Queue Length Aware Power Control for Delay-Constrained Communication over Fading Channels

Xiaochen Li, Xihua Dong, and Dapeng Wu

Abstract

In this paper, we study efficient power control schemes for delay sensitive communication over fading channels. Our objective is to find a power control law that optimizes the link layer performance, specifically, minimizes the packet drop probability, subject to a long-term average power constraint. We assume the buffer at the transmitter is finite; hence packet drop happens when the buffer is full. The fading channel under our study has a continuous state, e.g., Rayleigh fading. Since the channel state space is continuous, dynamic programming is not applicable for power control. In this paper, we propose a sub-optimal power control law based on a parametric approach. The proposed power control scheme tries to minimize the packet drop probability by considering the queue length, i.e., reducing the probability of those queue-length states that will cause full buffer. Simulation results show that our proposed power control scheme reduces the packet drop probability by one or two orders of magnitude, compared to the time domain water filling and the truncated channel inversion power control.

Index Terms

QoS, power control, delay-constrained communications, packet drop probability, queuing system.

I. Introduction

Real-time applications such as streaming multimedia will be supported in the next generation wireless networks. Services required by these applications are different from file transfer services

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in that they expect low transmission delay, i.e., delay-constrained communications. Providing quality of service (QoS) guarantees to multimedia applications poses a significant challenge for the design of wireless networks.

The capacity for delay-constrained communications has been studied from the information-theoretical point of view (pure physical (PHY) layer model). An elegant overview and a comprehensive list of references of the capacity of fading channels are provided in [1]. There are several capacity definitions for the physical layer delay-constrained systems, e.g. expected capacity [2], outage capacity [3], [4], and delay-limited capacity [5] [6]. The reliable transmission is achieved by encoding the information bits within M fading blocks to average out the Gaussian noise and fading process.

To achieve those delay-constrained capacities, it is implicity required that all the information are ready at the transmitter side at the beginning of the transmission. This physical layer model is not suitable for more complicated problems if the packets arrive at different times, or each packet has individual delay bound. These problems are common in packet switching networks. Essentially, the aforementioned difficulty stems from the fact that information-theoretical approaches only capture the variation of the channel but leave the variation of data source unconsidered. Therefore the link-PHY layer model is needed to study both of the two factors [7]. In a link-PHY layer model, both the arrival process and fading process contribute to the dynamics of the system. Hence the link-PHY layer model is more complicated than the PHY model. The transmission delay consists of two parts, coding delay and queuing delay in the buffer. With the knowledge of CSI at transmitter side, we can control the departure process to achieve certain performance optimization.

The optimal power control policy in a link-PHY layer model determines the transmission power based on the system state which is defined as a triplet of number of arrival packets, channel gain, and queue length of the current block [8] [9]. The power or energy efficient transmission with delay constraint under Additive White Gaussian Noise (AWGN) channel is studied in [10], [11] and [12], where the channel gain is constant and can be excluded from the system state. For fading channels, when fading process is modeled as a finite state Markov chain (FSMC) [13], the optimization problem forms a Markov decision problem which can be solved by dynamic programming approach. The optimal power control scheme and properties of average power/delay curve is studied in [8] for infinite buffer (no packet drop). For finite buffer situations, the optimal power control scheme is derived in [9] which minimizes the packet drop probability subject to an instantaneous packet error probability, or minimizes the total packet loss probability.

Dynamic programming is a powerful approach to solving optimal power/rate control problems under FSMC. For a continuous channel, i.e., Rayleigh fading or Nakagami fading channel, the dynamic programming method can not be applied because the state is continuous. In [14], a channel-gain-based (CGB) power control scheme is proposed to maximize the effective capacity [15] for delay-constrained transmissions, under continuous channel models. The transmission power only relies on the instantaneous channel gain. In [16], a hierarchical queue-length-aware (HQLA) power control scheme is proposed, where both channel gain and queue length affect the transmission power. The HQLA power control scheme is a heuristic solution. It reduces the transmission power when the channel capacity provided by the CGB power control exceeds the backlog in the buffer. It does not provide any guidance in designing the CGB portion of the power control scheme.

