Optimal Pricing for RAP in Heterogeneous Wireless Railway Networks

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Abstract: - To facilitate the journey of passengers, the modern railway system should support a wide range of on-board high-speed internet services. The Rail-track Access Points (RAPs) is an interesting idea to solve the increasing demands of passengers. These RAPs are deployed randomly along the railway line and supports high-speed data rates. RAPs are complementary to the cellular network base stations as heavy data request flushes it. In this paper, RAP and BS coexists in the network and how this model is going to help service providers, a revenue model is introduced. It also analyses the delay performance of the proposed user-RAP association scheme. Eventually, the passenger decides whether to associate with the RAP or not. Performance evaluations are done on the proposed user-RAP association scheme for the heterogeneous wireless railway communication networks.

Key-words: - payoff, access points, revenue, arrival rate, mean delay time, internet.

1 Introduction

The growth of wireless communication is at every corner of the world. It has now become the integrated part of human life. There is an increase in the use of personal wireless devices such as smart phones, tablets and laptops by the people. The transport industry in the past years has witnessed a high demand for internet services to provide on-board passengers with internet access on one hand and to ensure the safety of people and trains on the other hand [1]. As in case of high-speed trains most of the journeys takes a long duration, passengers may like to check their emails, surf a website or go for a real time multimedia streaming by accessing internet. To provide on-board internet services, a heterogeneous network architecture can be constructed that contains a series of RAPs. However, the RAP can only support intermittent wireless network coverage due to limited transmission power and hence, the delay time experienced by the passenger is one of the most delicate issue in railway communication network. As heavy data traffic flushes data delivery, RAPs are used complement to the BSs.

This work focusses on the problems of service regulations faced by any RAP connection in a heterogeneous wireless railway network where with the help of queueing game theoretic approach a RAP and BS coexist together. It considers the revenue model and derive association delay time on RAPs connection behaviours, i.e., a condition where a passenger should join the RAP or not. The performance evaluation is provided for the heterogeneous wireless railway networks to elucidate the proposed passenger-RAP association scheme.

2 Related Works

Many researches have been conducted on modern railway system to vantage passenger’s journey. An investigation on the optimal power allocation strategy via access points is studied for uplink transmission in high-speed trains [2]. In [3], the delay performance of the Internet multimedia streaming to satisfy passenger’s demand in the railway network is discussed. A delay analysis model is proposed in high speed train scenario through switch ports in carriages [4]. In recent literatures, the delay performance analysed on demand data delivery has sometimes came out to be inaccurate results [5]. In [6], [7] end-to-end delay bound is analysed for the data applications under the heterogeneous network for one server but the cooperation between RAPs and BSs is not considered in both the works. Therefore, it is needed to focus on the delay performance in railway communication system.

Researchers have shown their interests in queueing theory. Now it is all passenger's choice whether to associate with a queue or not, this shows that passengers are ready to wait for the service in queue or to leave the queue in order to maximize their own profit [8]. Hence, a reward-cost framework is easy to construct which explicate the passenger's choice. Z. Han et al. studied the queueing control in cognitive radio networks with random service interruptions [9]. With an optimal threshold, an individual decides whether a data packet should associate with the queue or not [10]. Since the channel characteristics are unknown to the system, this kind of technique cannot be used everywhere, especially in heterogeneous wireless railway network. Z. Chang et al. investigates a pricing strategy based on the queue length and the reward [11]. In [12], a social optimal strategy was developed from the view point of the customers that can be implemented on RAP. In [13], the channel ON-OFF process is discussed by using renewal theory. Here, the channel ON-OFF process is taken as the breakdown of the RAP. Hence, the first and second moment of service time is required to do the analysis. Since it is inefficient to access the BSs for the railway networks, the much higher data transmission rate of RAP can complement the connectivity.

Motivated by the previous problems our contribution to this paper is summarized below:

1. To study a RAP heterogeneous wireless railway network model. Several rail-track access points are widely deployed on a predefined railway line. It is assumed that passengers can decide whether to join the RAP service or to remain connected to the cellular network.
2. A symmetric game is proposed to maximize the passenger's reward which is influenced by the delay time that they may face in the queue of the RAP. Hence, an optimal pricing is presented during the data transmission to facilitate the passenger in deciding whether to associate with the RAP or not.

The remaining of the manuscript covers the system model of the proposed scheme in section 3, study of payoff model and queueing analysis in section 4, section 5 presents the simulation results followed by the conclusion in section 6.

