Progress In Electromagnetics Research C, Vol. 48, 133–139, 2014

An Efficient Fixed Rate Transmission Scheme over Delay-Constrained Wireless Fading Channels

Xiang Yu Gao and Yue Sheng Zhu*

Abstract—In this paper, we study the scheduler design over delay-constrained wireless communication links. Following a cross-layer design approach, the wireless system is modeled as a joint link-PHY layer architecture with a finite-length buffer and continuous-state fading links. A heuristic and efficient fixed rate transmission scheduler (FRT) scheme is proposed. We formulate and analyze the performance of the FRT scheme in terms of power efficiency and packet drop rate. Compared with variable rate schemes, the FRT scheme can considerably simplify the hardware implementation of the transmitter. In addition, the optimization of the FRT scheme can be conducted with significantly reduced computational cost by utilizing the sparse feature of the transition probability matrix. Moreover, the simulation results show that, the optimized average transmit power of the FRT scheme is only 0.5 dB higher than the known optimal variable rate scheme at the packet drop rate of 10^{-3}, indicating that the FRT scheme is quite power efficient as well. Therefore, we conclude that the FRT scheme is more feasible than variable rate schemes in practical delay-constrained wireless systems with regard to both hardware cost and power efficiency.

1. INTRODUCTION

Real-time applications, such as voice over IP and streaming multimedia, will become a dominant part of services provided in the mobile wireless networks. To promote such applications, high level of quality of services should be guaranteed. This poses great challenges in designing the schedulers since the status of wireless links varies from time to time. On the one hand, the schedulers are tasked to ensure most of data packets arrive before the delay bound is violated. On the other hand, the power budget of each link should also be scrutinized due to the limited battery capacity of mobile devices [1].

In consideration of both the delay and power constraints, a cross-layer system model, termed as link-PHY model has been proposed and employed in wireless systems [2–4]. This model takes into account the mismatch between the arrival rate of the data from the upper layer and the departure rate of the data to the physical layer. A buffer is placed at the link layer to coordinate the arrived data packets, and a scheduler is in charge of controlling the data departure according to the buffered data length and the channel state information (CSI) [3]. In the literature, numerous previous works studied the scheduler design problems in link-PHY models with various channel fading assumptions [2–4], performance measures [5, 6] and multiple antennas [8–10]. However, most of these works assume the buffer is with infinite length which is invalid in practice.

In this paper, we investigate the scheduler design for the link-PHY model with a finite-length buffer and continuous fading channels. The theoretically optimal scheduler for this model was studied in [7], where the proposed joint queue length aware scheduler scheme (JQLA) was a variable rate transmission scheme. Nonetheless, the high computational complexity of JQLA scheme poses a challenge to its

Received 11 November 2013, Accepted 12 March 2014, Scheduled 20 March 2014
* Corresponding author: Yue Sheng Zhu (zhuys@pkusz.edu.cn).
The authors are with the Communication and Information Security Lab, Shenzhen Graduate School, Peking University, Shenzhen, China.

implementation in practical systems. In this work, we propose to adopt the fixed rate scheduler scheme (FRT) to achieve a more efficient complexity-performance tradeoff, thus enabling the techniques more feasible in practical systems. The idea of promoting the FRT scheme is motivated by its reduced hardware requirements in a twofold manner. Firstly, with fixed coding rate the implementations of both the channel coding/modulation (CCM) and channel decoding/demodulation (CDD) modules can be significantly simplified. Secondly, since only one rate is selectable, the channel strength is naturally quantized to be 0 or 1. Therefore, the amount of CSI fed back to transmitter can be reduced. We formulate and optimize the performance of FRT scheme as well as comparing it with the JQLA scheme to study its performance efficiency.

This paper is organized as follows. In Section 2, the link-PHY system model is presented. We formulate and optimize the performance of the FRT scheme in Section 3. Simulation results and discussion are given in Section 4. Finally, we conclude the paper in Section 5.

2. SYSTEM MODEL

We consider a point-to-point communication scenario. The overall system diagram is illustrated in Figure 1, where solid arrows and dashed arrows represent data flows and parameter control flows respectively. The wireless channel is assumed to be with flat slow fading. The discrete-time model of the received signal in the n-th channel block, $y(n)$, is given by

$$y(n) = \sqrt{g(n)}x(n) + w(n), \tag{1}$$

where $x(n)$ denotes the transmitted signal, $g(n)$ the channel strength and $w(n)$ the additive white noise. The channel strength g follows a continuous-state distribution with respect to n. The probability density function and cumulative density function of the channel strength are denoted by $f_{CH}(g)$ and $F_{CH}(g)$ respectively. $w(n)$ is normally distributed with zero mean and unit variance.

