Location-Aware Dynamic Resource Management
for High-Speed Railway Wireless Communications

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Abstract

With the fast development of high-speed railway (HSR), the demand for mobile communication on high-speed trains is increasingly growing. This leads to significant attention on the study of resource management in HSR wireless communications with limited bandwidth. Resource management is a challenging problem due to heterogenous quality of service (QoS) requirements and dynamic characteristics of HSR wireless communications. In this article, we first provide a state-of-the-art overview on HSR wireless communications and the existing resource management schemes. Then a location-aware cross-layer optimization framework is developed for the dynamic resource management with realistic system model, where the train location information is exploited to facilitate dynamic design. Next we demonstrate the applications of stochastic network optimization theory in solving the dynamic resource management problem in HSR wireless communications. Finally, we highlight some future research directions for location-aware dynamic resource management in the conclusion.

I. INTRODUCTION

For the last two decades, intelligent transportation systems (ITS) have emerged as an efficient way of improving the performance of transportation systems. As an essential element of ITS, high-speed railway (HSR) has been developed rapidly as a fast, convenient and green public transportation system and would become the future trend of railway transportation worldwide. For instance, a high-speed rail plan has been outlined in America and the length of HSR lines in China will reach 18,000 km by 2020 [1]. Meanwhile, the issue of train operation safety has attracted more and more attention. A dedicated mobile communication system called the global
system for mobile communications for railway (GSM-R) was proposed by International Union of Railway (UIC) [2], which serves as a digital standard for railway communications and plays a key role in train operations.

GSM-R has been widely used for HSR communications in the world. However, GSM-R has some major shortcomings, such as insufficient capacity, low network utilization, and limited support for data services [1]. With the demand for HSR communications is increasingly growing, for example, the estimated wireless communication requirement could be as high as 65 Mbps per train [3], GSM-R cannot support such high data rate transmissions. Thus, the long-term evolution for railway (LTE-R) has been determined in the 7th World Congress on High-Speed Rail to be the next-generation communication system for HSR [2]. Broadband wireless communication on trains can enhance the train operation safety by allowing an operations center to monitor real-time train-related data information. In addition to the train control data transmission, LTE-R is also expected to provide passengers services such as Internet access and high-quality mobile video broadcasting. With the benefit of it, passengers can treat their journey as a seamless extension of their working or leisure environment.

To further relieve the contradiction between the increasing demand and limited bandwidth of HSR wireless communications, it is necessary to implement resource management to improve resource utilization efficiency and ensure quality of service (QoS) requirements. Resource management will be a key research challenge in HSR wireless communications, due to the following characteristics:

- **Channel characteristics:** The newly-built HSR routes are mainly composed of wide plain and viaduct, where the line-of-sight component is much stronger than the multipath components, which was confirmed by engineering measurements [3]. This implies that the propagation loss mainly depends on the signal transmission distance, which is directly related to the train location. Furthermore, the signal transmission distance is time-varying due to fast mobility, which further causes the fast-varying wireless channel. Thus, the real-time train location information can be fully used and low-complexity resource management is required to be adaptive to fast-varying wireless channel.

- **Service characteristics:** Multiple types of services are supported on the train, with dynamic characteristics and heterogenous QoS requirements [4]. Considering the dynamic characteristics such as bursty packet arrivals in practical HSR scenario, in order to improve
heterogeneous QoS performance, it is critical and challenging to design intelligent resource management schemes for dynamic service transmission in HSR wireless communications. The issue of prioritization and fairness among different services should be taken into account in developing resource management schemes.

The above characteristics make it challenging to implement resource management for HSR wireless communications. Thus, a new look into the resource management problem in HSR communications is urgently required, where the unique characteristics of HSR communications should be fully taken into consideration.

The rest of this article is organized as follows. An overview of HSR wireless communications is provided in Section II. This is followed by a survey on the existing resource management schemes, including power control, admission control and resource allocation schemes. In Section IV, the location-aware cross-layer optimization framework is developed for dynamic resource management problem in HSR wireless communications, and then we illustrate how to use stochastic network optimization theory to solve such a dynamic optimization problem. The performance evaluation is conducted under realistic conditions of HSR wireless communications in Section V, prior to the conclusion in Section VI.

