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Energy-Efficient Mobile Data Uploading from High-Speed Trains

Xiaoqiang Ma · Jiangchuan Liu · Hongbo Jiang

Abstract Recent decades have witnessed the fast development of high-speed railway systems in many countries, which have significantly shortened the travel time between distant cities. Accompanied with this convenience is the challenge for cell phone vendors to provide broadband Internet access for passengers, particularly considering the fast changing channel conditions in high-speed trains and the limited battery of cell phones, which often cannot be re-charged in trains. In this paper, inspired by the unique spatial-temporal characteristics of wireless signals along high-speed railways, we propose a novel energy-efficient scheduling approach for uploading data from cell phones, both with soft deadlines (e.g., documents) and hard deadlines (e.g., video streaming). Our solution effectively predicts the signal strength through its spatial-temporal periodicity in this new application scenario, and smartly adjusts the transmission rate to maximize the overall data transmission rate and yet conserves the energy consumption. Performance evaluation based on realistic railway scenarios and H.264 video traces demonstrate the effectiveness of our solution and its superiority as compared to the existing solutions.

Keywords high-speed railway · energy-efficient uploading

1 Introduction

Recent decades have witnessed the fast development of high-speed railway systems in many countries, such as Japan, France, China and so on (http://en.wikipedia.org/wiki/High-speed_rail). For example, China has already built up the world's longest high-speed rail network with about 7,431 km of routes within only several years. The scale of this network is still growing dramatically (http://en.wikipedia.org/wiki/Highspeed_rail_in_China). The speed of the trains can be as high as 350 km/h and thus the travel time between distant cities has been significantly shortened. Accompanied with this convenience, however, is the challenge to traditional cellular techniques. For example, the handover frequency will be very high without redesigning the base station deployment, leading to increased call blocking rate and call drop rate. The channel properties will change very quickly, which prevent the fast power control in WCDMA from accurately compensating for fading [1]. The Doppler shift will also be significant, which degrades the system performance. Since mobile communication has been an essential part of people's everyday life, cell phone service vendors are required to provide satisfactory quality of service to cell phone users even faced with these challenges.

A lot of work has been done towards overcoming the difficulties mentioned above. Markus [2] outlines the concept of a GSM-based communication system for high-speed Railway (GSM-R) and proposes to make some modifications to the standard GSM system. A

X. Ma · J. Liu (✉)
Computing Science School, Simon Fraser University,
Burnaby, BC, Canada V5A 1S6
e-mail: jcliu@sfu.ca

X. Ma
e-mail: xma10@cs.sfu.ca

H. Jiang
Department of Electronics and Information Engineering,
Huazhong University of Science and Technology,
Wuhan, Hubei, China 430074
e-mail: hongbojiang2004@gmail.com

linear coverage is preferred to area coverage to simplify handover. Frequency compensation is used to eliminate the Doppler shift. In [3], the authors compare the performance of both IS-95 and GSM at high speeds, and conclude that existing systems could work well, albeit with a reduced link budget and certain system management issues. However, they just focus on the quality of voice services and do not examine the influence on fast handover either. In order to provide broadband data services, satellite-to-Wi-Fi links have been combined for Internet access on the TGV trains in France. But this system can only support up to 50 passengers without upgrading existing infrastructure. In United Kingdom, the high-speed trains rely on a combination of satellite and cellular links to provide Internet access. Unfortunately, satellite links have limited bandwidth and long round trip times, which makes it not ideal for real-time and bandwidth-intensive applications [4].

Along with the emergence and maturity of 3G and 3.5G wireless networks, people have ubiquitous high-speed access to Internet. Band-intensive applications, such as video streaming (e.g., Youtube: http://www.youtube.com) and video calling (e.g., Facetime: http://www.apple.com/mac/facetime), increasingly gain popularity on powerful smart phones. Yet when moving with high speed, users would suffer from even severe performance degradation with streaming services [5]. To this end, the GSM Digital Remote RF Units (GRRU) private network [6] has been deployed along the Beijing-Tianjin Intercity Railway. It can provide better communication quality and use fewer handover/reselection compared with existing techniques.

