Age of Information Analysis for Cache-enabled UAV Networks

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***Abstract*—In this paper, we consider a freshness-aware cache-enabled unmanned aerial vehicle (UAV) network, where both UAV and base station (BS) can provide fresh contents to user equipment (UE). Specifically, we consider the content-centric association scheme. To analyze the data freshness, we derive the Age of Information (AoI) violation probability using stochastic geometry. Finally, we show the impact of UAVs altitude and cache size on the AoI violation probability.**

I. Introduction

Unmanned aerial vehicles (UAVs) become a reliable and cost-effective solution widely used in modern wireless networks, due to their mobility, flexibility, and low cost [1]. Existing research usually focuses on the capacity and the coverage of the UAV-enabled networks. However, with the development of Internet of Thing (IoT), various real time applications which require fresh data are spawned, and the date freshness is becoming increasingly important. To characterize the data freshness, a new performance metric, Age of Information (AoI), was presented, which is defined as the time elapsed since the most recently updated information [2].

Compare with the normal UAV networks, caching at UAVs can store the popular contents, and transmit those contents without backhaul, so the initial AoI of those content at UAV is zero. Also, the backhaul transmission pressure leads to the reduce of the backhaul load. Consequently, contents caching could improve the AoI in the UAV networks.

Therefore, in this paper, we analyze the AoI violation probability in cache-enabled UAV networks using stochastic geometry. The main contributions of this paper are as follows: We first develop a freshness-aware cache-enabled UAV network. We then derive the total average AoI violation probability formulas. Finally, we analyze the impact of the network parameters on the AoI violation probability.

II. System Model

A. Network Model

We consider a freshness-aware cache-enabled UAV network with single-antenna UAVs, single-antenna base stations (BSs), and single-antenna user equipments (UEs). The location of UAVs, BSs, and UEs are modeled as independent 2-dimensional homogeneous Poisson point processes (PPPs), denoted by Φ_{u}, Φ_{b}, and Φ_{m}, with densities λ_{u}, λ_{b}, and λ_{m}, respectively. The altitudes of UAVs and BSs are h_{u} and h_{b}, respectively. We assume that all UEs are on the ground, and each UE receives one content at a time slot. The UAV-UE link and BS-UE link share different spectrum bands, thus the bandwidths of UAV-UE link and BS-UE link are W_{u} and W_{b}, respectively.

B. Channel Model

For the UAV-UE and the BS-UE channel models, both the Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) links are considered. The LoS probability for the UAV-UE link and the BS-UE link with the horizontal distance r, denoted as $p_{\mathrm{u}}^{(\mathrm{L})}(r)$ and $p_{\mathrm{b}}^{(\mathrm{L})}(r)$, is given by [3]

$$p_{\tau}^{(\mathrm{L})}(r) = \frac{1}{1 + a\exp\left[-b\left(\theta_{\varepsilon} - a\right)\right]},\ \tau \in \{\mathrm{u,b}\}, \tag{1}$$

where a and b are environment constants, and $\theta_{\tau} = \frac{180}{\pi}\tan^{-1}\left(\frac{h_{\tau}}{r}\right)$ is the elevation angle of the transmitter type τ. So the NLoS probability of link τ is $p_{\tau}^{(\mathrm{N})}(r) = 1 - p_{\tau}^{(\mathrm{L})}(r)$. According to the LoS and NLoS condition, we consider different path loss exponents and channel fading models. The path loss exponents for LoS and NLoS links are respectively denoted by α_{L} and α_{N}, where $2 \leq \alpha_{\mathrm{L}} \leq \alpha_{\mathrm{N}}$. The small-scale fading for LoS and NLoS links are modeled as the Nakagami-m fading with channel gain $g_{\mathrm{L}} \sim \Gamma(m_{\mathrm{L}}, 1/m_{\mathrm{L}})$ and the Rayleigh fading with channel gain $g_{\mathrm{N}} \sim \Gamma(m_{\mathrm{N}}, 1/m_{\mathrm{N}}) = \exp(1)$, reaspectively, where $m_{\mathrm{N}} = 1$.