II. OVERVIEW OF HSR WIRELESS COMMUNICATIONS

A. Network Architecture for HSR Wireless Communications

A proper network architecture is the basis of broadband wireless communications for high-speed trains. A global overview of the network architecture for HSR wireless communications is depicted in Fig. 1. This network architecture is layered and consists of core network, access network and train network [4, 5].

1) Core Network: The core network provides services and data processing for HSR communications, including two major actors: central controller (CC) and content server (CS). The former is responsible for managing network resource and the latter is deployed in order to offload data traffic [6]. In LTE-R system, the core network will be based on an all-IP architecture, which implies that all services will be transmitted on the packet-switched domain.

2) Access Network: The access network is responsible for the data transmission between the fast moving train and the core network. The cellular wireless network is a common one, where base stations (BSs) are deployed along the rail line and provide a seamless coverage.
Some advanced transmission technologies can be used, such as orthogonal frequency division multiplexing (OFDM) and radio-over-fiber (RoF) [7].

3) **Train Network**: Broadband communications on the train are provided through the train access terminal (TAT). This TAT connects to the access network using an antenna mounted on top of the train. The incoming signal from the TAT is then fed to the access point (AP) for passengers wireless access or control elements for the train control.

This network architecture presents numerous advantages for HSR wireless communications,

- Since TAT acts as a transmission relay, penetration loss is avoided. With the help of TAT, the Doppler frequency shift and group handover can be handled easily.
- This architecture not only can provide multimedia services for passenger entertainment, but also can be used for railway signaling to increase railway transportation safety.

**B. Railway Services**

The availability of high-speed broadband connections on trains opens up possibilities for new categories of services. In general, two main groups are identified: critical core services and non-critical services. Critical core services include critical railway communications, train
operational voice and data services. The most common examples are onboard closed circuit television (CCTV) and communication-based train control (CBTC). The non-critical services include passenger experience services and business support services. The onboard multimedia entertainment for passengers has been achieved by an European HSR operator [5]. Some business-related services can be supported, such as remote diagnostics and location-based services.

The future HSR communication system can address both critical and non-critical services. Obviously, the QoS requirements of them are very different. The main requirements for non-critical services include coverage, network capacity and cost requirements, while requirements for critical services are mainly related to reliability, availability, and prioritization. The heterogenous QoS requirements have a significant effect on the resource management for HSR wireless communications.

C. Train Location Awareness

The deterministic train trajectory in HSR communication systems is a unique feature, which represents the location of a train at a specific time [6]. On one hand, since the train moves on a predetermined rail line and the velocity is relatively steady, the train trajectory information can be obtained in advance with high accuracy. On the other hand, many train positioning techniques are applied into HSR communication systems. Some devices are employed by the train to determine its location on the rails, such as global positioning system (GPS) and odometer. Furthermore, the position of the high-speed train can also be periodically calibrated with the balise, which is an electronic beacon or transponder placed between the rails of a railway as part of an automatic train protection system. From the above aspects, the real-time train location information can be obtained to enable efficient resource management.

III. Resource Management in HSR Wireless Communications

With growing demand for QoS features and multi-service support in HSR wireless communications, resource management has become crucial and attracted great attentions [6, 8–13]. The objective of resource management is to utilize the limited network resource such as power and spectrum resource as efficiently as possible for further improvement of system performance. In this section, we provide a comprehensive state-of-the-art review on resource management for HSR wireless communications, from three aspects: power control, admission control and
resource allocation. Some new challenging issues on resource management are introduced for HSR wireless communications.

