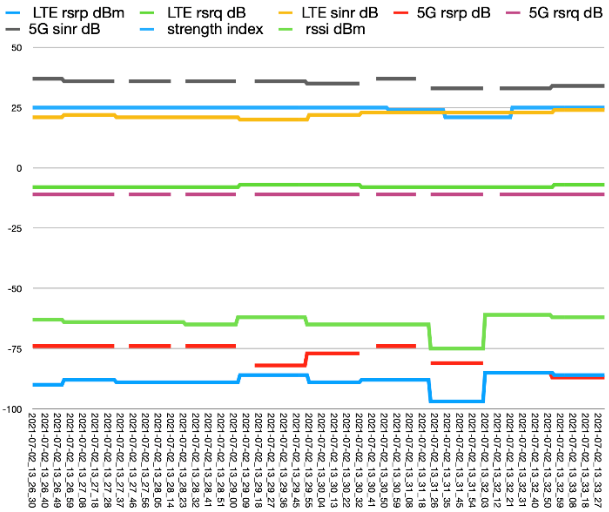


Figure 7. 5G Connectivity Stability (on a vertical scale signal strength, horizontal scale time).

4 Conclusion

Infrastructure construction is typically done on large-scale construction sites, with lengths ranging from kilometers to over 100 km. In addition to work machines, various vehicles, people and unexpected moving objects such as wild animals move on the construction sites. Unexpected work can also happen during the excavation work itself, the truck may drop more material than expected, or the cut ramp may collapse on the excavated cutting floor. As the control of work machines moves to an ever higher level of automation, the requirements of real-time are emphasized for reasons of efficiency and safety. An autonomous, unmanned excavator can basically work with its own sensors and control logic. However, in BIM based control, it must be possible to update the machine control model at any time using the real-time cloud service. To ensure work safety, the work machine is likely to have a continuous real-time wireless connection to the construction site safety system and associated sensors. Job control requires a real-time location of the implement and an accurate snapshot of the work done. Effective cooperation between automatic machines requires a continuous real-time exchange of information between the machines. This enables efficient and secure synchronization of work fleet work processes.

For remote control and automated movement detection, camera sensor and processing delays are significant in relation to network delays. Encryption processing performance is an important factor, too, especially on higher traffic loads. Encryption and decryption processing delays directly impact the end-user experienced latencies of applications. In current 5G networks, the uplink performance is the limiting factor that affects industrial usage. Most traffic is typically sent to the uplink direction in industrial use scenarios, including, e.g., camera streams. Available bandwidth for experimentation system is also limited compared to commercial networks.

For a remote controlling use scenario with real-time applications, network delays are more relevant to assessing the performance and quality of the network than maximum throughput capacity measurements. 5G can bring some benefits to autonomous excavation, especially more capacity to real-time information utilization. At the moment, 5G, however, needs careful planning and practical testing before moving to operative usage. The best scenario in operative usage is continuous monitoring of connection quality for the mission-critical real-time applications to detect connectivity disruptions before impacting efficiency and safety.

On remote infra construction sites, 5G can still meet challenges for sufficient coverage and especially uplink quality. On some large sites, it is likely that some supporting and backup networks are needed, e.g., WiFi or 4G LTE. In highly automated excavation, it will be essential to consider work management and division between central and edge.

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