Age of Information and Transmission Cost Trade-Off in NR-V2X SL Perception Messages

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***Abstract*—Connected automated vehicles are key components of Intelligent Transport Systems, acting as information sources that share their onboard sensor data with other road users. This paper introduces a novel queueing theory-based model to characterize a connected vehicle as a data source, determining the average number of objects perceived over time. This serves as a foundation for assessing how frequently the vehicle should broadcast update messages.**

To identify the most suitable update period, we formulate an optimization problem that minimizes an objective function accounting for both transmission and freshness costs. The transmission cost is quantified by the average data rate, while the freshness cost is evaluated using the average Peak Age of Information, an end-to-end metric that captures the timeliness of the received information. A closed-form solution is derived for this optimization problem under the Dynamic Scheduling scheme of the 5G New Radio Vehicle-to-Everything Side Link standard. Results indicate that the optimal update period depends on the velocity of the road occupants, their spatial rate, and the detection range of the connected vehicle, which is determined by its onboard equipment. Furthermore, when information timeliness is prioritized over transmission cost, it is shown that the optimal periodicity almost exclusively depends on the velocity of the objects along the road.

***Index Terms*—Connected Automated Vehicles, Cooperative Perception, NR-V2X, Age of Information, Vehicular Networks**

I. Introduction

In the domain of Intelligent Transport Systems, Connected Automated Vehicles (CAVs) play a crucial role in interacting with other road users and infrastructure. CAVs gather environmental information via onboard sensors and share it over the wireless channel through update messages. This data exchange enables advanced applications such as Cooperative Perception Services (CPSs), which aim to enhance road safety, sustainability, and efficiency.

The present study investigates the optimal frequency at which CAVs should broadcast updates about perceived objects, balancing two conflicting objectives: minimizing transmission cost and maximizing information freshness. These metrics are quantified using the average message generation rate and the average Peak Age of Information (PAoI) [1], respectively. Achieving this balance presents several challenges. Notably, the CAV must be accurately modeled as a traffic data source, and the vehicle's strategy for accessing the radio channel must be considered.

Several studies have explored the trade-off between transmission cost and information timeliness from a broad perspective. The authors of [2] investigate the interplay between stale information and the cost of updating it. In [3], an optimization framework is proposed that integrates energy consumption and information age for a source-monitor pair under varying update inter-generation times. Unlike these general approaches, this work focuses on a specific environment, namely the vehicular domain, and introduces a queueing theory-based model to statistically characterize the size of the update messages broadcast by CAVs.

Other relevant works include [4], which examines Vehicle-to-Infrastructure (V2I) communication, where CAVs share location data with Road Side Units (RSUs) and evaluates the impact of the Age of Information (AoI) on tracking accuracy, considering queueing delays at RSUs. Similarly, [5] minimizes the time-average cost in multi-node systems that transmit updates over unreliable wireless channels under AoI constraints. The authors of [6] address the AoI minimization problem in vehicular networks where cars communicate using 802.11p. They propose a rate adaptation algorithm that dynamically adjusts the vehicles' broadcast period to minimize the network-wide system age.

This study differs from previous investigations in several ways and puts forth the following novel contributions: (i) it develops a model of the CAV as a traffic source and leverages it to evaluate the size of update messages, which directly impacts transmission cost; (ii) it derives a closed-form expression for the average PAoI when CAVs communicate using the Dynamic Scheduling (DS) scheme of the 5G New Radio Vehicle-to-Everything Side Link (NR-V2X SL) standard; (iii) it incorporates the average PAoI into the objective function to be minimized; (iv) it analytically determines the optimal update periodicity that solves the minimization problem.

The analytical approach is particularly valuable in the vehicular context, as it reveals the influence of key parameters (such as vehicular densities and velocities, transmission reliability,

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and CAV detection range) on the optimal frequency of update messages.

The remainder of this paper is organized as follows. Section II introduces the model for characterizing CAVs as periodic traffic sources. Section III analytically derives the average PAoI of the DS scheme. Section IV formulates and solves the optimization problem. Section V presents numerical results for different road scenarios. Finally, Section VI summarizes the findings and draws the conclusions.

II. Road and CAV Model

This section puts forth a model of the CAV as a data traffic source, generating messages that inform nearby road occupants about the objects the CAV detects in the surroundings.

