Received March 17, 2017, accepted May 3, 2017, date of publication May 10, 2017, date of current version June 7, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2702616

Service-Oriented Power Allocation for High-Speed Railway Wireless Communications

TAO LI[1], KE XIONG[2,3], (Member, IEEE), PINGYI FAN[1], (Senior Member, IEEE), AND KHALED BEN LETAIEF[4], (Fellow, IEEE)

[1]Tsinghua National Laboratory for Information Science and Technology, and Department of Electronic Engineering, Tsinghua University, Beijing 100084, China
[2]School of Computer and Information Technology, Beijing Jiaotong University, Beijing 100044, China
[3]National Mobile Communications Research Laboratory, Southeast University, Nanjing 210018, China
[4]Department of Electronic and Computer Engineering, The Hong Kong University of Science and Technology, Hong Kong

Corresponding author: Ke Xiong (kxiong@bjtu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61171064, in part by the National Basic Research Program of China "973 Program" under Grant 2012CB316100(2), and in part by the Open Research Fund of National Mobile Communications Research Laboratory, Southeast University, under Grant 2014D03.

ABSTRACT The rapid development of high-speed railways (HSRs) all over the world is drawing much more attention on high-mobility wireless communication. For the wireless links that connect the passengers on the train to the cellular network, it is very essential to employ an appropriate power allocation strategy to guarantee the reliability and efficiency of information transmission. Therefore, this paper concentrates on evaluating the transmission performance of wireless links in the HSRs and attempting to derive an optimal power allocation strategy of this scenario. Considering the fact that the information transmitted between the train and the base station usually has diverse quality-of-service (QoS) requirements for various services, a QoS-based achievable rate region is utilized to characterize the transmission performance in this paper to instead of traditional single throughput. Based on it, a QoS-distinguished power allocation algorithm is derived to achieve the largest achievable rate region. It is proved that the traditional water-filling algorithm and the channel inverse algorithm can be regarded as two specific cases of this new algorithm. Besides, the robust performance of the proposed strategy is also discussed in detail under a non-uniform motion scenario, and its relative performance loss is evaluated in terms of energy consumption. Finally, we present a typical implementation example in a Rice fading environment when the data rate requirements are prior known.

INDEX TERMS Diverse quality-of-service (QoS) requirements, hybrid information, QoS-based achievable rate region, optimal power allocation algorithm.

I. INTRODUCTION

High speed railways (HSRs) is developing rapidly all over the world in recent years, especially in China, where twenty-two thousand kilometers of HSRs have been already built by the end of January 2017. Consequently, how to provide reliable and efficient information transmission service to connect the passengers on the high-speed train to the cellular network is an important problem that significantly deserve to investigate [1]. HSR communication has been considered as a typical scenario in future 5G systems, as shown in Figure 1, where the HSR users desire the reliable and high data rate wireless communication service to support their various information applications including online shopping, online video, online games and file downloading [1]–[4].

Many key technologies in wireless communication system need to be reconsidered under high mobility scenario, such as channel estimation, synchronization, multiple antenna technique, resource allocation, etc [5]–[8], [10]. For instance, Muneer and Sameer [5] proposed a pilot aided joint estimation technique for carrier frequency offsets and doubly selective channels , and a low complexity turbo equalization scheme for orthogonal frequency division multiple access (OFDMA) uplink systems with high mobility users. A novel Doppler shift estimation algorithm was presented in [6] by exploiting features of HSTs, i.e., regular and repetitive routes and timetables, via field tests. The work in [7] investigated the effect of distributed antenna techniques on the hand-off frequency of wireless communication system in HSRs. The upper and lower bounds of channel capacity of high mobility wireless channel were analyzed in [8] and [9]. Zhang *et al.* [10], [11] explored the system service that a high-speed train can get within the coverage of one base

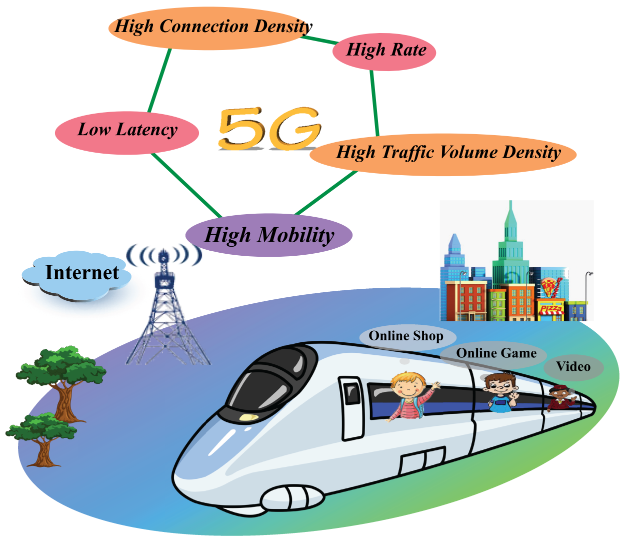

FIGURE 1. High-speed railway communication scenario in future 5G systems.

station, in which some base station deployment strategies were obtained.

Among them, power allocation, one of the most important methods to guarantee the reliability and efficiency of information transmission, is the main problem that this paper will concentrate on. There are a large amount of literatures in this research field. As we know, constant transmit power strategy is optimal in a time-invariant additive white Gaussian noise channel (AWGN) environment [12]. If the channel is time-varying, water-filling algorithm is a better choice in terms of throughput maximization [13]. On the other hand, if the information is sensitive to transmission delay, channel inversion algorithm presented in [14] is optimal. Effective capacity is another powerful method to describe the channel transmission capability for delay limited information transmission [15], [16]. In [17], it investigated the maximal ergodic throughput when outage probability is constrained. Besides, fairness among different users is also an important factor that needs to take into account in multi-user networks [18], [19].

It can be seen that the optimality of specific allocation strategy depends on the specific performance index. Considering the characters of information transmission in HSRs, under the widely used relay-aided two-hop system structure [1], the information transmitted between base station (BS) and access point (AP) is a compounded stream that comes from many different passengers on the train. Generally, different user may have different quality-of-service (QoS) requirement. For example, some person is running FTP download or cache-based information push service, which are sensitive to average rate and tolerated to delay. On the other hand, some passengers may use Voice communication or play interactive games, which are roughly sensitive to delay. That is to say, the hybrid information transmitted between BS and AP is a group of information flows with diverse QoS requirements, such as different data rates and maximal tolerant delays. Similar to the work in [20] that scheduling static and dynamic traffics separately in a data-center network, it is intuitive that better performance may be achieved if the system can provide differentiated service for different information flows based on the specific QoS requirements. As a result, a basic problem is naturally proposed: what is the optimal power allocation strategy for the hybrid information transmission in HSRs?

Based on above considerations, this paper focuses on the hybrid information transmission between BS and AP. Due to the different delay requirements of different information flows, the hybrid information stream is divided into two sub-streams, which are named as delay-sensitive stream and delay-insensitive stream, respectively. To characterize the performance of two information streams with different QoS requirements simultaneously transmission, a QoS-based achievable rate region is utilized as a metric, which can provide more insights for hybrid information transmission in HSRs. Correspondingly, an optimal power allocation strategy, named as QoS-distinguished power allocation algorithm, is derived to achieve the largest achievable rate region. For the robust performance of this new strategy, the performance loss in terms of energy consumption is also evaluated under a non-uniform motion scenario. At last, an implementation example is presented to show how to employ our developed theoretical results into practical system. Besides, it is worth noting that the delay considered here is caused by time variant characteristic of wireless channel. And the coding delay which was discussed in [21] is beyond the scope of this paper.

In summary, the main contributions of this paper can be concluded as follows:

- This paper proposes the basic idea that it is better to provide differentiated service for different information flows based on their QoS requirements. Both theoretical analysis and simulation results show that great improvement can be achieved compared with some traditional homogenous service strategies.
- With the help of conditional capacity function, we obtain an explicit closed-form expression for the optimal power allocation algorithm, which means that the largest achievable rate region can be reached with low implementation complexity.
- The robust performance of the new proposed algorithm under a non-uniform scenario has been analyzed in detail. And the performance loss caused by non-uniform motion is very light when the relative velocity shift is controlled in 1%, which can be achieved easily based on the state-of-art mechanical techniques.
- For providing more insights, an implementation example under a Rice fading environment is presented. The corresponding algorithm to realize the results developed by this paper is given. And the performance improvement of it is discussed in terms of energy consumption when compared with other traditional algorithms.

The rest of this paper is organized as follows. The system structure and wireless channel model are introduced in Section II. Diverse QoS requirements of multiple information flows in HSRs scenario, especially data rate and delay requirements, are presented in Section III. The performance analysis for hybrid information transmission in HSRs is discussed in Section IV, where a service-oriented power allocation algorithm is proposed. The robust performance of the new proposed allocation algorithm is investigated in Section V. An implementation example of our new developed power allocation algorithm is presented in Section VI. Lastly, some conclusions are given in Section VII.

II. PRELIMINARY

A. SYSTEM STRUCTURE AND PARAMETERIZATIONS

Fig. 2 illustrates the system structure diagram for a high speed railway wireless communication system, where BSs are uniformly deployed along one side of the railway with equal interval. The distance between BS and railway is d_0, the height of antenna equipped at each BS is h_0, and the coverage radius of each BS along railway is L. It is assumed in the most parts of this paper that a high-speed train is traveling along the line railway with a constant velocity, denoted as v_0. And the performance under a non-uniform motion scenario will be investigated in detail in Section V.