The transmitter consists of three parts: the link layer, physical layer and the resource scheduler [3, 7, 10]. At the link layer, we assume the data source is stable and data packets arrive at a constant rate of λ packets per channel. A link buffer modeled as a discrete-time finite-length queue with size M packets, is in place to store the arrived packets and coordinate them to the physical layer at the rate of $S(n)$ packets per channel. $S(n)$ is determined by the resource scheduler (see the dashed arrow attached with $S(n)$). On the other hand, the link buffer feds the occupied queue length $q(n)$ to the scheduler. If the buffer is fully occupied, the excess head-of-line packets are dropped. To avoid transmitting outdated packets, we can set the buffer length $M = \lambda(D_{\max} - D_c)$ where D_c is the channel encoding/decoding delay and $D_{\max}$ the delay bound. Thereby, the packet drop rate and the delay bound violation probability are equivalent [7].

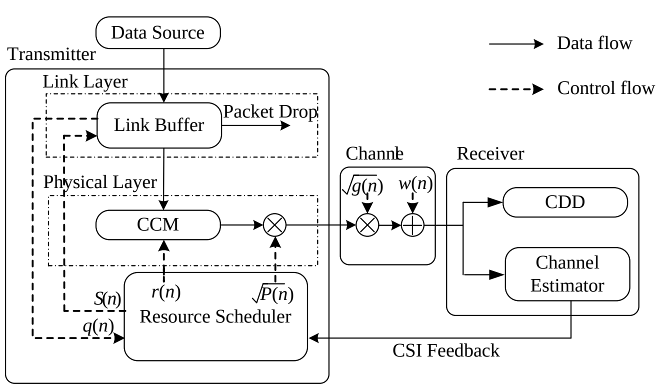

Figure 1. The link-PHY system model [3].

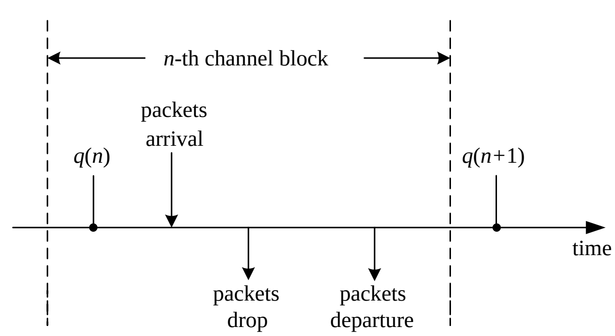

Figure 2. The update process of the buffer queue length from $q(n)$ to $q(n+1)$. Packets arrival increases the queue length whereas packets drop and departure reduce the queue length [7].

The update of the queue length $q(n)$ is shown in Figure 2 [7]. In the n-th channel block, after the arrival of new packets, the number of dropped packets is

$$d(n) = \max(0, q(n) + \lambda - M). \tag{2}$$

After the departure of $S(n)$ packets, the queue length is updated as

$$q(n+1) = \max(0, \min(M, q(n) + \lambda) - S(n)). \tag{3}$$

The sequence of $q(n)$ forms a homogeneous, irreducible, and aperiodic Markov chain, and $S(n)$ determines the steady state distribution of $q(n)$ which in turn determines the packets drop rate and average transmit power.

At the physical layer, the information bits sequence is encoded by the CCM module. We assume ideal channel coding in CCM module and denote the transmit information rate by $r(n)$. To guarantee $S(n)$ packets sent out during the channel block, $r(n)$ should satisfy

$$\left\lfloor \frac{WT}{L} r(n) \right\rfloor \geq S(n), \tag{4}$$

where T is the duration of transmission in sec, W the allocated channel bandwidth in Hz, and L the number of information bits in one packet. According to Shannon's capacity formula, the required transmit power $P(n)$ is given by

$$P(n) = \frac{2^{r(n)} - 1}{g(n)}, \tag{5}$$

to ensure full recovery of the transmitted information at the CDD module. In each channel block, the estimated present CSI is fed back to the transmitter. With the received $q(n)$ and CSI, the scheduler continuously updates $S(n)$, $r(n)$ and $P(n)$.

3. FIXED RATE TRANSMISSION SCHEME

For the system presented above, we study the FRT scheduler scheme where the resource scheduler takes the value of $r(n)$ from $\{r, 0\}$ for each channel block, i.e., CCM either encodes and transmits data at fixed rate r or keeps silent. The choice between transmit and not transmit is based on the present CSI and buffer status. Compared to variable rate schemes, the FRT scheme can be translated into a simpler and more implementable CCM and CDD hardware at the cost of some performance loss. In the following sections, we will show this performance loss of the FRT scheme is trivial in cases.

