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REVIEWS

Stochastic Polling Systems: Development and New Applications

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Abstract—This review presents new results obtained in the field of stochastic polling systems research. It systematizes the main directions of practical application of polling models for performance evaluation and design of wireless WMAN networks with centralized control mechanisms, 5G/6G cellular networks, Internet of Things networks, transportation and medical systems, etc. The prospects for the further development of applied research in this important area of queueing theory are discussed.

Keywords: Polling systems, telecommunication networks, 5G/6G, Internet of Things, transport control, healthcare systems

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1. INTRODUCTION

Mathematical models of stochastic polling systems have found extensive application in the design of communication, manufacturing, transportation, and medical systems, among others. These models are particularly effective for the evaluation of performance and the design of existing and prospective telecommunication network protocols that employ centralised control mechanisms.

Research into stochastic polling systems and the synthesis of results in this domain of queueing theory up to 1995 are documented in monographs [1, 2]. Because of their broad practical applications, the scholarly interest in polling systems remains undiminished. The past two decades have witnessed the publication of review papers [3–8], primarily focusing on the mathematical methodologies for their analysis. An exception is the 2011 review [9], which systematised the practical applications for stochastic polling models.

The rapid evolution and successive generational shifts in cellular networks, broadband wireless systems, industrial robotics, and various unmanned ground/air systems have necessitated the development of novel polling models and analytical techniques for performance assessment and system design. These include methods for analyzing systems with correlated arrival streams, characteristic of modern computational networks [10, 11], and machine learning approaches applied when traditional queueing-theoretic methods yield intractable or unobtainable analytical/numerical results [12, 13]. Despite a substantial volume of recent publications in the last decade, a comprehensive review systematizing new directions in the practical application of stochastic polling models remains absent. The present survey aims to address this gap.

The paper is structured as follows. Section 2 introduces fundamental concepts and describes the basic stochastic polling model, which constitutes the subject of most theoretical and applied work in the field. Section 3 examines the application of stochastic polling models for performance evaluation in IEEE 802.11 broadband wireless metropolitan area networks with centralized control.

Section 4 systematizes research on the application of centralized polling models in Internet of Things (IoT) and 5G/6G cellular networks. Section 5 discusses how stochastic polling models can help manage vehicular traffic at intersections. Section 6 describes the applications of polling systems in healthcare for the disease prognosis, diagnosis, and the hospital logistics. Section 7 outlines other applications including passive optical networks, energy consumption, and manufacturing processes. The Conclusion identifies prospective directions for further applied research in stochastic polling systems.

2. FUNDAMENTAL CONCEPTS AND THE BASIC STOCHASTIC POLLING MODEL

This section details the primary mathematical model underpinning most applied research on polling systems. Subsequent sections will provide concise descriptions of model variants where they diverge from this foundational framework.

A basic polling system comprises N ($N \geqslant 2$) queues (nodes, stations) with infinite waiting space and a single server. The server is a physical entity processing requests/customers. The service here providing an access to a specific resource (e.g., data channel access) contingent upon the model's context.

Customers arrive at queue Q_i according to a Poisson process with rate λ_i. Service times in Q_i are independent and identically distributed with distribution function $B_i(t)$, first and second moments b_i and $b_i^{(2)}$, and Laplace–Stieltjes Transform (LST) $\tilde{B}_i(x) = \int_0^\infty e^{-xt} dB_i(t)$, for $i = \overline{1, N}$. The server visits queues in a prescribed order, most commonly cyclic. During a visit, customers are served according to a specified discipline: *exhaustive* (server continues until the queue is empty), *gated* (only customers present at the polling moment are served), *globally-gated* (only customers present at the cycle start are served), or k_i*-limited* (at most k_i customers served per visit to Q_i). Comprehensive classifications are available in [4, 6].

The server switchover time to connect to Q_i is a random variable with distribution $S_i(t)$, moments s_i, $s_i^{(2)}$, and LST $\tilde{S}_i(x)$. For cyclic polling systems, the total switchover time per cycle has moments $s = \sum_{j=1}^N s_j$ and $s^{(2)} = s^2 + \sum_{j=1}^N (s_j^{(2)} - s_j^2)$. A *cycle* is the time to poll and serve all queues once. Under cyclic polling, the mean cycle time is $C = \frac{s}{1-\rho}$ where $\rho = \sum_{i=1}^N \rho_i$ is the total load and $\rho_i = \lambda_i b_i$ is the load of Q_i. Stability for exhaustive/gated systems requires $\rho < 1$; for k_i-limited service, this is supplemented by $\lambda_i < \frac{k_i(1-\rho_i)}{s}$ for all i.

The analytical challenge lies in constructing a multidimensional process capturing the polling dynamics, deriving stationary probabilities and mean performance metrics, and obtaining numerical solutions for large-scale systems.

Methodological approaches include mean-value analysis [14], the branching process method [15], and decomposable semi-regenerative process theory [16]. The predominant technique for cyclic/periodic systems is the probability generating function (the PGF) method [17] briefly outlined here for gated and exhaustive service.

Let X_i^j be the number of customers in Q_j when Q_i is polled, and define the PGF $G_i(\mathbf{z}) = \mathbf{E}\left[\prod_{j=1}^N z_j^{X_i^j}\right]$ with $\mathbf{z} = (z_1, \ldots, z_N)$.

