# Network-Controlled Repeater Aided Time-Sensitive Communications in Urban Vehicular Networks

Kai Dong, *Member, IEEE,* Hao Yu, *Member, IEEE,* Tarik Taleb, *Senior Member, IEEE,* Aydin Sezgin, *Senior Member, IEEE* and Sergiy A. Vorobyov, *Fellow, IEEE*

***Abstract*—Delivering time-sensitive (TS) information deterministically is vital for safety-related critical applications like vehicular networks. This letter presents a latency model for the TS packet delivery from the edge server to the vehicle. The Network-Controlled Repeater (NCR) is used to assist the packet delivery over random wireless channels where the finite-length packet transmission is considered. Simulations demonstrate the significant improvement of NCR in terms of success ratio for TS packet delivery and reveal key influencing factors, such as packet size and queuing delay at the edge server. This stresses on the need for efficient multi-user scheduling under performance and resource constraints in practical TS communications.**

***Index Terms*—Time Sensitive, Deterministic Networking, Vehicular Networks, Latency, Network-Controlled Repeater, Success Ratio.**

## I. Introduction

To enhance transportation safety in next-generation vehicular networks, it is crucial to share real-time, safety-related traffic information (e.g., from the edge server in proximity) within a local area with extremely low latency and high reliability. Specifically, TS packets containing local transportation information must be delivered deterministically from the edge server to the Vehicle User Equipment (VUE) via both wired and wireless links. This prompts the integration of Time-Sensitive Networking (TSN) capacity to wireless communications [1], [2]. The 3rd Generation Partnership Project (3GPP) Release 17 specifies the integrated network architecture of TSN and advanced wireless communication technologies, where the 5G System (5GS) acts as a bridge to forward TS packets to the next TSN node or end station [3]. However, the randomness of the wireless channel in mobile networks makes the delivery of packets within a low-latency budget more challenging compared to the stable radio paths in industrial Internet of Things (IoT) scenarios, where user positions are fixed [2].

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Kai Dong is with the Center of Wireless Communications, University of Oulu, 90570 Oulu, Finland. (e-mail: kai.dong@oulu.fi)

Hao Yu is with ICTFicial OY, 02130 Espoo, Finland. (*Corresponding Author*, e-mail: hao.yu@ictficial.com)

Tarik Taleb and Aydin Sezgin are with the Faculty of Electrical Engineering and Information Technology, Ruhr University Bochum, 44801 Bochum, Germany. (e-mail: tarik.taleb@rub.de; aydin.sezgin@rub.de)

Sergiy A. Vorobyov is with the Department of Information and Communications Engineering, Aalto University, 02150 Espoo, Finland (e-mail: sergiy.vorobyov@aalto.fi)

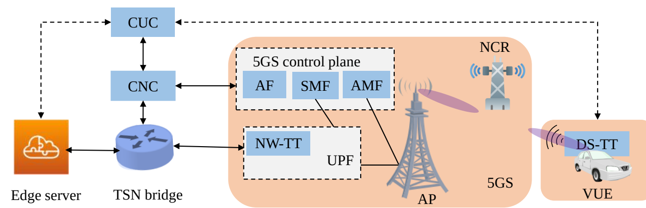


Fig. 1: System architecture of the integrated 5G-TSN system in vehicular networks.

TSN was developed by IEEE 802.1 to address the growing demands for deterministic and low-latency communications in industrial networks based on wireline transmissions [4]. Benefiting from the lower cost and higher flexibility of advanced wireless networks, TSN has extended its application to wireless fields (i.e., integrated 5G-TSN networks defined by 3GPP [3]), such as industrial automation, automotive systems, and real-time multimedia streaming [5]. In such an integrated 5G-TSN system, the 5GS acts as a bridge to support time-critical packet forwarding, as shown in the system architecture of urban vehicular networks depicted in Fig. 1.