In the context of the FRT scheduler scheme, the packet rate $S(n)$ takes the value from $S = \{\lfloor WTr/L \rfloor, 0\}$ according to (4). Note that the code rate $r = SL/WT$ makes no quantization errors to S, thus achieving the best power efficiency. Therefore, we assume this matching relationship holds in the following. The design of the resource scheduler focuses on selecting S and defining the transmit opportunities. Since the channel distribution is known at the transmitter and the buffer length $q(n)$ takes discrete values, the transmit opportunities can be defined as the active probability conditional on the buffer queue length. Denote the active probability by $\rho_0^{(q(n))}$, i.e., $\rho_0^{(q(n))} = \Pr\{S(n) = S|q(n)\}$.

For the link buffer, the sequence of $q(n)$ forms a homogeneous, irreducible, and aperiodic Markov chain and the defined transmit opportunities $\{\rho_0^{(q(n))}\}$ influence the transitions of the states of $q(n)$. In order to obtain the steady state distribution of $q(n)$, its $(M+1)\times(M+1)$ one step transition probability matrix $\mathbf{P}$ should be considered first. The i-th row and j-th column of $\mathbf{P}$, $0 \leq i, j \leq M$, is defined as

$$p_{i,j} = \Pr\{q(n+1) = j | q(n) = i\}. \tag{6}$$

Hence, $\rho_0^{(q(n))}$ forms the $\mathbf{P}$ in the following pattern:

$$\mathbf{P} = \begin{bmatrix} \rho_0^{(0)} & \dots & 1-\rho_0^{(0)} & 0 & \dots & \dots & 0 \\ \rho_0^{(1)} & \dots & 0 & 1-\rho_0^{(1)} & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \dots & \dots & \dots & \rho_0^{(M)} & \dots & 1-\rho_0^{(M)} \end{bmatrix}. \tag{7}$$

On each row of $\mathbf{P}$, only two non-zero entries $\rho_0^{(q(n))}$ and $1-\rho_0^{(q(n))}$ are located on the columns of $j_-^{(q(n))}$ and $j_+^{(q(n))}$ respectively, which are given by

$$\begin{aligned} j_-^{(q(n))} &= \max(0, \min(M, q(n)+\lambda) - S), \\ j_+^{(q(n))} &= \min(M, q(n)+\lambda). \end{aligned} \tag{8}$$

The steady state queue length distribution $\mathbf{\Pi} = [\pi_0, \pi_1, \ldots, \pi_M]$ can be obtained by

$$\begin{cases} \mathbf{\Pi P} = \mathbf{\Pi}, \\ \sum_{i=0}^{M} \pi_i = 1. \end{cases} \tag{9}$$

Note that $\mathbf{\Pi}$ is a left eigenvector of $\mathbf{P}$. In the steady state, i.e., $n \to \infty$, the packet drop rate is written as

$$P_{drop} = \frac{1}{\lambda} \sum_{i=M-\lambda}^{M} \pi_i \times (\lambda + i - M). \tag{10}$$

Recall that S and $\{\rho_0^{(q(n))}\}$ represent a binary transmission rule at physical layer. Implied by this rule, the optimal scheduler operates as follows: if channel strength $g \geq F_{CH}^{-1}(1-\rho_0^{(q(n))})$ then transmit at rate r; otherwise keep silent in this channel block. Thus, after some algebra from (5), the average transmit power is established to be

$$\bar{P} = \sum_{i\in U} \pi_i \frac{\min(M, i+\lambda)}{S} \int_{F_{CH}^{-1}(1-\rho_0^{(i)})}^{\infty} \frac{2^r - 1}{g} f_{CH}(g)dg + \sum_{i\notin U} \pi_i \int_{F_{CH}^{-1}(1-\rho_0^{(i)})}^{\infty} \frac{2^r - 1}{g} f_{CH}(g)dg, \tag{11}$$

where $U = \{i | \min(M, i+\lambda) < S\}$. For the queue length $i \in U$, only $\min(M, i+\lambda)/S$ of the transmit channel block is occupied and the discount factor $\min(M, i+\lambda)/S$ is included to account the non-occupied portion of the channel.

The goal of the resource scheduler design is to minimize the packet drop rate, i.e., delay bound violation rate, while meet the average transmit power constraint. Hence, the optimized performance of the FRT scheme can be formulated as the following constrained minimization:

$$\begin{aligned} \min_{\mathbf{P}, \mathbf{\Pi}} \quad & P_{drop} = \tfrac{1}{\lambda} \textstyle\sum_{i=M-\lambda}^{M} \pi_i (\lambda + i - M) \\ s.t. \quad & \bar{P} \leq P_0 \\ & \mathbf{\Pi P} = \mathbf{\Pi} \\ & \textstyle\sum_{i=0}^{M} \pi_i = 1. \end{aligned} \tag{12}$$

Note that in the formulation, we assume the active packet rate S is given aforehand.