In this paper, we propose a sub-optimal power control scheme which aims at minimizing the packet loss probability subject to a long-term average power constraint, for continuous channel model. We assume that the instantaneous channel capacity is achievable, therefore the packet loss probability (package loss consists of packet drop due to full buffer and package error due to channel distortion) reduces to packet drop probability. The method can be easily extended to solving the problem of minimizing the packet drop probability subject to a decoding error probability constraint. We assume the channel gain and the queue length affect the transmission power independently. The total transmission power is a multiplication of the CGB and queue-length-aware (QLA) power control schemes. We refer to this strategy as separate QLA (SQLA) power control. Both the CGB and QLA portion are optimized to minimize the packet drop probability.

The reminder of this chapter is organized as follows. Section II presents the system model. Section III describes the proposed power control scheme. Section IV presents the simulation results. Section V summarizes the paper.

II. System Model

We consider a node to node transmission model as illustrated in Fig. 1. The wireless channel undergoes flat slow fading, and the bandwidth is W. A flat slow fading channel can be modeled by a block-fading additive white Gaussian channel (BF-AWGN) [17], which belongs to a general class of block-interference channels introduced by McEliece and Stark [18]. The fading process is assumed to be i.i.d., and each block has duration T_b sec.. The channel gain of each block takes continuous value. Its marginal distribution is characterized by a continuous probability density function (pdf) $f_{CH}(g)$, $g \in [0, \infty)$. One block is the smallest time unit during which the transmitter conducts power and rate control operations. We assume the channel gain is perfectly known at the transmitter side, and the instantaneous channel capacity can be achieved during one block. Under this assumption, the transmission rate is uniquely determined by the transmission power through Shannon's capacity formula.

The data source generates packets at a constant rate μ packets per block. Each packet contains L bits. The power and rate control module determine the transmission power and rate (the number of packets that will be transmitted during one block) based on the information of the transmitter buffer occupancy and the instantaneous channel gain. The encoder and modulator then choose the appropriate coding and modulation scheme that matches the current block transmission power and rate.

The timing diagram of the system is illustrated in Fig. 2. The packets arrive at the transmission buffer at the beginning of each block. If the buffer can not accommodate all the arrival packets, some of the packets will be dropped. There are two strategies for packets drop: drop some of the arrival packets or drop the packets that have already been waiting in the buffer. For delay-constrained communications, the best strategy is to accommodate all the arrival packets and drop from the head of the buffer, since they are the packets which have the longest delay. After packets dropping, the remaining packets are pushed ahead, and the tail of the buffer is emptied for the new arrivals. After this, certain number of packets (determined by the rate control) are removed from the head of the buffer and be transmitted. Denote M the buffer size; $q(n)$ the number of packets in the buffer before the new arrival of the n-th block; $s(n)$ the number of packets that will be transmitted during the n-th block; $d(n)$ the number of packets to be dropped,

$$d(n) = \max(0, q(n) + \mu - M). \tag{1}$$

And the number of packets remains in the buffer before the transmission is

$$\begin{aligned} q_r(n) &= q(n) - d(n) \\ &= \min(M, q(n) + \mu). \end{aligned} \tag{2}$$

The system update function is,

$$\begin{aligned} q(n+1) &= \max(0, q_r(n) - s(n)) \\ &= \max(0, \min(M, q(n) + \mu) - s(n)). \end{aligned} \tag{3}$$

The sequence $\{q(n)\}$ forms a homogeneous, irreducible, and aperiodic Markov Chain. The steady state queue length distribution can be obtained from the one step transition probability matrix **P**. Since the buffer has finite capacity M, **P** is a square matrix of size $(M+1) \times (M+1)$. The i-th row j-th column of **P**, $0 \leq i, j \leq M$, is

$$p_{i,j} = \text{Prob}[q(n+1) = j | q(n) = i]. \tag{4}$$

Substitute (3) into (4),

$$p_{i,j} = \text{Prob}[\max(0, \min(M, i + \mu) - s(n)) = j | q(n) = i]. \tag{5}$$

To calculate $p_{i,j}$ for each pair of $\{i, j\}$, we consider two situations.