Recently, research on latency analysis of integrated 5G-TSN networks has gained attention. In [2], end-to-end (E2E) traffic scheduling in a 5G-TSN static industrial IoT network was investigated by evaluating the success ratio. The delay of a logistics closed-loop control on a remote programmable logic controller enabled by a 5G-TSN network was evaluated in [6]. E2E latency and throughput were analyzed in a 5G-TSN network to support non-real-time communications in a smart factory [7]. However, all these works focus on static industrial networks, where the impact of wireless transmission over random radio channels has not been considered. Additionally, emerging applications like autonomous driving pose new requirements on the integrated 5G-TSN network architecture to support mobility use cases. This makes it more challenging to guarantee the deterministic delivery of TS packets due to blockage or severe path loss in wireless communications at high-frequency bands. The NCR, an emerging type of network nodes [8]–[10], offers a potential and practical solution for mitigating signal degradation and blockages in vehicular networks by amplifying the received signal at the NCR before forwarding packets to the end VUE, without requiring major changes to the existing network infrastructure.

The contributions of this letter are as follows:

- We explore TS packet delivery over both wired and wireless links in the integrated 5G-TSN architecture to support mobile vehicular networks. In particular, the latency model is formulated without incorporating retransmission schemes, but the model is flexible enough to include retransmissions.

- A short-packet transmission mechanism is considered, as it is more practical given that TS information typically has a limited packet size. Furthermore, the NCR is used to enhance the success ratio of packet delivery over the wireless link between the AP and the VUE.
- Simulation results show that TS packet delivery, aided by the NCR, exhibits significant performance improvement in terms of the success ratio. Furthermore, it also demonstrates that influencing factors such as packet size, queuing delay at the edge server, and transmission power should be effectively addressed for multi-VUE scheduling under performance and resource constraints in TS communications.

## II. 5G-TSN Network Architecture

The integrated 5G-TSN architecture implemented in most industrial IoT networks primarily focuses on TS packet delivery to end devices with fixed positions, where a stable Line-of-Sight (LoS) wireless link is established between the AP and the end device [2], [6]. However, there has been limited investigations into 5G-TSN systems supporting mobile users, such as vehicular user equipment (VUE), where the wireless propagation link in high-frequency bands is prone to severe path loss and potential blockages. In this section, we present a 5G-TSN architecture for urban vehicular networks and formulate the upper bound latency of the wireless link between the AP and VUE to ensure TS packet delivery within a total latency budget of $\tau_{\rm th}$.

### A. Integrated 5G-TSN Network Architecture

The basic integrated architecture of TSN and 5G System (5GS) has been defined by 3GPP to support the TS communications in deterministic networking [3]. In such architecture, the 5GS can provide the same functionalities as the TSN bridge to forward the TS packet to the end VUE, as the system architecture depicted in Fig. 1. Specifically, the Device-Side TSN translator (DS-TT) and Network-side TSN Translator (NW-TT) are the input/output ports of the 5GS connected to the VUE and TSN bridge, respectively. These enable the 5GS to support the TS packet processing and forwarding as the TSN bridge. The control plane translation functionality within this integrated architecture is handled by the TSN Application Function (AF), Session Management Function (SMF) and Access and Mobility Management Function (AMF). It is responsible for managing information exchange with DS-TT or NW-TT and interacting with the Central Network Controller (CNC) to configure the 5GS for supporting TS communications. In such integrated architecture, 5GS reports the 5GS bridge information, such as bridge ID, NW-TT/DS-TT ports, supported bridge delay and so forth, to the CNC through the AF.