3 System Model

The system model of a railway communication network using RAP is shown in the Fig.1. The RAPs are deployed along the railway track in such a manner that it gives intermittent coverage due to limited transmission power. Hence, passengers can only get connected to the services when they are in transmission range of RAPs. The packet delay and also the fast handover is neglected here. It is assumed that the allocation of network resources to the RAP and BS is handled by central controller. Therefore, the passenger's request can enter the queue and wait till they get served.

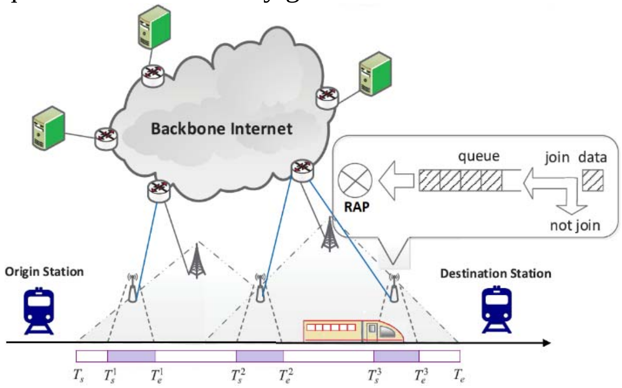

Fig. 1. *The System Model*

It is assumed that the train follows a straight path and the information can be generated in advance regarding the speed and the location of the train. As shown in the Fig.1, the train can travel between source and destination stations in the time duration $[T_s, T_e]$. We consider a scenario in which 3 RAPs are deployed along the railway line and hence for passengers there exist three separated time durations in which they can transfer the data packets. This can be represented by $[T_s^i, T_e^i]$, $i \in [1, \dots, I]$. Here, within the *i*th RAP, T_s^i represents the start time and T_e^i is the end time of the delivery. Assume that $T_s^i \leq T_e^i$, $T_s \leq T_s^1$,$T_e \geq T_e^1$ for $i \in [1, \dots, I]$. These RAPs are working cooperative in nature.

3.1 Service Process and Data Arrival Process

By considering the proposed system model, the passengers will decide whether they will associate with the RAP or not. If the queue of the RAP is full and no more data can be taken from the passenger, we assume that it can be transferred to the cellular base station. The customer arrival rate λ follows the exponential process and is i.i.d. in nature. For the simplicity of model, consider a M/G/1 queuing system to analyse the average queueing delay T (waiting time + service time) with service rate μ_x assumed to follow exponential distribution and i.i.d. at the RAP. The service time of the customer is denoted by μ_y. The breakdown of RAP is given by the exponential rate β. In rural area, the service interruption is less, thus $\beta = 1$ whereas for urban area $\beta = 2$. To save the cost of deployment and to satisfy the customer's demand, in urban region more RAPs is deployed as compare to the rural region. Here assume that $T_s^{i+1} - T_e^i$ is distributed exponentially at rate ϵ which is the time taken by the train to cover two isolated RAPs and the serving time $T_e^i - T_s^i$ of the RAP follow exponential process at a rate ϕ. The service order follows first come first served (FCFS) rule and also the queue information will be transferred to the next RAP when the train is not in the coverage range of the RAP.

During time duration *t*, the state of the queue is given by a pair (*N(t), I(t)*) at the RAP, which consists the status of the train position *I(t)* and the number of customers in the system, i.e., length of the queue *N(t)*. *I(t)* =1 when the train is in the transmission range, otherwise *I(t)*=0.

4 Queueing Analysis on User Association

The data transmission rate of RAP wireless link is much higher as compared to the base station wireless link. It is assumed that the customer after getting served by RAP can get reward for the successful service and also the cost of a customer that he is going to pay for the service will be the function of waiting time in the queue. Hence, considering the cost and reward a customer can get, he needs to make an irrevocable decision on whether to connect with the RAP as the customer after association cannot quite until being served. Since, the gap between two adjacent RAPs is very big, the customers will send create arriving requests by forming a queue before entering the covering range and will decide if they can wait in the queue until being served. This queue will get update each time a train passes the range. For the customers we introduce one more term payoff that will be the difference between cost and reward.

This work considers the scenario where all the RAPs deployed are working in cooperative manner. Optimal pricing technique is shown on one RAP. Here the customers are aware of the status of the queue and their aim is to maximize their payoffs. The revenue generated by the RAP is also formulated here.