1) $0 \leq i < M - \mu$, no packets dropping,

$$\begin{aligned} p_{i,j} &= \text{Prob}[\max(0, i + \mu - s(n)) = j | q(n) = i] \\ &= \begin{cases} \text{Prob}[s(n) \geq i + \mu | q(n) = i] & j = 0 \\ \text{Prob}[s(n) = i + \mu - j | q(n) = i] & 0 < j \leq i + \mu \\ 0 & i + \mu < j \leq M \end{cases}. \end{aligned} \tag{6}$$

2) $M - \mu \leq i \leq M$, some packets will be dropped,

$$\begin{aligned} p_{i,j} &= \text{Prob}[M - s(n) = j | q(n) = i] \\ &= \text{Prob}[s(n) = M - j | q(n) = i] \quad 0 \leq j \leq M. \end{aligned} \tag{7}$$

Denote $k_x^{(i)}$ the probability that x packets will be transmitted when the queue length is i,

$$k_x^{(i)} = \text{Prob}[s(n) = x | q(n) = i], \tag{8}$$

where

$$s(n) = \lfloor \frac{WT_b}{L} \log_2\left(1 + P(g(n), q(n))g(n)\right) \rfloor. \tag{9}$$

The elements $\{p_{i,j}\}$ are,

$$p_{i,j} = \begin{cases} \sum_{l=i+\mu}^{M} k_l^{(i)} & 0 \le i < M-\mu, j = 0 \\ k_{i+\mu-j}^{(i)} & 0 \le i < M-\mu, 0 < j \le i+\mu \\ k_{M-j}^{(i)} & M-\mu \le i \le M, 0 \le j \le M \\ 0 & \text{otherwise} \end{cases}. \tag{10}$$

Denote $c_x^{(i)}$ the probability that x or more than x packets will be transmitted when the queue length is i,

$$c_x^{(i)} = \sum_{l=x}^{M} k_l^{(i)}, \tag{11}$$

the transition probability matrix can be represented as:

$$\mathbf{P} = \begin{bmatrix} c_{\mu}^{(0)} & \cdots & k_0^{(0)} & 0 & \cdots & 0 \\ c_{\mu+1}^{(1)} & \cdots & k_1^{(1)} & k_0^{(1)} & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{M-1}^{(M-\mu-1)} & \cdots & \cdots & \cdots & \cdots & 0 \\ k_M^{(M-\mu)} & \cdots & \cdots & \cdots & \cdots & k_0^{(M-\mu)} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ k_M^{(M)} & \cdots & \cdots & \cdots & \cdots & k_0^{(M)} \end{bmatrix}. \tag{12}$$

The steady state queue length distribution is given by

$$\begin{cases} \boldsymbol{\pi} = \boldsymbol{\pi}\mathbf{P} \\ \sum_{i=0}^{M} \pi_i = 1 \end{cases}, \tag{13}$$

where $\boldsymbol{\pi} = [\pi_0, \pi_1, ..., \pi_M]$ is a $1 \times (M+1)$ row vector. The element π_i is the probability of the event that the queue length equals i when the queue enters the steady state,

$$\pi_i = \lim_{n \to \infty} \text{Prob}[q(n) = i]. \tag{14}$$

Knowing the steady state queue length distribution, we can now derive the packets drop probability. The packet drop probability is defined as the ratio of the number of dropped packets to the number of total arrival packets,

$$P_{drop} = \lim_{n\to\infty} \frac{\sum_{i=1}^{n} d(i)}{n\mu}. \tag{15}$$

Denote $L_d(n)$ the average packet drop in the first n-th blocks,

$$L_d(n) = \frac{\sum_{i=1}^{n} d(i)}{n}. \tag{16}$$

The packet drop probability is

$$P_{drop} = \frac{L_d(\infty)}{\mu}. \tag{17}$$

When the queue enters steady state,

$$\begin{aligned} L_d(\infty) &= \mathbf{E}_{q(\infty)}[d(\infty)] \\ &= \sum_{l=M-\mu}^{M} \text{Prob}[q(\infty) = l](\mu + l - M) \\ &= \sum_{l=M-\mu}^{M} \pi_l(\mu - l + M), \end{aligned} \tag{18}$$

where $d(\infty)$ and $q(\infty)$ denote the number of dropped packets and queue length when queue enters the steady state, respectively.