### B. Latency Model

Assume that the TSN system and the 5GS are precisely synchronized with their respective internal network clocks.[1] Local transportation data can be gathered through radar sensing or via uplink communication at the AP and subsequently cached at an edge server located in close proximity. The safety-critical transportation data must be periodically transmitted to VUEs within the AP's coverage area, subject to a strict latency budget, denoted as $\tau_{\rm th}$. The total downlink latency from the edge server to the VUE can be expressed as:

$$t_{\rm d} = t^{\rm s}_{\rm queue} + t^{\rm s}_{\rm st} + t_{\rm TSN} + t_{\rm 5GS} \tag{1}$$

where $t^{\rm s}_{\rm queue}$ denotes the queuing delay at the edge server, characterized as a fraction of the total latency budget $\tau_{\rm th}$, i.e., $t^{\rm s}_{\rm queue} = \alpha\tau_{\rm th}$, with $\alpha \in [0,1]$, $t^{\rm s}_{\rm st}$ is the time required for packet delivery from the edge server to the TSN bridge via the wired link, and $t_{\rm TSN}$ represents the time required for the packet to be forwarded from the edge server to the 5GS via the TSN bridge, which can be expressed as:

$$t_{\rm TSN} = t^{\rm TSN}_{\rm queue} + t^{\rm proc}_{\rm TSN} + t^{\rm tran}_{\rm TSN} + t^{\rm prop}_{\rm TSN} \tag{2}$$

where $t^{\rm TSN}_{\rm queue}$ represents the queuing delay at the TSN bridge which is assumed to be zero by utilizing a no-wait packet scheduling scheme [11], $t^{\rm proc}_{\rm TSN}$ represents the processing delay at the TSN bridge, $t^{\rm tran}_{\rm TSN}$ denotes the packet transmission delay at the TSN bridge, which is determined by the packet size $P$ (in bytes) and the wired bandwidth $b$, and $t^{\rm prop}_{\rm TSN}$ is the propagation delay required for the TS packet to transmit from the TSN bridge to the 5GS bridge.

The last term, $t_{\rm 5GS}$, in (1) represents the 5GS bridge delay and is expressed as:

$$t_{\rm 5GS} = t_{\rm NW-TT} + t^{\rm prop}_{\rm UPF-AP} + t^{\rm proc}_{\rm AP} + t_{\rm AP-UE} + t_{\rm DS-TT} \tag{3}$$

where $t_{\rm NW-TT}$ and $t_{\rm DS-TT}$ represent the residence times on the network side and the VUE side, respectively [2], $t^{\rm prop}_{\rm UPF-AP}$ denotes the propagation delay from the UPF to the AP, $t^{\rm proc}_{\rm AP}$ refers to the processing delay at the AP, $t_{\rm AP-UE}$ denotes the packet delivery time over the wireless channel from the AP to the VUE, with a zero-retransmission scheme adopted, but with the flexibility to incorporate a reasonable retransmission mechanism if required. Therefore, in the context of infrastructure deployment with specific hardware equipment and a no-wait queuing scheme, the only uncertain term in (3) is $t_{\rm AP-UE}$, i.e., the transmission latency between AP and the UE. This uncertainty arises from the randomness of the wireless channel and the effects of blockages, which will be addressed in detail in the signal model presented in the next section.

Furthermore, $t^{\rm s}_{\rm st}$ and $t^{\rm prop}_{\rm TSN}$ in (2), as well as $t^{\rm prop}_{\rm UPF-AP}$ in (3), are negligible due to the extremely short-range inter-node wireline transmission [2]. Therefore, the following delay condition must be satisfied for effective resource management to ensure deterministic packet delivery over the wireless link:

$$\begin{aligned} t_{\rm AP-UE} \leq (1-\alpha)\tau_{\rm th} - t^{\rm proc}_{\rm TSN} - t^{\rm tran}_{\rm TSN} \\ - t_{\rm NW-TT} - t^{\rm proc}_{\rm AP} - t_{\rm DS-TT} = \hat{\tau}_{\rm th}. \end{aligned} \tag{4}$$

[1]The synchronization procedure follows the method outlined in [2], which is beyond the scope of this letter.