In the analysis, the road is approximated by a straight line and the CAV travels according to a uniform motion with velocity $v_{ego} > 0$. The CAV detection range is denoted by $D_R > 0$, that is, if the CAV is in position x, its viewing horizon covers the interval $[x - D_R, x + D_R]$. D_R depends on the CAV equipment, consisting of different sensors, such as RADARs, LiDARs, and cameras. We further assume that:

(i) an object is always perceived by the CAV as soon as it enters its viewing horizon;

(ii) the CAV broadcasts update messages every T_{up} seconds to advertise the objects it perceives. In turn, connected road users and RSUs leverage this information to improve/broaden their environmental perception.

Objects along the road belong to different classes, e.g., vehicles, bicycles, and pedestrians, and are positioned uniformly along the road. A simple example is reported in Fig. 1. Each class is described by its spatial density (in objects per km) and velocity (km/h), the latter being a positive or negative constant depending on whether the class objects move in the same or opposite direction as the CAV.

Let $\hat{\Lambda}$ denote the aggregate spatial rate and p_i , $i = 1, 2, \ldots, H+1$, the probability of occurrence of the i-th class objects, where for class $H+1$ we assume $v_{H+1} = v_{ego}$, that is, class $H+1$ objects have the same speed as the considered CAV. Then, the spatial rate of the objects in the i-th class is

$$\hat{\lambda}_i = p_i \hat{\Lambda}\,. \tag{1}$$

Note that objects with the same velocity as the CAV indefinitely remain in the CAV viewing horizon. Their number is denoted by N_{H+1} and follows the Poisson distribution with mean $\mathbb{E}[N_{H+1}] = 2D_R \cdot \hat{\lambda}_{H+1}$.

On the other hand, class i objects, $i \neq H+1$, enter the viewing horizon of the CAV according to a Poisson process with intensity

$$\lambda_i = |v_{ego} - v_i| \hat{\lambda}_i \tag{2}$$

and stay in it for a finite time equal to

$$d_i = \frac{2D_R}{|v_{ego} - v_i|}\,. \tag{3}$$

It follows that $N(t)$, the number of objects the CAV perceives, excluding those with its same velocity, coincides with the

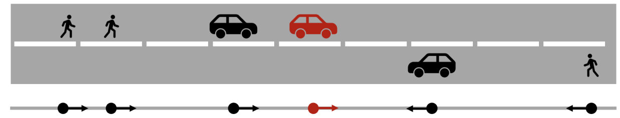


Fig. 1: Road model.

number of customers in an $M/D/\infty$ queue whose arrival rate is

$$\lambda = \sum_{i=1}^{H} \lambda_i \tag{4}$$

and the average service time

$$\mu = \sum_{i=1}^{H} \frac{\lambda_i}{\lambda} \cdot d_i \tag{5}$$

In steady state, the number of customers in an $M/D/\infty$ queue follows the Poisson distribution with mean

$$\mathbb{E}[N] = \lambda \cdot \mu = \lambda \cdot \sum_{i=1}^{H} \frac{\lambda_i}{\lambda} d_i = \sum_{i=1}^{H} \lambda_i d_i \tag{6}$$

which making use of (2) and (3) is equivalently written as

$$\mathbb{E}[N] = \sum_{i=1}^{H} |v_{ego} - v_i| \hat{\lambda}_i \cdot \frac{2D_R}{|v_{ego} - v_i|} = 2D_R \cdot \sum_{i=1}^{H} \hat{\lambda}_i\,. \tag{7}$$

Hence, the average number of objects in the CAV viewing horizon is

$$\begin{aligned} \mathbb{E}[N] + \mathbb{E}[N_{H+1}] &= 2D_R \cdot \sum_{i=1}^{H} \hat{\lambda}_i + 2D_R \cdot \hat{\lambda}_{H+1} = \\ &= 2D_R \cdot \sum_{i=1}^{H+1} \hat{\lambda}_i = 2D_R \cdot \hat{\Lambda}\,, \end{aligned} \tag{8}$$

which only depends on D_R, i.e., the CAV detection range, and $\hat{\Lambda}$, the aggregate spatial rate.

This result will be employed in Section IV, to evaluate the transmission cost that the CAV bears when transmitting variable-size messages with periodicity T_{up}.

