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A mathematical analysis of teleoperator optimization using multiple sensors

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Abstract

As the role of remote vehicle operation gains prominence, ensuring robust wireless communication systems is crucial. Prior studies have delved into various aspects of vehicle

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teleoperation, including its legal framework and workforce implications. Some have even formulated models to estimate the number of remote operators for large automated vehicle fleets. These models suggest that automated vehicles overseen by remote operators could supplant a significant portion of current driving jobs in the United States. Such findings underscore the need for governmental review and policy adjustment to better accommodate the burgeoning field of teleoperation, which could substantially accelerate the advancement of vehicle automation. The present study focuses on evaluating the reliability of a bi-directional communication channel based on key variable parameters. This assessment aids in determining the optimal parameter settings, thereby enhancing the effectiveness of teleoperation systems.

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Keywords: *Spectrum sensing, 5G security, Energy detection, Cognitive radio.*

1. Introduction

As advancements in communication technologies persist, new challenges emerge, one of which is teleoperation—the remote control of machinery. Initially limited to small toys operated within proximity, teleoperation has evolved to encompass more complex applications like automated vehicles. Research in this area is diverse, with some studies focusing on the Human-Machine Interface (HMI) for vehicle teleoperation. For instance, the authors in [1] evaluated a prototype HMI design with various screens for controlling SAE Level 4 automated vehicles. This prototype was tested by thirteen end-users from public transport control centers in Germany and received favorable reviews. Other research aims to clarify the field by classifying and defining teleoperation concepts and terminologies. In [2] systematically reviewed fallback solutions in teleoperation, categorizing them into six types: Direct Control, Shared Control, Trajectory Guidance, Waypoint Guidance, Interactive Path Planning, and Perception Modification. Additionally, the authors in [3] surveyed terminologies related to remote human input systems for automated driving, proposing a taxonomy that could help standardize language and reduce ambiguity in the realm of vehicle teleoperation. In [4] tackled one of the most pressing issues in teleoperation systems for automated vehicles—latency between the teleoperation workstation and the automated vehicles themselves. Their work offers valuable insights into optimal site selection for teleoperation workstations. While existing literature has explored various facets of automated vehicle teleoperation, such as legal considerations, job implications, HMI design and evaluation [5], and concept and terminology classification [6], there remain notable gaps in the research landscape. For instance:

- Research is scant on deploying and evaluating fully operational automated vehicles that integrate a teleoperation solution in real-world settings.
- Gaining insights into the acceptance, perception, and support needs from remote drivers' viewpoint is crucial for designing and developing secure, efficient, and user-friendly teleoperation systems for automated vehicles. Yet, there is a lack of information concerning remote drivers' specific needs and requirements in their interactions with automated cars. This knowledge gap could hinder the advancement and practical implementation of higher-level automation systems (SAE Level 4 and above), consequently impeding automated vehicles from realizing their anticipated environmental, economic, safety, and social advantages [7]. The next step is to expand the system. Instead of remote controlling an RC car, truckers may be able to control their trucks from their home remotely. Because driving cars is already highly dangerous, the user must maintain a reliable connection between the operator and the teleoperator. The system to analyze is a two-way communication link between a vehicle and its operator. The two share the same bandwidth used to send and receive messages. To test the reliability of the channel, the signal-to-noise ratio (SNR) and effective coding rate (ECR) will be used to determine the channel's outage probability.

$$P_e(R,\gamma) = Q\left(\frac{C(\gamma)-R}{\sqrt{\frac{2\gamma}{1+\gamma}}}\right) \quad (1)$$

2. System Model

First, the outage probabilities of the channel will be calculated over an array of values. Then, the produced values will be tested over a simulated network link over UDP and TCP models. The argument of the $Q(z)$ function is a standardized variable. Its mean is the effective coding rate, the sample is the channel capacity, and its variance is the denominator. The distribution is based on the complementary error function. The $Q(z)$ function is a normalization of said function [8].

$$Q(z) = \frac{1}{2}erfc\left(\frac{z}{\sqrt{2}}\right) \quad (2)$$

$$\max[C(\gamma)] = 6.9088 \approx 6.9 \quad (3)$$

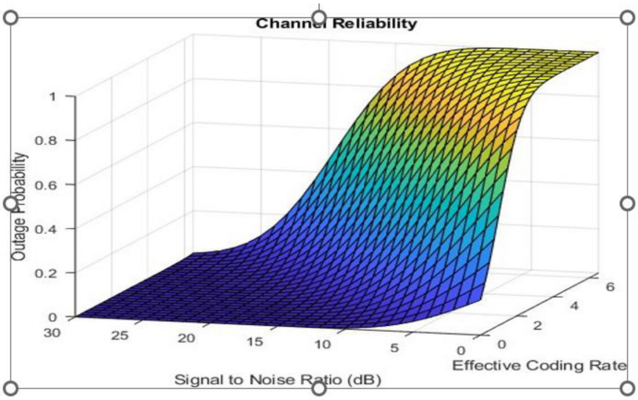

Figure 1

Outage probability due to SNR and ECR

As shown in Figure 1, the outage probability is low for high SNR values and high for high ECRs. For values above 25dB, the SNR trumps the error produced by the ECR. The outage probability of a channel is the probability that the track breaches a minimum threshold value for its bit error rate. Next, the SNR and ECRs will calculate delay, jitter, and loss across the connection. This will quantify the degree of severity associated with the input's respective outage probability.