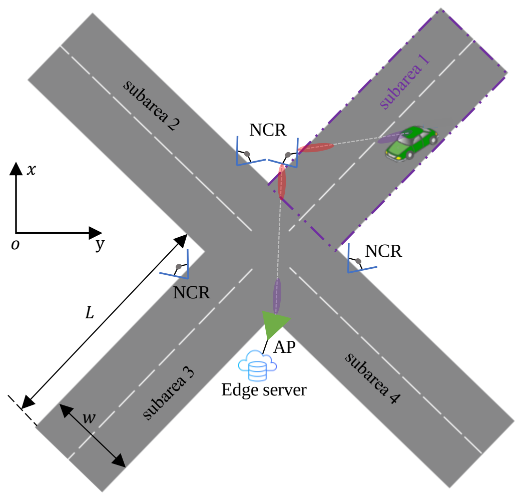


Fig. 2: NCR-aided TS packet delivery in an intersection vehicular scenario: the safety-related information cached at the edge server is scheduled to be sent to the end VUE via the 5G-TSN networks.

## III. Signal Model

Consider the integrated 5G-TSN architecture deployed in an intersection vehicular scenario, as illustrated in Fig. 2, to deliver the collected safety-critical transportation information from the edge server to the VUE. The AP is located at coordinates $[x_0, y_0]$, and is equipped with a Uniform Linear Array (ULA) of $N_\mathrm{a}$ antenna elements at a height of $h_0$. To compensate for severe path loss and mitigate the blockage effects of the Direct Link (DL) between the AP and VUE, four NCRs are deployed at the corners of each subarea, each with a height of $h_\mathrm{r}$. Here, we focus on one of these road segments, namely subarea 1 (as illustrated in Fig. 2), to evaluate the performance of TS packet delivery to the VUE. The other three segments have similar properties and are omitted for brevity. The VUE, equipped with a ULA of $N_\mathrm{v}$ antenna elements, is randomly distributed in this subarea and follows a Poisson point process [12], with an antenna height of $h_\mathrm{v}$. Furthermore, each NCR is equipped with two antenna panels, each with a ULA consisting of $N_\mathrm{r} = N_\mathrm{a}/2$ antenna elements [8]. This road segment is assumed to have two lanes, with a length $L$ and a width $w$.

### A. Signal Model

Assume the transmitted symbol is complex normal distributed as $s \sim \mathcal{CN}(0, p_\mathrm{s})$ where $p_\mathrm{s}$ denotes the transmit power at AP. The received signal at the VUE through a block-faded DL channel $\mathbf{H}_\mathrm{dl} \in \mathbb{C}^{N_\mathrm{v}\times N_\mathrm{a}}$ can be written as

$$y_\mathrm{dl} = \mathbf{w}_\mathrm{v}^H \mathbf{H}_\mathrm{dl}\mathbf{f}_\mathrm{a} s + \mathbf{w}_\mathrm{v}^H \mathbf{n}_\mathrm{dl} \tag{5}$$

where $\mathbf{f}_\mathrm{a} \in \mathbb{C}^{N_\mathrm{a}\times 1}$ and $\mathbf{w}_\mathrm{v} \in \mathbb{C}^{N_\mathrm{v}\times 1}$ denote the beamforming precoder and combiner at AP and VUE, respectively, and $\mathbf{n}_\mathrm{dl} \in \mathbb{C}^{N_\mathrm{v}\times 1} \sim \mathcal{CN}(\mathbf{0}, \sigma_\mathrm{n}^2 \mathbf{I}_{N_\mathrm{v}})$ is the noise vector with $\sigma_\mathrm{n}^2$ representing the noise power.

