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Link QoS analysis of 5G-enabled V2V network based on vehicular cloud

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Dear editor,

The fifth generation (5G) communication technologies, especially for millimeter wave (mmWave) technology, have a huge application for satisfying different service requirements in vehicular networks, e.g., the vehicle-to-vehicle (V2V) network. In the mmWave V2V network, a reliable link quality-of-service (QoS) is particularly important because it brings reliable message transmissions for various service requirements. For a vehicular network, low data collision and low delay are most important for safe data transmission, because they could ensure a higher QoS, especially in terms of real-time and reliable data link communication. Ref. [1] concentrated on the performance analysis of 5G software-defined vehicular networks, in which vehicles are connected by a multihop relay method. Refs. [2, 3] presented mmWave communication technology as a type of 5G mobile communication technology adopted for V2V multihop wireless communications among vehicles.

We aim at modeling the link QoS indicator (LQSI) to evaluate the link QoS in the 5G-enabled V2V network. The LQSI model primarily considers the transmission success probability and transmission delay. Further, we investigate the relationship between network parameters and link QoS. Based on the LQSI, the vehicle attempting transmission could select an optimal link to transmit service messages. For link selection, vehicular cloud (VC) technology is introduced to complete the complicated calculation.

System model. We consider a unidirectional three-lane highway in an urban area (Appendix A). The vehicle v_a establishes mmWave multihop communication links using 60-GHz frequency to communicate with the vehicle v_b under the non-line-of-sight (NLOS) scenario without considering interference. We assume many potential communication links between the vehicles v_a and v_b, which constitute a link set C, $C \supseteq c_i$, $i \in \{1, 2, \dots, k, \dots, x\}$, where x is decided by the practical V2V network. Using one link c_k in link set C as an example, other links have a similar analysis method. The link c_k that is constituted by $n-2$ relay vehicles is mapped to the one-directional V2V communication link (Appendix A). The vehicle v_a is placed at the origin and labeled 1 in a line, and other vehicles are placed in turn and labeled as $2, \dots, n$. The distance between the vehicle v_a and the vehicle v_b is L. We assume that the vehicles have same maximum mmWave transmission range, R_T, $R_T \ll L$.

Let l_i, $i = \{1, 2, \dots, n-1\}$ be the adjacent distance between vehicle i and vehicle $i+1$. Thus, $\sum_{i=1}^{n-1} l_i \doteq L$. The connectivity of link c_k depends on the interval l_i. If $l_i \leqslant R_T$, this link is available. The vehicle $i-1$ and the vehicle $i+1$ cannot simultaneously communicate to the vehicle i because the physical link connectivity may suffer from the interference generated by other vehicles.

Because the vehicle arrival process obeys a Pois-

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son process in a sparse area [4], the probability cumulative distributive of n vehicles in link c_k can be given by

$$P_{c_k}(n,L)=\frac{(\rho_l L)^n \mathrm{e}^{-\rho_l L}}{n!}, \tag{1}$$

where ρ_l is the spatial density of vehicles, defined as the number of vehicles per meter. In addition, the joint distribution of distance l_i between adjacent vehicles can be defined as a uniform distribution on the road with time.

LQSI definition. Inspired by [5], we define an LQSI model to analyze link c_k with QoS. Hence, the LQSI is defined as

$$I_{c_k}=\alpha P_{c_k}+\beta D_{c_k},\ \{\alpha+\beta=1 \mid \alpha,\beta\in[0,1]\}, \tag{2}$$

where P_{c_k} and D_{c_k} represent the connectivity probability and the transmission delay of link c_k, respectively. The weight factors α and β represent different service requirements. For calculation convenience, D_{c_k} is given by $D_{c_k}=1-\frac{T_{c_k}}{T_{\text{toler}}}$, $D_{c_k}\in(-\infty,1)$. Therefore, Eq. (2) can be rewritten by

$$I_{c_k}=\alpha P_{c_k}+\beta\left(1-\frac{T_{c_k}}{T_{\text{toler}}}\right), \tag{3}$$

where T_{c_k} is the transmission delay of the communication link, T_{toler} is the maximum delay of the transmission link that can be tolerated; Further, if $D_{c_k}<0$, it means that the transmission delay of the link c_k is larger than the maximum delay tolerable time T_{toler}.

