AoI-Aware Markov Decision Policies for Caching

I. INTRODUCTION

Motivation. Smart vehicles intelligently interact with their surroundings in real-time to determine the optimal driving decisions and assist drivers for safe and fast driving. For the purpose of rapid and accurate driving decisions to ensure the driving stability in fast-moving vehicle network environments, many research contributions are proposed including data transmission control considering the data freshness, e.g., age-of-information (AoI) [1]. Because road-side traffic information is delay-sensitive for connected vehicles, the data freshness is critical for optimizing the performance of link connectivity in vehicular networks. Therefore, cache-assisted connected vehicles have been widely considered for delay-sensitive data delivery and AoI-aware fresh content management.

Related Work. The AoI is a metric for information freshness that measures the time that elapses since the last received fresh update was generated at the source [2]. In the environment where data updates are required (e.g., mobile device’s recent position, speed, and other control information), the analysis and optimization of AoI have been extensively studied in various scenarios [3]. Moreover, the applications and usages of the concept of AoI are also widely studied, e.g., ultra-reliable vehicular communications [4]. Lastly, AoI is utilized as an important performance evaluation criteria in random access and caching replacement research [5].

Contribution. We propose a joint cache replacement and content delivery scheme in cache-assisted connected vehicles that minimizes the network cost while limiting the AoI of traffic conditions. The proposed scheme adaptively controls the tradeoff between the content AoI and network resource consumption, depending on rapidly changing road environments, user mobility, as well as the AoI of contents.

II. AOI-AWARE MDP FOR CACHING

In our reference network model, we assume cache replacements of roadside units (RSUs) and content delivery from RSUs to user vehicles (UVs) can be separately performed.

A. Overall Architecture

There are $N_u$ UVs, $N_R$ RSUs, and one macro base station (MBS) are deployed around the straight road. The road has $L$ regions, the conditions of the regions are not all the same and one content is created for each region. MBS is in the center of the entire road, and RSUs which cover $L'$ regions are deployed at specific distance intervals. The UVs, which are thead-hoc smart connected vehicles, move in one direction and request the RSU for the contents they need and receive necessary information through them. Each RSU is a service provider that delivers content directly to the UVs. Because contents cached in the RSU get older, cache management is necessary to maintain the freshness of cached contents. Suppose that the MBS has all the new contents generated at each time slot, and observes the cache states of all RSUs; therefore, it periodically decides what contents and which RSUs have to be updated for providing the fresh information to UVs. In addition, we assume that all contents have the same file size and different maximum AoI value limits.

B. Cache Management via Markov Decision Process (MDP)

For optimizing cache management of RSUs by the MBS, maximizing a total utility which is the summation of AoI value and communication cost. We define our own MDP model with the definitions of states $S$, actions $A$, and $R$, as follows.

- **State ($S$)**. The state contains AoI of all contents in the system and the content population that each RSU has. AoI information includes maximum AoI value and AoI of the contents which are stored in MBS and RSUs.

- **Action ($A$)**. In MDP, there is only one action variable. That means whether the content in the RSU is updated or not by MBS. The action is expressed as binary, when the variable has 1, the content update is occurred. Each RSU has several contents and only one content is updated at a time. The action is denoted as $x_k^h(t)$, $k$ and $h$ indices are for RSUs and contents in an RSU.

- **Reward ($R$)**. The reward function is the combination of AoI utility of RSUs weighted by $w$ and the network cost of the MBS for cache replacements of RSUs (negative reward), as,
\[ U(t) = U_{\text{AoI}}^{\text{RSU}}(t) - w - U_{\text{MBS}}^{\text{RSU}}(t) \]  
\[ U_{\text{AoI}}^{\text{RSU}}(t) = \sum_{k=1}^{N_R} \sum_{h=1}^{L} A_{k,h}^{\max}(x_{k,h}(t))p_{k,h}(t) \]  
\[ U_{\text{MBS}}^{\text{RSU}}(t) = \sum_{k=1}^{N_R} \sum_{h=1}^{L} C_{k,h}(x_{k,h}^c(t)) \]