In complex urban vehicular networks, DL communications operating in mmWave/THz bands are prone to be blocked by surrounding objects. Here, we represent DL communications in a LoS propagation condition with a probability that follows the 3GPP-defined model [13]:

$$Pr_\mathrm{LoS} = \begin{cases} 1, & \text{if } d_\mathrm{2D} \le 18 \text{ m} \\ \frac{18}{d_\mathrm{2D}} + \exp\left(-\frac{d_\mathrm{2D}}{63}\right)\left(1 - \frac{18}{d_\mathrm{2D}}\right), & \text{if } d_\mathrm{2D} > 18 \text{ m} \end{cases} \tag{6}$$

where $d_\mathrm{2D}$ denotes the two-dimensional (2D) distance in $x \times y$ plane between the AP and VUE. Then the random LoS event of the direct AP-VUE link can be modelled using Bernoulli distribution with probability $Pr_\mathrm{LoS}$. Alternatively, the knife-edge theory can be used to derive the effective height of the first Fresnel ellipsoid at the blocker position to further determine if the direct link is in LoS or Non-LoS for the given blockers [12], which is out of the scope of this letter.

When the DL channel becomes too weak due to large distances or blockages, the AP schedules the relaying link through the NCR to enhance the E2E link quality. Then the received signal at the NCR can be expressed as

$$x_\mathrm{ncr} = \mathbf{w}_\mathrm{r}^H \mathbf{H}_\mathrm{ar}\mathbf{f}_\mathrm{a} s_1 + \mathbf{w}_\mathrm{r}^H \mathbf{n}_\mathrm{br} = \varrho s_1 + \tilde{n}_\mathrm{br} \tag{7}$$

where $\mathbf{H}_\mathrm{ar} \in \mathbb{C}^{N_\mathrm{r}\times N_\mathrm{a}}$ denotes the block-fading channel matrix between the AP and NCR, $\mathbf{w}_\mathrm{r} \in \mathbb{C}^{N_\mathrm{r}\times 1}$ is the beamforming combiner at the NCR, $s_1$ is the same transmit symbol as in (5) but with a transmit power $\tilde{p}_\mathrm{s}$, i.e., $s_1 \sim \mathcal{CN}(0, \tilde{p}_\mathrm{s})$, $\mathbf{n}_\mathrm{br} \in \mathbb{C}^{N_\mathrm{r}\times 1} \sim \mathcal{CN}(\mathbf{0}, \sigma_1^2 \mathbf{I}_{N_\mathrm{r}})$ is the noise vector with each entry having zero mean and variance $\sigma_1^2$. The second equality in (7) holds due to the stable link conditions between the AP and NCR, resulting from their fixed deployment positions in practice.

With an amplification factor $g$ applied to the received signal $x_\mathrm{ncr}$ at the NCR, the received signal at the VUE can be expressed as:

$$\begin{aligned} y_\mathrm{ncr} &= \mathbf{w}_\mathrm{v}^H \mathbf{H}_\mathrm{rv}\mathbf{f}_\mathrm{r} x_\mathrm{ncr} + \mathbf{w}_\mathrm{v}^H \mathbf{n}_\mathrm{rv} \\ &= \underbrace{g\varrho \mathbf{w}_\mathrm{v}^H \mathbf{H}_\mathrm{rv}\mathbf{f}_\mathrm{r} s_1}_{\text{Signal}} + \underbrace{g\mathbf{w}_\mathrm{v}^H \mathbf{H}_\mathrm{rv}\mathbf{f}_\mathrm{r}\tilde{n}_\mathrm{br} + \mathbf{w}_\mathrm{v}^H \mathbf{n}_\mathrm{rv}}_{\text{Noise}} \end{aligned} \tag{8}$$

where $\mathbf{H}_\mathrm{rv} \in \mathbb{C}^{N_\mathrm{v}\times N_\mathrm{r}}$ denotes the block-fading channel matrix between the NCR and VUE, $\mathbf{f}_\mathrm{r} \in \mathbb{C}^{N_\mathrm{r}\times 1}$ and $\mathbf{w}_\mathrm{v} \in \mathbb{C}^{N_\mathrm{v}\times 1}$ are the beamforming precoder and combiner at the NCR and VUE, respectively, $\mathbf{n}_\mathrm{rv} \in \mathbb{C}^{N_\mathrm{v}\times 1} \sim \mathcal{CN}(\mathbf{0}, \sigma_2^2 \mathbf{I}_{N_\mathrm{v}})$ represents the Gaussian noise vector, and the amplification factor is given as $g = \sqrt{\frac{p_\mathrm{r}}{\tilde{p}_\mathrm{s}|h_\mathrm{ar}|^2 + \sigma_1^2}}$ with $p_\mathrm{r}$ being the transmit power at the NCR, and $|h_\mathrm{ar}|^2$ representing the channel gain for the block-fading channel between AP and NCR. Noted that we set $p_\mathrm{s} = p_\mathrm{r} + \tilde{p}_\mathrm{s}$ for a fair comparison with the DL communications, which will be detailed addressed in the simulations.