Now we have solutions to improve the channel properties, but we still face another key problem that band-intensive applications consume a large amount of energy on data transmission and thus cell phones will run out of power in a short time. This phenomenon is especially obvious when the signal is weak, since cell phones need to amplify the signal [7]. When mobile users are on high-speed trains, their cell phones will work under fast-changing signal strength, mainly caused by the varying distance between cell phones and base stations. Cell phones need to implement power control on the uplink to compensate for the fading effect such that the received power level at base stations will stay fairly constant [1]. It is intuitive to transmit more data when the signal is strong and less data when the signal is weak. In this paper, we propose an energy-efficient uploading approach for both delay-tolerant and real-time transmission. Our contribution is twofold. We are the first to consider the high-speed railway scenario with channel properties changing very fast. Second, based on the periodicity of channel condition, we propose a conservative transmission strategy to save energy. We verify our approach on H.264 video traces and simulated results show that our strategy is energy-efficient for uploading with both soft deadlines and hard deadlines.

The remainder of this paper is organized as follows, In Section 2, we introduce some related work on energy efficient approaches in wireless and cellular networks. In Section 3, we propose the energy model and system design. We describe our algorithm in Section 4 and present the simulation results on video traces in Section 5. Section 6 gives some discussion and we conclude this paper in Section 7.

2 Related work

Existing techniques can already guarantee high-quality voice services for users at high speed. Yet providing high speed data transmission for people in fast-moving vehicles is still an open issue. The FAMOUS [8] architecture is proposed to offer multimedia services to fast moving users. For the train scenario, the authors propose to combine a Radio-over-Fiber (ROF) network with movable cells. Fokum and Frost [4] present a comprehensive survey of approaches for providing broadband Internet access to trains. They present a taxonomy of architecture according to access network technologies including ROF, IEEE 802.11, satellite and so on. They then compare various implementations in both Europe and North America and summarize the lessons we can learn from.

In the research field of wireless networks, the cross-layer design approach is proposed to achieve better system performance. In a traditional layered scheme, each layer is relatively independent of other layers, which simplifies the protocol design and implementation. However, wireless channel properties are time-varying, caused by fading effects, roaming between heterogeneous networks, variation in moving speed and other factors, which requires the cooperation of different layers to select the optimal transmission strategy [9]. In [10], the authors summarize the challenges and principles of cross-layer wireless multimedia transmission and propose a new paradigm to improve multimedia streaming quality and reduce power consumption. Eric et al. [11] further explore a cross-layer design framework for real-time video streaming in Ad hoc networks.

Signal strength can be viewed as the reflector of current channel properties. If we can predict the signal strength, adjustment can be made in advance. In [12], the authors propose a long range on-line prediction method, which is location-independent. However, they only verify their method at walking speeds, where the signal strength does not change very fast. There have been also related work based on trace analysis [7] and user mobility [13]. Power control is closely coupled with signal strength. It is especially important for uplink to keep the received signal strength level at base stations within slight variation. Without power control, we will see the so-called *near-far problem* in CDMA systems [1]. A lot of previous works have been done to implement efficient and accurate power control [14–16]. However, power control will significantly increase the transmission energy consumption when mobile users are far from base stations. Energy-efficient scheduling is needed, so that more data is transmitted under good channel condition and data transmission rate is reduced when signal strength is weak. This is the basic motivation of our work. We will describe our system design in detail in the next section.

3 System model

3.1 Energy model

In this section, we first establish the energy model in the high-speed railway scenario. We will then use simulation results based on this model to illustrate the motivation in implementing energy–efficient data transmission.

Path loss model, which is important for link budget, has attracted the interest of many researchers. The basic model [17] is as follows:

$$PL(d) = PL(d_0) + 10n \log\left(\frac{d}{d_0}\right) + X_\sigma \tag{1}$$

where $PL(d)$ is the average path loss value at distance d from a measured location to the transmitter; n is the path loss exponent, which depends on the environment; d_0 is the close-in reference distance, and $\overline{PL}(d_0)$ is based on either practical measurements or on a free space path loss model at distance d_0 from the transmitter; X_σ is a zero-mean Ganssian distributed random variable (in dB) with standard deviation σ (also in dB), and is computed from measured data.