A. Power Control

Compared with the traditional cellular communications, there are three unique features in HSR wireless communications, i.e., the deterministic moving direction, relatively steady moving speed and the accurate train location information. The data transmission rate is highly determined by transmit power and signal transmission distance, thus these features make it necessary and feasible to implement power control along the time. To achieve different optimization objectives under average power constraint, four power allocation schemes have been proposed in [8]. A constant power allocation scheme is mainly for the purpose of convenience in the engineering implementation. In order to provide a stable transmission rate and achieve the best fairness along the time, much power is used in the channel inversion power allocation scheme to compensate those bad channel states when the train is far from the BS. Similar to the traditional water filling method, the water-filling power allocation scheme can maximum the total transmission rate within one BS, whereas the train will generally suffer from starvation when it is near the cell edge. Finally, the proportional fair power allocation scheme can achieve a trade-off between the total transmission rate and the fairness along the time.

Challenges: Since the above power allocation schemes are determined in advance, when the actual data traffic is low or the channel state is good, the power consumption may be lower than the predetermined power allocation, which results in a waste of energy. Dynamic power control is necessary and should be adaptive to the time-varying channel state and data traffic. Power control will be challenging when considering the QoS requirements such as delay constraint [9]. This is even more difficult due to heterogeneous QoS requirements and fast-varying wireless channels in HSR wireless communications.

B. Admission Control

Admission control is an essential tool for the network congestion in HSR wireless communications, which restricts the access to communication network based on the remaining network resource and the QoS guarantee. In admission control schemes for GSM-R system, an arrival service is accepted or rejected depending on whether the required QoS of the arrival service can
be fulfilled while guaranteeing the required QoS of all on-going services [10]. The call-level QoS performances are considered in circuit-switched GSM-R system, such as call dropping probability and call blocking probability. In addition, handover-based admission control is a feature in HSR wireless communications. If the services are dropped by the next cell when handover occurs, it will cause severe service interruption, thus resource reservation approach is required for prioritizing and protecting handover services [11]. Meanwhile, for the new request services, service priority needs to be considered in admission control, where the highest priority should be given to critical core services.

Challenges: Since LTE-R will become a packet-switched communication system, the packet-level features such as the packet arrival rate, packet queueing delay and packet delivery ratio requirement could be explored to improve the system performance. Furthermore, admission control is conducted based on the network capacity, which is directly related to power control. However, the existing admission control schemes are developed under a constant power assumption. Thus, the significant challenge is how to jointly optimize admission control and power control so as to further improve QoS performance.

C. Resource Allocation

Resource allocation plays an important role in improving resource utilization efficiency and QoS performance. In HSR scenario, the effect of Doppler shift caused by high mobility results in inter-carrier interference, which is obviously not negligible and may degrade system performance. Thus, the resource allocation problem in HSR wireless communications with OFDM technology has attracted great research interest [12]. However, it focuses only on optimizing the physical layer performance metrics such as sum throughput or total transmit power, and the resultant resource allocation schemes are adaptive to the channel condition only. In practical HSR communications, it is necessary to focus on cross-layer optimization, which considers bursty packet arrivals and delay performance in addition to the physical layer performance. The utility-based optimization is an effective way to achieve cross-layer resource allocation. In HSR cellular wireless networks, [4] studies efficient on-demand service delivery problem from a cross-layer perspective. Based on the train trajectory information, the optimal resource allocation problem is formulated to maximize the total utility of delivered services under the service deadline constraints.
**Challenges:** The above works treat the resource allocation problem with the assumption of a constant transmit power. When delivering multiple services between the ground and the train, the total allocated resource is controlled by the instantaneous power consumption. Therefore, it is necessary and challenging to jointly consider the resource allocation among the services and the power control along the time \[13\]. Moreover, there are some dynamic characteristics such as time-varying wireless channel and dynamic service arrivals, which make the resource allocation more challenging.

**IV. Location-Aware Dynamic Resource Management in HSR Wireless Communications**

Dynamic resource management has received little attention in HSR wireless communications due to its design complexity compared with the peer problem with static system model. Considering the dynamic characteristics and train location awareness in piratical HSR scenario, we investigate the location-aware dynamic resource management problem in HSR wireless communications, which can jointly optimize admission control, power control and resource allocation.