III. Radio Access Strategy

When investigating information freshness, a crucial role is played by the radio communication technology the CAV adopts. This work focuses on the NR-V2X SL solution and the DS access strategy, adopting its average Peak Age of Information, $\mathbb{E}[\text{PAoI}]$, as the figure of merit that captures information freshness.

In the following, the NR-V2X SL and DS features relevant to the determination of $\mathbb{E}[\text{PAoI}]$ are reviewed, and $\mathbb{E}[\text{PAoI}]$ is then computed.

The NR-V2X SL physical layer employs Orthogonal Frequency Division Multiplexing (OFDM) on a frequency band made of contiguous resource blocks, further organized in subchannels. In the time domain, the reference unit is the time slot. The resource block and the time slot duration depend on ν, the OFDM numerology; namely, every resource block occupies $2^{\nu} \times 180$ KHz, and every time slot lasts for $2^{-\nu} \times 1$ ms, $\nu = 0, 1, 2$. In NR-V2X SL, the message to be sent over the air is encapsulated in a data unit called Transport Block (TB) and paired with some additional SL Control Information (SCI); the TB and the SCI are transmitted over one or more subchannels during one time slot.

Regarding the rules for selecting the radio resources, we center our attention on the DS scheme introduced in Release 16 of the NR-V2X SL specifications. DS is one of the two strategies envisioned to let vehicles gain access to the radio channel in a distributed manner, with no network supervision, especially suited to handle variable-size data traffic [7]. In the DS scheme, assuming no retransmissions are envisioned, the CAV that has a message ready for transmission at time t, randomly and uniformly selects the required subchannels in a time window that opens at $t + T_1$ and ends at T_2, $T_{2,min} \leq T_2 \leq PDB$, where T_1 is a processing time, $T_{2,min}$ is a value that depends on the OFDM subcarrier spacing, and PDB is the Packet Delay Budget, i.e., the maximum latency the message can bear [8]. In the following, T_1 is neglected, an assumption widely accepted in the literature [7], [9]. To determine $\mathbb{E}[\text{PAoI}]$, we assume that the sequence of time slots in the selection window W is a temporal continuum. Denoting by t_i the time at which the i-th message is generated by the CAV and by t_{tx_i} the time at which the message is transmitted, the following relation holds

$$t_{tx_i} = t_i + U \,, \tag{9}$$

where U is a uniformly distributed random variable in $[0, T_2]$. Assume the message is successfully received at time t_{rx_i}; as the processing and propagation delays are negligible in single-hop, short-range vehicular communications, t_{rx_i} is well approximated by

$$t_{rx_i} = t_{tx_i} + t_s = t_i + U + t_s \,. \tag{10}$$

where t_s denotes the slot time.

Let the random variable K be the number of consecutive message losses after the successful reception of the i-th message. Given the next correctly received message is the $i + k + 1$-th, the PAoI conditioned to $K = k$ losses is

$$\text{PAoI}_k = t_{rx_{i+k+1}} - t_i \,, \tag{11}$$

which making use of (10) becomes

$$\text{PAoI}_k = t_{i+k+1} + U + t_s - t_i \,. \tag{12}$$

The last expression is more aptly re-written as

$$\begin{aligned} \text{PAoI}_k &= (t_{i+k+1} - t_{i+k}) + (t_{i+k} - t_{i+k-1}) + \ldots \\ &\ldots + (t_{i+2} - t_{i+1}) + (t_{i+1} - t_i) + U + t_s = \\ &\simeq \sum_{j=i}^{i+k} X_j + U \,, \end{aligned} \tag{13}$$

where $X_j = t_{j+1} - t_j$ is the inter-generation time between the j-th and the $j + 1$-th messages, and t_s contribution has been neglected, as $t_s << X_j, \forall j$. Recalling that the inter-generation time is constant and equal to T_{up}, the average PAoI, $\mathbb{E}[\text{PAoI}]$, is obtained from (13) unconditioning with respect to k and U,

$$\mathbb{E}[\text{PAoI}] = (\mathbb{E}[K] + 1) \cdot T_{up} + \frac{T_2}{2} \,. \tag{14}$$

