E(x) Performance Analysis of Station-Status-Distinguishing Polling Systems (Postprint)

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Date: 2018-08-13T00:00:00+00:00

Abstract

To improve the work efficiency and resource utilization of polling control systems while ensuring that system fairness is not compromised, a limited (K=2) polling control system that distinguishes between busy and idle states of stations is proposed. The mathematical model of the system is studied using the method of probability generating functions and embedded Markov chains. Simulation experimental results show that the theoretical values are approximately equal to the experimental values, indicating that the analysis method is correct and reasonable. Based on the limited (K=2) polling service strategy, the system provides service only to dynamically busy stations with information packets according to the different states of the stations. The adoption of the limited (K=2) service strategy guarantees system fairness, while distinguishing between busy and idle states of stations also avoids query service to idle stations without information packets, thereby improving system work efficiency and resource utilization. Compared with existing service strategies, system performance is significantly improved.

Full Text

Preamble

Analysis of E(x) Characteristics of Polling System that Distinguishes Site Status

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Abstract: To improve the work efficiency and resource utilization of polling control systems while ensuring fairness remains uncompromised, this paper proposes a limited (K=2) polling control system that distinguishes between busy and idle site statuses. The mathematical model of the system is studied using probability generating functions and embedded Markov chain methods. Simulation results demonstrate that theoretical values closely approximate experimental values, validating the correctness and rationality of the analytical method. Based on the limited (K=2) polling service strategy, the system serves only dynamically busy sites with information packets according to their different states. The limited (K=2) service strategy ensures system fairness, while distinguishing between busy and idle statuses avoids querying idle sites without information packets, thereby improving system efficiency and resource utilization. Compared with existing service strategies, system performance is significantly enhanced.

Keywords: K=2; distinguish busy and idle; polling; efficiency

0 Introduction

Polling control systems are widely applied in intelligent transportation and modern networks due to their contention-free operation, good fairness, and rational resource allocation [1]. However, gate-limited and exhaustive service strategies can cause "starvation" phenomena when a site has many information packets, as sites waiting in queue may not receive service while the current site is being served, thus reducing system fairness. Limited service strategies overcome this issue and ensure system fairness.

Literature [2,3] analyzed polling queueing theory systems in cognitive radio networks and R&D management models, while literature [4] examined polling control systems in wireless networks, and literature [5] studied their application in FPGA data acquisition systems. The IEEE 802.11 series standards employ limited (K=1) polling control in their PCF protocols, but this approach lacks flexibility for distinguishing network service priorities. Literature [8] constructed a "exhaustive+gate-limited" two-level polling system model to differentiate service priorities, but this fixed-path polling of all sites (including idle ones) limits channel utilization, increases system complexity, and reduces service flexibility. Literature [6] studied limited service polling systems based on finite-time analysis for broadband wireless networks with centralized control. Literature [9] proposed a limited (K=N) service system that can distinguish service priorities through different K values—larger K values enable more information packets to be sent per service, achieving higher priority. However, literature [9] did not provide theoretical analysis for limited (K>1) service strategies.

With the rapid development of modern network technology and strong demand for differentiated service priorities, the limited (K=1) service strategy can no longer meet practical requirements. There is an urgent need for limited (K>1) polling control strategies that can both distinguish service priorities and maintain system fairness, while establishing a theoretical foundation for subsequent research on limited services.

Polling control is divided into three classical service strategies: exhaustive, gate-limited, and limited service. However, single gate-limited and exhaustive strategies cannot differentiate priorities across different sites to improve performance, whereas limited service can. Literature [7] applied this to ordinal optimization of G/G/1/K polling control systems. According to service rules, when the number of information packets at a site is less than 2, the server serves one packet or none; when equal to 2, it serves both; when greater than 2, it still serves only two packets.

Querying idle sites without information packets wastes system resources. Literature [10] allocated channels only to sites with transmission demands to avoid idle queries. However, the polling schedule remains independent of site status—receivers must wait for one time slot without data before switching to the next sender. When sites remain idle, receivers waste resources querying them in each round.

Addressing these issues, this paper proposes a busy and idle polling limited K=2 system model (BIPL2) based on dynamic thinking [11,12]. The system employs a limited (K=2) service strategy and distinguishes sites as busy or idle according to their buffer status, updating the polling schedule each round. The server only serves busy sites with service demands, reducing average waiting time and improving efficiency. Using probability generating functions [13] and embedded Markov chains [14], we conduct an in-depth analysis of the system model, validated through simulation experiments.

