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Peak Age of Information Analysis for Virtual Reality in Terahertz Communications

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***Abstract*—Virtual Reality (VR) is one of the new promising use cases of the next generation wireless communications which requires high-throughput, low-latency, and reliable communications. For such services, the freshness of data could be measured by the age of information (AoI) metric. In this paper, we assume indoor small-cell Terahertz communications to serve VR users. Taking into account the wave propagation characteristics of the Terahertz communications and interference modeling in the small-cell networks, average peak AoI (PAoI) is investigated to analyse downlink data transmission to the VR users. Each small base station (SBS) is modeled by two M/M/1 and M/G/1 queues; One for data processing of VR data and the other for storing and transmitting information over the Terahertz channel in presence of blockage probability. Then, the average PAoI is extended to simultaneously support multi VR users with an SBS, and for a special case of large signaling bandwidth, average PAoI is also discussed. Finally, numerical results are provided to investigate the effects of signaling bandwidth, blockage probability, cell-density, and interference coverage of SBSs on the average PAoI of the considered system.**

***Index Terms*—Peak age of information, virtual reality, queuing theory, Terahertz communications.**

I. Introduction

The development of the time-critical services, e.g. Internet of things (IoT), autonomous driving vehicles, unmanned aerial vehicle (UAV) and virtual reality (VR), have gained research interests and they can be categorized as one of the main 5G use cases named as ultra-reliable and low-latency communications (URLLC) [1]. Besides improving the spectral efficiency or decreasing the end-to-end delay of the system, such services share a common requirement, which is preserving *freshness* of data or status-update. To measure the level of freshness, the age of information (AoI) and the peak age of (PAoI) metrics have been recently introduced [2]–[8], which are basically different to the conventional delay and latency analyses of the system.

The AoI is firstly introduced in [2], and is defined as the time elapsed since the generation time of the most recent status update successfully received at the receiver. On the other hand, the PAoI provides information about the maximum value of AoI for each update [3]. Since PAoI captures the extent to which the update information is stale and also is easier to trace and compute, it has been regarded as an efficient new metric to investigate the freshness of the delivered information in VR services [4].

To provide wireless VR services and support 360° high quality images to the end-user, high-data rate communications is also required. Thus, the Terahertz (THz) communication is suggested in [9], and the conventional *delay* and reliability analyses of a cellular VR network are also studied. The study in [10] combines both visual and haptic modalities in the context of mobile VR network design, while in [11] proposes a joint proactive computing and millimeter wave resource allocation scheme under *latency* and reliability constraints. It is worth noting that the previous works [9]–[12] only have investigated the delay, reliability and throughput, and the freshness of information is *not* considered.

In recent years, interesting analyses on the freshness of data have been presented for the time-critical applications. The main contribution of [13] is to go beyond the conventional average AoI notion by developing a novel framework to characterize and optimize the tail of the AoI in URLLC vehicular networks. Focusing on the IoT networks with multiple information sources, [14] has considered general service time distributions and minimizes the cost of the PAoI in a system with heterogeneous service requirements. It is also assumed that the service requirements of different entities are modeled by quasi-convex cost functions of the PAoI. The work in [15] has formulated the average PAoI minimization problem to jointly optimize the UAV's flight trajectory, energy allocations and service time durations for transmitting update packets at both the source and the UAV nodes.

Although VR services are analysed in the literature form the different perspectives, to the best of our knowledge, analysis of providing fresh information to the VR user over a Terahertz communications channel in presence of possible link blockage is not investigated. Hence in this paper, we consider an indoor small-cell network wherein small base stations (SBSs) which are working at Terahertz frequency are distributed over the coverage area, and each SBS while serving its own VR users may interfere with other SBSs as well. At each SBS two queues are used. The first queue is modeled by an M/M/1 for processing 360° VR image request, and the second one is M/G/1 to store and transmit the VR image over the Terahertz channel. Due to the randomness of the interference signal, the service time of the second queue is modeled by a random variable and its behavior is characterized. For the proposed system, the average PAoI is derived. Moreover, the results are extended to consider the case in which multi-VR user(s)