4.1 Revenue Model

The customers of the train have the data packets to be transferred. They can obtain a reward ψ after they get served by the RAP which can be any form of benefit. For customer, we represent the cost by $\chi(T)$ which increases with *T*. Here we plead a linear example and assume that $\chi(T)$=*CT* where *C* is the value of unit cost. We assume that for *m* = 0, *K* is positive to avoid the trivial situation when *m* = 0 and *K* = 0, which leads to

$$\psi > \left(1 + \frac{\epsilon}{\phi}\right)\frac{C}{\mu_x} + \frac{C\,\epsilon}{\phi(\lambda + \phi + \epsilon)}. \quad (1)$$

For customers we can make use a generic payoff model, commonly referred as queueing analysis [14], [15].

When the train is moving, the queue information is forwarded from one RAP to the next RAP and accordingly *T* is derived theoretically. For a customer the payoff is given by

$$K = \psi - CT \quad (2)$$

This function is defined by T which include service time and waiting time *T* that depends on the status of the queue and the decision of the customers regarding association with the RAP. If there is a positive payoff, the customers prefer to join the RAP but if there is a negative payoff, the customers choose not to connect with the RAP. If the payoff is 0, the customers take neutral decision. In this sense, the customers are said to be risk neutral in nature [16]. Using the parameter of waiting time in the queue denoted by *W* induced by the arrival rate λ, the average queueing delay *T* is obtained as,

$$T = W + \mu_E. \quad (3)$$

Using Pollaczek-Khinchin formula [18], the average waiting time is given by,

$$W = \frac{\lambda\,\mu_E{}^2}{2\,(1-\lambda\,\mu_E)}. \quad (4)$$

When the service time of RAP μ_x and the service time of incoming customers μ_y both follows exponential distributions, then the first and second moments are obtained as

$$\mu_E = \frac{1}{\mu_y}\left(1 + \frac{\beta}{\mu_x}\right) \quad (5)$$

$$\mu_E{}^2 = \frac{2}{\mu_y{}^2} + \frac{2\,\beta}{\mu_x{}^2\mu_y{}^2} + \frac{2\,\beta}{\mu_x{}^2\mu_y} + \frac{4\,\beta}{\mu_x\mu_y{}^2} \quad (6)$$

By using (3) and (4), obtain *T* as

$$T = \frac{\lambda\,\mu_E{}^2}{2\,(1-\lambda\,\mu_E)} + \mu_E \quad . \quad (7)$$

To study the revenue model, analyse the probability *q* of the customers who decides to join the queue. Customers selfishly choose *q* to obtain non-negative reward and finishes the service with arrival rate λ. Then, there exists a unique equilibrium arrival rate λ_e as follows

$$\lambda_e = \frac{2(\psi - K - C\mu_E)}{2\,\psi\,\mu_E - 2\,K\,\mu_E + C\,\mu_E{}^2 - 2\,C\,\mu_E{}^2}. \quad (8)$$

For a given effective rate λ_e

$$q(\psi - C\,T - K) = 0. \quad (9)$$

In particular, the customer decides whether to join or balk based on the revenue charged by the RAP. By considering the fact that the RAP's goal is to maximize the revenue by fixing an admission fee, the revenue model can be obtained as

$$\pi_K = \lambda_e K. \quad (10)$$

In order to make (10) into a convex form, replace π_K to π_{λ_e} and develop an equivalent form as given

$$\pi_{\lambda_e} = \lambda_e[\,\psi - C\,T\,]. \quad (11)$$

As T is convex and an increasingly continuous function, the π_{λ_e} in the interval $(0,1/\mu_E)$ is strongly concave function. Here by the setting first derivative of π_{λ_e} to zero, it produces a unique optimal solution λ_e^o as follows

$$\lambda_e^o = \frac{1}{\mu_E} - \frac{\sqrt{C\,\mu_E{}^2\,\Omega}}{\mu_E\,\Omega} \quad (12)$$

where $\Omega = C\mu_E{}^2 + 2\psi\mu_E - 2C\mu_E{}^2$. To achieve the maximum revenue from customers, the RAP can adjust the arrival rate λ_e^o of the incoming customers in the queue.