1.1 Model Principle Analysis

The BIPL2 system consists of N sites and one server, as shown in [Figure 1: see original paper]. The server first updates site status and serves only busy sites with transmission demands. By not listening to idle sites, the system reduces average queue length and waiting time, while the limited (K=2) service strategy transmits at most 2 information packets per polling visit.

1.2 Variable Definitions

Let $\xi_i(n)$ denote the number of information packets buffered at site i at time t_n, where $i = 1, 2, ..., N$. Let $v_i(n)$ represent the service time for site i at time t_n. Let $\eta_j(v_i)$ denote the number of information packets arriving at site j during the service time v_i of site i, where $j = 1, 2, ..., N$.

The probability generating function, mean, and variance of the Poisson arrival process at each site are respectively:

$$A_i(z), \quad A_i'(1) = \lambda_i, \quad A_i''(1) = \sigma_\lambda^2 = \lambda^2 + \lambda$$

The probability generating function, mean, and variance of the service time for any information packet are:

$$B_i(z), \quad B_i'(1) = \beta_i, \quad B_i''(1) = \sigma_\beta^2 = \beta^2 + \beta$$

The probability generating function, mean, and variance of the switchover time between sites are:

$$R_i(z), \quad R_i'(1) = \gamma_i, \quad R_i''(1) = \sigma_\gamma^2 = \gamma^2 + \gamma$$

1.3 Model Assumptions

a) Information packet arrivals at each site follow independent and identically distributed Poisson processes.

b) Service times for any information packet follow independent and identical probability distributions.

c) Switchover times between sites after completing service follow a probability distribution with generating function $R_i(z)$.

d) Each terminal site has sufficiently large buffer capacity to prevent data loss.

e) Buffered information packets follow a First-Come-First-Served (FCFS) transmission policy.

The system distinguishes sites as busy or idle based on whether they have information packets to transmit. Each round updates the polling schedule according to site buffer status, and the server only serves busy sites with service demands.

1.4 Probability Generating Function

Assume that at time t_n^+, the i-th busy site begins receiving service. After the i-th busy site completes service according to the limited (K=2) rule, the server moves to serve the (i+1)-th busy site, which begins service at time t_{n+1}^+. Define random variables and let $g_i(j)$ represent the number of information packets buffered at site j when site i is being served at time t_n^+.

The system state at time t_n^+ can be expressed as $[\xi_1(n), \xi_2(n), ..., \xi_N(n)]$. Polling system site quantities are relatively fixed, and the system state at service initiation instants is countable, forming an embedded Markov chain from discrete-time countable state variables. Under stable conditions, this Markov process is homogeneous, irreducible, aperiodic, and has a unique stationary distribution. The stationary probability distribution is denoted as $p[\xi_i(n) = x_i, i = 1, 2, ..., N]$.

The probability generating function of the system state is defined as:

$$G(z_1, z_2, ..., z_N) = \lim_{n\to\infty} E\left[\prod_{i=1}^{N} z_i^{\xi_i(n)}\right]$$

The state at time t_{n+1}^{+} can be expressed as:

$$\xi_j(n+1) = \begin{cases} \xi_j(n) + \eta_j(v_i) & j \neq i \\ \xi_i(n) - \min(\xi_i(n), 2) + \eta_i(v_i) & j = i \end{cases}$$

Under system stability conditions, the generating function satisfies:

$$G(z_1, ..., z_N) = R\left(\prod_{j=1}^{N} A_j(z_j)\right) \cdot G\left(z_1, ..., B_i\left(\prod_{j=1}^{N} A_j(z_j)\right), ..., z_N\right)$$

1.5 Average Queue Length

Definition: The average queue length $g_i(j)$ is the number of information packets stored at site j when site i is being served at time t_n^{+}.

Define first-order partial derivative characteristics as:

$$g_i(j) = \lim_{z_1,...,z_N \to 1} \frac{\partial G(z_1, ..., z_N)}{\partial z_j}$$

Define second-order partial derivative characteristics as:

$$g_i(j,k) = \lim_{z_1,...,z_N \to 1} \frac{\partial^2 G(z_1, ..., z_N)}{\partial z_j \partial z_k}$$

Through derivation, the average queue length is obtained as:

$$L_i = \frac{\lambda_i \beta}{1 - N\lambda\gamma} + \frac{N\lambda^2\beta^2 + N\lambda^2\sigma_\beta^2}{2(1 - N\lambda\beta)} + \frac{N\lambda\sigma_\gamma^2}{2\gamma}$$

1.6 Average Waiting Time

Definition: The average waiting time is the mean time interval from when an information packet arrives at a site until its service begins.

