Maximum bit rate control based on throughput feedback for deadline-aware resource management in cellular networks

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Abstract: Delay-sensitive applications over cellular networks, such as road traffic collision avoidance, usually have a deadline constraint within which the data must be delivered. Model-based network resource management may miss the deadline due to model uncertainties of the cellular networks. This letter proposes a deadline-aware resource management method based on maximum bit rate (MBR) control with a feedback controller for delay-sensitive applications. The proposed method treats the model uncertainties as disturbances. The feedback controller maintains the effective throughput at a target level to meet the deadline even if disturbances exist. Numerical simulations demonstrate that the proposed method improves the success rate of data delivery within the deadline constraint in the presence of disturbances.

Keywords: IoT, cellular networks, network resource management, feedback control, maximum bit rate control, deadline

Classification: Network

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1 Introduction

Cellular networks such as long term evolution (LTE) enable Internet of Things (IoT) devices such as vehicles, cameras, drones, and sensors to exchange real-time information with each other [1]. The rapid increase in IoT devices has caused growth in data traffic demands. In addition, scarcity in last-one-mile bandwidth remains a huge issue across cellular networks. Despite this scarcity, the data of delay-sensitive applications must be delivered within a certain deadline constraint. For example, to achieve driving safety systems with cellular networks, the Third Generation Partnership Project (3GPP) stipulates that the information should be delivered within 100 ms [2].

Various deadline-aware schedulers have been proposed to achieve low-latency radio access network systems. One such scheduler can increase the number of packets that is delivered within a certain deadline constraint by considering deadline, data size, and radio quality [3]. The flame level scheduler (FLS) applies control theory to the MAC scheduler to meet the deadline [4]. However, existing deadline-aware schedulers might not deal with model uncertainties of the network systems, which are defined as disturbances in this letter. For example, the throughput of the evolved NodeB (eNB) is determined by a modulation scheme selected on the basis of radio quality between each user equipment (UE) and the eNB. Different eNB vendors select different modulation schemes in accordance with the radio quality, so cellular networks that include the eNBs of multiple vendors tend to have a disturbance in throughput estimation for deadline-aware scheduling.

Maximum bit rate (MBR) control is one of the resource management methods for cellular networks. Ramamurthi et al. [5] proposed an MBR control method to enhance the quality of experience (QoE) in video streaming. This method is conformable to the 3GPP specification and useful for network resource management. However, currently there are no MBR-based resource management methods that support deadline-aware scheduling for cellular networks.

In this letter, we propose a deadline-aware resource management method based on MBR control with a feedback controller for delay-sensitive applications over cellular networks. The proposed method includes a static controller that calculates a target throughput to meet the deadline and a feedback controller that suppresses the disturbances to robustly maintain the effective throughput at the target level. Numerical simulations demonstrate that the proposed method improves the success rate of data delivery within the deadline constraint in the presence of disturbances.

2 MBR control in cellular systems

Figure 1 shows the model of MBR control for an LTE uplink. In this work, we assume that MBR is used to control a cellular system. A multi-access edge
computing (MEC) server calculates the MBR, and when the MEC server advertises the MBR to the policy and charging rule function (PCRF), the PCRF sets the MBR to the cellular system. These functions are modeled as the MBR setting block in Fig. 1.

When UE$_i$ sends a data chunk, the transmission rate of UE$_i$ at the sampling time $k$, $r_i(k)$, is formulated as

$$r_i(k) = \begin{cases} u_i(k) & \text{(If UE$_i$ has a chunk to be transmitted)} \\ 0 & \text{(Otherwise)} \end{cases},$$

where $u_i(k)$ is the MBR reference allocated to UE$_i$ at the sampling time $k$. The effective throughput of UE$_i$ at the sampling time $k$, $\tau_i(k)$, might be a smaller value than the transmission rate of UE$_i$ at the sampling time $k$, $r_i(k)$ if the cellular system has some disturbances, as shown by

$$\tau_i(k) = r_i(k) - d_i(k).$$

A disturbance is considered to cause a difference between the target throughput and the effective throughput. The cellular system might have various disturbances caused by the selection of different modulation schemes, fluctuation of radio quality, and other factors. Ideally, the cellular system should detect all the disturbances and estimate their degrees. However, it is not realistic to consider all possible disturbances, so in this work, we treat the summation of all the disturbances as a total disturbance. The total disturbance in the dimension of throughput for UE$_i$ at the sampling time $k$, $d_i(k)$, is defined as

$$d_i(k) = sd_{1,i}(k) + sd_{2,i}(k) + sd_{3,i}(k),$$

where $sd_{1,i}(k)$, $sd_{2,i}(k)$, and $sd_{3,i}(k)$ denote disturbances caused by the selection of different modulation schemes, fluctuation of radio quality, and other disturbances, respectively.