C. Content Placement

We consider a finite content library as $\mathcal{E} = \{e_1, ..., e_i, ..., e_E\}$, where e_i is the i-th most popular content, and the number of total contents is E. We assume that each content has the same content size S. Using the Zipf distribition, the request probability of the i-th most popular content given by

$$p_i = \frac{i^{-\kappa}}{\sum_{j=1}^{E} j^{-\kappa}}, \tag{2}$$

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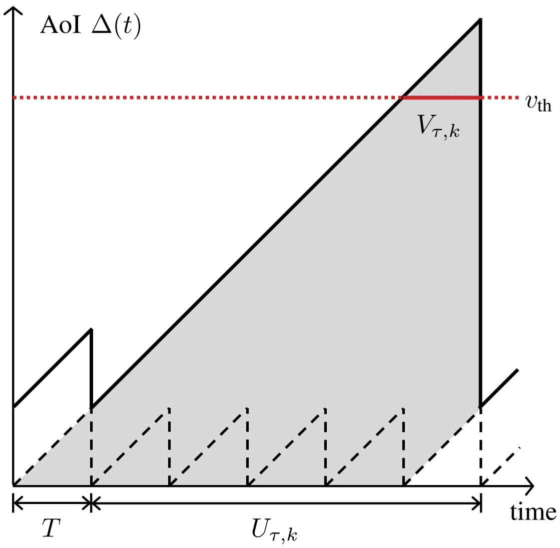

Fig. 1. AoI at the typical UE which is associated with the transmitter type τ

where κ is the popularity skewness of Zipf distribution. We assume that each UAV caches C contents, and the contents are sorted by the order of the most popular contents (MPC) caching strategy. Hence the cache hit probability of the content which UE requests is given by $q_{\text{hit}} = \sum_{i=1}^{C} p_i$.

D. Association Strategy

We consider a content-centric association scheme. If the content requested from the UE is caching at UAV, then the UE is associated with the UAV which provides the strongest average received power. Otherwise, the UE is associated with the BS which provides the strongest average received power.

E. Signal-to-interference ratio (SIR) and Mean Load

We focus on the interference-limited environment. The SIR at the typical UE when associated with the transmitter type τ in the link type ε is expressed as

$$\text{SIR}_{\tau,\text{o}}^{(\varepsilon)} = \frac{g_\varepsilon \left({y_{\tau,\text{o}}^{(\varepsilon)}}^2 + {h_\tau}^2 \right)^{-\frac{\alpha_\varepsilon}{2}}}{I_{\tau,\text{o}}^{(\varepsilon)}}, \ \tau \in \{\text{u,b}\}, \varepsilon \in \{\text{L,N}\}, \quad (3)$$

where $y_{\tau,\text{o}}^{(\varepsilon)}$ is the horizontal distance between the typical UE and the associated transmitter type τ in the link type ε, $I_{\tau,\text{o}}^{(\varepsilon)}$ is the interference for the typical UE in Φ_τ.

According to Corollary 1 of [4], the mean load of the link from the transmitter type τ to the typical UE is approximated as

$$L_\tau = \begin{cases} 1 + \dfrac{1.28\lambda_{\text{m}} q_{\text{hit}}}{\lambda_{\text{u}}}, & \tau = \text{u}, \\ 1 + \dfrac{1.28\lambda_{\text{m}}(1 - q_{\text{hit}})}{\lambda_{\text{b}}}, & \tau = \text{b}. \end{cases} \quad (4)$$

F. AoI Model

Fig. 1 is the AoI at the typical UE which is associated with the transmitter type τ. As shown in Fig. 1, T is the transmission time period at the BS and the UAV, and $U_{\tau,k}$ is the kth successful update period time for the typical UE when the UE is associated with the transmitter type τ. We assume that each UAV and BS always transmit fresh contents.

III. Performance Analysis

A. Successful Transmission Probability

The probability density function (PDF) of horizontal distance between the typical UE and the transmitter type τ in the link type ε is given as

$$f_{r_{\tau,\text{o}}^{(\varepsilon)}}(r) = 2\pi\lambda_\tau r p_\tau^{(\varepsilon)}(r) \exp\left(-2\pi\lambda_\tau \int_0^r p_\tau^{(\varepsilon)}(z) z dz \right), \quad (5)$$

where $r_{\tau,\text{o}}^{(\varepsilon)}$ is the horizontal distance between the typical UE and the transmitter type τ in the link type ε.