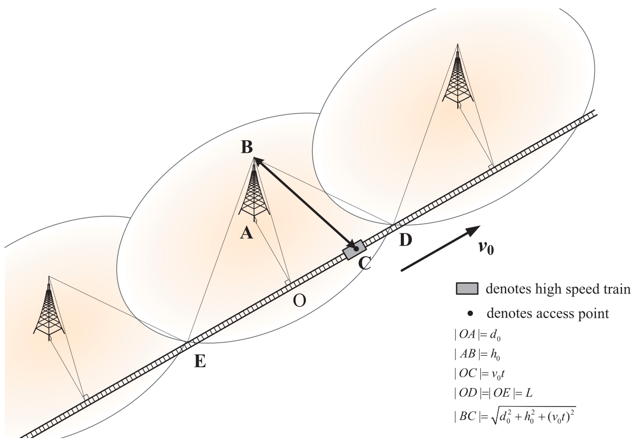

FIGURE 2. The structure diagram for a wireless communication system in high-speed railways that exchanges information between high-speed train and base station.

To avoid serious penetration loss caused by metal carriage and large amounts of handoff operations between adjacent cells, users on the train usually connect to the BS in cellular network with the help of access point (AP), which is installed on the roof of train to construct a two-hop structure. Since transmission process between AP and users on the train is the same as traditional network, some well-developed technologies, such as Wi-Fi, can solve this problem very well. Thus, this paper concentrates on the transmission process between the mobile AP and BS. Provided that AP is equipped with only one antenna, so the train can be regarded as a mobile mass point on the railway. For formulating the problem conveniently, it is assumed that the system time t is equal to 0 when the train passes the point O in Fig. 2. Since transmission process along time is periodic based on the above assumptions, we just need to investigate the information transmission problem under the coverage of one BS, which can reflect all the characteristics of this system. That is to say, the system time range that will be taken into account is $t \in [-\frac{L}{v_0}, \frac{L}{v_0}]$ without any other specific declarations in the sequel. Under above assumptions, the real-time location of train is $v_0 t$ at system time t (where $t \in [-\frac{L}{v_0}, \frac{L}{v_0}]$), and the corresponding transmission distance between BS and AP can be expressed as $d(t) = \sqrt{d_0^2 + h_0^2 + (v_0 t)^2}$, both of which are precisely known by the system.

B. WIRELESS CHANNEL MODEL

Provided that decode-and-forward relay scheme is employed at AP, the channel between AP and BS is equivalent to a typical point-to-point transmission process, since AP can gather the multiple information flows from different users on the train. Let $x(t)$ and $y(t)$ be input and output signals, respectively. Generally, $x(t)$ can be assumed as a stochastic process with zero mean and unit variance. The available frequency bandwidth is B. Then, the baseband-equivalent instantaneous-time model for the channel between AP and BS can be expressed as follows

$$y(t) = \sqrt{P(t)} h(t) x(t) + n(t), \quad (1)$$

where $P(t)$ and $h(t)$ are transmit power and channel fading coefficient at system time t, respectively. $n(t)$ is additive complex cycle symmetric Gaussian noise with zero mean and variance σ_0^2.

The corresponding instantaneous information transmission capacity at system time t is expressed as follows, which can be achieved by Gaussian-type input signal

$$R(t) = B \log_2 \left(1 + \frac{P(t)|h(t)|^2}{\sigma_0^2} \right). \quad (2)$$

It needs to mention that the simple propagation attenuation model [22] is employed in Section IV and Section V. Namely, $h(t) = \sqrt{\frac{G}{d(t)^\alpha}}$, where G denotes constant power gain and α is path loss exponent. Two reasons motivate us to employ this model: 1) Line-of-sight (LOS) component is always dominant in HSRs scenario since majority of HSRs is running over a viaduct in plain area where is in the absence of scatterer [23]–[25]. 2) The main problem that we focus on is to evaluate the performance limits of wireless links between mobile AP and BS when differentiated service is provided for different information flows. In addition, a more complex model in which fasting fading is also taken into account will be employed in Section VI, namely, $h(t) = \sqrt{\frac{G}{d(t)^\alpha}} \beta(t)$, where $\beta(t)$ denotes the small-scale fading coefficient. A specific algorithm will be given to explain how to employ these results developed by this paper under a Rice fast fading environment.

III. DIVERSE QoS REQUIREMENTS IN HSRs SCENARIO

Generally speaking, multiple information flows from different users (or applications) on the train have diverse QoS requirements, such as data rate, maximal tolerated delay,

delay violation probability, etc. As a result, the information transmitted between AP and BS is a hybrid information flow with diverse QoS requirements. With the help of large enough buffer at transmitter, delay violation phenomenon only occurs when practical transmission delay exceeds the maximal tolerated value.

As we know, regardless of the delay requirement, water-filling algorithm is optimal for power allocation in terms of maximizing data rate, while widely used channel inversion algorithm is optimal if the service is sensitive to delay. In fact, the optimality of traditional power allocation algorithm depends on the specific QoS requirement. Namely, water-filling algorithm is optimized with respect to rate while channel inversion algorithm is with respect to delay. Considering the fact that the information transmitted between AP and BS is a hybrid version that has diverse QoS requirements, traditional algorithms cannot keep optimal in this new scenario, which motivates us to propose a QoS-based allocation algorithm to match with this kind of information.

Specifically, assuming N different information flows need to be transmitted between the mobile AP and BS as shown in Fig. 2, we denote the vectors of data rate requirements and maximal tolerated delays as $\mathbf{R} = (R_1, R_2 ... R_N)$ and $\tau = (\tau_1, \tau_2 ... \tau_N)$, respectively. For simplicity, we consider it as two classes of information flows. For the i-th information flow, if $\tau_i \geq \frac{2L}{v_0}$ ($\frac{2L}{v_0}$ is the operation period of HSR), it is classified as delay-insensitive information since we can wait for the next peak $R(t)$ to transmit it effectively without delay violation. Otherwise, if $\tau_i < \frac{2L}{v_0}$, we refer it to as delay-sensitive information, which needs to be transmitted immediately to avoid delay violation. Thus, the hybrid information flows between AP and BS can be divided into two sub-streams based on the delay requirements, i.e., delay-insensitive stream and delay-sensitive stream. Let the sums of data rate requirements for delay-insensitive and delay-sensitive information streams among the N information flows be R_{di} and R_{ds}, respectively. Under above assumptions, they can be given by

$$R_{di} = \sum_{\{i|\tau_i \geq \frac{2L}{v_0}\}} R_i, \quad R_{ds} = \sum_{\{i|\tau_i < \frac{2L}{v_0}\}} R_i. \tag{3}$$

For hybrid information with diverse QoS requirements in HSRs under uniform motion state, it is natural that data rate pair (R_{di}, R_{ds}) is a better metric than traditional unique capacity parameter, to provide more insight of channel characteristic. When the average transmit power is constrained at transmitter, it is apparent that there exists a tradeoff between R_{di} and R_{ds}. As a result, we give the definition of QoS-based achievable rate region Ψ to characterize the system performance limits of wireless communication channel in HSR scenario.

Definition 1: QoS-based achievable rate region Ψ is defined as the convex hull of all feasible delay-insensitive information rate and delay-sensitive information rate pair (R_{di}, R_{ds}) under the average transmit power constraint.

IV. PERFORMANCE ANALYSIS FOR INFORMATION TRANSMISSION IN HSRs SCENARIO

This section will investigate the information transmission limits of the system shown as in Fig. 2, namely to obtain the expression for the boundary of achievable rate region Ψ and the corresponding optimal power allocation algorithm. To serve as baselines, two traditional allocation algorithms that correspond to two extreme cases, either R_{di} or R_{ds} is equal to zero, will be presented firstly. Then, the expression of QoS-based achievable rate region in HSRs will be derived with the help of conditional capacity function. Lastly, some simulation results and comments will be given.

A. SEVERAL TRADITIONAL POWER ALLOCATION ALGORITHMS

For the extreme case that $R_{di} = 0$, it means all information to transmit is delay-sensitive, which corresponds to the maximal achievable value of R_{ds}, denoted as $R_{ds}^{\max}$. Provided that average transmit power is P_0, $R_{ds}^{\max}$ can be modeled as the solution to the following optimization problem.

$$R_{ds}^{\max} = \max_{P(t)} \min \left\{ R(t) \middle| t \in [-\tfrac{L}{v_0}, \tfrac{L}{v_0}] \right\} \tag{4}$$

$$\text{s.t.} \quad \frac{v_0}{2L} \int_{-\frac{L}{v_0}}^{\frac{L}{v_0}} P(t)dt \leq P_0 \tag{5}$$

Lemma 1 (Channel Inversion Algorithm): When R_{di} is 0, the maximal achievable value of R_{ds} is

$$R_{ds}^{\max} = B \log_2 \left(1 + \frac{GP_0 \cdot \frac{2L}{v_0}}{\sigma_0^2 \int_{-\frac{L}{v_0}}^{\frac{L}{v_0}} d(t)^{\alpha} dt} \right), \tag{6}$$

where

$$P_{ci}^{*}(t) = \frac{d(t)^{\alpha} \sigma_0^2}{G} \left(2^{\frac{R_{ds,max}}{B}} - 1 \right), t \in \left[-\tfrac{L}{v_0}, \tfrac{L}{v_0} \right]. \tag{7}$$

Proof: Substituting (2) into (4), based on the optimization method in [14], the expression of $P^{*}(t)$ can be obtained, which is shown in (7). Then, substituting (7) into (5), the result in (6) can be obtained through some manipulations. ■

For the case that $R_{ds} = 0$, it means that all the transmitted information is insensitive to transmission delay. The maximal achievable value of R_{di}, denoted as $R_{di}^{\max}$, can be modeled as the solution to the following problem.