Connectivity probability of link c_k. In the link c_k, the segment between two adjacent vehicles has identical statistics. The connectivity problem with the one-dimensional line segment can be transformed into a circle analysis problem and edge effects are ignored. Vehicles in the link c_k are separated evenly and located on the circle.

Let a be the ratio of the mmWave transmission range R_T and the communication distance L between source vehicle v_a and destination vehicle v_b. Hence, $a\triangleq\frac{R_T}{L}$. To ensure the connectivity of a circle with n vehicles in the link c_k, every link segment or arc l_i, $i=\{1,2,\ldots,n-1\}$ in the circle must be connected. The probability that the i-th arc l_i has a gap in the whole circle arc is given as [6]

$$g_n(i)=\begin{cases}(1-ia)^{n-2}, & \text{if}\quad i\leqslant\lfloor a^{-1}\rfloor,\\ 0, & \text{if}\quad i>\lfloor a^{-1}\rfloor,\end{cases} \tag{4}$$

where $\lfloor\cdot\rfloor$ is the round down function.

From (4), the probability that i disconnected gaps exist in the link c_k is

$$g_n(i)=\begin{cases}\binom{n-1}{i}\sum\limits_{j=0}^{\lfloor a^{-1}\rfloor}\binom{n-1-i}{j}(-1)^j\\ \cdot(1-(i+j)a)^{n-2}, & \text{if } i\leqslant\lfloor a^{-1}\rfloor,\\ 0, & \text{if } i>\lfloor a^{-1}\rfloor,\end{cases} \tag{5}$$

where $i=1,2,\ldots,n-1$.

When every link l_i is connected, the whole link c_k is fully connected. Therefore, we can derive the transmission successful probability of the link c_k by (4) and (5) as

$$P_{c_k}=\sum_{j=0}^{\lfloor a^{-1}\rfloor}\binom{n-1}{j}(-1)^j(1-ja)^{n-2}. \tag{6}$$

Based on (1), the transmission successful probability of the link c_k in the steady state is obtained by

$$P_{c_k}=\mathrm{e}^{-\lambda_l L}\sum_{n=2}^{\infty}\sum_{j=0}^{\lfloor a^{-1}\rfloor}\binom{n-1}{j}(-1)^j \cdot(1-ja)^{n-2}\frac{(\lambda_l L)^{n-2}}{(n-2)!}, \tag{7}$$

where the probability (7) can be interpreted as the percentage of time that the V2V network is fully connected.

Delay of link c_k. The transmission delay of the multihop link c_k, T_{c_k}, can be written as

$$T_{c_k}=\sum_{i=1}^{n}T_{\text{one-hop}}+(n-1)T_t, \tag{8}$$

where $T_{\text{one-hop}}$ is the average transmission delay between adjacent vehicles, and T_t represents the message processing time at each relay vehicle.

The average transmission delay of one-hop link in link c_k is derived by [1]

$$T_{\text{one-hop}}=\frac{t_{\text{slot}}}{P_{\text{one-hop}}}, \tag{9}$$

where t_{slot} is the channel transmission slot, and $P_{\text{one-hop}}$ is the successful transmission probability of a one-hop link in link c_k.

In this study, the large-scale fading $S(l_i)$ for a one-hop link l_i can be written as

$$S(l_i)=\mathrm{PL}(l_0)+10\zeta\log_{10}\gamma-\varsigma, \tag{10}$$

where $\mathrm{PL}(l_0)$ is the free-space path loss at reference distance l_0; γ is the distance ratio, denoted as $\gamma=l_j/l_0$, which is replaced by $\lfloor D/R_T\rfloor$; ζ is the path loss exponent; ς is the loss coefficient, $\varsigma\sim(0,\sigma^2)$; σ is the standard deviation.