**A. System Model**

We develop a general system model for HSR wireless communications when the train travels from an origin station to a destination station at a constant speed \(v\). A slot-based transmission scheme is considered for delivering \(K\) types of service, where the travel time is divided into slots of equal duration \(T_s\). In order to have a tractable model, we make the following assumptions. First, the cellular network can provide seamless coverage and the impact of handover can be ignored. Second, since the transmission rate in the train is sufficiently large, the communication bottleneck lies in the hop from BS to the train, hence we focus our attention on the transmission of this hop. In the following, we present a detailed description on the system model from a perspective of protocol layers, including physical (PHY) layer, media access (MAC) layer, application (APP) layer.

1) **Location-aware PHY Layer Model:** As shown in Fig. \[1\] each BS with height \(h\) in cellular wireless network is located at a vertical distance of \(d_0\) from the rail line with the cell radius \(R\). Given the real-time train location information, the distance between BS antenna and train
\( d(t) \) at slot \( t \) can be obtained based on geometry knowledge. The BS transmit power \( P(t) \) at slot \( t \) is limited by the maximum value \( P_{\text{max}} \) and average value \( P_{\text{av}} \). With the help of location information and according to Shannon’s theorem, the transmission rate at slot \( t \) can be expressed by \( R(t) = W \log_2 \left(1 + \frac{P(t)}{W N_0 d^\alpha(t)} \right) \) bits/s, where \( W \) is the system bandwidth, \( N_0 \) is the noise power spectral density and \( \alpha \) is the pathloss exponent. Suppose that a packet is the fundamental unit of transmission with equal size \( L \) bits, hence the maximum number of transmitted packets at slot \( t \) is \( C(t) = \lfloor R(t) T_s/L \rfloor \), where \( \lfloor x \rfloor \) denotes the largest integer not greater than \( x \).

2) Queue-based MAC Layer Model: In the core network, each CS is equipped with a buffer and can provide one type of service. Therefore, we can see \( K \) queues from the perspective of MAC layer. Let \( Q_k(t) \) denote the number of packets at slot \( t \) in the buffer \( k \). The dynamics of each queue are controlled by admission control and resource allocation actions. Specifically, at each slot, the admission control action \( r_k(t) \) determines the number of packets from the newly arriving packets to be stored into the buffer \( k \). Obviously, the admitted packets can no more than the new arrivals and some packets may be dropped. The resource allocation action \( \mu_k(t) \) determines the number of packets removed from the buffer \( k \) for transmission. Likewise, the allocated packets can not exceed the available packets and some packets will be left in the buffer. In addition, the total number of allocated packets is limited by the link capacity, which is directly controlled by the transmit power.

3) Utility-based APP Layer Model: In the APP layer, the packet arrival process for each service is assumed to be independent and identically distributed across slots. At slot \( t \), the number of new arrival packets of service \( k \) is denoted by \( A_k(t) \), which follows the Poisson distribution with average rate \( \lambda_k \). The utility function \( \phi_k(r) \) is used to describe the relationship between allocated data rate and obtained utility for service \( k \). In general, the utility grows as the allocated rate increases. Equal rate allocation does not provide equal utility, which is interpreted as equal service satisfaction. Moreover, to achieve equal utility, the different rates should be allocated to the services according to their types, which results in more efficient utilization of the network resources. Thus, we consider utility-based resource management instead of rate-based resource management for HSR wireless communications.
B. Location-Aware Cross-Layer Optimization Framework

For clearly illustrating the dynamic resource management problem, we develop a location-aware cross-layer optimization framework in Fig. 2. At the PHY layer, the channel state information (CSI) allows an observation of good transmission opportunity based on the time-distance mapping. At the MAC layer, the queue state information (QSI) provides the urgency of queueing data. At the APP layer, service characteristic information (SCI) is collected to represent the service characteristic, e.g., bursty packet arrivals and rate-utility relationship. The control actions at slot $t$, including power control $P(t)$ and admission control $r_k(t)$ as well as resource allocation $\mu_k(t)$, should be taken dynamically based on CSI from PHY layer, QSI from MAC layer and SCI from APP layer.