$$R_{di}^{\max} = \max_{p(t)} \left\{ \frac{v_0}{2L} \int_{-\frac{L}{v_0}}^{\frac{L}{v_0}} R(t)dt \right\} \tag{8}$$

$$\text{s.t.} \quad \frac{v_0}{2L} \int_{-\frac{L}{v_0}}^{\frac{L}{v_0}} P(t)dt \leq P_0 \tag{8a}$$

Lemma 2 (Water-Filling Algorithm): When R_{ds} is 0, the maximal achievable value of R_{di} is

$$R_{di}^{\max} = \frac{v_0}{2L} \int_{-\frac{L}{v_0}}^{\frac{L}{v_0}} B \log_2 \left(1 + \frac{GP_{wf}^{*}(t)}{d(t)^{\alpha} \sigma_0^2} \right) dt, \tag{9}$$

where (λ_1 is a constant value determined by average transmit power constraint in (8a))

$$P^*_{wf}(t) = \frac{B}{\lambda_1} - \frac{d(t)^\alpha \sigma_0^2}{G}, t \in \left[-\frac{L}{v_0}, \frac{L}{v_0}\right]. \tag{10}$$

B. PROBLEM FORMULATION FOR HYBRID INFORMATION TRANSMISSION IN HSRs

For the general case in which neither R_{di} nor R_{ds} is zero, it is obvious that the rate pair (R_{di}, R_{ds}) is located within the two-dimensional region $[0, R_{di}^{\max}] \times [0, R_{ds}^{\max}]$. Two objective functions R_{di} and R_{ds} should be considered together, which is a typical multi-objective optimization problem. That is to say, the main task in this subsection is to maximize the achievable rate region under the total average transmit power constraint.

Since the QoS requirement of delay-sensitive information stream is more rigorous than that of delay-insensitive information stream, R_{ds} should be given priority in time-variant scenario. Thus, in order to obtain the boundary line of QoS-based achievable rate region, the basic idea of our method to explore it is to maximize the delay-insensitive average information rate R_{di} with the limited average transmit power constraint after the delay-sensitive average information rate requirement R_{ds} has been satisfied. In order to make the discussion in the sequel more clear, we give the definition of conditional capacity function as follows.

Definition 2: conditional capacity function $C_{R_{ds}}$ is defined as the maximal achievable value of delay-insensitive average information rate R_{di} when transmit power is constrained to P_0 and delay-sensitive information rate is constrained to R_{ds}.

According to the Definition 2, the QoS-based achievable rate region can be expressed as

$$\Psi = \{(R_{di}, R_{ds}) | 0 \leq R_{ds} \leq R_{ds}^{\max}, 0 \leq R_{di} \leq C_{R_{ds}}\} \tag{11}$$

Provided that the average transmit power is P_0, when the delay-sensitive transmission rate requirement is R_{ds}, the optimization problem for $C_{R_{ds}}$ can be model as

$$C_{R_{ds}} = \max_{P(t)} \left\{ \frac{v_0}{2L} \int_{-\frac{L}{v_0}}^{\frac{L}{v_0}} [R(t) - R_{ds}]\, dt \right\} \tag{12}$$

$$\text{s.t.} \quad \frac{v_0}{2L} \int_{-\frac{L}{v_0}}^{\frac{L}{v_0}} P(t) dt \leq P_0 \tag{12a}$$

$$R(t) = B \log_2 \left(1 + \frac{GP(t)}{d(t)^\alpha \sigma_0^2}\right) \tag{12b}$$

$$R(t) \geq R_{ds} \geq 0, t \in [-\tfrac{L}{v_0}, \tfrac{L}{v_0}] \tag{12c}$$

where the constraint (12a) denotes average transmit power constraint, the constraint (12b) denotes instantaneous information transmission throughput at system time t, and the inequality in (12c) denotes the constraint of real-time (delay sensitive) information data rate requirement.

C. PROBLEM SOLVING

Proposition 1: When average transmit power is P_0 and data rate requirement for delay-sensitive information is R_{ds}, the conditional capacity function $C_{R_{ds}}$ can be expressed as

$$C_{R_{ds}} = \frac{v_0}{2L} \int_{-\frac{L}{v_0}}^{\frac{L}{v_0}} \left[B \log_2 \left(1 + \frac{GP^*_{hb}(t)}{d(t)^\alpha \sigma_0^2}\right) - R_{ds} \right] dt. \tag{13}$$

The corresponding optimal power allocation algorithm $P^*_{hb}(t)$ is

$$P^*_{hb}(t) = \left(\frac{d(t)^\alpha \sigma_0^2}{G} \left(2^{\frac{R_{ds}}{B}} - 1\right), \frac{B}{\lambda_2} - \frac{d(t)^\alpha \sigma_0^2}{G} \right)^+, \quad t \in \left[-\frac{L}{v_0}, \frac{L}{v_0}\right], \tag{14}$$

where operation $(x_1, x_2)^+$ denotes the larger one between x_1 and x_2, λ_2 is a constant value which is determined by the average power constraint in (12a). *Proof:* See the Appendix A. ■

For description convenience, the power allocation strategy described in (14) is called as service-oriented power allocation algorithm. In the new proposed algorithm, delay-sensitive information transmission requirement is considered separately with the delay-insensitive information, which makes the system more efficient in the respect of hybrid information transmission. Besides, according to the (14), it can be observed that $P^*_{hb}(t)$ will degrade to channel inversion algorithm $P^*_{ci}(t)$ when R_{ds} is equal to $R_{ds,max}$ and $P^*_{hb}(t)$ will degrade to water-filling algorithm $P^*_{wf}(t)$ when R_{ds} is equal to 0. Consequently, channel inversion algorithm and water-filling algorithm can be regarded as two extreme cases of the results in (14). That is to say, the service-oriented power allocation algorithm, bridging the gap between traditional water-filling algorithm and channel inversion algorithm, is a more efficient method to improve the transmission performance of hybrid information flows with diverse QoS requirements.

D. SIMULATION RESULTS AND COMMENTS

Some simulation results will be given in this subsection to illustrate the superiority of the service-oriented power allocation algorithm developed by this paper compared with other conventional algorithms. For the system shown in Fig. 2, it is assumed that the distance between BS and railway d_0 is 2 m, the height of antenna at BS h_0 is 10 m and the coverage radius of each BS along railway L is 500 m. The velocity of high-speed train v_0 is 100 m/s (e.g. 360 km/h). The antenna gain G is 1, path loss exponent α is 2 and the bandwidth of frequency B is 20 MHz. We will compare the transmission performance of different power allocation strategies in terms of QoS-based achievable rate region with average transmit power constraint.

Fig. 3 plots the simulation results when the average signal to noise ratio (SNR) P_0/σ_0^2 is 30 dB, which presents the performance of four different algorithms: constant power algorithm, channel inversion algorithm, water-filling algorithm and service-oriented allocation algorithm. It can be seen from Fig. 3 that the new proposed algorithm is superior to any other algorithms. Constant power algorithm is not optimal for all cases due to the time-varying characteristic of

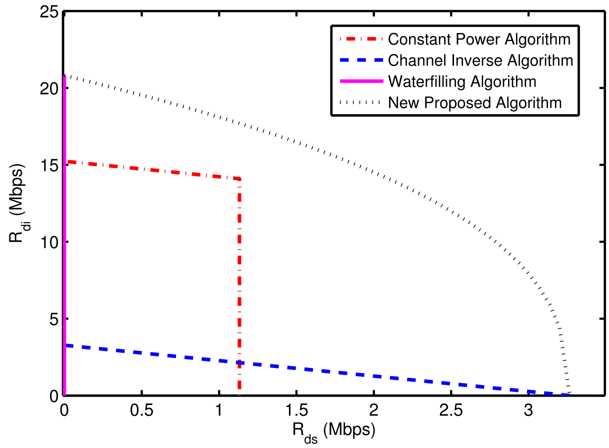

FIGURE 3. The QoS-based achievable rate regions under four different power allocation strategies when average signal to noise ratio P_0/σ_0^2 is 30dB, which contains: constant power algorithm, channel inversion algorithm, water-filling algorithm and service-oriented allocation algorithm.

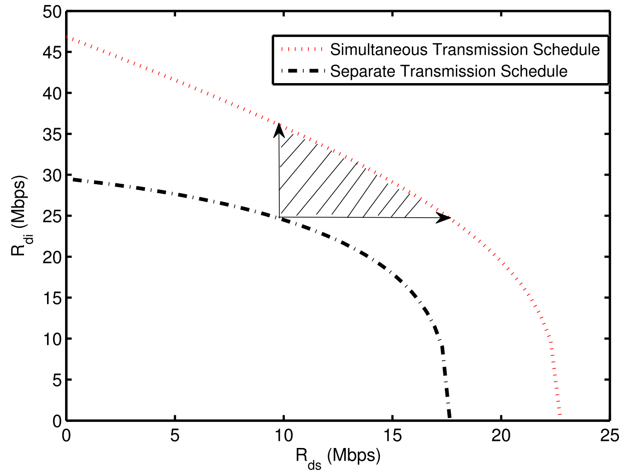

FIGURE 4. The achievable rate regions under simultaneous transmission schedule and separated transmission schedule, respectively, when there are two available channels and the total average SNR P_0/σ_0^2 is 40 dB.

channel, which accords with the intuition. Channel inversion algorithm is optimal if and only if $R_{di} = 0$, and water-filling algorithm is optimal if and only if $R_{ds} = 0$. service-oriented allocation algorithm bridges the gap between channel inversion algorithm and water-filling algorithm, and provides the largest achievable rate region. The achievable rate region in other traditional algorithms is just a subset of that in service-oriented power allocation algorithm.