The default statistical parameters in (10) are configured as follows [7]: $\mathrm{PL}(d_0) = 68$ dB, $\varsigma = 2.17$ and $\sigma = 0.88$. Therefore, Eq. (10) is rewritten as

$$S(l_i) = 68 + 21.7 \log_{10} \gamma - \varsigma. \tag{11}$$

For adjacent vehicles, the transmission successful probability of a one-hop link, $P_{\text{one-hop}}$, is derived by

$$\begin{aligned} &P_{\text{one-hop}} \\ &\quad = P(P_{\text{tr}}(\text{dB}) - N_0 B_{\text{mW}} - S \geqslant \text{th}(\text{dB})), \end{aligned} \tag{12}$$

where P_{tr} is the vehicle transmission power, N_0 is the noise power spectrum density, B_{mW} is the mmWave bandwidth, and th is the signal-to-noise ratio (SNR) at the receiver vehicle. Substituting (11) into (12), the transmission successful probability in the one-hop transmission is expressed by

$$P_{\text{one-hop}} = P(\varsigma \geqslant b(\gamma)), \tag{13}$$

where $b(\gamma) = P_{\text{tr}}(\text{dB}) - N_0 B_{\text{mW}} - \text{th}(\text{dB}) - 68 - 21.7 \log_{10} \gamma$, which is the transmission successful probability of the one-hop transmission in one slot. Further, Eq. (13) can be calculated as

$$P_{\text{one-hop}} = \frac{1}{2} \left(1 + \text{erf} \left(\frac{b(\gamma)}{\sqrt{2}\sigma} \right) \right), \tag{14}$$

where $\text{erf}(\cdot)$ is the error function.

Substituting (14) into (9), the average transmission delay of the one-hop link with c_k is rewritten by

$$T_{\text{one-hop}} = \frac{2t_{\text{slot}}}{\hbar(\gamma)}, \tag{15}$$

where $\hbar(\gamma) = 1 + \text{erf}(\frac{b(\gamma)}{\sqrt{2}\sigma})$.

The transmission delay of link c_k, denoted as T_{c_k}, in (8) can be simplified as

$$T_{c_k} = n \cdot T_{\text{one-hop}} + (n-1) \cdot T_t. \tag{16}$$

Submitting (15) into (16), the total transmission delay of link c_k is derived by

$$T_{c_k} = n \cdot \frac{2t_{\text{slot}}}{\hbar(r)} + (n-1) \cdot T_t. \tag{17}$$

Thus, we have derived the connectivity probability P_{c_k} and multihop link transmission delay T_{c_k} for link c_k; substituting (6) and (17) into (3), the LQSI I_{c_k} is expressed by

$$\begin{aligned} I^*_{c_k} &= \alpha P_{c_k} + \beta \frac{T_{c_k}}{T_{\text{toler}}} \\ &= \alpha \left(\sum_{j=0}^{\lfloor a^{-1} \rfloor} \binom{n-1}{j} (-1)^j (1-ja)^{n-2} \right) \\ &\quad + \beta \left(1 - \frac{n \cdot \frac{2t_{\text{slot}}}{1+\text{erf}(\frac{b(r)}{\sqrt{2}\sigma})} + (n-1) \cdot T_t}{T_{\text{toler}}} \right). \end{aligned} \tag{18}$$

Optimal link selection in set C. From the analysis of the link c_k based on the LQSI model, other links in set C have a similar analysis. Therefore, an optimal link in set C can be denoted as

$$c^* = \text{argmax} \ \{I^*_{c_i}\}, \ i \in \{1, 2, \dots, k, \dots, x\}. \tag{19}$$

For link selection (Appendix B), VC computing (VCC) technology is adopted to provide computational service for vehicles at a low cost [8]. VC can be deployed to support the services of various traffic events by a static infrastructure, such as roadside units. Thus, complicated calculations related to the vehicles in the recognition algorithm can be simplified and message processing time can be reduced. Specifically, an optimal link is always found to achieve different QoSs in the V2V network.

The source vehicle v_a acquires an optimal link c^* data after VC processing. Subsequently, the attempted transmission messages are transmitted to the destination vehicle v_b along the multihop relay link c^*.

Appendix C has a specific experimental verification process.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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