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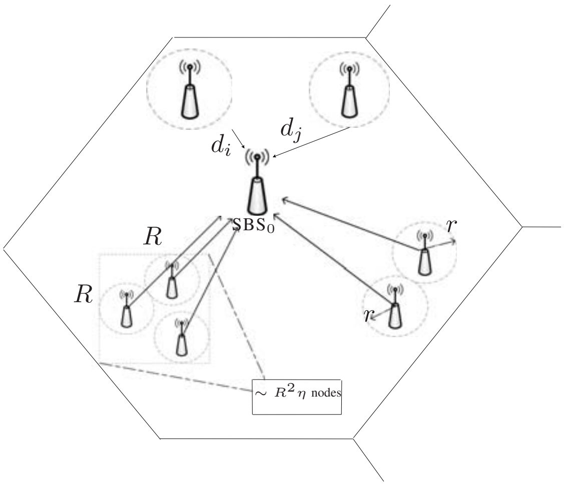

Fig. 1: Isotropic homogeneous MHCCP deployed small-cell indoor network.

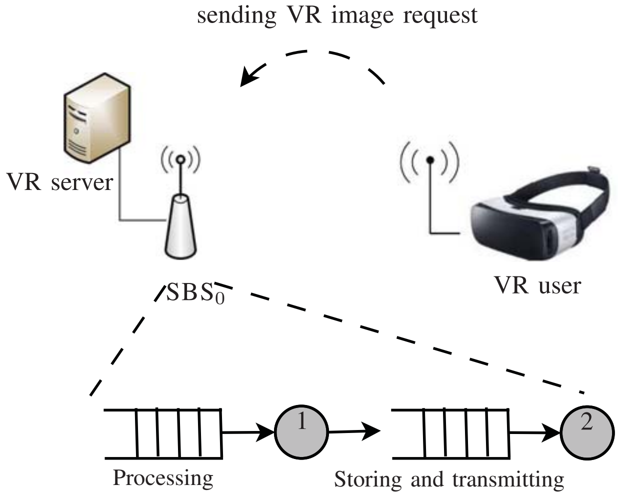

Fig. 2: Serving a VR user with a given SBS.

simultaneously send their requests to an SBS. Also, a special case of serving VR users via a very-large signaling bandwidth is also discussed. Finally, numerical results are presented to highlight how the average PAoI behaves as a function of system parameters.

The organization of the paper is outlined as follows. Section II provides the considered system model and assumptions. In Section III, the average PAoI is investigated. Section IV presents numerical results and the corresponding discussions, finally the paper is concluded in Section V.

II. System Model

Let us assume an indoor small-cell network to serve VR users. As demonstrated in Fig. 1, all the nodes are distributed according to an isotropic homogeneous Matern hardcore point process (MHCCP) with density η such that the two SBSs cannot be closer than r meter [16]. As depicted in Fig. 2, firstly a VR user sends its request to its serving SBS. Then, the SBS processes the request, prepares and transmits data over a Terahertz downlink data transmission to the VR user. Conventionally, the data processing at the SBS is modeled by two queues Q_1 and Q_2; The first queue processes 360^0 VR image and the second one is for storing and then transmitting the VR image over the Terahertz downlink channel. It is also assumed that the sizes of buffers are infinite and the first-come first-served policy is used at the SBSs. By assuming the Poisson arrival process for requesting a VR image and an exponential distribution of the service time, Q_1 is modeled by an M/M/1 queue. To ensure the stability of the first queue Q_1, we must have $\mu > \lambda$ where λ is mean arrival rate and μ is the mean service rate of Q_1. The second queue Q_2 is an M/G/1 queue and according to Burke's theorem [17] Q_2 follows the Poisson process with the rate μ [9] .

Before analysing PAoI in the proposed system, in the following, we briefly introduce the SINR analysis, interference modeling and data transmission delay characteristics.