It has been demonstrated that new proposed power allocation algorithm is the most powerful strategy when both delay-sensitive and delay-insensitive information streams are simultaneously transmitted over the same wireless channel. Then, as a comparison, we consider another case in which two sub-channels are available, denoted as *sub-channel A* and *sub-channel B*, respectively. Each of the channels has the same parameters as stated for Fig. 3. In fact, we can also construct two sub-channels by dividing one channel into two by multiplex technique in certain domain, such as frequency division multiplex (FDM) or time division multiplex (TDM). In this case, a simple but widely used scheduling is to transmit different information streams over different sub-channels, respectively, which is called as separate transmission schedule. For example, *sub-channel A* loads the delay-sensitive information stream while *sub-channel B* loads the delay-insensitive information stream. That is, each channel is loaded with service with unique QoS requirement, and traditional optimal power allocation strategy is available once again. Channel inversion algorithm is adopted for power allocation in *sub-channel A* while water-filling algorithm is used for power allocation *sub-channel B*. According to above considerations, a basic problem will be proposed naturally: compared with the separate transmission schedule as introduced above, whether simultaneous transmission schedule with service-oriented power allocation algorithm can still obtain a better choice?

Fig. 4 plots the simulation results under simultaneous transmission scheduling and separated transmission scheduling in terms of achievable rate region when there are two available sub-channels and the total average SNR P_0/σ_0^2 is 40 dB. In simultaneous transmission scheduling, the transmit power is optimized based on QoS requirements by the service-oriented allocation algorithm. On the other hand, in separated transmission scheduling, water-filling algorithm is used for the channel that loads delay-insensitive information flow while channel inversion algorithm is used for the channel that loads delay-sensitive information flow. It can be seen from Fig. 4 that the performance of simultaneous transmission scheduling is apparently better than that of separated transmission scheduling in terms of achievable rate region. For example, 10 Mbps delay-sensitive information and 25 Mbps delay-insensitive information can be transmitted under separated transmission scheduling between BS and AP at the same time. Whereas, if simultaneous transmission scheduling with QoS-based power allocation is employed, the system can work under arbitrary possible point inside the shaded area shown in Fig. 4, in which both R_{di} and R_{ds} are larger than these in separated transmission scheduling, to achieve a better transmission performance. Specifically, 7.5 Mbps more delay sensitive information or 12 Mbps delay-insensitive information can be transmitted with the same average transmit power constraint. Even for the extreme case, such as $R_{ds} = 0$, simultaneous transmission scheduling is better than separated scheduling, the performance gain is nearly 57% with respect to throughput. It is because that all degree of freedom in wireless channel can be made full use in simultaneous transmission scheduling, which is great helpful to improve system performance. In summary, simultaneous transmission scheduling is a good choice even when there are multiple available channels.

V. ROBUST PERFORMANCE DISCUSSION IN A NON-UNIFORM MOTION SCENARIO

For the case that high-speed train travels along a line railway with a constant velocity, the transmission performance limit and corresponding optimal power allocation algorithm have been already derived. However, it is very difficult to keep ideal uniform motion in practical system. The generalized case is that the instantaneous traveling speed is always a stochastic process which varies along time within a limited range. Thus, this section attempts to analyze the robust performance of service-oriented power allocation strategy in the non-uniform motion scenario, and discusses the performance loss of it compared with ideal uniform motion scenario. Firstly, we formulate the problem for non-uniform motion scenario in terms of achievable rate region, where some constraints that the instantaneous velocity needs to meet are given. Though a universal case can not be obtained, we consider the worst case based on the principle of minimizing energy consumption to serve as the lower bound for system transmission performance in non-uniform motion scenario, and the performance loss is analyzed in terms of both achievable rate region and energy consumption.

A. FORMULATING THE PROBLEM

In practical HSR system, the whole train is accurately controlled by a servosystem. However, due to some non-ideal factors of system, the practical instantaneous speed of the train is usually time varying around the mean value so that $v(t)$ should be modeled as a stochastic process. Before formulating the problem, we need to consider the characteristics of $v(t)$, which will play an important role in the following discussion.

Provided that the mean value of $v(t)$ is v_0, most of all, $v(t)$ should be limited within a small range in normal running state, to guarantee the operation security. Secondly, the running time of each high-speed train must be coincide with time table strictly. So it is reasonable to assume that the average time that the train takes to pass through the whole coverage of one BS is equal to $\frac{2L}{v_0}$, since driver has enough time to control the train to meet the operation time requirement during this period. Thus, considering the operation characteristics of practical HSRs, $v(t)$ under normal operation state must satisfy the following constraints.

CONSTRAINT 1

The instantaneous speed $v(t)$ cannot exceed the maximum limit allowed by the system, which is expressed as

$$v(t) \in [v_0 - \Delta v, v_0 + \Delta v], \tag{15}$$

where Δv denotes the maximum allowable shift of instantaneous speed, the value of which is usually very small compared with v_0. For example, the value of ratio $\Delta v / v_0$ in HSRs connecting Beijing and Shanghai in China is less than 1%.

CONSTRAINT 2

The average speed during the coverage of each BS must be strictly equal to the mean value

$$\frac{v_0}{2L} \int_{-\frac{L}{v_0}}^{\frac{L}{v_0}} v(t)dt = v_0. \tag{16}$$

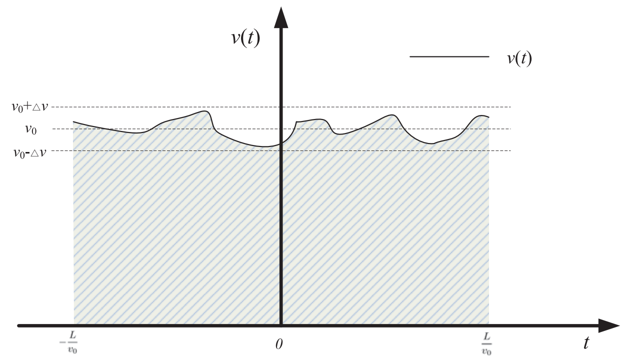

FIGURE 5. An example for instantaneous speed realization $v(t)$ that meets the constraints in (15-16).

For description convenience, it is assumed that the system time is $t = -\frac{L}{v_0}$ at the moment that the train passes through the point E in Fig. 2. Since the average value of $v(t)$ is fixed to v_0, combining the above constraint in (16), the system time period that the train travels from the point E to point D is still $[-\frac{L}{v_0}, \frac{L}{v_0}]$. So the information flow classification method for (R_{di}, R_{ds}) presented in Section III is still reasonable in non-uniform motion scenario. Thus, we can still focus on the performance analysis during the period $t \in [-\frac{L}{v_0}, \frac{L}{v_0}]$ from a perspective of QoS-based achievable rate region, which can reflect all the characteristics of system. The corresponding transmission distance at system time t is

$$d(t) = \sqrt{d_0^2 + h_0^2 + (\int_{-\frac{L}{v_0}}^{t} v(\tau)d\tau - L)^2}, \ t \in \left[-\frac{L}{v_0}, \frac{L}{v_0}\right]. \tag{17}$$

Fig. 5 illustrates an example for the instantaneous speed realization $v(t)$, which is varying along time between the two extreme lines $v(t) = v_0 - \Delta v$ and $v(t) = v_0 + \Delta v$. The integration of $v(t)$ with respect to time during the period $t \in [-\frac{L}{v_0}, \frac{L}{v_0}]$ in the shadow region is equal to $2L$ according to the constraint in (16).

As a result, both $d(t)$ and $R(t)$ are stochastic functions with respect to $v(t)$. Let the set Γ denote all possible distribution for the train's instantaneous speed $v(t)$ that meet the constraints in (15-16). Under the non-uniform motion case, the system performance is limited by the infimum over all possible realization of velocity to guarantee the QoS requirements. The problem that solve the expression of conditional capacity function in this case can be written as the following optimization problem.

$$C_{R_{ds}} = \min_{v(t)\in\Gamma} \left\{ \max_{P(t)} \left\{ \frac{v_0}{2L} \int_{-\frac{L}{v_0}}^{\frac{L}{v_0}} [R(t) - R_{ds}]\, dt \right\} \right\} \tag{18}$$

$$\text{s.t.} \quad R(t) = B \log_2 \left(1 + \frac{GP(t)}{d(t)^{\alpha} \sigma_0^2} \right), \tag{18a}$$

$$\frac{v_0}{2L} \int_{-\frac{L}{v_0}}^{\frac{L}{v_0}} P(t)dt \le P_0, \tag{18b}$$

$$0 \le R_{ds} \le \min_{v(t)\in\Gamma} \{R(t)\},\ t \in \left[-\frac{L}{v_0}, \frac{L}{v_0}\right], \tag{18c}$$

$$v(t) \in [v_0 - \Delta v, v_0 + \Delta v], \tag{18d}$$

$$\frac{v_0}{2L}\int_{-\frac{L}{v_0}}^{\frac{L}{v_0}} v(t)dt = v_0. \tag{18e}$$

Though it is very difficult to obtain an universal generalized solution to the problem in (18), we can investigate the lower bound performance of this system based on a deterministic worst case realization of $v(t)$, which will be introduced in the next subsection. Besides, it needs to mention that the robust performance analysis in this section focuses on the mismatch between non-uniform motion and service-oriented power allocation algorithm, not the performance loss caused by instantaneous speed estimation error. Since the transmission speed of feedback information from train is much faster than the variation rate of instantaneous speed, it is reasonable to assume that the control center at base station still can track the variation of instantaneous speed very well in this case.

B. PERFORMANCE ANALYSIS BASED ON A DETERMINISTIC WORST CASE

As is shown in Fig. 5, $v(t)$ can be arbitrary time-domain function that meets the above two constraints in (15-16). This subsection will propose a deterministic worst case for instantaneous speed realization in terms of energy consumption minimization, to serve as a lower bound for the system performance of the general case.