The above parameters statistically describe the path loss model. The path loss can be transformed from the measured received signal strength as [18]:

$$P_r(d) = P_t + G - PL(d) - PL_{\text{other}} \tag{2}$$

where $P_r(d)$ and P_t (both in dBm) are the power level of received signal and transmitted signal, respectively; G is the antenna gain and PL_{other} is the attenuation caused by other factors. G and PL_{other} are constants for the same type of base stations.

Equation 1 implies that the large-scale variation of path loss which only depends on the distance from the transmitter. In real life, especially in metropolitan areas with dense buildings, the small-scale fading and multipath effect will cause rapid and significant changes in signal strength over a small travel distance or time interval. However, since most high-speed railways are constructed in suburban and rural areas that can be approximately regarded as open space environment, multipath effect can be largely neglected.

As mentioned in Section 2, power control needs to be implemented on cell phones to compensate for the variation of path loss. The power needed to transmit a bit at distance d is [19]:

$$u(d) = ad^n + c \tag{3}$$

where a and c are constants; n is the path loss exponent. For the sake of simplicity, in the remaining part of this paper, we only consider the former part on the right side of the above equation, ad^n, as the transmission consumption and use $p(d)$ to denote it. In practice, however, the distance can not be directly measured, so cell phones can adjust transmission power based on received signal strength. The ratio of transmission power at different places A and B is then given by:

$$\frac{p(d_A)}{p(d_B)} = 10^{\frac{P_r(d_B)-P_r(d_A)}{10}} \tag{4}$$

where d_A and d_B are the distances from the transmitter at A and B, respectively.

To better illustrate the fast-changing received signal strength and transmission power as well as the relationship between them, we now show a series of simulated results. Our simulation is based on the path loss model in open area in [18], which is measured along the “Zhengzhou–Xi’an” high speed railway environment at the 930 MHz band:

$$P_r(d) = 6.0246 - 21.226 \log(d) \tag{5}$$

The standard deviation of shadowing is chosen as 2.09.

In order to reduce the construction cost and keep trains running at relatively constant speed, the high speed railway is almost a straight line in a considerably long segment. We give the Beijing–Tianjing Intercity Railway as an example in Fig. 1.

This construction strategy simplifies the evaluation of path loss along the railway. In our simulation, we use a straight line to represent a segment of 35 km railway, along which 18 base stations every 2 km have been deployed. The straight distance between each base station and the rail is 150 m. We calculate the received signal

Fig. 1 Beijing–Tianjin Intercity Railway from Google map (http://maps.google.com)

strength every 10 m, and the transmission energy at each location is represented by the ratio of it to the minimum energy consumption along the this segment of rail. We use the ratio rather than an absolute value of power consumption because the ratio is independent of the types of base stations and cell phones that are used, and thus our model can work in general cases.

From Figs. 2 and 3 we can find out that the difference of received signal strength can be as high as 20 dB and the maximum transmission energy is over 100 times more than the minimum. The peaks in Fig. 2 and the troughs in Fig. 3 correspond to the locations with the minimum distance of 150 m to base stations. The relationship is very clear: the cell phones consume much more power on transmitting bits to the base stations when the signal is weak. As such, it is intuitive to design an energy-efficient scheduling method, by which most data can be transmitted when the signal strength is strong. Furthermore, the variations of both signal strength and transmission power are nearly periodic, which makes the signal prediction much easier for the high-speed train scenario.