Similarly, the average transmission power is,

$$\begin{aligned} \overline{P} &= \lim_{n\to\infty} \mathbf{E}_{g(n),q(n)}[P(g(n), q(n))] \\ &\overset{(a)}{=} \sum_{l=0}^{M} \pi_l \mathbf{E}_{g(n)}[P(g(n), l)], \end{aligned} \tag{19}$$

where $P(g(n), q(n))$ is the transmission power, as a function of $g(n)$ and $q(n)$. Step (a) holds because $g(n)$ and $q(n)$ are independent. In the following discussions we will neglect block index n, since the channel gains are i.i.d., and the queue length distribution does not change in the steady state, We formulate the optimization problem as follows,

$$\begin{aligned} \min_{P(g,q)} \quad & P_{drop} = \frac{1}{\mu}\sum_{l=M-\mu}^{M} \pi_l(\mu - l + M) \\ s.t. \quad & \sum_{l=0}^{M} \pi_l \mathbf{E}_g[P(g,l)] \leq P_0 \\ & P(g,q) \geq 0 \\ & \boldsymbol{\pi} = \boldsymbol{\pi}\mathbf{P}(P(g,q)), \\ & \textstyle\sum_{i=0}^{M} \pi_i = 1 \end{aligned} \tag{20}$$

where $\mathbf{P}(P(g,q))$ implies that the transition probability matrix is a function of power control $P(g,q)$.

III. Separate QLA Power Control

Lagrangian method has been applied to find the stationary points of a constrained optimization problem. However, using lagrangian method to solve (20) is not an easy task. Because without knowing the exact form of $P(g,q)$, the probability in (8) can not be derived. And we do not know the explicit expression of $\{\pi_i\}$ as a function of $P(g,q)$. Therefore we seek for sub-optimal solutions. Like linear minimum-mean-square-error (MMSE) detection, which only gives optimal solution in the linear sub-space, we assume $P(g,q)$ has certain structure, and solve (20) in that sub-space. We first assume the channel gain and queue length affect the transmission power independently,

$$P(g,q) = f(g)h(q). \tag{21}$$

$f(g)$ and $h(q)$ are the CGB and QLA portion of the transmission power, respectively. Since the buffer length is M, the queue length q takes value in $0, 1, ..., M$ only. Let vector $\mathbf{H} = [h(0), h(1), ..., h(M)]^T$, the QLA portion of the transmission power is uniquely determined by $\mathbf{H}$. Except for the non-negative condition, we do not need further assumption about $h(q)$.

The channel gain g is continuous. Without knowing the exact expression of $f(g)$, we still can not find the probabilities in (8). Therefore we need to make assumptions about the form of $f(g)$. $f(g)$ is expected to have optimal performance for delay-constrained communications. Consider two extreme cases, $M = \infty$ and $M = 1$. Time domain water filling (TDWF) [19] and truncated channel inversion (TCI) [20] power control are known to be optimal in these two cases, respectively. $f(g)$ should have a general form which includes TDWF and TCI. Therefore we assume

$$f(g,\boldsymbol{\alpha}) = \begin{cases} \alpha_1 + \frac{\alpha_2}{g} & g > g_0 \\ 0 & g < g_0 \end{cases}, \tag{22}$$

where $\boldsymbol{\alpha} = [\alpha_1, \alpha_2, g_0]^T$. By properly choosing parameters α_1, α_2, g_0, $f(g,\boldsymbol{\alpha})$ in (22) can be configured to three widely used power control schemes, i.e., TDWF, TCI and constant power control (CONST), as listed in Table I.

Changing the values of α_1, α_2 and g_0 gives a family of power control schemes which lie between TDWF and TCI. Substituting (21) into (19), the average power constraint is

$$\sum_{i=0}^{M} \pi_i h(i) \mathbf{E}_g[f(g,\boldsymbol{\alpha})] \leq P_0. \tag{23}$$

For Rayleigh distributed channel, the probability density function (pdf) of g is

$$f_{CH}(g) = \lambda e^{-\lambda g}. \tag{24}$$

Average $f(g)$ over g gives

$$\begin{aligned} \mathbf{E}_g[f(g,\boldsymbol{\alpha})] &= \int_{g_0}^{\infty} (\alpha_1 + \frac{\alpha_2}{g}) f_{CH}(g) dg \\ &= \alpha_1 e^{-\lambda g_0} + \lambda \alpha_2 \Gamma_0(g_0 \lambda), \end{aligned} \tag{25}$$

where $\Gamma_0(x)$ is the upper incomplete gamma function defined as

$$\Gamma_0(x) = \int_x^{\infty} \frac{e^{-t}}{t} dt. \tag{26}$$

The nonnegative constraint $P(g,q) \geq 0$ implies $\mathbf{H} \geq 0$ and $f(g,\boldsymbol{\alpha}) \geq 0$. The cutoff threshold g_0 is always greater than or equal to zero. Solving for $f(g,\boldsymbol{\alpha}) \geq 0$ yields

$$\begin{cases} \alpha_1 \geq 0, \quad g_0 \geq 0 & \text{If} \quad \alpha_2 \geq 0 \\ \alpha_1 + \frac{\alpha_2}{g_0} \geq 0, \quad g_0 \geq 0 & \text{If} \quad \alpha_2 < 0 \end{cases}. \tag{27}$$