A. *SINR Analysis for Terahertz Channel*

Let us assume a line-of-sight point-to-point channel to model the conventional Terahertz channel. It is worth noting that, besides the conventional geometric path loss and the thermal noise, Terahertz wave propagation suffers also both from *molecular absorption* loss and *molecular noise*, as well [18].

- The total path loss $L(f, d)$, which is consist of the absorption loss $L_A(f, d)$ and the propagation loss $L_P(f, d)$, is given as follows [18]

$$L(f, d) = L_P(f, d) \times L_A(f, d) = \left(\frac{4\pi f d}{c}\right)^2 \frac{1}{\tau(f, d)}, \quad (1)$$

  where f denotes the operating Terahertz frequency, d represents the distance between the VR user and the serving SBS, and c is the speed of light. Also, $\tau(f, d)$ is the transmittance of the medium following the Beer-Lambert law, such that $\tau(f, d) \approx e^{-K(f)d}$, wherein $K(f)$ is the overall absorption coefficient of the medium.
- To calculate the SINR, let us assume that there exist $M+1$ active SBSs in the indoor given area with transmitting power p_i for $i = 0, 1, 2, ..., M$, respectively. Therefore, while the target VR user is receiving its signal from the supporting SBS_0 located at distance d_0, the VR user also receives *interference* signal from ith SBS, for all $i = 1, 2, ..., M$, which is located at distance d_i from the user. Thus, the signal-to-interference-plus-noise ratio (SINR) at the desired VR user served by SBS_0 is given by [18]

$$\mathrm{SINR}(\boldsymbol{d}, \boldsymbol{p}, f) = \frac{p_0^{RX}(d_0, p_0, f)}{N(\boldsymbol{d}, \boldsymbol{p}, f) + I(\boldsymbol{d}, \boldsymbol{p}, f)}, \quad (2)$$

  where $p_0^{RX}(d_0, p_0, f) = p_0 A_0 d_0^{-2} e^{-K(f)d_0}$ denotes the received signal power at the VR user from the associated SBS_0 such that $A_0 = \frac{c^2}{16\pi^2 f^2}$.

  The total noise power $N(.)$ which includes the conventional *thermal* and *molecular* noises is denoted by

$$N(\boldsymbol{d},\boldsymbol{p},f) = N_0 + \sum_{i=1}^{M} p_i A_0 d_i^{-2}(1 - e^{-K(f)d_i}), \quad (3)$$

where $\boldsymbol{p} \triangleq [p_1, p_2, ..., p_M]$, $\boldsymbol{d} \triangleq [d_1, d_2, ..., d_M]$, and

$$N_0 = k_B T + p_0 A_0 d_0^{-2}(1 - e^{-K(f)d_0}), \quad (4)$$

where k_B is the Boltzmann constant and T is the temperature in Kelvin.
Moreover, the superimposed interference power is formulated as

$$I(\boldsymbol{d},\boldsymbol{p},f) = \sum_{i=1}^{M} p_i A_0 d_i^{-2} e^{-K(f)d_i}. \quad (5)$$

By substituting (3) and (5) into (2), we have

$$\mathrm{SINR}(\boldsymbol{d},\boldsymbol{p},f) = \frac{p_0 A_0 d_0^{-2} e^{-K(f)d_0}}{N_0 + \sum_{i=1}^{M} p_i A_0 d_i^{-2}}. \quad (6)$$

B. Interference Analysis

It is worth mentioning that due to the random locations of SBSs and the target VR user, the final interference power in (6) can be modeled by a random variable. The probability density function (p.d.f) of this random interference is modeled by [18]

$$g(I) = \frac{1}{\sqrt{2\pi}\sigma_I} \exp\left(-\frac{(I-\mu_I)^2}{2\sigma_I^2}\right), \quad (7)$$

where μ_I and σ_I^2 respectively denote the mean and variance of the interference, and are given by [18]

$$\mu_I = pA_0 \left(\frac{\ln(\Omega) - \ln(r)}{\Omega^2 - r^2}\right)\left(\frac{\pi\Omega^2\eta}{2}\right), \quad (8)$$

$$\sigma_I^2 = (pA_0)^2 \left(\frac{\pi\Omega^2\eta}{2}\right)\left(\frac{1}{2r^2\Omega^2}\right), \quad (9)$$

where r is a minimum distance between the two SBSs, Ω is the area of presence of non-negligible interference and p is transmission power in the case that all the SBSs have the same power so the subscript i is omitted.