Proposition 2: The deterministic worst case for $v(t)$ realization that satisfies the constraints in (15-16) is a two-value function, which is expressed as the Eqn. (19). Namely, HSR runs with the lowest allowable speed $v_0 - \Delta v$ in the far region of base station coverage while runs with the highest allowable speed $v_0 + \Delta v$ in the near region.

$$v(t) = \begin{cases} v_0 - \Delta v, & \text{if } t \in [-\frac{L}{v_0}, -\frac{L}{2v_0}] \cup [\frac{L}{2v_0}, \frac{L}{v_0}], \\ v_0 + \Delta v, & \text{if } t \in [-\frac{L}{2v_0}, \frac{L}{2v_0}]. \end{cases} \tag{19}$$

Proof: See Appendix B. ∎

An intuitive proof of it is also given here to describe this problem more clear. Informally speaking, from a perspective of information transmission within a cell coverage, it is intuitive that the position on the railway that is far away from base station is more adverse for information transmission than the position that is near to base station on the railway due to great path loss. Since the total time that a train takes to pass through a base station coverage is fixed due to the constraint (16), it is better to spend more time in the region near to base station while spending less time in the region far from base station. Inversely, we can obtain a deterministic worst case of $v(t)$ realization for information transmission in HSRs, which is presented as Proposition 2.

Substituting the expression of the deterministic worst case shown in (19) into the problem in (18), the stochastic process of $v(t)$ can be removed by introducing the deterministic worst case, which is very helpful for the problem solving in (18). Thus, similar to the results in Proposition 1, the conditional capacity function $C_{R_{ds}}$ in this case can be expressed as

$$C_{R_{ds}} = \frac{v_0}{L}\int_0^{\frac{L}{2v_0}} \left[B\log_2\left(1 + \frac{GP_b^*(t)}{d_1(t)^\alpha \sigma_0^2}\right)\right]dt + \frac{v_0}{L}\int_{\frac{L}{2v_0}}^{\frac{L}{v_0}} \left[B\log_2\left(1 + \frac{GP_b^*(t)}{d_2(t)^\alpha \sigma_0^2}\right)\right]dt - R_{ds} \tag{20}$$

where

$$d_1(t) = \sqrt{d_0^2 + h_0^2 + [(v_0 + \Delta v)t]^2} \tag{21a}$$

$$d_2(t) = \sqrt{d_0^2 + h_0^2 + [(v_0 - \Delta v)t + \frac{\Delta v}{v_0}L]^2} \tag{21b}$$

$$P_b^*(t) = \begin{cases} \left(\frac{d_1(t)^\alpha \sigma_0^2}{G}\left(2^{\frac{R_{ds}}{B}} - 1\right), \frac{B}{\lambda_3 \ln 2} - \frac{d_1(t)^\alpha \sigma_0^2}{G}\right)^+, \\ \qquad t \in [0, \frac{L}{2v_0}] \\ \left(\frac{d_2(t)^\alpha \sigma_0^2}{G}\left(2^{\frac{R_{ds}}{B}} - 1\right), \frac{B}{\lambda_3 \ln 2} - \frac{d_2(t)^\alpha \sigma_0^2}{G}\right)^+, \\ \qquad t \in [\frac{L}{2v_0}, \frac{L}{v_0}] \end{cases} \tag{21c}$$

where λ_3 is determined by the constraint in (18b).

Based on the above results, the QoS-based achievable rate region $\{(R_{di}, R_{ds})\}$ under non-uniform motion scenario can be derived. Fig. 6 shows the corresponding achievable rate regions when average SNR value P_0/σ_0^2 is 40 dB, which contains three cases: $\Delta v/v_0$ is 0, 0.02 and 0.05, respectively. Obviously, the case that $\Delta v/v_0 = 0$ is equivalent to the uniform motion scenario that has been discussed in Section IV. It can be seen that non-uniform characteristic of instantaneous velocity can degrade the transmission performance in HSRs. However, the deterioration is not serious compared with ideal uniform motion scenario. Considering the fact that the relative value of velocity shift $\Delta v/v_0$ is usually less than 0.01 in practical system, such as the HSRs connection Beijing and Shanghai in China, it can be concluded that the effect of non-uniform motion on the transmission performance is very slight in terms of QoS-based achievable rate region.

The transmission performance in a non-uniform motion scenario under the same transmit power constraint has been investigated in Fig. 6. To maintain the reliability of QoS requirements all the time, the data rate requirements should be guaranteed even under the worst case. It means that some extra transmit power is essential to against the possible worst velocity realization case for non-uniform motion scenario, which can be regarded as the performance loss caused by non-ideal uniform motion of train. Fig. 7 shows the normalized minimum required transmit power as a function of maximal velocity shift ratio $\Delta v/v_0$ with respect to that in uniform motion scenario, where (R_{di}, R_{ds}) is equal to (30, 10) Mbps.

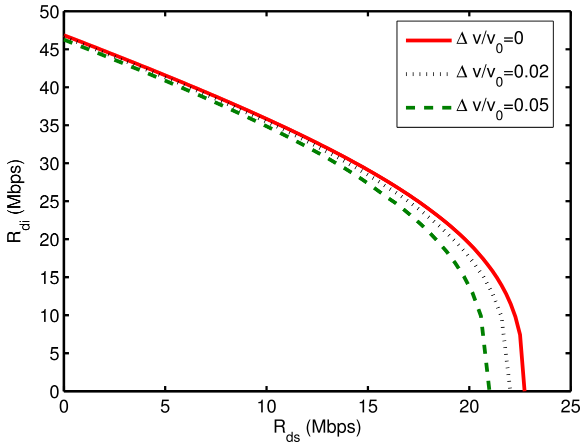

FIGURE 6. The QoS-based achievable rate regions in non-uniform motion when average SNR value P_0/σ_0^2 is 40 dB, which contains three cases: $\Delta v/v_0$ is 0, 0.02 and 0.05, respectively.

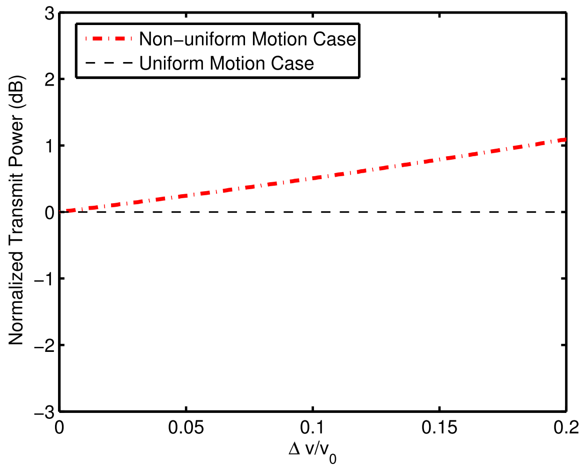

FIGURE 7. The normalized minimum required average transmit power as a function of maximal velocity shift ratio with respect to that in uniform motion case, where data rate requirement pair (R_{di}, R_{ds}) is (30, 10) Mbps.

The baseline of uniform motion case is also shown to serve as a comparison. As observed from Fig. 7, the performance loss caused by non-ideal uniform motion can be limited within 1dB even when the relative velocity shift ratio is approach to 0.2. As we know, the value of $\Delta v/v_0$ under normal running status in practical system is strictly controlled within the range [0, 0.01] due to the security consideration. Thus, it can be concluded that the performance loss is further small within the acceptable range.

VI. A TYPICAL IMPLEMENTATION IN PRACTICAL SYSTEM

The transmission performance for hybrid information in HSRs has already been analyzed in detail, and the advantages of the new proposed power allocation algorithm is indicated with respect to QoS-based achievable rate region. To provide more insights, this section presents a typical implementation to explain how to employ these results developed by this paper into practical wireless communication system in HSRs.

Generally speaking, the information data rate requirements (R_{di}, R_{ds}) between mobile AP and BS always can be prior known at the beginning of the transmission. Since the transmitter in HSRs scenario usually has sufficient power, (R_{di}, R_{ds}) can be satisfied on the condition that large enough transmit power has been dedicated for them. As a result, the design objective in this condition is to obtain an transmission strategy that corresponds to the minimal energy consumption when all the QoS requirements have been satisfied. At least two reasons motivate us to do this work, namely for energy saving and for minimizing the electromagnetic pollution.

Considering a more practical fading channel environment, we use an identical and independent distributed (i.i.d) Rice fading model to character the wireless links between BS and mobile AP, since there usually exists a dominant line-of-sight component in this environment [23]. The channel fading coefficient in this case is expressed as

$$h(t) = \sqrt{\frac{P(t)}{d(t)^{\alpha}}}\beta(t), \quad t \in \left[-\tfrac{L}{v_0}, \tfrac{L}{v_0}\right], \tag{22}$$

where the amplitude of $\beta(t)$ satisfies Rice distribution with parameter K and unit variance, the probability density function of which is

$$f(x) = x(K+1)\cdot \exp\left(-\frac{K+1}{2}x^2 - K\right) \cdot I_0\left(x\sqrt{2K(K+1)}\right). \tag{23}$$

And the corresponding transmission capacity between AP and BS at system time t is

$$R(t) = B\log_2\left(1 + \frac{GP(t)|\beta(t)|^2}{d(t)^{\alpha}\sigma_0^2}\right), \; t \in \left[-\tfrac{L}{v_0}, \tfrac{L}{v_0}\right]. \tag{24}$$

As observed from (24), the time variation of the channel status comes from two aspects. One is the position information variation $d(t)$, which has been made full use of in our service-oriented power allocation algorithm to achieve a better transmission performance. The other one is the fast fading coefficient $\beta(t)$. However, we can not utilize $\beta(t)$ as well as that we have done for $d(t)$ due to the randomness of $\beta(t)$. Inversely, to guarantee the reliability of transmission, instantaneous transmit power $P(t)$ should offset the effect of $\beta(t)$ to keep a controllable transmission performance. For formulating problem convenient, we rewrite the transmit power expression as $P(t) = \frac{P'(t)}{|\beta(t)|^2}$, and the residual task is to optimize the performance with respect to $P'(t)$.