Notice that when $\alpha_2 < 0$, $\alpha_1 \geq -\frac{\alpha_2}{g_0} > 0$. Solution to $f(g,\boldsymbol{\alpha}) \geq 0$ can be simplified to

$$\begin{cases} g_0 \geq 0 \\ \alpha_1 \geq 0 \\ \alpha_1 + \frac{\alpha_2}{g_0} \geq 0 \end{cases}. \tag{28}$$

Now we will derive transition probability matrix $\mathbf{P}$ as a function of $\mathbf{H}$ and $\boldsymbol{\alpha}$, denoted as $\mathbf{P}(\mathbf{H}, \boldsymbol{\alpha})$. Substitute (22) and (21) into (9) (assume $g_0 = 0$),

$$s(g, q) = \lfloor \frac{T_b W}{L} \log_2(\widetilde{a}_1(q) g + \widetilde{a}_2(q)) \rfloor, \tag{29}$$

where $\tilde{a}_1(q) = \alpha_1 h(q)$, $\tilde{a}_2(q) = 1 + \alpha_2 h(q)$. Since $\alpha_1 \geq 0$, (29) is an increasing function of g. The minimum channel gain for transmitting x packets is

$$\begin{aligned} b_x^{(q)} &= \min\{g | s(g, q) = x\} \\ &= \begin{cases} \frac{1}{\tilde{a}_1(q)} (2^{\frac{xL}{T_b B}} - \tilde{a}_2(i)) & 0 < x \leq M \\ 0 & x = 0 \end{cases}. \end{aligned} \tag{30}$$

$b_x^{(q)}$ are boundaries of channel gains to calculate probability $k_x^{(i)}$. Substituting (29), (30) and (24) into (8),

$$\begin{aligned} k_x^{(i)} &= \text{Prob}[b_x^{(i)} \leq g < b_{x+1}^{(i)}], \forall x < M \\ &= \text{Prob}[g \geq b_x^{(i)}] - \text{Prob}[g \geq b_{x+1}^{(i)}] \\ &= e^{-\lambda b_x^{(i)}} - e^{-\lambda b_{x+1}^{(i)}}. \end{aligned} \tag{31}$$

For $g_0 > 0$, the channel gain boundaries of k_x^i are amended according to the relative value between g_0 and $\{b_x^{(i)}\}$

$$k_0^{(i)} = 1 - e^{-\lambda \max(b_1^{(i)}, g_0)} \tag{32a}$$

$$k_x^{(i)} = \begin{cases} e^{-\lambda b_x^{(i)}} - e^{-\lambda b_{x+1}^{(i)}}, & g_0 < b_x^{(i)} \\ e^{-\lambda g_0} - e^{-\lambda b_{x+1}^{(i)}}, & b_x^{(i)} \leq g_0 < b_{x+1}^{(i)}, \\ & 1 \leq x \leq M-1 \\ 0, & g_0 \geq b_{x+1}^{(i)} \end{cases} \tag{32b}$$

$$k_M^{(i)} = 1 - \sum_{l=0}^{M-1} (k_l^{(i)}). \tag{32c}$$

Substituting (32) into (11) and (12), we obtain the transition probability matrix $\mathbf{P}(\mathbf{H}, \boldsymbol{\alpha})$.

In summary, the optimization problem for the SQLA power control scheme is

$$\begin{aligned}
\min_{\mathbf{H},\boldsymbol{\alpha}} \quad & P_{drop} = \tfrac{1}{\mu} \sum_{l=M-\mu}^{M} \pi_l(\mu - l + M) \\
s.t. \quad & \alpha_1 e^{-\lambda g_0} + \lambda \alpha_2 \Gamma_0(g_0 \lambda) \leq P_0 \\
& \mathbf{H} \geq 0 \\
& g_0 \geq 0 \\
& \alpha_1 \geq 0 \\
& \alpha_1 + \tfrac{\alpha_2}{g_0} \geq 0 \\
& \boldsymbol{\pi} = \boldsymbol{\pi} \mathbf{P}(\mathbf{H}, \boldsymbol{\alpha})
\end{aligned} \tag{33}$$

The numerical solution can be found by sequential quadratic programming (SQP) method [21, page 576].