Based on the developed framework, the dynamic resource management problem can be stated as: when the train travels along the rail, jointly considering system dynamic characteristics, i.e., the bursty packet arrivals and time-varying wireless channel, the resource management controller determines the optimal control actions to maximize the long-term satisfaction of services under...
the system constraints. Mathematically, from the dynamic optimization perspective, the objective is to maximize a sum of utility function of average data rate $\sum_k \phi_k(\tau_k)$, under the average power constraint, queue stability constraint, and the constraints on control actions mentioned in queue model. In the mathematical model, $\pi$ represents the long-term time average expectation of the quantity $x$.

C. Stochastic Network Optimization Theory for Dynamic Resource Management

Stochastic network optimization theory is a modern theory of analysis, control, and optimization for dynamic networks [14]. It focuses on communication and queueing systems, including wireless networks with time-varying channels, mobility, and randomly arriving traffic. In the following, we illustrate how to solve the formulated dynamic resource management problem using the stochastic network optimization theory, including four steps.

Step 1 (Objective Function Transformation): It is hard to directly solve the problem that involves maximizing a function of time averages. However, the objective function can be equivalently transformed to maximize a single time average of a function $\sum_k \phi_k(\gamma_k)$. This transformation is achieved through the use of auxiliary variable $\gamma_k(t)$ and a virtual queue $Z_k(t)$. The auxiliary variable and admission control action $r_k(t)$ act as the arrival and service rate for the virtual queue, respectively. The equivalence could be established based on Jensen’s inequality.

Step 2 (Average Power Constraint Transformation): To handle average time constraint, another virtual queue $X(t)$ is involved, where $P(t)$ and $P_{av}$ act as the arrival and service rate for this virtual queue, respectively. Based on Lyapunov stability theory, if the virtual queue is stable, then the average power constraint can be satisfied. Thus, the average power constraint can be transformed into a single queue stability problem.

Step 3 (Lyapunov Drift-based Queue Stability): To construct above two virtual queues can facilitate the problem transformation. Next, we define a function $L(t)$ as the sum of squares of backlog in all virtual and actual queues on slot $t$. This is call as Lyapunov function, and it is a scalar measure of queue congestion. Intuitively, if the function is small, then all queues are small, and if the function is large, then at least one queue is large. The Lyapunov drift $\Delta(t)$ denotes the difference in the Lyapunov function from one slot to the next. If control actions are taken every slot $t$ to greedily minimize $\Delta(t)$, then backlogs are consistently pushed towards a lower congestion state, which intuitively maintains queue stability.
Step 4 (Drift-Plus-Penalty based Problem Decompositions): Minimizing the Lyapunov drift can maintain the stability of all virtual and actual queues. However, the objective function has not yet been incorporated. Thus, the control actions should be taken to greedily minimize the drift-plus-penalty expression $\Delta(t) - V \sum_k \phi_k(\gamma_k)$, where $V$ is a non-negative control parameter that represents the weight on how much we emphasize the sum utility maximization. Since the expression $\Delta(t)$ is too complicated to be solved directly, it can be replaced by its upper bound. Then it can be observed that the drift-plus-penalty expression is of separable structure, which motivates us to determine the auxiliary variables $\gamma_k(t)$ and admission control actions $r_k(t)$ as well as resource allocation actions $\mu_k(t)$ in an alternative optimization fashion. Thus, the original problem is decomposed into three subproblems, namely utility maximization, admission control, and resource allocation [15]. All the subproblems are convex problem, which can be solved easily.

D. Location-aware Dynamic Resource Management Scheme

Based on the above problem transformation and decomposition, a location-aware dynamic resource management scheme is proposed as shown in Fig. 3. All system parameters should be initialized before the trip begins. At each slot, the train location information is obtained first, and then three subproblems are solved based on the observation of the CSI, QSI and SCI. At the end of each slot, all virtual and actual queues are updated. This process will be repeated until the train arrives at the destination.