C. Data Transmission Delay Analysis

Service time of the second queue, i.e. s [second], is equal to the transmission delay, i.e. time of channel use, for sending data packet of size L [bits] over the downlink channel from the SBS_0 to the VR user. Therefore, the channel capacity of the Terahertz channel subject to the blockage [19] is defined as; Channel Capacity $:= \frac{L}{s} = p'W \log_2(1 + \mathrm{SINR})$ [bits/s], where W is the signal bandwidth, and $1 - p'$ represents the blockage probability of the Terahertz communications link.

Taking into account the randomness of the interference power in the SINR term, and after mathematical manipulations as presented in [9, Lemma 1], the p.d.f of the modified service time of Q_2 becomes

$$\psi_T(s) = \frac{\zeta}{\sqrt{2\pi}\sigma_I} \exp\left(-\frac{(\gamma-\mu_I)^2}{2\sigma_I^2}\right), \quad (10)$$

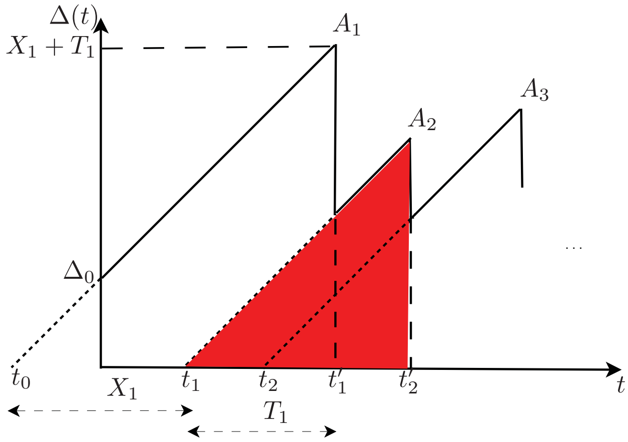

Fig. 3: A sample of the age evolution for a VR-SBS pair.

where

$$\zeta = \frac{\ln 2 (p_0^{RX} L) 2^{\frac{L}{p'Ws}}}{p'Ws^2(2^{\frac{L}{p'Ws}} - 1)^2}, \quad (11)$$

$$\gamma = \frac{(1 - 2^{\frac{L}{p'Ws}})N_0 + p_0^{RX}}{2^{\frac{L}{p'Ws}} - 1}. \quad (12)$$

Note that p.d.f of the service time does not follow the normal distribution because of the dependency of the parameters ζ and γ on the service time s.

III. Average Paek Age of Information Analysis

The well-known Age of Information (AoI) is used as a measure of the freshness of data at the VR user. The AoI at the VR user for time stamp t is defined as the following random process

$$\Delta(t) = t - U(t), \quad (13)$$

where $U(t)$ is the time at which the most recently received packet at the VR user was generated at the serving SBS node. Fig. 3, presents a sample of the age evolution for the considered SBS-VR pair with an initial age Δ_0. The peak values on the sawtooth curve, i.e. A_i for $i = 1, 2, \cdots$, indicate the maximum value of the AoI immediately before receiving an update. The peak value of the age provides information about the worst case of age. This metric is investigated in the literature due to possible simpler analysis and chance of closed-form computation.

Let X_i be the interarrival time of the i-th update, and $T_i = S_i + W_i$ be the corresponding system time where W_i and S_i are the i-th update of the waiting time and the service time, respectively. Then, the PAoI metric is defined as the value of age achieved immediately before receiving the i-th update;

$$A_i = X_i + T_i. \quad (14)$$

Note that the peak of age is a discrete stochastic process that takes values at the time instances.