where $\mathbb{E}[K]$ denotes the average number of consecutive losses the message transmission incurs into. If messages are independently affected by losses and $P_{succ}(d_{t,r})$ gives the probability of successful message reception when the distance between the transmitting and the receiving CAVs is equal to $d_{t,r}$, then K follows the geometric distribution with parameter $P_{succ}(d_{t,r})$ and support $\{0, 1, 2, ...\}$. Accordingly,

$$\mathbb{E}[K] = \frac{1 - P_{succ}(d_{t,r})}{P_{succ}(d_{t,r})} \,. \tag{15}$$

Finally, replacing (15) in (14),

$$\mathbb{E}[\text{PAoI}] = \frac{T_{up}}{P_{succ}(d_{t,r})} + \frac{T_2}{2} \,. \tag{16}$$

Last expression evidences that $\mathbb{E}[\text{PAoI}]$ is heavily influenced by the non-ideal communication conditions, whose effects are captured by $P_{succ}(d_{t,r})$; furthermore, $\mathbb{E}[\text{PAoI}]$ lower bound is $T_{up} + T_2/2$, asymptotically achieved for $P_{succ}(d_{t,r}) \to 1$.

IV. Optimization Problem

To identify the optimal update periodicity, two different aspects should be considered: the cost of the update message transmission on the radio channel and the information freshness guaranteed to the messages. Based on these considerations, we introduce the cost function $C(T_{up})$, defined as

$$C(T_{up}) = (1 - \alpha) \cdot \frac{C_{tr}(T_{up})}{\beta_{tr}} + \alpha \cdot \frac{C_{fr}(T_{up})}{\beta_{fr}} \tag{17}$$

where $C_{tr}(T_{up})$ is the transmission cost, $C_{fr}(T_{up})$ is the freshness cost, α is a weighting factor, $\alpha \in [0, 1]$, and β_{tr}, β_{fr} are proper normalization factors, set equal to the maximum transmission and freshness cost, respectively.

In (17), $C_{tr}(T_{up})$ is set equal to the average rate at which the update messages are generated, in bit/s. Recalling that $\mathbb{E}[N + N_0]$ denotes the average number of objects the update message advertises (the ones inside the CAV viewing horizon), given the constant S_0 represents the message header, and l_{bits} the number of bits that conveys information about the single object, the average message size, $\mathbb{E}[S]$, is

$$\mathbb{E}[S] = S_0 + \mathbb{E}[N + N_0] \cdot l_{bits} \,, \tag{18}$$

where $\mathbb{E}[N + N_0]$ is given by (8), so that

$$C_{tr}(T_{up}) = \frac{\mathbb{E}[S]}{T_{up}} = \frac{S_0 + 2D_R \cdot \hat{\Lambda} \cdot l_{\text{bits}}}{T_{up}} \,. \tag{19}$$

The freshness cost $C_{fr}(T_{up})$ is set equal to the average PAoI, which quantifies the average message recency,

$$C_{fr}(T_{up}) = \mathbb{E}[\text{PAoI}] \tag{20}$$

and recalling (16) we write

$$C_{fr}(T_{up}) = \frac{T_{up}}{P_{succ}(d_{t,r})} + \frac{T_2}{2} \,. \tag{21}$$

Given $[T_{min}, T_{max}]$ is the range of T_{up} admitted values, S_{max} the maximum message size, and P_{min} the minimum tolerable $P_{succ}(d_{t,r})$ value, then the normalization factors in (17) become

$$\beta_{tr} = \frac{S_{max}}{T_{min}} \tag{22}$$

and

$$\beta_{fr} = \frac{T_{max}}{P_{min}} + \frac{T_2}{2}\,. \tag{23}$$

The optimization problem to solve is

$$\min_{T_{up}} \left\{ \frac{(1-\alpha)}{\beta_{tr}} \frac{S_0 + 2D_R\hat{\Lambda} l_b}{T_{\text{up}}} + \frac{\alpha}{\beta_{\text{fr}}} \left(\frac{T_{\text{up}}}{P_{succ}(d_{t,r})} + \frac{T_2}{2} \right) \right\}$$
$$\text{s.t.} \quad max\{T_{min}, T_2\} \le T_{up} < T_{max} \tag{24}$$