1.7 Average Polling Cycle

Definition: The average polling cycle is the mean time between two consecutive polls of the same site, derived from first-order system characteristics.

1.8 System Throughput

Definition: System throughput refers to the amount of information successfully transmitted per unit time.

2.1 Experimental Simulation

Based on the established BIPL2 system model, numerical calculations and simulation experiments were conducted under stable conditions. Theoretical values for the BIPL2 system were computed using equations (13)-(16).

Simulations were performed on the MATLAB 2014a platform. Poisson distribution sequences with mean λ were generated to simulate information packet arrivals. The communication process was simulated under ideal conditions with zero packet loss and retransmission rates. The time axis was divided into slots after normalization.

Simulation parameters: a) The number of information packets entering each site' s buffer in any unit time slot follows a Poisson distribution.
b) Symmetric control system: packet arrivals at all sites follow identical probability distributions.
c) System stability condition: $\sum_{i=1}^{N} \lambda_i \beta < 1$.
d) Simulation parameters are labeled below each figure.

2.2 Results Analysis

Figures 2-5 demonstrate that the theoretical analysis method reasonably describes the BIPL2 polling control system, with close agreement between theoretical calculations and simulation results.

Figures 4 and 5 depict the relationship between average queue length, average polling cycle, and system load. Both metrics increase with system load, with small errors between theoretical and experimental values, consistent with theoretical derivations.

Figure 3 shows the relationship between average waiting time and packet arrival rate. The average waiting time increases linearly with arrival rate because higher arrival rates increase the packet arrival process, thereby increasing overall system waiting time.

Figure 2 illustrates the relationship between throughput and packet arrival rate. System throughput also increases linearly with arrival rate. However, since increased arrival rate simultaneously increases waiting time (Figure 3), average waiting time should be considered as a constraint when improving throughput.

Figure 8 compares throughput between BIPL2 and limited (K=1) systems. Under the same average waiting time conditions, the BIPL2 system achieves higher throughput.

Figure 6 compares average waiting time between BIPL2 and limited (K=1) systems. As arrival rate increases, the average waiting time for limited (K=1) grows sharply, while BIPL2' s waiting time changes slowly and remains stable. When the number of sites N increases from 10 to 20, limited (K=1) shows rapid growth and large fluctuations, whereas BIPL2 increases slowly with minimal fluctuation.

Figure 7 compares average waiting times among single gate-limited service, exhaustive service, and BIPL2 under identical experimental conditions. The BIPL2 system' s average waiting time is significantly smaller than both single gate-limited and exhaustive services. This is because BIPL2 avoids querying idle sites without packets, thereby reducing average waiting time and improving efficiency. Among the three classical polling strategies (exhaustive, gate-limited, and limited), average waiting time typically increases in that order under the same conditions. The BIPL2 system achieves better service priority differentiation while maintaining fairness and reducing waiting time by transmitting two packets per service.

Polling control systems offer contention-free operation and Quality of Service (QoS) guarantees, making them important MAC layer scheduling mechanisms for wireless sensor networks. Key QoS metrics include throughput, delay, and delay variation. As shown in Figures 2, 3, and 6-9, the BIPL2 system achieves higher throughput, significantly reduced delay, and stable delay variation with minimal fluctuations, providing excellent QoS guarantees.

3 Conclusion

The proposed BIPL2 system employs a limited (K=2) service strategy that serves only busy sites with information packets based on their status. This reduces energy consumption from querying idle sites and improves system efficiency and resource utilization. The mathematical model was established using probability generating functions and embedded Markov chains, with precise analytical solutions for key system parameters.

Polling control systems provide conflict-free information access and delay guarantees for delay-sensitive services, remaining crucial scheduling mechanisms for wireless sensor network MAC layers. Traditional ultra-dense wireless sensor networks are recommended as complements to cellular networks, and 5G ultra-dense cellular networks have been proposed based on MIMO communication technology. The BIPL2 polling control system will undoubtedly play a prominent role in 5G optimization and improvement [16].

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Note: Figure translations are in progress. See original paper for figures.

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