As we are interested in small AoI, analysing *average* PAoI is of interest to show that how PAoI behaves. Thus, the average

PAoI in the status update system is defined as

$$A = \mathbb{E}[X+T] = \mathbb{E}[X+S+W], \tag{15}$$

where $\mathbb{E}[.]$ is the statistical expectation operator.

In the following, we derive the average PAoI, for one and multi-VR user(s).

A. One VR User

For the proposed system wherein one target VR user is served by SBS_0 in presence of interfering SBSs, the average PAoI is given in Theorem 1.

Theorem 1. *The average PAoI is given by*

$$\begin{aligned} A_{one} &= A_{Q_1} + A_{Q_2} \\ &= \frac{1}{\lambda} + \frac{1}{\mu}\left(2 + \frac{\lambda}{\mu-\lambda}\right) \\ &+ \int_0^\infty s\psi_T(s)ds + \frac{\mu\int_0^\infty s^2\psi_T(s)ds}{2\left(1-\mu\int_0^\infty s\psi_T(s)ds\right)}, \end{aligned} \tag{16}$$

where λ is the mean arrival rate, μ is the mean service rate of Q_1, and $\psi_T(s)$, which is given in (10), represents the p.d.f of the transmission delay of the network, i.e. the service time of Q_2.

Proof. The proof is given in Appendix A. □

Remark 1. *Using a larger signaling bandwidth or utilizing a laser beam instead of the Terahertz communications, the p.d.f given in (10) tends to a delta function and the second queue becomes an M/D/1 one. For this case, the average PAoI with deterministic delay s_0 becomes*

$$\begin{aligned} A_{one-laser} =& \frac{1}{\lambda} + \frac{1}{\mu}\left(2 + \frac{\lambda}{\mu-\lambda}\right) \\ &+ s_0 + \frac{\mu s_0^2}{2\left(1-\mu s_0\right)}. \end{aligned} \tag{17}$$

To highlight the effect of larger bandwidth on the p.d.f of the transmission delay, Fig. 4 is provided. It is shown that as the signaling bandwidth increases, the p.d.f approaches a delta function, i.e. the transmission delay becomes deterministic and tends to 0.034, and the average PAoI becomes 5.2.

B. Multi-VR Users

Suppose that N VR users simultaneously send their VR image requests to SBS_0. It is assumed that they request the same VR image. For this case, the SBS_0 processes the requests, prepares and transmits data over Terahertz channels to the Multi-VR user(s). As the packets have equal lengths, the time is divided into the same slots to transmit a packet from the buffer to the target VR user. Therefore, the second queue Q_2 becomes M/G/N instead of M/G/1, which indicates a multi-server queueing model. The difference between the average PAoI for an M/G/1 queue and an M/G/N one is in deriving the average waiting time $\mathbb{E}[W]$. Thus, in the following theorem, the PAoI is presented to consider the multi-user extension.

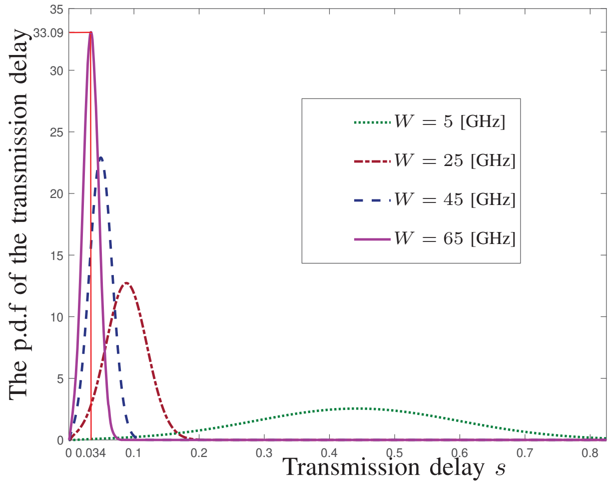

Fig. 4: The p.d.f of the service time for different signalling bandwidth.