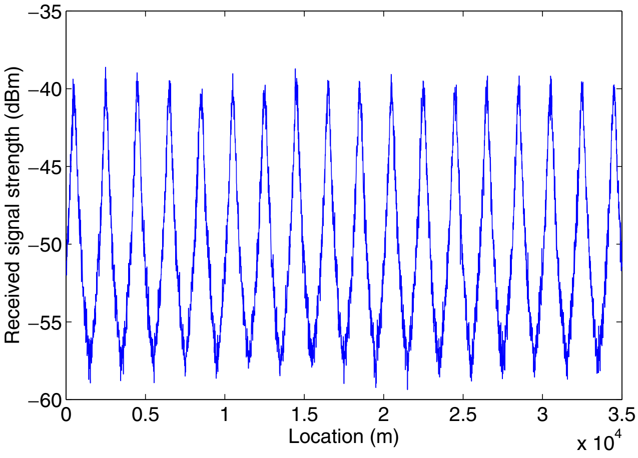

Fig. 2 Received signal strength along the railway

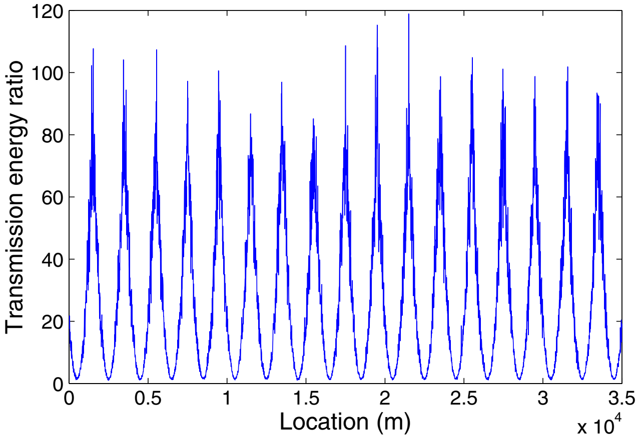

Fig. 3 Transmission energy ratio along the railway

3.2 System design

We now propose our system design based on the previous energy model. The basic idea is that the cell phone first makes on-line prediction of the signal strength based on historical values, and schedules the data transmission according to the application requirements.

As mentioned before, the signal strength changes periodically with location. The reason is that base stations are deployed with equal distance between each other, and the railway is a near straight line in a long segment. Moreover, since trains run at a relatively constant speed, we can also observe this periodicity in the time domain. In our setting, the period is about 20.6 s. Although the above assumptions may not be strictly satisfied in real life, slight deviations will not make much difference to this spatial-temporal periodicity. This periodicity provides us a basic understanding of the structure of channel properties and can be used to predict the signal strength. After collecting the signal strength for a period, this spatial-temporal relationship can be easily computed. In combination with the current received signal strength, we can get an quick evaluation on where we are and what will happen in the future. Then the scheduling strategy for transmission can be

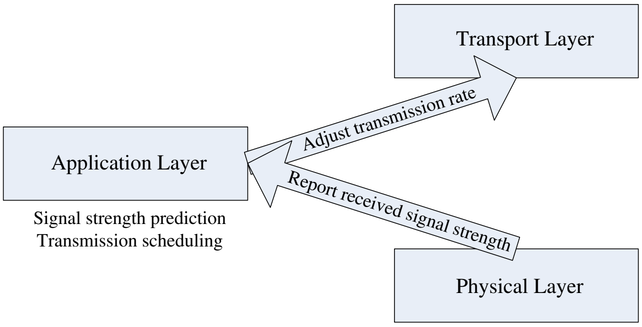

Fig. 4 Framework of our system

figured out. We can slow down the transmission rate when the signal strength is weak to save energy. This can be done in this application scenario because we know in the near future, the signal strength will be much stronger.

The framework of our system is as shown in Fig. 4.

Our system is application-layer centric. It requires the cooperation of the application layer, the transport layer, and the physical layer. The application layer is responsible for predicting the signal strength in the future based on the reports from the physical layer. It then makes a schedule for energy-efficient data transmission, subjecting to the quality of service requirement of specific applications. We will describe our algorithm in detail in Section 4.

4 Algorithm

Our algorithm consists of two parts, namely signal strength prediction and energy-efficient scheduling.