To identify its solution, that we term $T^{\star}_{up}$, we first solve the unbounded problem. To do so, we compute the first derivative of the cost function, $C'(T_{up})$, given by

$$C'(T_{up}) = -\frac{(1-\alpha)}{\beta_{tr}} \frac{S_0 + 2D_R\hat{\Lambda} l_b}{T_{up}^2} + \frac{\alpha}{\beta_{fr} P_{succ}(d_{t,r})}\,, \tag{25}$$

set it equal to zero and solve for T_{up}. Considering that $T_{up} \ge max\{T_{min}, T_2\} > 0$, the solution of the unbounded problem results

$$\tilde{T}_{up} = \sqrt{\frac{(1-\alpha)\cdot(S_0 + 2D_R\hat{\Lambda} l_b)\cdot P_{succ}(d_{t,r})\beta_{fr}}{\alpha\beta_{tr}}}\,. \tag{26}$$

As $C' < 0$ if $T_{up} < \tilde{T}_{up}$, and $C' > 0$ if $T_{up} > \tilde{T}_{up}$, the cost function is monotonically decreasing in $(0, \tilde{T}_{up})$ and monotonically increasing in $(\tilde{T}_{up}, +\infty)$. Hence, $\tilde{T}_{up}$ is the unique update time which guarantees the minimum cost. Recalling the bounds, the optimal update period for the problem in (24) is

$$T^{\star}_{up} = \\ = \begin{cases} max\{T_{min}, T_2\}, & \tilde{T}_{up} < max\{T_{min}, T_2\} \\ \tilde{T}_{up}, & max\{T_{min}, T_2\} \le \tilde{T}_{up} < T_{max} \\ T_{max}, & \tilde{T}_{up} \ge T_{max} \end{cases} \tag{27}$$

V. Numerical Results

This section analyzes the solution to the optimization problem in two illustrative road settings. The first scenario consists of a straight urban road, where objects (vehicles and pedestrians) move either in a concordant or discordant fashion compared to the CAV. The CAV velocity is $v_{ego} = 50$ km/h, the vehicles' velocity is ± 50 km/h, and the pedestrians' velocity is ± 3 km/h. The second setting is a straight suburban road, populated by trucks and other vehicles, again moving in the same or opposite direction as the CAV. Here, $v_{ego} = 100$ km/h, the vehicles' velocity is ± 100 km/h, and the trucks' velocity is ± 70 km/h. These assumptions map into the presence of $H + 1 = 4$ classes of objects, the fourth class including those objects that have the same velocity as the CAV. Table I reports the absolute and relative speeds along with the service times for the different classes, i.e., the times the objects remain in the CAV viewing horizon.

To set S_0, the message header size, and l_{bits}, the number of bits required for the transmission of the information about one object, we refer to the format of the Cooperative Perception Messages (CPMs) introduced in [10]. Accordingly, we choose $S_0 = 30$ bytes, which corresponds to the size of the CPM overhead; moreover, we fix $l_b = 57$ bytes, which reflects the size of the CPM field providing the object informative elements. To assign a reasonable value to the maximum CPM size, S_{max}, we exploit the findings in [11] and select $S_{max} = 750$ bytes, the maximum observed message size. We select T_{min}, the lowest T_{up} periodicity, coincident with the lowest CPM inter-generation time, which is equal to 100 ms [10]; furthermore, $T_{max} = d_1$, to guarantee that even the fastest objects (i.e., the ones that remain in the CAV viewing horizon for the shortest time and correspond to the customers with the shortest service time) are included in the update messages.

As regards the radio access mechanism, the DS selection window duration, T_2, is $T_2 = 100$ ms. This value guarantees the ordered packet reception even in the limiting case in which $T_{up} = T_{min} = 100$ ms. For safety applications like advanced driving and extended sensors, the success probability, $P_{succ}(d_{t,r})$, has to take on values in $[0.9, 0.99999]$ [8]. Unless otherwise stated, we set $P_{succ}(d_{t,r}) = 0.9$, corresponding to the maximum tolerated distance between the CAV that transmits update messages and the receiving vehicles.

Fig. 2 displays the optimal $T^{\star}_{up}$ values in the analyzed driving settings, for different values of α and $\hat{\Lambda}$. The red surfaces refer to a detection range $D_R = 50$ m (defined by ETSI as the lowest range for medium-range RADARs [12]), the green ones to $D_R = 250$ m (defined by ETSI as the highest range for long-range RADARs [12]). Note that, when the freshness cost is weighted more than the transmission cost, the optimal update period is nearly independent on the spatial distribution of the objects populating the road, $\hat{\Lambda}$, as well as on the D_R value.