Theorem 2. *The average PAoI for a system with two queues in tandem M/M/1 and M/G/N is given by*

$$\begin{aligned} A_{multi} =& \frac{1}{\lambda} + \frac{1}{\mu}\left(2 + \frac{\lambda}{\mu-\lambda}\right) \\ &+ \int_0^\infty s\psi_T(s)ds + \frac{(C^2+1)P(N,\rho)}{2\left(\frac{N}{\int_0^\infty s\psi_T(s)ds} - \mu\right)} \end{aligned} \tag{18}$$

where $\rho = \mu\mathbb{E}[s]$ is the server utilization, C is the coefficient of variation of the service time distribution

$$C = \frac{\sqrt{\mathbb{E}[S^2] - \mathbb{E}^2[S]}}{\mathbb{E}[S]}, \tag{19}$$

and

$$P(N,\rho) = \frac{1}{1 + (1-\rho)\left(\frac{N!}{(N\rho)^N}\right)\sum_{k=1}^{N-1}\frac{(N\rho)^k}{k!}}. \tag{20}$$

Sketch of proof: Using Kingman's law of congestion and after some mathematical manipulations, one can prove the results.

Remark 2. *By substituting $C = 0$ and $\psi_T(s) = \delta(s - s_0)$ in (18), one can achieve the results for the large-bandwidth signal transmissions.*

IV. Numerical Results and Discussions

In this section, we present our numerical results. Similar to [9], the following parameters are assumed; $T = 300$ [Kelvin], $p = 1$ [Watt], $f = 1$ [THz], and $K(f) = 0.0016$ [m^{-1}]. Also, the SBSs are located in an indoor square area of size 20 [m] $\times$ 20 [m].

Fig. 5 compares the average PAoI for different values of the minimum distance r between the SBSs versus the bandwidth W [GHz]. We consider the $\lambda = 0.6$ [packets/s] and $\mu = 1$

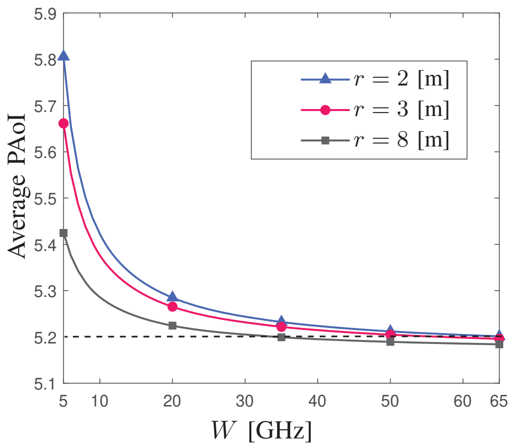

Fig. 5: Average PAoI versus bandwidth.

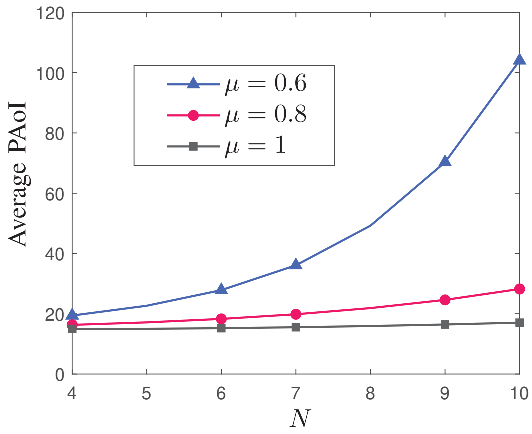

Fig. 7: Average PAoI versus number of users for multi-VR scenario.

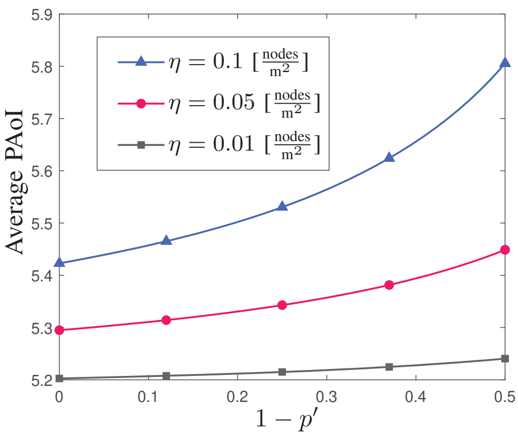

Fig. 6: Average PAoI versus blockage probability.