4.1 Signal strength prediction

We assume that the base stations are of the same type, and the environmental conditions have no significant change for a relatively long segment of railway, for example, tens of kilometres. Then the large-scale variation of the signal strength depends only on the distance from the cell phone to its connected base station. The cell phone first collects traces of received signal strength values at a constant frequency (In our experiment, we collected three periods of signal strengths to obtain the statistics such as the mean value and standard deviation). Since the train runs at a relatively constant speed, the period of variation T can be easily computed. Then we can have a coarse evaluation of the signal strength for the future. Suppose the current time is t_1 and the received signal strength is $P(t_1)$, and the average received signal strength at the corresponding time in the collected traces $(t-T,\ t-2T...)$ is $\overline{P(t_1)}$. We can use weighted sum $(1-\alpha)*\overline{P(t_1)}+\alpha*P(t_1)$ as the prediction of the signal strength at time instance t_1+T.

The prediction algorithm is summarized as follows:

Algorithm 1 Signal strength prediction

```
Collect traces of received signal strength for some time
Calculate the period $T$
Calculate the average received signal strength at each point in a period
Use the weighted sum of average value and current value as the prediction value in the next period
Use the current value to refresh the average value
```

By using the above algorithm, the application layer can predict the signal strength in the next few periods and schedule the data transmission to save energy. We will evaluate the prediction accuracy of our algorithm in Section 5.

Accurate signal strength prediction, however, is not enough. There is still another important issue that needs to be clarified. That is, how to decide whether the signal strength is strong or not if we know its exact value. In our system, we use a simple threshold-based method. In Fig. 2, the span of the signal strength is about 20 dB, so the threshold can be set as 10 dB lower than the maximum value (about −49 dB). The energy ratio at the threshold value is 10, which is still low compared to the peak value (nearly 120). As a result, the signal strength with a value larger than this threshold will be considered strong.

4.2 Energy-efficient scheduling

After predicting the signal strength for the future, we now strive to schedule the data transmission to save energy based on the prediction.

We consider two uploading scenarios. In the first scenario, cell phone users want to finish uploading files, for example some pictures or documents, within some time. There is no deadline for any segment of the file. We call this situation as uploading with soft deadlines. In the second scenario, mobile users want to share a movie with his friend. Once starting transmission, each frame or picture of this movie has a deadline. If one frame arrives at his friend's device later than the deadline, it will not be played and will also influence the decoding of some other frames [20]. We refer to this as uploading with hard deadlines. The uploading strategies for these two kinds of applications are different and we present each of them as follows.

Uploading with soft deadlines For a file with a size of N bits and a soft deadline of D seconds, we first calculate the number of periods needed to finish transmission, which is $\frac{D}{T}$. Then during one period, we need to at least upload $\frac{N}{D/T} = \frac{NT}{D}$ bits. Using prediction, we can compute the duration time of strong signal strength, t_s. During t_s, We choose a constant rate, r_s, which is much higher than $\frac{N}{D}$, so that more data can be uploaded with low power consumption. On the other hand, the rate at which we upload when the signal is weak is:

$$r_w = \frac{\frac{NT}{D} - r_s t_s}{T - t_s} \tag{6}$$

In the last period, the remaining time before the deadline is a fraction of the period T, so we have two choices, increasing r_2 in order to finish uploading before the deadline, or still using the energy-efficient strategy regardless of possibility of lateness. We choose the second method to save more energy, which works well for this *soft deadline* scenario.

Uploading with hard deadlines For video streaming, the situation is a bit more complicated. Each frame has its deadline, and if it arrives at a receiver's device later than its deadline, the receiver may experience a severe degradation of quality of experience (QoE) [20]. So in our transmission we try to prevent lateness for each frame's deadline, thus referred to as hard deadlines.

Another fact worthy of noting is that although the play time of each frame is the same, the size of each frame can vary a lot, as illustrated in Fig. 5.

Here we extract the information of the first 8,000 frames from the video traces available at http://trace.eas.asu.edu/tracemain.html. The frame rate is 25 FPS (frames per second) and is encoded in the H.264 video coding standard which provides competitive quality at low bit rates. Details can be found in http://trace.eas.asu.edu/tracemain.html and [21, 22]. The varying frame size with the same play time leads to varying frame bit rates. As a result, we need to dynamically change the transmission rate so that each frame will not miss its deadline, which is the key difference from uploading with soft deadlines.