Assuming the channel matrices (i.e., $\mathbf{H}_\mathrm{j}, \mathrm{j} \in \{\mathrm{dl}, \mathrm{ar}, \mathrm{rv}\}$) are accurately estimated[2], the corresponding precoder and combiner can be derived from the Singular Value Decomposition (SVD) of the channel matrix $\mathbf{H}_\mathrm{j}$. Consequently, the received Signal-to-Noise Ratio (SNR) at the VUE[3], for either

[2] The channel estimation approaches are detailed, for example in [14], [15], which is beyond the scope of this work.

[3] We focus on exploring the TS packet delivery scheme to the target VUE via the integrated 5G-TSN architecture. However, interference can be flexibly incorporated in the denominator for multi-VUE multi-flow scenarios without affecting the overall framework.

the DL or NCR-aided relaying link, are given by:

$$\gamma_{\rm dl} = \frac{p_{\rm s}|\mathbf{w}_{\rm v}^H \mathbf{H}_{\rm dl}\mathbf{f}_{\rm a}|^2}{\sigma_{\rm n}^2}, \tag{9}$$

$$\gamma_{\rm ncr} = \frac{\tilde{p}_{\rm s} g^2 \varrho^2 |\mathbf{w}_{\rm v}^H \mathbf{H}_{\rm rv}\mathbf{f}_{\rm r}|^2}{\sigma_1^2 g^2 |\mathbf{w}_{\rm v}^H \mathbf{H}_{\rm rv}\mathbf{f}_{\rm r}|^2 + \sigma_2^2}. \tag{10}$$

### *B. Short Packet Communications*

Since safety-related packets typically have limited size, the Shannon capacity assumption with infinite blocklength becomes inaccurate for calculating the achievable data rate due to the comparable size of the payload and control signaling [16]. This discrepancy further impacts the packet transmission delay, as well as the packet delivery success ratio. To address this, we consider a short packet transmission scheme based on the results in [16]. Given a decoding error probability of $\epsilon$ at the VUE and a blocklength $U$, the achievable transmission rate can be approximated as:

$$R \approx B\left[\log_2(1+\gamma_{\rm i}) - \sqrt{\frac{V}{U}}Q^{-1}(\epsilon)\right] \tag{11}$$

where $B$ is the allocated bandwidth, $\gamma_{\rm i}, {\rm i} \in \{\rm dl, ncr\}$ are defined in (9)-(10), $V = 1-(1+\gamma_{\rm i})^{-2}$ represents the channel dispersion, and $Q^{-1}(\cdot)$ denotes the inverse of the Gaussian $Q$-function $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt$.

To meet the latency requirement stated in (4), the minimum bit rate must be guaranteed, i.e., $R \geq R_{\rm min}$ where $R_{\rm min} = \frac{8P}{\hat{\tau}_{\rm th}}$ and $P$ denotes the packet size in bytes. Otherwise, the TS packet delivery target is considered a failure. A detailed performance evaluation will be presented in the following section.