As stated in Section IV, providing differentiated service for different information flows based on QoS requirement can match the power allocation profile well with the hybrid information flows. The optimization object in this section is to minimize the average transmit power that is needed to support the data rate pair (R_{di}, R_{ds}), which can be modeled as the following optimization problem on the condition that R_{di} and R_{ds} are given.

$$P_{min} = \mathbb{E}\left\{\min_{P'(t)}\left[\frac{v_0}{2L}\int_{-\frac{L}{v_0}}^{\frac{L}{v_0}}\frac{P'(t)}{|\beta(t)|^2}dt\right]\right\} \tag{25}$$

$$\text{s.t.} \quad R(t) = B\log_2\left(1+\frac{GP'(t)}{d(t)^\alpha\sigma_0^2}\right), \tag{25a}$$

$$0 \le R_{di} \le \frac{v_0}{2L}\int_{-\frac{L}{v_0}}^{\frac{L}{v_0}}[R(t)-R_{ds}]dt \tag{25b}$$

$$0 \le R_{ds} \le R(t),\ t \in \left[-\frac{L}{v_0}, \frac{L}{v_0}\right] \tag{25c}$$

where the constraint (25a) denotes instantaneous transmit capacity limit in a Rice fading environment. The constraints (25b) and (25c) denote the data rate requirements for delay-insensitive and delay-sensitive information streams, respectively. And the statistical mean operation in (25) is with respect to the fast fading coefficient $\beta(t)$.

It can be seen that the optimization problem in (25) is similar to that in Section IV after the manipulation $P(t) = \frac{P'(t)}{|\beta(t)|^2}$. Thus, some conclusions can be obtained as follows.

Proposition 3: When information data rate requirements (R_{di}, R_{ds}) are given, the optimal allocation strategy in terms of minimizing energy consumption is

$$P_m^*(t) = \left(\frac{d(t)^\alpha\sigma_0^2}{G}(2^{\frac{R_{ds}}{B}}-1), \frac{B}{\lambda_4\ln 2} - \frac{d(t)^\alpha\sigma_0^2}{G}\right)^+ \cdot \frac{1}{|\beta(t)|^2},\quad t \in \left[-\frac{L}{v_0}, \frac{L}{v_0}\right], \tag{26}$$

where the constant value λ_4 is determined by the following constraint

$$R_{di} = \frac{v_0}{2L}\int_{-\frac{L}{v_0}}^{\frac{L}{v_0}}\left[B\log_2\left(1+\frac{GP_m^*(t)|\beta(t)|^2}{d(t)^\alpha\sigma_0^2}\right) - R_{ds}\right]dt. \tag{27}$$

As a result, the minimum transmit power P_{min} can be expressed as:

$$P_{min} = \mathbb{E}\left\{\frac{v_0}{2L}\int_{-\frac{L}{v_0}}^{\frac{L}{v_0}}P_m^*(t)dt\right\}. \tag{28}$$

The proof of Proposition 3 is similar to that of Proposition 1, which is neglected in this Section. Based on the results above, provided that the acceptable error for numerical calculation is ε, we can give a specific algorithm for the power allocation strategy described in Proposition 3, which is shown as Algorithm 1. The original maximum value for $\lambda_{4,max}$, namely A_0 in Algorithm 1, can be set as a rule of thumb, and the convergency of Algorithm 1 can be confirmed by the monotony relationship between R_{di} and the value of λ_4.

Provided that the system parameters are the same as those in Fig.3, based on Algorithm 1, Table I gives the minimum required average transmit power under four different power allocation algorithms when data rate pair (R_{di}, R_{ds}) are shown in the first column and $K = 4$, (where it is assumed that $\sigma_0^2 = 1$). In the table, the abbreviations of CPA, WFA, CIA and NPA denote constant power algorithm, water-filling algorithm, channel inversion algorithm and new proposed algorithm, respectively. The minimum required average transmit power that corresponds to the optimal allocation algorithm in each considered instance (R_{di}, R_{ds}) are highlighted with red colour.

It can be observed that NPA is the best strategy in all considered instance (R_{di}, R_{ds}) in terms of minimizing transmit power, namely, obtaining the highest efficiency of energy. Since the delay-insensitive information is also regarded as delay-sensitive information under CIA, the required transmit power will stay the same on the condition that the sum of R_{di} and R_{ds} is fixed, which is shown in the forth column of Table I. Compared with NPA, the performance of WFA deteriorates very heavily unless $R_{ds} = 0$ while the performance of CIA is also very bad unless $R_{di} = 0$. It is because that both WFA and CIA can only satisfy unique QoS requirement at a time, they will become mismatch with respect to hybrid information transmission. Besides, CPA is not optimal in all the cases that has been considered in Table I, which agrees with the results obtained in the previous section.

Algorithm 1 Calculating the Optimal Power Allocation Strategy and the Minimal Required Average Transmit Power That Can Support the QoS Requirements

Require:
The data rate requirements pair (R_{ds}, R_{di});
The parameters for system deployment d_0, h_0 and L;
Ensure:
The optimal power allocation strategy $P_m^*(t)$;
The minimal requirement average transmit power P_{min};
1: set an original value: $\lambda_{4,min} = 0$ and $\lambda_{4,max} = A_0$;
2: $\lambda_4 = \frac{1}{2}(\lambda_{4,min} + \lambda_{4,max})$;
3: calculate current data rate of delay-insensitive information $R_{di}(\lambda_4)$ on condition of λ_4 by substituting λ_4 into Eqn. (26-27);
4: **if** $|R_{di}(\lambda_4) - R_{di}| < \varepsilon$ **then**
5: goto to Step (15);
6: **else**
7: **if** $R_{di}(\lambda_4) > R_{di}$ **then**
8: $\lambda_{4,max} = \lambda_4$;
9: **else**
10: $\lambda_{4,min} = \lambda_4$;
11: **end if**
12: return to Step (2);
13: **end if**
14: calculating the optimal power allocation strategy $P_m^*(t)$ by substituting λ_4 into (26);
15: calculating minimal average transmit power P_{min} by substituting $P_m^*(t)$ into Eqn. (28).

TABLE 1. The minimum average transmit power under four different power allocation algorithms when (R_{di}, R_{ds}) is given.

Data Rate Pair (R_{di}, R_{ds}) (Mbps)	CPA (mW)	WFA (mW)	CIA (mW)	NPA (mW)
(20, 0)	2332.4	1263.5	11356	1263.5
(15, 5)	6440.8	29126	11356	2809.4
(10,10)	14101	36785	11356	4974
(5, 15)	23209	45895	11356	7801
(0, 20)	34041	56726	11356	11356

After the optimal power allocation algorithm for hybrid information transmission in HSRs in terms of minimizing average transmit power has been given in (26), another interesting observation about the relationship between average transmit power and train's velocity can be drawn from these results, which is expressed as Proposition 4.

Proposition 4: If service-oriented power allocation algorithm is employed in HSRs, the average transmit power is independent with the velocity of train when transmission data rate requirements (R_{di}, R_{ds}) are given. Namely, it is only determined by the deployment parameters of cellular network. *Proof:* See Appendix C. ■

Based on these results, it can be concluded that the system parameter setting is independent with the velocity of train, which is very beneficial to the feasibility of applying this algorithm in HSRs.

VII. CONCLUSION

This paper investigated the transmission problem for the wireless links that connects high-speed train and the cellular network. Since the information transmitted between them has diverse QoS requirements, differentiated service should be provided to improve the overall performance. As a result, a QoS-based achievable rate region is utilized as a metric in this paper to measure the system performance after we have divided the hybrid information into two sub streams. The corresponding service-oriented power allocation algorithm was also derived to achieve the largest achievable rate region, which can bridge the gap between traditional water-filling algorithm and channel inverse algorithm. In the non-uniform motion scenario, we discussed the robust performance of the new proposed allocation algorithm. The performance loss of it was evaluated in terms of both achievable rate region and energy consumption minimization. Lastly, a typical implementation was presented in detail to show how to employ these results developed by this paper into practical system.

APPENDIX A
PROOF OF PROPOSITION 1

From the systematic level, the transmit power can be divided into two parts: one for delay-sensitive information stream and the other for delay-insensitive information stream, which are denoted as $P_1(t)$ and $P_2(t)$, respectively. The whole transmit power at system time t is

$$P(t) = P_1(t) + P_2(t), t \in \left[-\frac{L}{v_0}, \frac{L}{v_0}\right]. \tag{29}$$

Since R_{ds} is the delay-sensitive information rate that must be satisfied with priority, the expression of $P_1(t)$ can be derived based on the principle of avoiding outage event.

$$P_1(t) = \frac{d(t)^\alpha \sigma_0^2}{G}\left(2^{\frac{R_{ds}}{B}} - 1\right), t \in \left[-\frac{L}{v_0}, \frac{L}{v_0}\right]. \tag{30}$$

Then, according to the Lagrange method, we can establish the following function

$$F = \frac{v_0}{2L}\int_{-\frac{L}{v_0}}^{\frac{L}{v_0}} B\log_2\left(1 + \frac{G(P_1(t)+P_2(t))}{d(t)^\alpha\sigma_0^2}\right)dt - R_{ds} - \lambda_2 \cdot \frac{1}{2L/v_0}\int_{-\frac{L}{v_0}}^{\frac{L}{v_0}} (P_1(t)+P_2(t))\,dt. \tag{31}$$

By setting the first-order derivation of function F with respect to $P_2(t)$ to equal zero, we can get the expression of $P_2(t)$, which is expressed as

$$P_2(t) = \left(\frac{B}{\lambda_2 \ln 2} - \frac{d(t)^\alpha\sigma_0^2}{G} - P_1(t), 0\right)^+, t \in \left[-\frac{L}{v_0}, \frac{L}{v_0}\right], \tag{32}$$

where operation $(x_1, x_2)^+$ denotes the larger one between x_1 and x_2. λ_2 is a constant value which is determined by the average power constraint in (12a).