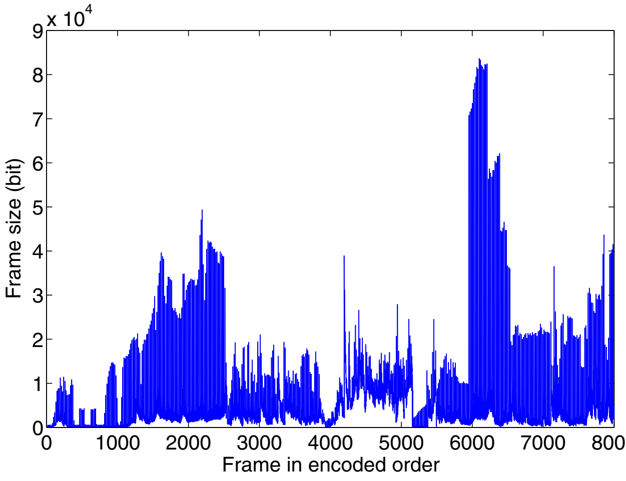

Fig. 5 Frame size of each frame

The transmission algorithm for video streaming is described as follows. We use d to denote the maximum delay that the receiver can tolerate, and d' to denote the propagation delay. For each frame i, we use s_i to denote its size, t_i to denote its starting time for uploading, and d_i to denote its deadline to arrive at the receiver. The minimum rate to transmit it is then:

$$r_i = \frac{s_i}{d_i - d' - t_i} \tag{7}$$

The computation of d_i is based on the structure of the group of pictures (GOP) of the video. For example, suppose that frame j is a B frame, and is followed by frame i that is a P frame in the same GOP. Frame j is encoded after frame i while displayed before frame i. Then the deadline for frame i is given as:

$$d_i = d_j + d \tag{8}$$

However, it is impractical and costly to allocate a particular transmission rate for each frame and the energy model is not taken into consideration, either. Our strategy is that we still upload at rate r_s during t_s (the mean frame bit rate is much less than r_s), and compute the transmission rate when the signal is weak, segment by segment, r_w. The details of our algorithm are as follows:

Algorithm 2 Uploading with hard deadlines

```
While there is frame to upload
    If the signal strength is strong
        Upload at rate $r_s$
    Else if the signal strength is weak
        Calculate the deadlines of follow-up
         frames according to Eq. 8
        Calculate the transmission rates of
         frames follow-up according to Eq. 7
        Find the frame $i$ such that its transmission
         rate $r_i$ is larger than that of its previous
         frames and its follow-up frame
        Upload frame $i$ and its previous frames at
         rate $r_i$
```

There are some points that need to be clarified in the above algorithm. First, it is implemented simultaneously with the signal strength prediction algorithm since we need to decide whether the current signal strength is strong or weak. Second, for the follow-up frames, we need to set a parameter of window size W that represents the number of the follow-up frames to be included into computation. The value of W depends on the deviation of frame size. If the size only changes slightly, we can set it larger; if the size changes significantly, we can set it to a smaller value.

5 Performance evaluation

In this section, we perform simulations to evaluate our algorithms and also give some analysis based on the results. We use the experimental settings mentioned in Section 3. We use Matlab R2010b (http://www.mathworks.com/) as our simulation tool. We ran each experiment ten times, and calculated the mean value and standard deviation for each data point. In the following figures, we plot the mean values associated with errors bars with 95% confidence level.

5.1 Signal strength prediction

We first show the accuracy of our signal strength prediction algorithm. By calculating the relative errors with different choices of α, we can choose the α with smallest error in our following simulation. We use the first three periods of values as the collected traces and calculate the average value at each point. The fourth period is regarded as the current value and is used to predict the corresponding value in the fifth period. α is chosen from 0 to 1 with an interval of 0.125. The simulation results are shown in Fig. 6.

It is clearly that, with $\alpha = 0.25$, the prediction algorithm produces the smallest relative error. Hence, we choose this value in the.