[Gbps]. As expected, by increasing r the interference decreases so the average PAoI declines. In all cases, higher bandwidth results in lower average PAoI as well. According to Remark 1, for $W = 65$ [GHz] the *asymptotic* average PAoI reaches 5.2.

The effect of direct Terahertz link blockage probability on the average PAoI is investigated in Fig. 6, for various amounts of density η. As the density increases, the average PAoI increases, e.g. $\eta = 0.05$ [nodes/m^{-2}] in our scenario is equal to have 20 SBSs in an indoor area and $\eta = 0.1$ [nodes/m^{-2}] is equal to have 40 SBSs. So, increasing the SBSs increases the level of interference, and higher average PAoI is expected. Furthermore, by increasing the blockage probability, the average PAoI increases.

In Fig. 7, the average PAoI is plotted versus the number of users for multi-VR under different values of the service rate μ. As depicted, by increasing the number of served users by an SBS, average PAoI exponentially increases. For different values of the service rate μ, by increasing μ, the average PAoI decreases.

V. Conclusions

We analysed the average PAoI for an indoor small-cell downlink Terahertz communications to support VR users. Two queues are considered at each SBS; One M/M/1 queue for the data processing of VR requests, and the other M/G/1 queue is used for storing and transmission. Taking into account the Terahertz channel capacity characteristics and stochastic behavior of the interfering SBSs, the average PAoI is derived for serving one or multi-VR user(s) by a given SBS. Finally, through comprehensive numerical results, the average PAoI is analysed to clarify how it changes by signaling bandwidth, blockage probability and the number of serving VR users simultaneously by an SBS.

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APPENDIX A
PROOF OF THEOREM 1

As mentioned earlier, Q_1 is an $M/M/1$ queue with the mean arrival rate $\lambda = \frac{1}{\mathbb{E}[X_{Q_1}]}$ and the mean service rate $\mu = \frac{1}{\mathbb{E}[S_{Q_1}]}$. Hence, the average PAoI becomes

$$A_{Q_1} = \frac{1}{\lambda} + \frac{1}{\mu} + \frac{\lambda}{\mu(\mu - \lambda)}, \tag{21}$$

where the mean waiting time of an $M/M/1$ queue is $\mathbb{E}[W_{Q_1}]$.

The Q_2 is considered to be an $M/G/1$ queue. According to the Burke's theorem, the mean arrival rate of Q_2 is equal to the mean service rate of Q_1. Therefore, the average PAoI for an $M/G/1$ system is given by

$$A_{Q_2} = \frac{1}{\mu} + \mathbb{E}[S_{Q_2}] + \frac{\mu\mathbb{E}[S_{Q_2}^2]}{2(1 - \mu\mathbb{E}[S_{Q_2}])}. \tag{22}$$

The result is derived from the P-K formula for the system time T provided in [17], thus we have

$$\mathbb{E}[S_{Q_2}] = \int_0^\infty s\psi_T(s)ds, \tag{23}$$

$$\mathbb{E}[S_{Q_2}^2] = \int_0^\infty s^2\psi_T(s)ds, \tag{24}$$

where $\psi_T(s)$ is the p.d.f of the transmission delay of our proposed network which is the service time of Q_2.

Since the system consist of the two queues in tandem, the total PAoI is defined as follows

$$A_{one} = A_{Q_1} + A_{Q_2}. \tag{25}$$

By substituting the A_{Q_1} and A_{Q_2} in above equation, the average PAoI is derived as (16). It is worth noting that due to the complex p.d.f of the service time, one cannot derive a closed-form of average PAoI, so the results are discussed numerically.