IV. Simulation Results

Fig. 3 and Fig. 4 illustrate two examples of SQLA power controls, for stringent delay constraint and loose delay constraint, respectively. The probability mass function of analysis results are obtained by solving equation (13). The simulation parameters and the resulting packet drop probabilities are listed in Table II and Table III. When $\mu = 25$, the delay constraint is stringent, the CGB part of the power control is similar to TCI. While when $\mu = 5$, the delay constraint is loose, the CGB part of the power control is similar to TDWF. The tail distribution of the queue length is approximately exponential. This is consistent with the large deviation theory, which indicates that when $M/\mu \to \infty$, the asymptotic tail distribution of queue length decays exponentially [15]. Notice that, when M/μ is small, i.e. in Fig. 3(c), the queue length distribution does not have exponential decay property.

As a comparison, the TCI and TDWF power control for $\mu = 25$ and $\mu = 5$ are also illustrated. They use the same average power as the SQLA power control scheme. The resulting packet drop probabilities are 0.08 for TCI and 0.14 for TDWF; while the SQLA power control has packet drop probability at approximately 10^{-3}. The packet drop probability is reduced by one to two orders of magnitude under the SQLA power control scheme, which successfully suppresses the probability of the last μ queue states, resulting in a lower packet drop probability.

Fig. 5 illustrates the packet drop probability vs. average power for SQLA, TDWF, and TCI power control schemes. It is observed that SQLA achieves approximately 9 dB gain over TDWF and TCI when the packet drop probability is 10^{-3}.

V. Conclusion

In this paper, we studied the link-PHY layer power control schemes that minimizes the packet drop probability for a queueing system with finite size buffer. We proposed a sub-optimal power control scheme, SQLA, which assumes the channel gain and queue length affect the transmission power independently. These two factors form the CGB and QLA part of the SQLA power control. The CGB part of the power control has a general formulation. TDWF and TCI power control scheme which maximize the ergodic capacity and delay-limited capacity, respectively, are two special cases of the CGB part of SQLA. The whole SQLA power control scheme can be parameterized by $M+4$ parameters. And we optimize these parameters to minimize the packet drop probability. Under the same average power constraint, the proposed SQLA power control scheme reduces the packet drop probability by one to two order of magnitude, compared to the existing CGB power control schemes; e.g., the proposed SQLA power control achieves a packet drop probability of 10^{-3} while the time domain water filling power control achieves a packet drop probability of 0.14. This demonstrates the superiority of the proposed SQLA power control over the existing CGB power control schemes.

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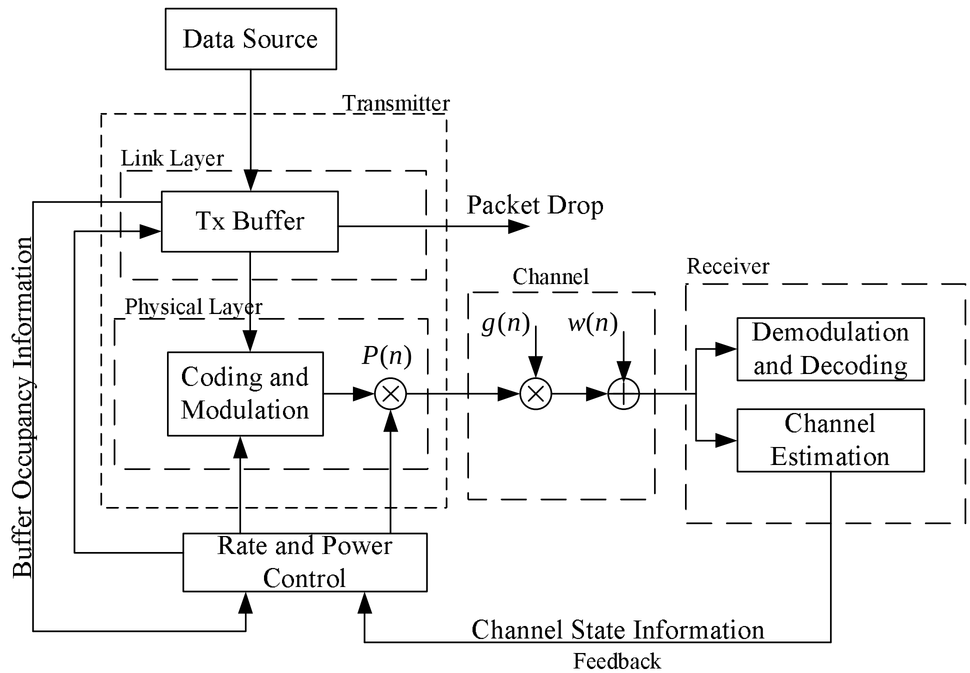