5.2 Uploading with soft deadlines

In this part, we evaluate the performance of our energy-efficient algorithm for uploading with soft deadlines. We assume that a user wants to upload a file with the size of 5 Mbytes within a soft deadline D. We compare our method with a typical strategy that uploads at a maximum constant rate to achieve the best time-efficiency (time-efficient strategy). We set the maximum constant rate to be 256 kbits/s (this rate is also the rate for transmission when the signal is strong).

In our simulation, the soft deadline, D, is set from 180 to 220 s. Here we briefly explain how to compute the energy consumption ratio. As mentioned in Section 3.1, we calculate the received signal strength and energy radio of each location every 10 m. We assume that both the signal strength and energy ratio will not dramatically change during the next 10 m. During data transmission, we can keep track of how many bits of data transmitted and calculate the energy consumption during each interval of 10 m. Therefore, the total energy consumption can be computed by summing up the energy consumption in each interval. The energy consumption ratio in Fig. 7 is the result of the total energy consumption of the time-efficient strategy divided by that of our method. The higher the ratio is, the less energy is consumed.

We can see that the energy consumption decreases with the soft deadline (Fig. 8). The reason is that with

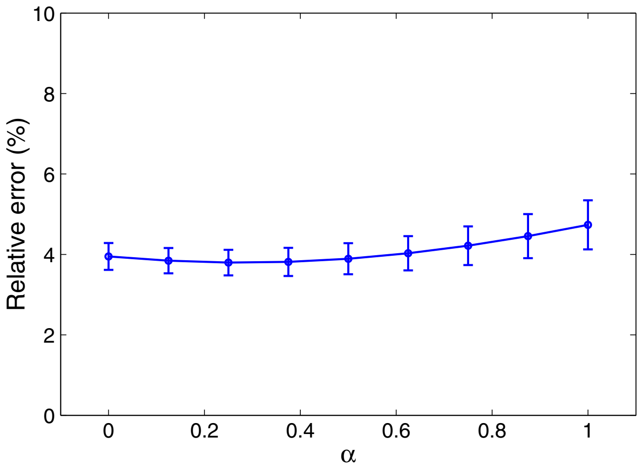

Fig. 6 Relative errors of prediction with different α

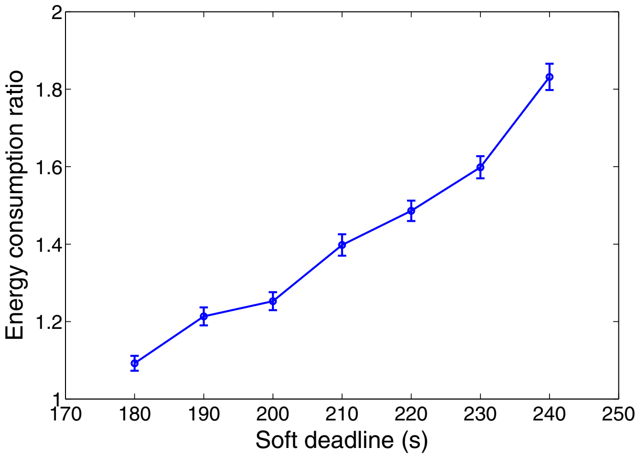

Fig. 7 Energy consumption ratio with different soft deadlines

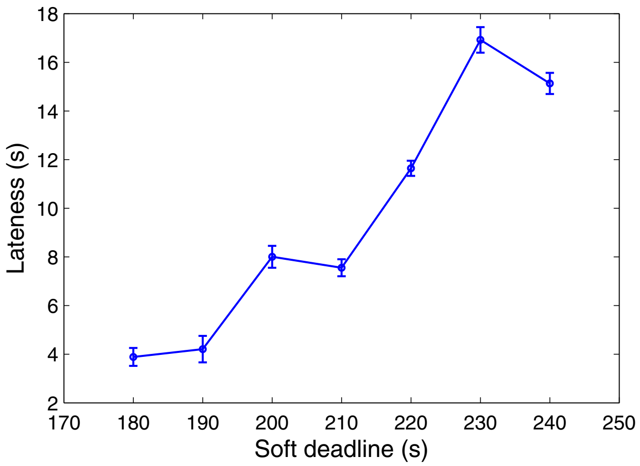

Fig. 8 Lateness with different soft deadlines

larger value of the deadline, r_w will be lower according to Eq. 6, while r_s keeps constant all the time, implying that more data will be uploaded when the signal is strong. As a result, the energy consumption will be less. The lateness that is the actual uploading time minus the corresponding soft deadline, however, increases with the soft deadline, which is also caused by the smaller r_w. The error of prediction can also affect the lateness.