Combining the results in (30) and (32), the corresponding optimal power allocation strategy can be expressed as

$$P_{hb}^*(t) = \left(\frac{d(t)^\alpha\sigma_0^2}{G}\left(2^{\frac{R_{ds}}{B}} - 1\right), \frac{B}{\lambda_2 \ln 2} - \frac{d(t)^\alpha\sigma_0^2}{G}\right)^+, \quad t \in \left[-\frac{L}{v_0}, \frac{L}{v_0}\right]. \tag{33}$$

The two information streams simultaneous transmission scheme in (33) can be realized by superposition coding technique, which has been used to achieve the capacity bound of multiple access channel. It needs to mention that the problem this paper focuses on is different from traditional research topics for multiple access channel, since two streams in this paper have different QoS requirements along time domain, we make use of it to provide a differentiated service to achieve a better performance, and our main task is to obtain the optimal time-domain power allocation strategy to support the largest QoS-based achievable rate region.

Besides, substituting (33) into (12), the expression of conditional capacity function can be obtained

$$C_{R_{ds}} = \frac{v_0}{2L}\int_{-\frac{L}{v_0}}^{\frac{L}{v_0}}\left[B\log_2\left(1 + \frac{GP_{hb}^*(t)}{d(t)^\alpha\sigma_0^2}\right) - R_{ds}\right]dt. \tag{34}$$

Thus, the conclusions in Proposition 1 have been proved.

APPENDIX B
PROOF OF PROPOSITION 2

Firstly, it can be confirmed that the expression of instantaneous speed in (19) satisfies the constraints in (15) and (16). Then, we will prove the worst property of it by contradiction in terms of energy consumption maximization

It is a typical two-value piecewise function. The whole period $[-\frac{L}{v_0}, \frac{L}{v_0}]$ can be divided into two phases: the phase one is with velocity $v_0+\Delta v$ and the phase two is with velocity $v_0-\Delta v$, the demarcation point of which is $\frac{v_0+\Delta v}{v_0}\frac{L}{2}$ away from the point O in Fig. 2. The total energy consumption during the period $[-\frac{L}{v_0}, \frac{L}{v_0}]$ can be expressed as

$$E = 2\int_0^{\frac{L}{2v_0}} P(l(v+\Delta v, t))dt + 2\int_{\frac{L}{2v_0}}^{\frac{L}{v_0}} P(l(v-\Delta v, t))dt \tag{35}$$

where $l(v+\Delta v, t)$ denotes the transmission distance between BS and AP when velocity is $v+\Delta v$ at system time t, and $P(l(v+\Delta v, t))$ denotes the instantaneous transmit power.

Assuming the velocity $v_0+\Delta v$ is not optimal for the first phase. Due to the constraint in (15), the optimal value $v(t)$ may be arbitrary time varying one or time non-varying one that is less than $v_0+\Delta v$. As a result, due to the decrement of velocity, the time range of the first phase will become large, which is denoted as $\frac{L}{v_0}+\Delta t$. Since the total time that the train travels from E to D is limited to $\frac{2L}{v_0}$ based on the constraint in (16), the time length that the second phase experiences should be $\frac{L}{v_0}-\Delta t$. Now we calculate the total energy consumption under above assumption.

$$\begin{aligned} E' = {} & 2\int_0^{\frac{L}{2v_0}+\Delta t} P\left(l\left(v(t), t\right)\right) dt \\ & + 2\int_{\frac{L}{2v_0}+\Delta t}^{\frac{L}{v_0}} P(l(v-\Delta v, t))dt \end{aligned} \tag{36}$$

Comparing (35) with (36), it can be observed that the train will spend more time in the position that is close to the base station and spend less time in the position that is far from base station. Thus, energy consumption will become less, namely $E' \leq E$. So the velocity should be equal to $v_0+\Delta v$ in phase one in terms of maximizing energy consumption, to establish a worst case for the realization of $v(t)$.

Similar results can be extended for instantaneous velocity during the phase two. Thus, the expression in (19) is the worst case. So the Proposition 2 has been proved.

APPENDIX C
PROOF OF PROPOSITION 4

It is obvious that the average transmit power can be calculated by the Eqn. (26)-(28) when the data rate pair (R_{di}, R_{ds}) is given. Then, through a variable substitution $v_0 t = Lx$, and using $\frac{Lx}{v_0}$ to take place of t, we can rewritten the Equations (26)-(28) as:

$$P_m^*(x) = \left(\frac{d(x)^\alpha\sigma_0^2}{G}\left(2^{\frac{R_{ds}}{B}}-1\right), \frac{B}{\lambda_3} - \frac{d(x)^\alpha\sigma_0^2}{G}\right)^+ \cdot \frac{1}{|\beta(t)|^2} \tag{37}$$

$$R_{di} = \int_0^1 \left[B\log_2\left(1+\frac{GP_m^*(x)|\beta(t)|^2}{d(x)^\alpha\sigma_0^2}\right) - R_{ds}\right] dx \tag{38}$$

$$P_{min} = \int_0^1 P_m^*(x)dx \tag{39}$$

where

$$d(x)^\alpha = [d_0^2 + h_0^2 + (Lx)^2]^{\frac{\alpha}{2}} \tag{40}$$

It can be seen that the variable v_0 is not contained in the equation set shown in (37)-(40). As a consequence, the average transmit power P_{min} is independent with the velocity of train, and is only determined by deployment parameters.

Thus, the Proposition 4 has been proved.

REFERENCES

[1] J. Wu and P. Fan, "A survey on high mobility wireless communications: Challenges, opportunities and solutions," *IEEE Access*, vol. 4, pp. 450–476, 2016.

[2] C. Zhang, P. Fan, K. Xiong, and P. Fan, "Optimal power allocation with delay constraint for signal transmission from a moving train to base stations in high-speed railway scenarios," *IEEE Trans. Veh. Technol.*, vol. 64, no. 12, pp. 5775–5788, Dec. 2015.

[3] N. Sun, Y. Zhao, L. Sun, and Q. Wu, "Distributed and dynamic resource management for wireless service delivery to high-speed trains," *IEEE Access*, vol. 5, pp. 620–632, 2017.

[4] K. Xiong, Y. Zhang, P. Fan, and H.-C. Yang, "Evaluation framework for user experience in 5G systems: On systematic rateless-coded transmissions," *IEEE Access*, vol. 4, pp. 9108–9118, 2016.

[5] P. Muneer, S. M. Sameer, "Joint ML estimation of CFO and channel, and a low complexity turbo equalization technique for high mobility OFDMA uplinks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 7, pp. 3642–3654, Jul. 2015.

[6] Z. W. Hou, Y. Q. Zhou, L. Tian, J. L. Shi, Y. H. Li, and B. Vucetic, "Radio environment map aided Doppler shift estimation in LTE railway," *IEEE Trans. Veh. Tech.*, to be published, doi: 10.1109/TVT.2016.2599558.

[7] J. Wang, H. Zhu, and N. J. Gomes, "Distributed antenna systems for mobile communications in high speed trains," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 4, pp. 675–683, May 2012.

[8] Y. Dong and P. Fan, "Bounds on the average transmission rate in high speed railway wireless communications," in *Proc. IEEE HMWC*, Shanghai, China, Nov. 2013, pp. 142–145.

[9] Y. Dong, C. Zhang, P. Fan, and P. Fan, "Power-space functions in high speed railway wireless communications," *J. Commun. Netw.*, vol. 17, no. 3, pp. 231–240, Jun. 2015.

[10] C. Zhang, P. Fan, Y. Dong, and K. Xiong, "Channel service based high-speed railway base station arrangement," in *Proc. IEEE HMWC*, Chengdu, China, Nov. 2012, pp. 1–5.

[11] C. Zhang, P. Fan, Y. Dong, and K. Xiong, "Service-based high-speed railway base station arrangement," *Wireless Commun. Mobile Comput.*, vol. 15, no. 13, pp. 1681–1694, Sep. 2015.

[12] R. G. Gallager, *Principles of Digital Communication*. Cambridge, U.K.: Cambridge Univ. Press, 2008.

[13] D. N. C. Tse and S. V. Hanly, "Multiaccess fading channels. I. Polymatroid structure, optimal resource allocation and throughput capacities," *IEEE Trans. Inf. Theory*, vol. 44, no. 7, pp. 2796–2815, Nov. 1998.

[14] A. J. Goldsmith and P. P. Varaiya, "Capacity of fading channels with channel side information," *IEEE Trans. Inf. Theory*, vol. 43, no. 6, pp. 1986–1992, Jun. 1997.

[15] D. Wu and R. Negi, "Effective capacity: A wireless link model for support of quality of service," *IEEE Trans. Wireless Commun.*, vol. 2, no. 4, pp. 630–643, Jul. 2003.

[16] S. Efazati, and P. Azmi, "Effective capacity maximization in multirelay networks with a novel cross-layer transmission framework and power-allocation scheme," *IEEE Trans. Veh. Technol.*, vol. 63, no. 4, pp. 1691–1702, May 2014.