When $\alpha = 0.8$, Table II further compares the optimal periodicity to deliver update messages, $T^{\star}_{up}$, for $P_{succ}(d_{t,r}) = 0.9$ and 0.99999, revealing that there are very small changes. Equivalently stated, $T^{\star}_{up}$, the solution to the optimization problem, is nearly independent of the distance $d_{t,r}$ between the CAV and the vehicle(s) receiving the update messages.

VI. Conclusions

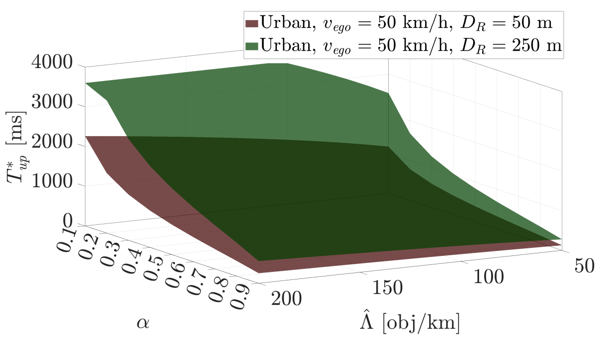
This paper introduced a novel queueing theory approach to model the CAV as a traffic source, based on the objects the vehicle perceives over time and advertises through periodic update messages. Moreover, an objective function was defined, that accounts for transmission and freshness costs; the optimal message periodicity that minimizes this function was determined when the access strategy to the shared radio channel is the DS scheme of the 5G NR-V2X SL standard. The results revealed how the optimal update period should be selected depending on the scenario – urban or suburban,

TABLE I: Classes participating in the queue for the considered driving scenarios.

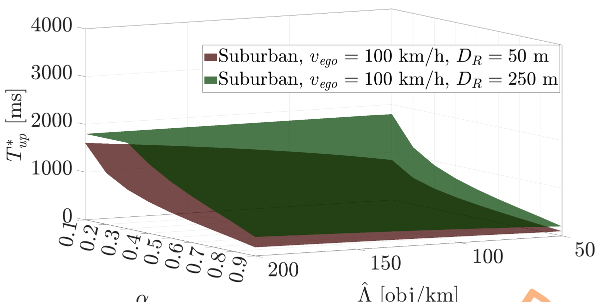
	Urban scenario, $v_{ego} = 50$ km/h			**Suburban scenario,** $v_{ego} = 100$ km/h		
	class 1	**class 2**	**class 3**	**class 1**	**class 2**	**class 3**
v_i [km/h]	-50	-3	3	-100	-70	70
$\|v_{ego} - v_i\|$ [km/h]	100	53	47	200	170	30
d_i [s]	3.6	6.79	7.66	1.8	2.12	12

TABLE II: Optimal update period and success probability, $\alpha = 0.8$.

	$T^{\star}_{up}$ [ms]					
	Urban scenario, $v_{ego} = 50$ Km/h			**Suburban scenario,** $v_{ego} = 100$ Km/h		
	$\hat{\Lambda} = 50$ obj/km	$\hat{\Lambda}$ = 100 obj/km	$\hat{\Lambda} = 200$ obj/km	$\hat{\Lambda} = 50$ obj/km	$\hat{\Lambda} = 100$ obj/km	$\hat{\Lambda} = 200$ obj/km
$P_{succ}(d_{t,r}) = 0.9$	196	270	377	139	192	268
$P_{succ}(d_{t,r}) = 0.99999$	206	285	397	147	203	283



(a) Urban scenario, $v_{ego} = 50$ km/h.



(b) Suburban scenario, $v_{ego} = 100$ km/h.

Fig. 2: $T^{\star}_{up}$ in different driving scenarios, for different α, $\hat{\Lambda}$, and D_R values.

the detection range of the CAV equipment, and the density of the objects on the road. When more emphasis is given to the information recency, it was further shown that the optimal periodicity almost exclusively depends on the driving setting, i.e., the velocities of the objects populating the road, and is modestly affected by the probability of successfully receiving the packets, given the latter is confined to the $[0.9, 0.99999]$ interval.

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