Based on (5), the conditional PDF of the horizontal distance between the typical UE and the associated transmitter which is the transmitter type τ in the link type ε is given by

$$f_{y_{\tau,\text{o}}^{(\varepsilon)}}(y) = \exp\left(-2\pi\lambda_\tau \int_0^{d_\tau^{(\varepsilon,\varepsilon^c)}(y)} p_\tau^{(\varepsilon^c)}(z) z dz \right) f_{r_{\tau,\text{o}}^{(\varepsilon)}}(y), \quad (6)$$

where

$$d_\tau^{(a,b)}(y) = \max\left\{ \left[\left(y^2 + h_\tau^2\right)^{\frac{\alpha_a}{\alpha_b}} - h_\tau^2 \right]^{\frac{1}{2}}, 0 \right\}, \quad (7)$$

where $\varepsilon \in \{\text{L,N}\}$, and $\varepsilon^c = \{\text{L,N}\} \backslash \varepsilon$.

Using (6), the conditional successful transmission probability (STP) for the typical UE when associated with the transmitter type τ is given as

$$\begin{aligned} p_{\text{s},\tau} &= \sum_{\varepsilon \in \{\text{L,N}\}} \mathbb{P}\left[\text{SIR}_{\tau,\text{o}}^{(\varepsilon)} > \zeta_\tau \right] \\ &= \sum_{\varepsilon \in \{\text{L,N}\}} \int_0^\infty \sum_{k=0}^{m_\varepsilon - 1} \left[\frac{\left(-s_\tau^{(\varepsilon)}\right)^k}{k!} \frac{\text{d}^k}{\text{d}{s_\tau^{(\varepsilon)}}^k} \mathcal{L}_{I_{\tau,\text{o}}^{(\varepsilon)}}\left(s_\tau^{(\varepsilon)}\right) \right] f_{y_{\tau,\text{o}}^{(\varepsilon)}}(y) dy, \end{aligned} \quad (8)$$

where $\zeta_\tau = 2^{\frac{SL_\tau}{TW_\tau}} - 1$ is the SIR threshold, $s_\tau^{(\varepsilon)} = \frac{m_\varepsilon \zeta_\tau}{(y^2 + h_\tau^2)^{-\frac{\alpha_\varepsilon}{2}}}$, and the Laplace transform of the interference for the typical UE when associated with the transmitter type τ in the link type ε, $\mathcal{L}_{I_{\tau,\text{o}}^{(\varepsilon)}}(s)$, is given as

$$\begin{aligned} \mathcal{L}_{I_{\tau,\text{o}}^{(\varepsilon)}}(s) = \exp\Bigg[&- 2\pi\lambda_\tau \sum_{z \in \{\text{L,N}\}} \int_{d_\tau^{(\varepsilon,z)}(y)}^\infty p_\tau^{(z)}(t) t \\ &\times \left(1 - \frac{1}{\left[1 + \frac{s}{m_z} \left(t^2 + h_\tau^2\right)^{\frac{\alpha_z}{2}} \right]^{m_z}} \right) dt \Bigg]. \end{aligned} \quad (9)$$

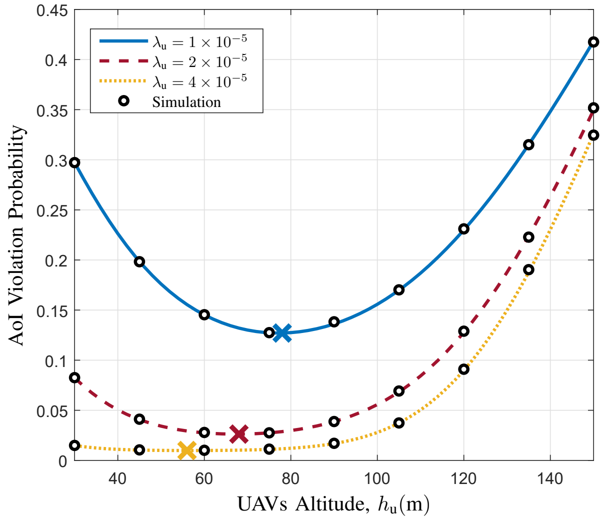

Fig. 2. AoI violation probability versus the UAVs altitude with different UAVs densities.