The key difficulty in solving (12) lies in the non-linear power constraint, where two related groups of entry variables from $\mathbf{P}$ and $\mathbf{\Pi}$ interact with each other. A typical way of treating such a situation is to numerically solve one group of variables from the other group and then optimize the problem iteratively. Previous proposed algorithms generally optimize the problem in a way of solving $\mathbf{P}$ from $\mathbf{\Pi}$ because less variables are involved in $\mathbf{\Pi}$, and for any given $\mathbf{\Pi}$, solving $\mathbf{P}$ that minimizes the power while satisfying (9) is a convex optimization problem [7]. The algorithms are with high complexity since they optimize two problems in a roll for each iteration.

For the FRT scheme, because $\mathbf{P}$ is sparse and solely determined by the $(M+1)$-size probability vector, denoted by $\vec{\rho}_0 = [\rho_0^{(0)}, \rho_0^{(1)}, \ldots, \rho_0^{(M)}]$ as shown in (7), the problem scale of solving $\mathbf{P}$ is similar as that of solving $\mathbf{\Pi}$. Hence, we propose to take the alternative way of solving $\mathbf{\Pi}$ from solving $\mathbf{P}$ and transform $\mathbf{\Pi}$, $\bar{P}$ and P_{drop} into functions of $\vec{\rho}_0$. After this, (12) is reformulated as follows

$$\begin{aligned} \min_{\vec{\rho}_0} \quad & P_{drop} = \tfrac{1}{\lambda} \textstyle\sum_{i=M-\lambda}^{M} (\lambda + i - M) \times \pi_i(\vec{\rho}_0) \\ s.t. \quad & \bar{P}(\vec{\rho}_0) \leq P_0 \\ & \mathbf{\Pi P} = \mathbf{\Pi} \\ & 0 \leq \vec{\rho}_0 \leq 1. \end{aligned} \tag{13}$$

Compared to (12), formulation (13) avoids the aforementioned nested loop in each optimization iteration since it is straightforward to solve $\mathbf{\Pi}$ from $\mathbf{P}$ by (9). In addition, solving $\mathbf{\Pi}$ from $\vec{\rho}_0$ is equivalently solving a group of sparse linear equations where fast estimation algorithm can be employed to improve the optimization speed. For (13), we employ the merit-function sequential quadratic programming (MSQP) method, which guarantees convergence to a local optimum. Details of the MSQP optimization algorithm is referred to [11, Page 583].

4. SIMULATION RESULTS AND DISCUSSION

In this section, we present the optimized performance of FRT as well as comparing it with that of the JQLA scheme. The simulation results are obtained by solving (13) and then utilizing the optimized scheduling scheme to get the packet drop rate and average transmit power with 1,000,000 channel realizations. The illustrated channel fading process is Rayleigh, i.e., $f_{CH}(g) = e^{-g}$ and $F_{CH}(g) = 1 - e^{-g}$.

Figure 3 compares the performances of JQLA and FRT under various S. From Figure 3, we can make two interesting observations. Firstly, the performance of FRT with a proper S is extremely close to that of JQLA, indicating that FRT can achieve a fairly efficient tradeoff between complexity and performance. For example, at packet drop rate of 10^{-3}, the gap between FRT with $S = 30$ and JQLA is only 0.5 dB. Note that this is where JQLA realizes nearly 10 dB power gain over time domain water-filling algorithm (WF) as reported in [7, 10]. Secondly, the packet rate S should be larger than λ to realize the near JQLA performance. The convergence speed from the performance with $S = \lambda$ to that with optimized S is rapid (see the curves with $S = 10$, $S = 11$ and $S = 20$ in Figure 3).

We further compare FRT and JQLA under different λ in Figure 4. The FRT curves are with the optimal S which is obtained by discrete full search. In practice, the optimization of S for FRT can be done in a rough way since the convergence speed is rapid and the marginal merit by inducing more iterations is trivial. It is shown in Figure 4 that as the delay constraint gets more stringent, i.e., larger λ, the performance gap becomes larger and rate flexibility is worth more, and vice versa. Similarly, from Figure 5 we can observe that the gap between FRT and JQLA shrinks (widens) as larger (smaller) portion of the channel is allocated to the link, i.e., larger (smaller) WT/L. Hence, in the case of either less stringent delay requirements or sufficient channel resource, the FRT scheme is more advantageous.