## IV. Simulation Results

Given a critical latency threshold of $\tau_{\rm th} = 1$ ms in the integrated 5G-TSN vehicular networks depicted in Fig. 2, we will compare the success ratio of TS packet delivery via the DL (with and without the blockage) and the NCR aided packet forwarding scheme. And we define the average success ratio as:

$$Pr_{\rm success} = \frac{\sum_{z=1}^{Z} \mathbb{1}_{R \geq R_{\rm min}}}{Z} \times 100\% \tag{12}$$

where $Z$ represents the number of Monte Carlo iterations for random VUE positions, $\mathbb{1}_{R \geq R_{\rm min}}$ is the indicator function which equals to 1 if the condition $R \geq R_{\rm min}$ is met and 0, otherwise. In particular, we set $L = 200\,$m$, w = 6\,$m$, N_{\rm a} = 32, N_{\rm v} = 16, Z = 10^4, \sigma_1^2 = \sigma_2^2 = \sigma_{\rm n}^2 = -85\,$dBm$, t_{\rm NW-TT} = t_{\rm DS-TT} = 50\,\mu$s [17], $t_{\rm TSN}^{\rm proc} = 1.5\,\mu$s [7], $t_{\rm AP}^{\rm proc} = 107\,\mu$s [18], $\epsilon = 10^{-4}$. Note that an additional processing delay is introduced at the NCR for the NCR-aided link, and we assume the delay to be equal to half of that at the AP (i.e., 0.5 $t_{\rm AP}^{\rm proc}$). Furthermore, we set equal power allocation for the DL and NCR-aided links, i.e., $p_{\rm s} = \tilde{p}_{\rm s} + p_{\rm r}$, for a fair comparison, where the allocation of $\tilde{p}_{\rm s}$ and $p_{\rm r}$ is proportional to the corresponding link path loss.

Under limited resources, e.g., $p_{\rm s} = 5$ dBm, $B = 5$ MHz, we evaluate the success ratio of TS packet delivery with and without the NCR link, as shown in Fig. 3(a). Compared to the