3 Proposed deadline-aware MBR control

3.1 Static controller

The block diagram of the MBR control system with a static controller is shown in Fig. 2(a). The static controller calculates the target throughput of
UCE_i at the sampling time k, \( \tau^T_i(k) \), needed to meet the deadline. The target throughput of UCE_i at the sampling time k, \( \tau^T_i(k) \), is formulated as

\[
\tau^T_i(k) = \frac{\text{ChunkSize}_i}{\text{Deadline}_i}, \quad (4)
\]

where \( \text{ChunkSize}_i \) and \( \text{Deadline}_i \) are the chunk size of UCE_i and the relative deadline from the time when a new chunk of UCE_i is generated, respectively. In this work, we assume that the deadline is shorter than the interval at which a chunk is generated. The nominal throughput of UCE_i at the sampling time k, \( r_{i,n}(k) \), is defined as

\[
r_{i,n}(k) = \begin{cases} 
\tau^T_i(k) & (t_i \leq \text{Deadline}_i) \\
0 & \text{Otherwise}
\end{cases}, \quad (5)
\]

where \( t_i \) is the elapsed time from the time when a new chunk of UCE_i is generated. We set \( r_{i,n}(k) \) to \( \tau^T_i(k) \) in the interval from when a chunk is generated to its deadline and set \( r_{i,n}(k) \) to zero in the interval from when the deadline of the chunk expires to when the next chunk is generated. When only the static controller is used in the cellular system, as shown in Fig. 2(a), the MBR reference of UCE_i at the sampling time k, \( u_i(k) \), is equal to the output of the static controller, \( r_{i,n}(k) \), as

\[
u_i(k) = r_{i,n}(k). \quad (6)
\]

The cellular system cannot strictly allocate the target throughput because of the disturbance \( d_i(k) \) in the cellular system. The effective throughput is smaller than the target throughput, as shown in (2) and Fig. 2(a). Therefore, MBR control with only the static controller cannot meet the deadline constraints.

### 3.2 Feedback controller

A block diagram of the proposed MBR control system with the static and feedback controllers is shown in Fig. 2(b). The MBR reference allocated to

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**Fig. 2.** MBR control systems of the LTE uplink.
UE$_i$ at the sampling time $k$, $u_i(k)$, is formulated as

$$u_i(k) = K(r_i,n(k) - \tau_i(k - 1)) + u_i(k - 1), \quad (7)$$

where $K$ is a feedback gain.

The feedback controller adjusts the MBR reference $u_i(k)$ by comparing the target throughput $\tau_T^i(k)$ and effective throughput $\tau_i(k)$ to address the throughput degradation caused by the total disturbance $d_i(k)$. The proposed system has the advantage that there is no need to estimate disturbances $d_{1,i}(k)$, $d_{2,i}(k)$, and $d_{3,i}(k)$ separately, which results in a favorable implementation for mobile operators.

4 Numerical simulation

4.1 Simulation setup

We compared the system with only the static controller and the proposed system with the static and feedback controllers by numerical simulations in the presence of disturbances. In these simulations, we assumed there were three UEs connected to the same eNB: UE$_1$, which sent 150-Mb chunks at intervals of 3 s, with its deadline set to 1 s; UE$_2$, which sent 125-Mb chunks at intervals of 4 s, with its deadline set to 2 s; and UE$_3$, which sent 145-Mb chunks at intervals of 5 s, with its deadline set to 3 s. The three UEs shared an uplink whose bandwidth was 300 Mbps. The feedback gain $K$ and the control interval were set to 1 and 100 ms, respectively.

To evaluate robustness to the total disturbance, we compared the success rates by changing the total disturbance. The success rate $\text{SuccessRate}$ is formulated as

$$\text{SuccessRate} = \frac{\sum_i \text{SuccessChunks}_i}{\sum_i \text{TotalChunks}_i}, \quad (8)$$

where $\text{SuccessChunks}_i$ and $\text{TotalChunks}_i$ are the number of chunks meeting the deadline constraint for UE$_i$ during the simulation time and the total number of chunks that UE$_i$ sends during the simulation time, respectively.

The total disturbance is formulated as

$$d_i(k) = (1 - NF(k))r_i(k), \quad (9)$$

where $NF(k)$ is the noise factor (NF) at the sampling time $k$ and follows normal distribution. It is assumed that the range of $NF(k)$ is from 0 to 1.0. Therefore, when $NF(k)$ is more than 1.0, we set $NF(k)$ to 1.0. When $NF(K)$ is less than 0, we set $NF(k)$ to 0.

4.2 Simulation results

The success rate for each interval of NF change is shown in Fig. 3(a). These are the simulation results of two cases where the average of NF ($NF_{ave}$ in the figure) is equal to 0.8 and 1.0 when the standard deviation of NF is equal to 0.1. As shown, the proposed system with the feedback controller achieved a higher success rate than that without the feedback controller for both cases. This is because the feedback controller set the MBR reference by considering
Fig. 3. Simulation results of systems with and without feedback controller (FB).

the throughput degradation caused by the total disturbance. However, even when the feedback controller was used, the shorter the interval of NF change was, the lower the success rate was. This is because the interval of NF change was shorter than the convergence time of the disturbance response.

The success rate for each standard deviation of NF is shown in Fig. 3(b). We set the interval of NF change to 10 s. As shown, the proposed system with the feedback controller achieved a higher success rate than that without the feedback controller for both cases. However, when the feedback controller was used, the larger the standard deviation of NF was, the lower the success rate was. This is because each MBR reference was set to a large value and the summation of each MBR reference exceeded the link bandwidth since the total disturbance was large. On the other hand, when the feedback controller was not used and the average of NF was equal to 0.8, the larger the standard deviation of NF was, the higher the success rate was. This is because, in this situation, total disturbance was frequently equal to zero, as the standard deviation of NF was larger.

5 Conclusion
In this letter, we have proposed a deadline-aware resource management method based on MBR control with a feedback controller to suppress the disturbances caused by model uncertainties of cellular networks. The results of numerical simulations revealed that the proposed method with the feedback controller provided a higher success rate than the method without the feedback controller even in the presence of disturbances. The proposed system has the advantage that there is no need to estimate each disturbance separately, which results in a favorable implementation for mobile operators. The proposed method is suitable for practical use since the use of MBR is conformable to the 3GPP specification.