where \( U_{\text{AoI}}^{\text{RSU}}(t) \) means the proportion of the current AoI value of the RSU \( A_{k,h}^{\max}(x_{k,h}(t)) \) to the reference maximum AoI \( A_{k,h}^{\max} \). When the action variable is 1, the old content of RSU is replaced by the new version which is stored in the MBS. \( U_{\text{MBS}}^{\text{RSU}}(t) \) is the negative utility which represents the communication resource using cost \( C_{k,h}(t) \) for the \( h \)-th content in \( k \)-th RSU.

**C. Lyapunov-based Service Control**

For the UV service optimization of each RSU, the object is meeting trade-off between latency of UV \((Q[t])\) which can be represented as queue and RSU communication cost (i.e., \(C(\alpha[t])\)) before UV leaves the RSU coverage. At the same time, guaranteeing the valid service content before the waiting time is expired is also considered. We propose an optimization algorithm based on Lyapunov optimization \([6]\), as follows,

\[ \min : \lim_{T \to \infty} \frac{1}{T} \sum_{t=1}^{T} C(\alpha(t)) \]

subject to queue stability, i.e., \( \lim_{T \to \infty} \frac{1}{T} \sum_{t=1}^{T} Q[t] < \infty \)

and AoI requirements, i.e., \( \sum_{t=1}^{T} A(\alpha(t)) \leq A_{k,h}^{\max} \). Based on Lyapunov control \([7]\), the optimal decision whether the service UV at this time is as (5),

\[ \alpha^*[t] \leftarrow \arg \min_{\alpha[t] \in S} \left[ V \cdot C(\alpha(t)) - Q[t]b(\alpha(t)) \right] \]

where \( \alpha^*[t], S, V, \) and \( b(\alpha[t]) \) are optimal decision at \( t \), set of all possible decisions \( \alpha[t] \), tradeoff co-efficient, and departure (i.e., processing speed) with \( \alpha[t] \), respectively.

In order to verify whether (5) works as desired, it can be confirmed by evaluating following two extreme two cases. If \( Q[t] = 0 \), the (5) will focus on maximizing \( b(\alpha[t]) \) by deciding UV service at that time. The queue which has the accumulated time is emptied by \( b(\alpha[t]) \) and the queue pursues stability.

**III. PERFORMANCE EVALUATION**

The road environment is divided by several regions and has a different state, and each state has a different maximum value. All regions are covered by 5 RSUs, and only the content of the region covered by the RSU is cached. In this simulation, the initial content AoI value of the MBS and RSU, and the status for each region are determined as random. Similarly, the content requested by the UV to the RSU is randomly generated. Performance evaluations based on MDP and Lyapunov optimization are conducted by 1000 iteration, respectively. Fig. 1a shows the content AoI change and the cumulative reward. Here, there are 4 RSUs and each RSU has 5 cached content. Totally, 20 contents are managed by MBS, each content is updated before the AoI value exceeds the maximum \( A_{k,h}^{\max} \). Instead of showing the AoI changes of all contents, we select two contents in the cache of RSU 1 and show them over time unit. In Fig. 1a, we check the cumulative reward of MBS by the proposed update decision also continues to rise. The reward is obtained by managing 4 RSUs’ cache and calculated by (1) based on the Aol utility of RSUs and the network cost of the MBS. Fig. 1b shows the latency of UV \((Q[t])\). There is a service decision in the RSU at an appropriate time to satisfy the stability of the queue. That means the proposed method considers trade-off between cost and latency compared to the other two algorithms.

**IV. CONCLUDING REMARKS**

This paper proposed a two-stage joint Aol-aware cache management and content delivery scheme for providing fresh road contents to connected vehicles. We present an MDP-based algorithm for cache management of RSUs to limit the Aol of cached contents. In addition, the content delivery from cache-enabled RSUs to UVs is adaptively optimized depending on the current Aol of contents and rapidly time-varying traffic conditions under the Lyapunov-based control.

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