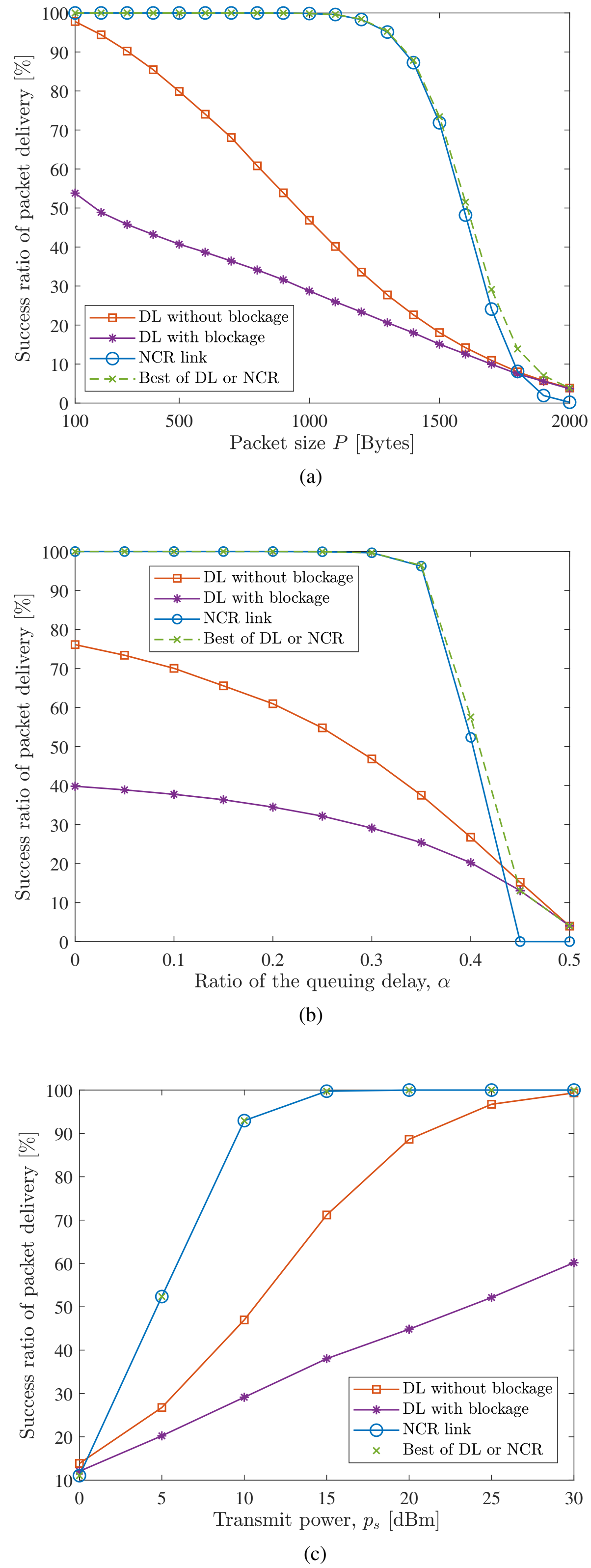


Fig. 3: Success ratio evaluation of the TS packet delivery under latency budget $\tau_{\rm th} = 1$ ms, given by: (a) $p_{\rm s} = 5$ dBm, $B = 5$ MHz, $\alpha = 0.2$; (b) $p_{\rm s} = 5$ dBm, $B = 5$ MHz, $P = 800$ bytes; (c) $\alpha = 0.4$, $B = 5$ MHz, $P = 800$ bytes.

ideal link condition without any blockage, the success ratio of TS packet delivery via the DL with the potential blockage (denoted as "DL with blockage") reaches only approximately 54% for a small packet size of 100 bytes. As the packet size increases, the success ratio of the DL (without or with potential blockage) experiences a significant decrease. However, the NCR-aided link can still guarantee a 100% success ratio for packet sizes up to 1100 bytes, even under this limited resources and stringent latency constraints.

A larger queuing delay at the edge server results in a critically reduced remaining latency budget for packet delivery via the wireless link between the AP and VUE. Consequently, the success ratio for the NCR-aided propagation link experiences a significant decrease when $\alpha \geq 0.35$ and completely loses its advantage when $\alpha \geq 0.45$, as shown in Fig. 3(b). This is because the additional processing delay introduced at the NCR makes it more challenging to guarantee link success when the queuing delay is substantial. However, the NCR-aided link maintains a 100% success ratio when $\alpha \leq 0.3$, achieving an improvement of approximately 24% in the success ratio compared to the DL without blockage, even when $\alpha = 0$.

Under a relevant large queuing delay ratio $\alpha = 0.4$ and a packet size of $P = 800$ bytes, the success ratio is evaluated by varying the transmit power in Fig. 3(c). A 100% success rate for packet delivery is guaranteed for $p_{\mathrm{s}} \geq 15$ dBm with the aid of the NCR. However, achieving the same 100% success ratio for DL without any blockage requires double the transmit power. The situation worsens significantly when considering the potential blockage effect (DL with blockage), where only an approximate 60% success ratio is achieved, even with $p_{\mathrm{s}} = 30$ dBm.

It can be concluded from Fig. 3 that the success ratio is affected by several factors, including packet size, queuing delay at the edge server for scheduling, and transmit power. Therefore, an efficient resource scheduling optimization is needed to guarantee the deterministic delivery of TS packets.

## V. Conclusion and Discussion

In this letter, we explore TS packet delivery over both wired and wireless links within the integrated 5G-TSN network architecture for urban vehicular networks. Specifically, we formulate a latency model for packet transmission from the edge server to the end VUE and demonstrate the effectiveness of the NCR in mitigating blockages to improve the success ratio of TS packet delivery. Simulation results show that the success ratio is affected by multiple factors, including packet size, the queuing delay ratio at the edge server, and transmit power. This calls for efficient resource management schemes to ensure deterministic TS packet delivery. In addition to optimizing the data rate or latency, an alternative and intriguing optimization objective for multiple VUEs could be minimizing the overall resource cost in terms of power and bandwidth, subject to performance requirements and resource constraints.

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