Fig. 1. System model.

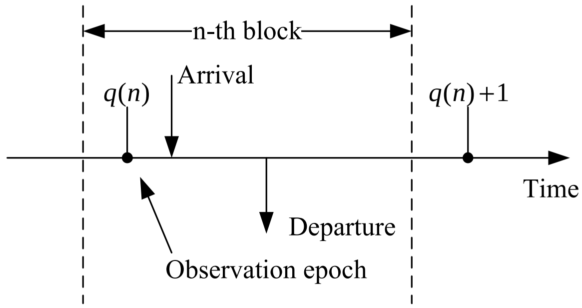
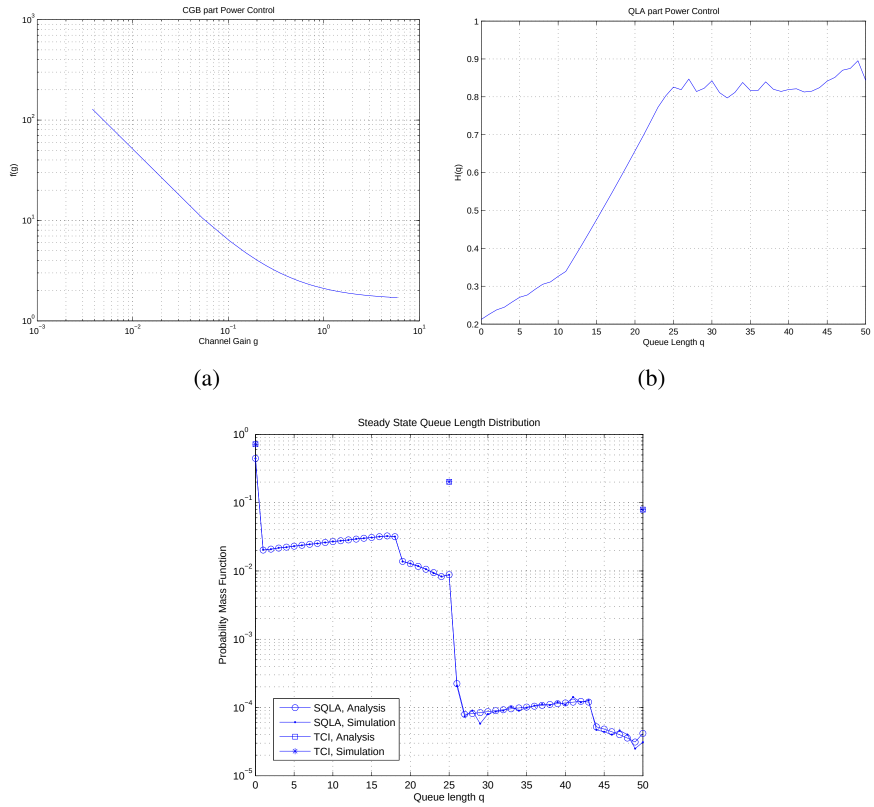


Fig. 2. Update of queue length.



(a) (b)

(c)

Fig. 3. SQLA, $\mu = 25$, $M = 50$. (a). $f(g)$ of SQLA power control; (b). $H(q)$ of SQLA power control; (c). Queue length distribution of SQLA power control.