In a UDP model, as shown in Figure 2, the transmission rate is constant [9].

The transmitter sends packets to the receiver with no feedback from it. While TCP fixes detected losses, UDP ignores them. Based on the SNRs and effective coding rates, a QAM-16 Link is simulated to calculate bit error rates (BERs). This associates an outage probability with a respective BER. For simplicity, every packet sent will be the effective coding rate times 256 bits. This message is sent over the QAM-16 link. Thus, a total of 256R bits will be transmitted per simulation. The message encounters an

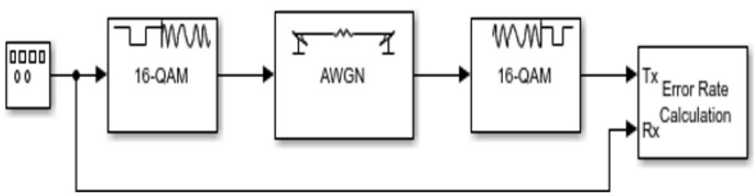

Figure 2

A common communication link setting

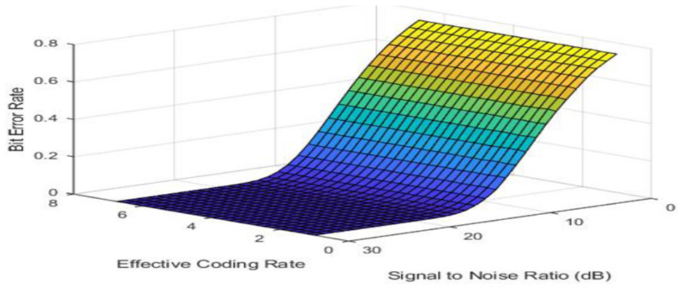

Figure 3

BER based on SNR and ECR

AWGN channel, which generates noise based on the SNR. After it is demodulated, the BER is calculated for each pair of inputs (SNR and ECR.

Figure 3 shows that the BER did not vary as the ECR increased. Only the SNR affected the behavior of the BER. It may be that the message is too small, but larger values. The transmission rate will increase in a TCP model as no errors are detected. As soon as an error emerges, the rate drops by half its current value. For this simulation, the outage probability will act as the probability of loss. As the ECR increases, so will its probability of loss. Furthermore, the transmission rate will be limited to the same integer values as the ECR (it is not a realistic number but still demonstrates the behavior of TCP).

Figure 4 illustrates the coding rate's behavior across 1,000 TCP cycles with a constant SNR of 25 dB. The mode of the RoT peaks at 6.75, and excluding outliers, the channel's minimum supported speed is 3.25. The

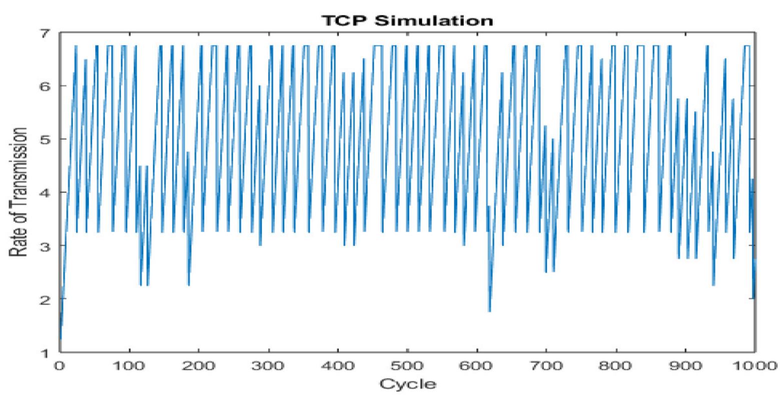

Figure 4

Rate of Transmission over 1000 cycles

distinction between UDP and TCP extends beyond error detection; while UDP maintains a consistent RoT, TCP allows for variability in RoT. Additionally, UDP experiences measured loss, whereas TCP does not, thanks to its error detection capabilities. As a result, only delays will be considered in this analysis. When TCP detects an error, the number of cycles needed for recovery translates into the channel's resulting delay. Data input will be encoded with its corresponding Error Correction Rate (ECR), and a variable number of bits will be transmitted based on the transmission rate mu (bits per cycle). TCP operates through a three-way handshake: a data packet is sent, an acknowledgment is received confirming the packet's receipt, and a final acknowledgment is sent back to confirm that the acknowledgment was received. This process takes three cycles to complete. The probability of error is influenced by the outage probability, which the SNR and ECR determine. However, any drop in the transmission rate will result in a delay. These delays will be summed and divided by the total number of cycles to calculate the ratio of delays [9-12].

$$\%delay = \frac{n}{999} \tag{4}$$

Where n is the number of delays that occurred over all 999 cycles, the rate of transmission and delays is shown in Figures 5 and 6, comparing the TCP test (blue) with the constant data rate (red) for different test situations.