V. PERFORMANCE EVALUATION

We conduct simulation experiments to evaluate the dynamic resource management scheme for HSR wireless communications. Since the admission control is involved, the packet delivery ratio requirement is critical for service’s satisfaction. Thus, we consider the piecewise linear utility function $\phi_k(\gamma_k) = \nu_k \min[\gamma_k, x_k \lambda_k]$ to represent the rate-utility relationship for service $k$, where $\nu_k$ and $x_k$ denote the priority and desired delivery ratio, respectively. As in [6], we consider a synthetic train mobility model. The detailed simulation parameters are summarized in Table I.

Fig. 4(a) and Fig. 4(b) show queue backlog and packet dropped for service 1, respectively. We can see that the queue backlog increases and more packets are dropped when the train locates at the cell edge, although more power is consumed in Fig. 4(c). This is because the long-distance
signal transmission causes large propagation loss. The similar results can be obtained for other services. From the view of user experience, communication interrupt is prone to happen there.

Fig. 5(a) and Fig. 5(b) explore the throughput-backlog tradeoff with different $V$ under the same delivery ratio requirement $x_k = 1$ and different priorities. The average throughput for all service increase with $V$ and the service with high priority gets a large one, while the average queue backlogs are near linearly increasing. Fig. 5(c) illustrates the achieved delivery ratios for the services with different delivery ratio requirements and the same priority $v_k = 10$. Since a

TABLE I
PARAMETERS IN SIMULATION

| Parameter | Description             | Value   | Parameter | Description             | Value   |
|-----------|-------------------------|---------|-----------|-------------------------|---------|
| $P_{av}$  | average power constraint| 35 W    | $P_{max}$ | maximum transmit power  | 45 W    |
| $B$       | system bandwidth        | 5 MHz   | $v$       | constant moving speed   | 100 m/s |
| $L$       | packet size             | 240 bits| $R$       | cell radius             | 1.5 km  |
| $T_s$     | slot duration           | 1 ms    | $d_0$     | distance between BS and rail | 50 m  |
| $\alpha$  | pathloss exponent       | 4       | $K$       | number of services      | 4       |
| $h$       | height of BS antenna    | 50 m    | $\lambda_k$ | packet arrival rate   | 30 packets/slot |

Fig. 3. Location-aware dynamic resource management scheme
large $V$ gives a high priority on throughput, more packets will be admitted into the buffers, thus the large $V$ will result in the improvement of the delivery ratio performance. More importantly, the achieved delivery ratio for each service is close to its desired delivery ratio when $V$ is larger than 10. From Fig. 5, we can conclude that choosing a large $V$ can push the average throughput towards the average arrival rate, and also push the achieved delivery ratio towards the desired delivery ratio requirement. However, it is at the expense of large buffer size.

**VI. Conclusions and Future Work**

This article has provided a literature survey on state-of-the-art resource management schemes for HSR wireless communications, where the admission control, power control, and resource
allocation studied in existing literature are summarized. Since most of the existing work focuses on the static system model due to its simplicity, we have made an initial attempt at establishing an location-aware cross-layer optimization framework for the dynamic resource management with more realistic system model. The stochastic network optimization theory is exploited to solve the formulated dynamic resource management problem. A location-aware dynamic resource management scheme is then developed for practical implementation and its performance is evaluated under realistic conditions of HSR wireless communications.

There are several directions for future work. First of all, more practical channel models, such as the position-based channel model [3], should be taken into consideration into the dynamic resource management scheme. Furthermore, studies on the effects of location uncertainty and small-scale fading are needed to assess performance in practical HSR scenario. Another important issue is the heterogeneous QoS considerations, where providing the precise QoS supports such as queuing delay and reliability requirement needs to be further studied. Additionally, the dynamic resource management to improve the multimedia transmission quality in HSR wireless communications is also an interesting and challenging issue.

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