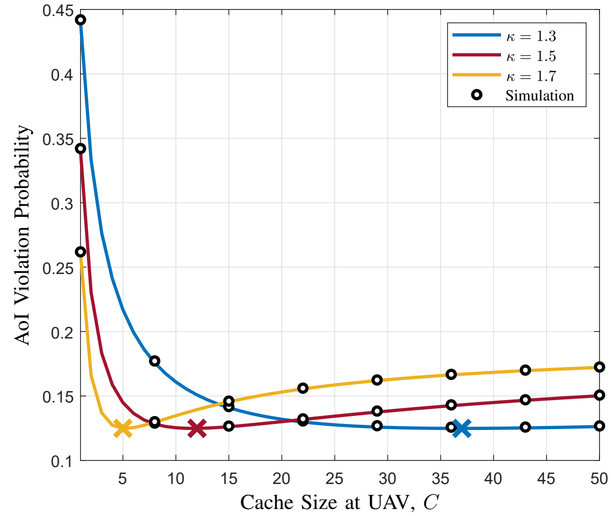

Fig. 3. AoI violation probability versus the cache size at UAV with different parameters of content popularity.

B. Violation Probability

Using (8), the AoI violation probability when the typical UE is associated with the transmitter type τ according to the violation threshold v_{th} is given by [5]

$$p_{\text{v},\tau}(v_{\text{th}}) = (1 - p_{\text{s},\tau})^{x_{\text{th}}-1}, \ \tau \in \{\text{u},\text{b}\}, \tag{10}$$

where $x_{\text{th}} = \left\lceil \frac{v_{\text{th}}}{T} \right\rceil$. Therefore, the total AoI violation probability is derived as

$$p_{\text{v}}(v_{\text{th}}) = q_{\text{hit}} p_{\text{v,u}}(v_{\text{th}}) + (1 - q_{\text{hit}})\, p_{\text{v,b}}(v_{\text{th}}). \tag{11}$$

IV. Numerical Results

In this section, we evaluate the AoI violation probability according to the network parameters. Unless otherwise specified, the values of the simulation parameters are $\lambda_{\text{u}} = 10^{-5}\text{node/m}^2$, $\lambda_{\text{b}} = 6 \times 10^{-6}\text{node/m}^2$, $\lambda_{\text{m}} = 10^{-3}\text{node/m}^2$, $h_{\text{u}} = 70\text{m}$, $h_{\text{u}} = 20\text{m}$, $W_{\text{u}} = 10\text{MHz}$, $W_{\text{b}} = 10\text{MHz}$, $S = 40\text{KB}$, $T = 0.2\text{s}$, $x_{\text{th}} = 5$, $\alpha_{\text{L}} = 2.5$, $\alpha_{\text{N}} = 4$, $a = 12.0810$, $b = 0.1139$, $m_{\text{L}} = 3$, $E = 1000$, $C = 20$, and $\kappa = 1.5$.

Figure 2 presents the AoI violation probability versus the UAVs altitude with different UAVs densities. We can see that there exists the optimal UAVs altitude to achieve the minimum AoI violation probability. For the small UAVs altitude, as the UAVs altitude increases, the LoS probability between the UE and the serving UAV increases, which leads to the decrease of the AoI violation probability. However, as the UAVs altitude keeps increasing, for the UE, the serving distance with the serving UAV and the interference from other UAVs increases much faster, which results in the increase of the AoI violation probability. We can also observe that the optimal altitude decrease when the UAVs density is increasing.

Figure 3 shows the AoI violation probability versus the cache size at UAV with different parameters of content popularity. It is shown that there exists the optimal cache size to achieve the minimum AoI violation probability. For the small cache size, by increasing the cache size, the content hit probability for UE increases, and the load of the BS-UE link decreases, leading to a decrease in the AoI violation probability. Conversely, the load of the UAV-UE link increases much faster. We also see that the optimal cache size decreases when the content popularity parameter is increasing.

V. Conclusion

In this paper, we analyzed the AoI violation probability in the cache-enabled UAV network, where both UAV and BS can provide services to the UE. We derived the AoI violation probability using stochastic geometry. We showed that the AoI violation probability could be improved by network parameters such as the UAVs altitude and the cache size.

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