4.2 Queuing Analysis When both *I(t)* and *N(t)* are known

Here, for customers arriving with the data requests both *N(t)* and *I(t)* can be generated [17]. A pure threshold strategy (PT1) is considered when the customers will be knowing the queue length and the train position, specified by the pair $(m_e(0), m_e(1))$. The customer decide according to the threshold $m_e(I(t))$ of the queue length whether to associate or not. We can define PT1 as at arriving time *t*, inspect *(N(t), I(t))*, and if $N(t) \leq m_e(I(t))$ then associate with RAP otherwise remain connected to cellular network by default. Hence, just before the arrival of customer, the expected waiting time is given as

$$T(m,i) = (m+1)\left(\frac{\epsilon}{\phi}+1\right)\left(\frac{1}{\mu}\right) + (1-i)\left(\frac{1}{\epsilon}\right). \quad (13)$$

Accordingly, the thresholds $(m_e(0), m_e(1))$ where PT1 is a poorly dominant strategy can be presented as

$$((m_e(0), m_e(1)) = \left(\left\lfloor\frac{\psi\,\mu\,\phi - C\,\mu}{C(\epsilon+\phi)}\right\rfloor - 1, \left\lfloor\frac{\psi\,\mu\,\phi}{C(\epsilon+\phi)}\right\rfloor - 1\right). \quad (14)$$

Based on (13), the payoff of the customer who enters the queue with state *(m, i)* is given by

$$K(m,i) = \psi - CT(m,i). \quad (15)$$

It is observed from (15) that if $K(m,i) > 0$, a customer will join with the RAP. We assume that the connection between customer and BS is occurring in a natural way and if the customer finds it beneficial, they will connect to the RAP. The payoff is considered to be positive in this case. In the case when the customer decides to stay in the cellular network, the payoff is assumed to be less than 0. Hence, if $K(m,i) = 0$ for m, the customer will connect to the RAP if and only if the total customers in the queue $m = m_e(i), \forall \in \{0,1\}$ and $(m_e(0), m_e(1))$ can be found in (14).

5 Numerical Results

Simulation results are obtained on the system model to explore the effect of several parameters on the behaviour of the passengers of the train. The equilibrium strategy for arrival rate is satisfied by considering different situations. Fig. 2 describes the relationship between the payoff K and customers equilibrium arrival rate λ_e. With the increase in arrival rate, the price also increases. With the higher number of customers in queue of the RAP, the price charged is also increased.

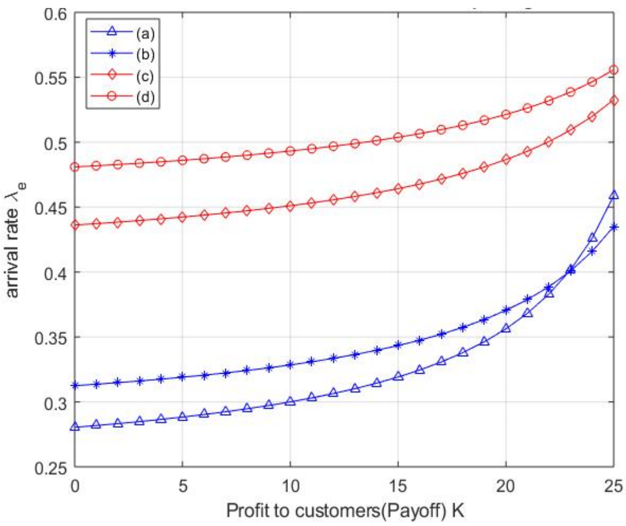

Fig. 2. *Individual customer arrival rate λ_e vs. payoff K with $\psi = 100$, C=1 in four case: (a) β=2, μ_y=1.2, μ_x=0.5; (b) β=2, μ_y=1.2, μ_x=0.6; (c) β=1.5, μ_y=1.2, μ_x=0.5; (d) β=1.5, μ_y=1.2, μ_x=0.6.*

Fig. 3 shows the shape of revenue analysed for different values of channel availability β. For β=1, there is higher number of passengers trying to associate with RAP and hence the revenue generated by the RAP is higher for lesser value of β.

For the case studied, it is assumed that the queue length and train position are known to the upcoming passengers. In the Fig. 4, the expected mean time is plotted with the number of customers *m* in queue. It shows that when the greater number of customers choose to wait for getting served in the queue, expected delay time increases. But after a certain extent, customers will avoid to join RAP and will remain in the cellular network.