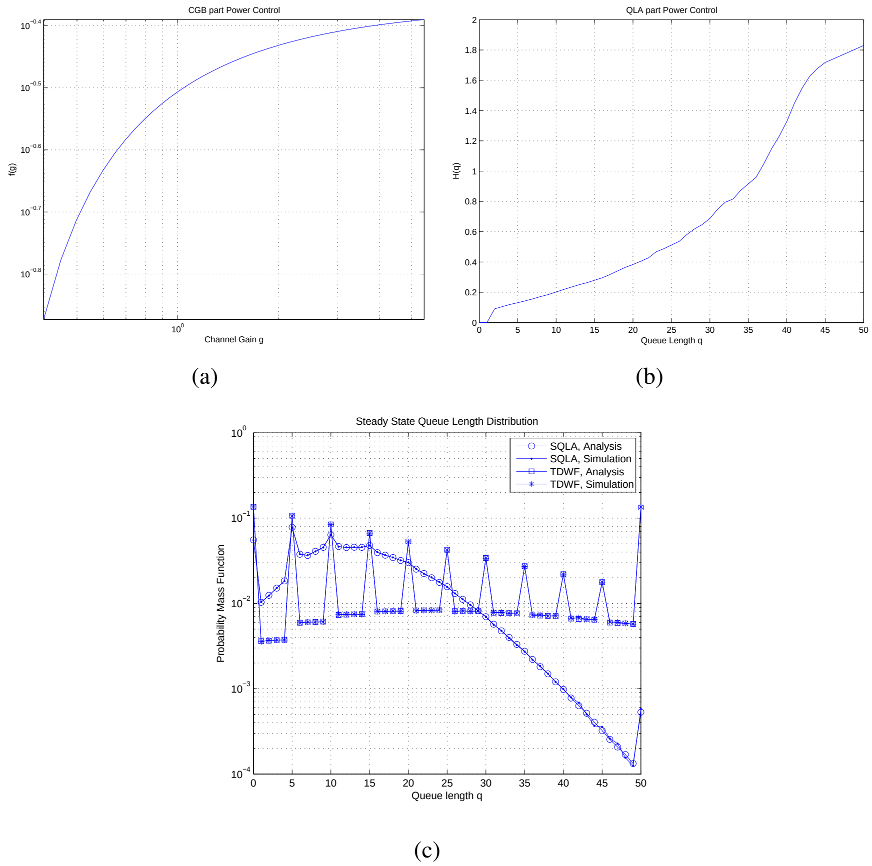


Fig. 4. SQLA, $\mu = 5$, $M = 50$. (a). $f(g)$ of SQLA power control; (b). $H(q)$ of SQLA power control; (c). Queue length distribution of SQLA power control.

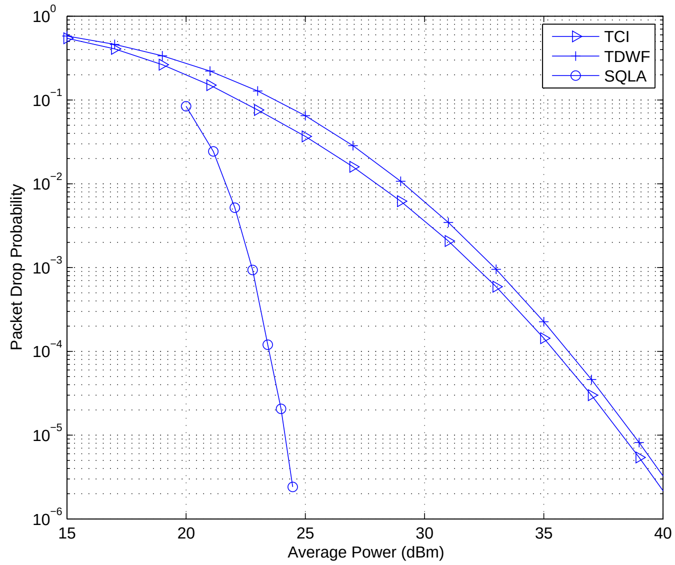


Fig. 5. Packet drop probability v.s. average power, $\mu = 10$, $M = 50$.

TABLE I

CONFIGURATION OF $f(g)$.

α_1	α_2	g_0	Power Control Scheme
> 0	0	0	CONST
$\frac{1}{g_0}$	-1	> 0	TDWF
0	> 0	> 0	TCI

TABLE II

SIMULATION PARAMETERS FOR SQLA.

WT_b/L	50	
λ	1	
M	50	
μ	25	5
P_0	1.31	0.057

TABLE III

SIMULATION RESULTS.

μ	25	5
P_{drop} (SQLA)	0.9e-3	1e-3
P_{drop} (CGB)	0.08 (TCI)	0.14 (TDWF)