In this instance, the SNR was maintained at a constant 20 dB. Each red pulse signifies a delay, occurring 98 times throughout the entire simulation, which translates to a delay presence of 9.81%. Regarding the total transmission time, if we assume the one-way propagation time to be

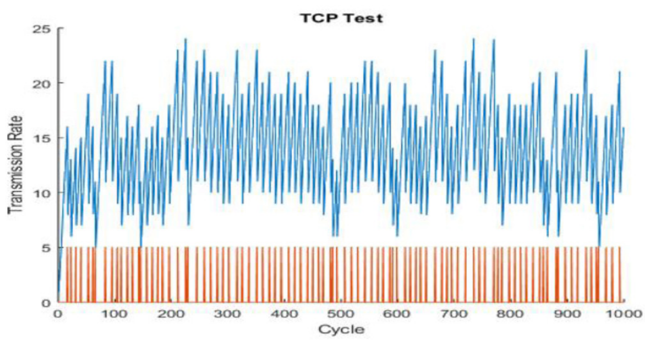

Figure 5

Rate of Transmission and Delays over 999 cycles

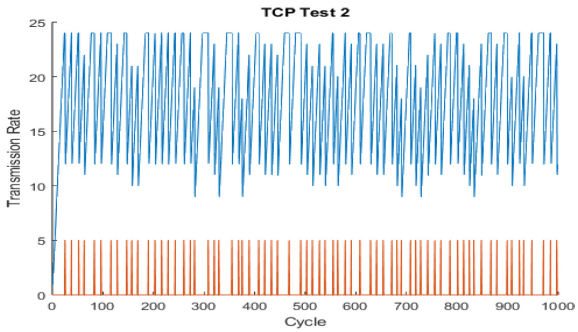

Figure 6

Rate of Transmission and Delays over 999 cycles

τ, then the actual duration required to complete the simulation is given by equation (5).

$$\sum \tau_1 = (999 + n_1)\tau : n_1 = 98. \tag{5}$$

This time, an SNR of 25dB was held constant. This time, there are only 69 delays. This results in a shorter time to transmit. This is a delay presence of 6.91%.

$$\sum \tau_2 = (999 + n_2)\tau : n_2 = 69 \tag{6}$$

Figure 7 shows the transmission rate and outage probability concerning the SNR, for both TCP and constant data rate transmission. As the SNR increases, the average minimum rate of transmission also increases. For an SNR of 20dB, the total propagation time maps to an outage probability. An ECR of 4 will be held constant to determine the outage probability.

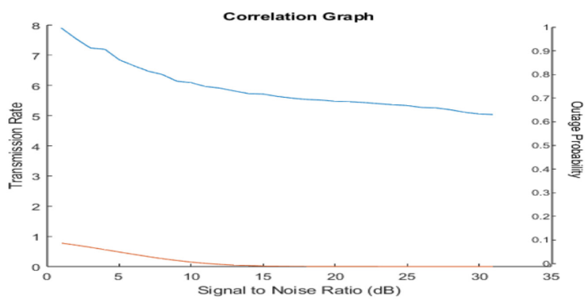

Figure 7

Propagation Time as it relates to Outage Probability

4. Conclusion

Existing research has covered various aspects of teleoperation in automated vehicles, such as legal considerations, workforce implications, Human-Machine Interface (HMI) design and evaluation, and the classification and definition of relevant concepts and terminologies. Despite this, notable research gaps persist. One such gap is the assessment of outage probability under different channel conditions. For this study, we focus on a single vehicle equipped with multiple sensors and a teleoperator responsible for remote control via wireless communication. Our study is mainly concerned with scenarios that have bandwidth limitations and strict delay constraints. We assume a transmission format with an N-channel is available to both the sensor and the teleoperator, allowing us to model finite delays and bandwidth. Outage probability is a useful metric for evaluating channel effectiveness and applies to UDP and TCP protocols. While outage probability primarily measures error rates exceeding a certain threshold, it can also be used to assess the delay in a TCP stream, thereby offering insights into the Quality of Service (QoS) behaviors of networks for telematic connectivity. This has practical implications for the applicability of teleoperation systems. Future research could explore the integration of teleoperation with autonomous driving to optimize the performance of autonomy-assisted vehicular control.

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