[17] J. Luo, R. Yates, and P. Spasojevic, "Service outage based power and rate allocation for parallel fading channels," *IEEE Trans. Inf. Theory*, vol. 51, no. 7, pp. 2594–2611, Jul. 2005.

[18] Y. Dong, P. Fan, and K. B. Letaief, "High-speed railway wireless communications: Efficiency versus fairness," *IEEE Trans. Veh. Technol.*, vol. 63, no. 2, pp. 925–930, Feb. 2014.

[19] H. Shi, R. V. Prasad, E. Onur, and I. G. M. M. Niemegeers, "Fairness in wireless networks: Issues, measures and challenges," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 5–24, 1st Quart., 2014.

[20] Z. Z. Cao, M. Kodialam, and T. V. Lakshman, "Joint static and dynamic traffic scheduling in data center networks," in *Proc. IEEE INFOCOM*, Apr. 2014, pp. 2445–2453.

[21] R. A. Berry and R. G. Gallager, "Communication over fading channels with delay constraints," *IEEE Trans. Inf. Theory*, vol. 48, no. 51, pp. 1135–1149, May 2002.

[22] D. N. C. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge, U.K.: Cambridge Univ. Press, 2005.

[23] L. Liu *et al.*, "Position-based modeling for wireless channel on high-speed railway under a viaduct at 2.35 GHz," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 4, pp. 834–845, May 2012.

[24] T. Li, Z. Chen, C. Zhang, and P. Fan, "How channel fadings affect the system service of high speed railway communications," in *Proc. IEEE HMWC*, Shanghai, China, Nov. 2013, pp. 137–141.

[25] W. Luo, X. Fang, M. Cheng, and Y. Zhao, "Efficient multiple-group multiple-antenna (MGMA) scheme for high-speed railway viaducts," *IEEE Trans. Veh. Technol.*, vol. 62, no. 6, pp. 2558–2569, Jul. 2013.

[26] T. Li, P. Fan, K. Xiong, and K. B. Letaief, "QoS-distinguished achievable rate region for high speed railway wireless communications," in *Proc. IEEE WCNC*, New Orleans, LA, USA, Mar. 2015, pp. 2044–2049.

[27] E. Biglieri, J. Proakis, and S. Shamai (Shitz), "Fading channels: Information-theoretic and communications aspects," *IEEE Trans. Inf. Theory*, vol. 44, no. 6, pp. 2619–2692, Oct. 1998.

[28] S. V. Hanly and D. N. C. Tse, "Multiaccess fading channels. II. Delay-limited capacities," *IEEE Trans. Inf. Theory*, vol. 44, no. 7, pp. 2816–2831, Nov. 1998.

TAO LI received the B.S. and M.S. degrees from the School of Electronic and Information Engineering, Harbin Institute of Technology, China, in 2010 and 2012, respectively. He is currently pursuing the Ph.D. degree with the Department of Electronic Engineering, Tsinghua University, Beijing, China. From 2014 to 2015, he was a Research Scholar with the Department of Electrical Engineering, Columbia University, USA. His current research interests include high-mobility wireless communications, wireless cooperative networks, and energy harvesting. He was a recipient of the Best Paper Awards of the 2013 International Workshop on High Mobility Wireless Communications and the 2014 IEEE Global Communications Conference (GLOBECOM). He is a Reviewer of several journals of the IEEE Communication Society, including the IEEE COMMUNICATION LETTERS, the IEEE WIRELESS COMMUNICATIONS LETTERS, and the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS. He has also served as a Reviewer for several international conferences, including the IEEE GLOBECOM and PIMRC.

KE XIONG (M'14) received the B.S. and Ph.D. degrees from Beijing Jiaotong University (BJTU), Beijing, China, in 2004 and 2010, respectively. From 2010 to 2013, he was a Post-Doctoral Research Fellow with the Department of Electrical Engineering, Tsinghua University, Beijing. Since 2013, he has been a Lecturer with BJTU. He is currently an Associate Professor with the School of Computer and Information Technology, BJTU. From 2015 to 2016, he was a Visiting Scholar with the University of Maryland, College Park. He has authored over 60 academic papers in referred journals and conferences. He is a member of the China Computer Federation and also a Senior Member of the Chinese Institute of Electronics. His current research interests include wireless cooperative networks, wireless powered networks, and network information theory.

Dr. Xiong serves as an Associate Editor-in-Chief of the Chinese journal New Industrialization Strategy, and the Editor of the Computer Engineering & Software. He is currently the Leading Editor of the Special Issue Recent Advances in Wireless Powered Communication Networks for EURASIP *Journal on Wireless Communications and Networking*. He also serves as a Reviewer of over 15 international journals, including the IEEE TRANSACTIONS ON SIGNAL PROCESSING, the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, the IEEE TRANSACTIONS ON COMMUNICATIONS, the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, the IEEE COMMUNICATION LETTERS, the IEEE SIGNAL PROCESSING LETTERS, and the IEEE WIRELESS COMMUNICATION LETTERS. He also served as a Session Chair for the IEEE GLOBECOM'2012, IET ICWMMN'2013, IEEE ICC'2013, and ACM MOMM'2014, and the Publicity and Publication Chair for the IEEE HMWC'2014, as well as the TPC Co-Chair of the IET ICWMMN'2017.

PINGYI FAN (M'03–SM'09) received the B.S. degrees from the Department of Mathematics, Hebei University, in 1985, and the M.S. degrees from Nankai University in 1990, and the Ph.D. degree from the Department of Electronic Engineering, Tsinghua University, Beijing, China, in 1994. He is currently a Professor with the Department of EE, Tsinghua University. From 1997 to 1998, he was a Research Associate with The Hong Kong University of Science and Technology. From 1998 to 1999, he was a Research Fellow with the University of Delaware, USA. In 2005, he was a Visiting Professor with NICT, Japan. From 2005 to 2014, he visited The Hong Kong University of Science and Technology for many times, and in 2011, he was a Visiting Professor with the Institute of Network Coding, Chinese University of Hong Kong. He is an Oversea Member of the IEICE. He has attended to organize many international conferences, including as a General Co-Chair of the IEEE VTS HMWC2014, a TPC Co-Chair of the IEEE International Conference on Wireless Communications, Networking and Information Security (WCNIS 2010), and a TPC member of the IEEE ICC, GLOBECOM, WCNC, VTC, and Inforcom.

He has served as an Editor of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, *Inderscience International Journal of Ad Hoc and Ubiquitous Computing*, and *Journal of Wireless Communication and Mobile Computing* (Wiley). He is also a Reviewer of over 30 international journals, including 20 IEEE Journals and eight EURASIP journals. He was a recipient of some academic awards, including the IEEE GLOBECOM'14 Best Paper Award, the IEEE WCNC'08 Best Paper Award, the ACM IWCMC'10 Best Paper Award, and the IEEE ComSoc Excellent Editor Award for the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS in 2009. His main research interests include the B5G technology in wireless communications, such as MIMO and OFDMA, Network Coding, Network Information Theory, and Big Data Analysis.

KHALED BEN LETAIEF (S'85–M'86–SM'97–F'03) received the B.S. (Hons.), M.S., and Ph.D. degrees in electrical engineering from Purdue University, West Lafayette, IN, USA. From 1990 to 1993, he was a Faculty Member with the University of Melbourne, Parkville, VIC, Australia. He has been with The Hong Kong University of Science and Technology, Hong Kong, since 1993, where he is known as one of the HKUST's most distinguished professors for his boundless energy, collegial nature, dedication, and excellence in research, education, and service. While at HKUST, he has held numerous administrative positions, including the Chair Professor and the Dean of the School of Engineering, HKUST, the Head of the Department Electronic and Computer Engineering, the Director of the Center for Wireless IC Design, the Director of the Huawei Innovation Laboratory, and the Director of the Hong Kong Telecom Institute of Information Technology. In 2015, he joined HBKU as Provost to help establish a research-intensive university in Qatar in partnership with strategic partners that include Northwestern, CMU, Cornell, and Texas A&M. He is an internationally recognized Leader in wireless communications and networks and served as a Consultant for different organizations, including Huawei, ASTRI, ZTE, Nortel, PricewaterhouseCoopers, and Motorola.

He is the Founding Editor-in-Chief of the IEEE Transactions on Wireless Communications and has served on the Editorial Board of other prestigious journals. He has also been involved in organizing a number of flagship international conferences and events. In addition to his active research and professional activities, he has been a Dedicated Teacher committed to excellence in teaching and scholarship. He is recognized as a Long-Time Volunteer with dedicated service to professional societies and in particular the IEEE, where he has served in many leadership positions. These include the Treasurer of the IEEE Communications Society, the Vice President for Conferences of the IEEE Communications Society, the Vice President for the Technical Activities of the IEEE Communications Society, the Chair of the IEEE Committee on Wireless Communications, and the Elected Member of the IEEE Product Services and Publications Board. He is a Fellow of the HKIE. He is currently serving as the IEEE Communications Society Director of Journals. He is also recognized by Thomson Reuters as an ISI Highly Cited Researcher. He was a recipient of the Mangoon Teaching Award from Purdue University in 1990, the Teaching Excellence Appreciation Award by the School of Engineering, HKUST (four times), and the Michael G. Gale Medal for Distinguished Teaching (highest university-wide teaching award and only one recipient/year is honored for his/her contributions). He was also a recipient of many other distinguished awards and honors, including the 2007 IEEE Communications Society Joseph LoCicero Publications Exemplary Award, the 2009 IEEE Marconi Prize Award in Wireless Communications, the 2010 Purdue University Outstanding Electrical and Computer Engineer Award, the 2011 IEEE Communications Society Harold Sobol Award, the 2011 IEEE Wireless Communications Technical Committee Recognition Award, and 12 IEEE Best Paper Awards.