Moreover, on the same software/hardware platform, we observe that the complexity of the optimization algorithm in terms of runtime, is on average reduced by the order of M for FRT comparing to that of JQLA. The reduced complexity enables the optimization algorithm more feasible in the case of large M, i.e., large buffer size.

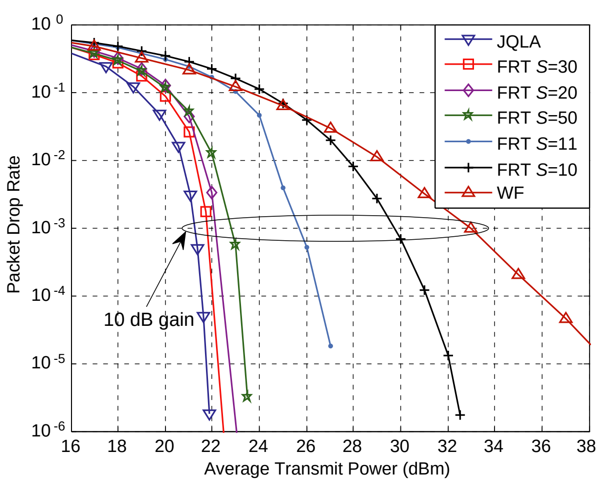

Figure 3. Performance of FRT, JQLA and WF with $M = 50$, $\lambda = 10$ and $WT/L = 50$.

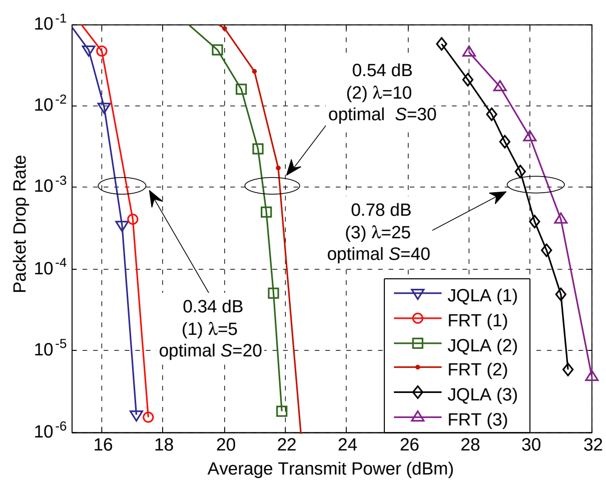

Figure 4. Performance of FRT and JQLA under various λ with $M = 50$ and $WT/L = 50$.

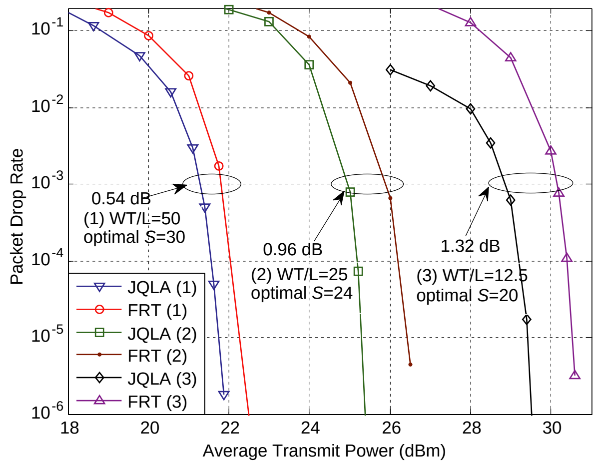

Figure 5. Performance of FRT and JQLA under various WT/L with $M = 50$ and $\lambda = 10$.

5. CONCLUSION

In this paper, we have studied the FRT scheduler scheme in the link-PHY system model. Compared with the variable rate scheme, the FRT scheme can be translated into reduced complexities of both the optimization algorithm and transmitter hardware. We have formulated and solved the performance optimization problem for the FRT scheme. From the simulation results, it is observed that the performance gap between the FRT scheme and the known optimal variable rate JQLA scheme is not significant. This implies that the FRT scheme can achieve most of the queue-length-aware performance gain that observed in JQLA scheme. In addition, it is shown that as the delay constraint becomes less stringent or the link is allocated more bandwidth, the performance of the FRT scheme further approaches to that of the JQLA scheme, indicating that the FRT scheme is preferable to the JQLA scheme under these conditions due to its low complexity. The results of the FRT scheduler scheme in this paper provide insights into the practical design of delay-constrained wireless systems.

ACKNOWLEDGMENT

The authors would like to thank Prof. Li Ping for the heuristic discussion with him.

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