5.3 Uploading with hard deadline

For uploading with hard deadlines, we compare the energy consumption of the proposed Algorithm 2 with the time-efficiency strategy with different delays.

We set the value of the maximum delay d in Eq. 8 that a receiver can tolerate from 1 to 5 s. The simulation results is shown in Fig. 9. The energy consumption ratio is calculated in the same way as mentioned previously.

We notice that the energy consumption ratio increases with the value of delay. The reason is that with a larger value of delay, when the signal strength is weak, the transmission rates of frames will be lower according to Eqs. 7 and 8. A too large delay, however, will increase the delay jitter and cause a discernible degradation of QoE. We find that 3–5 s achieve an appropriate trade-off between the energy consumption and QoE. The ratio is slightly smaller than that for uploading with soft deadlines, because in step 6 of Algorithm 2, we choose a local maximum transmission rate, and so the transmission rates of the previous frames are higher than needed. This overprovision is indispensable in order to prevent from lateness.

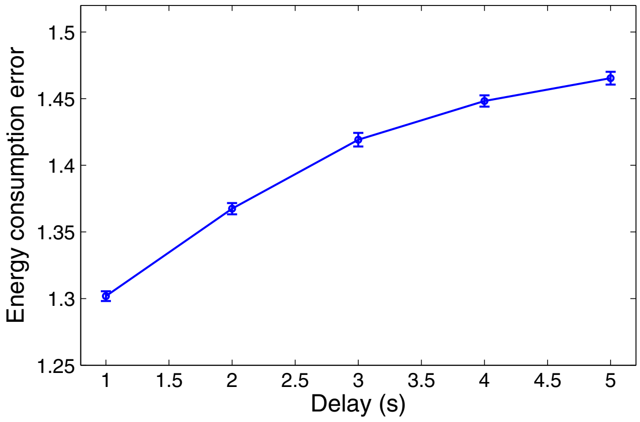

Fig. 9 Energy consumption ratio with different delay requirement

6 Discussion

In this section, we will discuss some practical issues worthy of noting.

First, the speed of trains is not absolutely constant. Instead, it can be increased and decreased, and can also have some fluctuations. The change of speed will affect the accuracy of signal strength prediction. GPS can be used to get the location information. But it consumes a lot of power to track satellites [7]. Moreover, due to the long propagation delay of satellite communication links and the high speed of trains, the error of localization can be very significant. Recently, Constandache et al. [23] propose a novel localization approach for mobile phones, which can be utilized in our system. Electronic compasses and acclerometers, which are readily available in modern cell phones, can also be utilized to figure the location information, which is more energy-efficient and accurate than GPS.

Second, the distance between base stations may not be equal. To solve this problem, the mobile phone users go opposite directions can exchange the location information of base stations and the statistical information of signal strength. This can help to improve the prediction accuracy. These kinds of information can be also saved in base stations and fetched by the passing by cell phones.

At last, the threshold to decide whether a signal is strong or not can be adjusted according to the remaining battery capacity or users' choices. A higher threshold will save more energy but may leads to increased lateness and higher possibility of missing deadlines.

7 Conclusion

The rapid development of high-speed trains raises new challenges to cell phone vendors with respect to QoS management. The limited battery capacity and the increasingly popular bandwidth-intensive and power-hungry applications, such as files sharing and video streaming, attract a lot of researchers to address the power control problem to prolong the battery life. In this paper, by utilizing the construction feature of high-speed railways and the base stations as well as the motion feature of trains, we proposed energy-efficient approaches for uploading with soft and hard deadline. We also proposed an accurate signal strength prediction algorithm to aid our transmission scheduling. In future work, we plan to explore the hierarchical structure of frames to improve our scheduling algorithm for uploading with hard deadline.

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