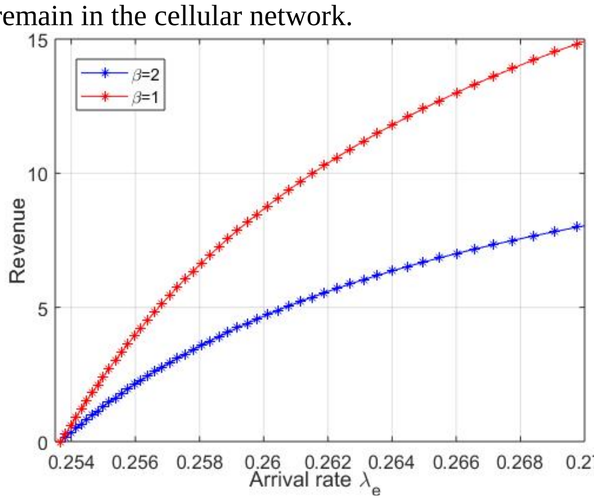

Fig. 3. *The revenue vs. equilibrium arrival rate with R=100, C=1, μ_y=1.2, μ_x=0.5 at β=1 and β=2.*

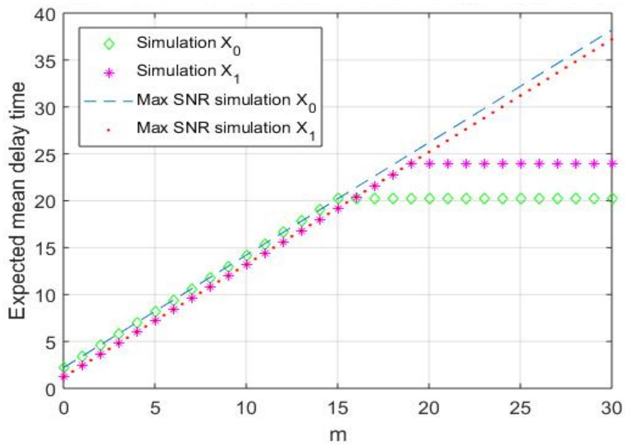

Fig. 4. *Expected mean delay time versus m when $\mu_x = 5, \phi = 0.2, \epsilon = 1, \lambda = 0.5, , \psi = 25, C = 1$.*

From Fig. 5 we can find the thresholds; accordingly, the customer will choose to stay in the queue. We can see the monotonical decrease with the distance between two adjacent RAPs in the thresholds $m_e(I(t)), \forall I(t) \in \{0,1\}$.

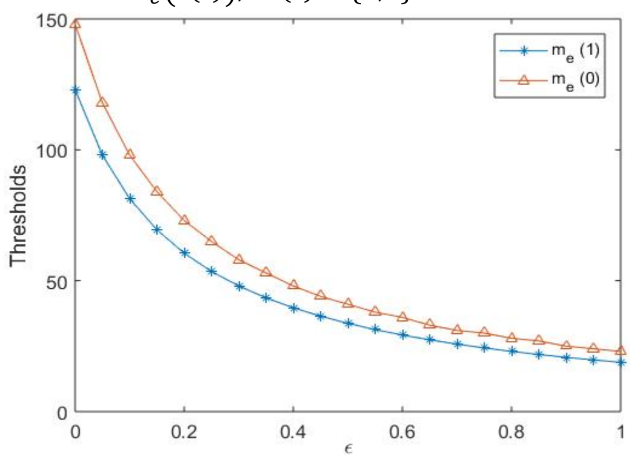

Fig. 5. *Thresholds versus ϵ when $\mu_x = 5, \phi = 0.2, \psi = 25, C = 1, \lambda = 0.5$.*

With the increase in ϵ, a greater number of data transmission fail. It can be found that the threshold is higher for *I(t)*=1, i.e., when the train is travelling in the coverage network of RAP. The customers prefer to join RAP and sustains a longer queue.

6 Conclusion

In this paper, a scenario of modern railway communication system is discussed where a series of Rail-track Access Points (RAPs) that are capable of providing high speed internet are deployed randomly across the railway lines. To satisfy the customer's demand, this system is adequate for providing a wide variety of on-board services. The problems faced by the customer in a heterogeneous wireless railway network while connecting to the RAPs are analysed here. We carried out the analysis on the expected mean delay time when the queue length and the status of the system are known to the arriving customers of the RAP. To decide whether to join the RAP or not the revenue model is proposed which gives the idea of optimal pricing. The proposed user-RAP association scheme can help in providing data connectivity in heterogeneous wireless railway network.

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