For gated service, these functions satisfy

$$G_{i+1}(\mathbf{z}) = G_i\left(z_1, z_2, \ldots, z_{i-1}, \tilde{B}_i\left[\sum_{j=1}^N \lambda_j (1-z_j)\right], z_{i+1}, \ldots, z_N\right) \tilde{S}_{i+1}\left[\sum_{j=1}^N \lambda_j (1-z_j)\right], \quad i = \overline{1, N}. \quad (1)$$

The mean queue lengths $f_i(j) = \mathbf{E}[X_i^j]$ are solutions to a linear system yielding:

$$\begin{aligned} f_{i+1}(j) &= f_i(j) + \lambda_j b_i f_i(i) + \lambda_j s_{i+1}, \quad j \neq i, \\ f_{i+1}(i) &= \lambda_i b_i f_i(i) + \lambda_i s_{i+1}, \quad i = \overline{1, N}. \end{aligned} \tag{2}$$

Second moments are obtained via further differentiation, leading to the mean waiting time $W_i = \frac{(1+\rho_i) f_i(i,i)}{2\lambda_i^2 C}$.

For exhaustive service, the relations become:

$$G_{i+1}(\mathbf{z}) = G_i\left(z_1, \ldots, z_{i-1}, \tilde{\theta}_i\left[\sum_{\substack{j=1 \\ j\neq i}}^{N} \lambda_j(1 - z_j)\right], z_{i+1}, \ldots, z_N\right) \tilde{S}_{i+1}\left[\sum_{j=1}^{N} \lambda_j(1 - z_j)\right],$$

where $\tilde{\theta}_i(w)$, the LST of a busy period in the corresponding $M/G/1$ queue for Q_i, satisfies

$$\tilde{\theta}_i(w) = \tilde{B}_i(w + \lambda_i - \lambda_i \tilde{\theta}_i(w)). \tag{3}$$

The mean waiting time is then $W_i = \frac{\lambda_i b_i^{(2)}}{2(1-\rho_i)} + \frac{f_i(i,i)}{2\lambda_i^2(1-\rho_i)C}$.

Other analytical methods include functional computation [18], matrix-analytic approaches [19], heavy-traffic asymptotics [20, 21], and the pseudo-conservation law [22], detailed in [5, 6].

3. APPLICATION OF STOCHASTIC POLLING MODELS FOR PERFORMANCE EVALUATION AND DESIGN OF BROADBAND WIRELESS METROPOLITAN AREA NETWORKS

A Wireless Metropolitan Area Network (WMAN) is a type of wireless network designed to provide telecommunications coverage over a broad geographical area. WMANs consist of a series of interconnected wireless base stations or access points strategically located throughout a metropolitan area. These base stations communicate with each other and with end-user devices to enable efficient and seamless data transmission.

In wireless metropolitan networks operating under IEEE 802.11 standard protocols, centralized polling mechanisms are widely employed. Among these protocols, which implement cyclic polling of subscriber terminals by a base station (access point server), are the Point Coordination Function (PCF) and its evolution—the Hybrid Coordination Function (HCF) and the HCF Controlled Channel Access (HCCA) protocol [23]. The use of these protocols in metropolitan networks characterized by high-rise buildings and radio interference helps mitigate the hidden terminal problem, efficiently schedules station access to the wireless channel, provides flexible control over the radio cell operation, and allows dynamic adjustment of its parameters according to the current situation.

References [24–26] present a comparative analysis of various polling schemes for evaluating the performance characteristics of IEEE 802.11 PCF metropolitan networks. They also propose an adaptive polling model that not only addresses the hidden terminal problem but also optimizes access to the data transmission channel. It is worth noting that the adaptive polling scheme and its first protocol version were initially described in [27–29].

In the adaptive polling scheme, the order of queue visits remains cyclic, but the server does not visit (does not poll) queues that were empty at the time of polling in the previous cycle. For asymmetric systems with non-zero switchover times, adaptive polling reduces the mean polling cycle time and, consequently, enhances wireless network performance.

The formula for the mean cycle time from Section 2 in this case takes the form

$$C = \frac{\sum_{i=1}^{N} s_i u_i + \beta \prod_{i=1}^{N}(1-u_i)}{1-\rho}$$

where $u_i = \frac{1}{1+e^{-\lambda_i C}}$ is the probability that queue Q_i is visited by the server in an arbitrary cycle, $i = \overline{1,N}$, and β is the mean idle (waiting) time of the server when all queues in sequence are found empty during polling and must be skipped. The server waiting time is introduced here to eliminate empty polling cycles.

In the case of the gated service discipline, the system (1) for the PGFs $G_i(\mathbf{z})$, $i = \overline{1,N}$ takes the form:

$$\begin{aligned} G_i(\mathbf{z}) &= (1-u_i)u_{i-1}\mathcal{M}_{i+1}^{(1)}(\mathbf{z}) + \ldots + (1-u_1)\cdots(1-u_{N-1})u_N\mathcal{M}_{i+1}^{(N-1)}(\mathbf{z}) \\ &\quad + (1-u_1)\cdots(1-u_N)\mathcal{M}_{i+1}^{(N)}(\mathbf{z}) + u_i\mathcal{M}_{i+1}^{(0)}(\mathbf{z}), \end{aligned} \tag{4}$$

where

$$\mathcal{M}_{i+1}^{(l)}(\mathbf{z}) = G_{i-l}\left(z_1,\ldots,z_{i-l},\widetilde{B}_{i-l}\left(\sum_{j=1}^{N}\lambda_j(1-z_j)\right),z_{i-l+2},\ldots,z_N\right)\widetilde{S}_{i-l+1}\left[\sum_{j=1}^{N}\lambda_j(1-z_j)\right],$$

$$\begin{aligned} \mathcal{M}_{i+1}^{(N)}(\mathbf{z}) &= G_{i-N}\left(z_1,\ldots,z_{i-N},\widetilde{B}_{i-N}\left(\sum_{j=1}^{N}\lambda_j(1-z_j)\right),z_{i-N+2},\ldots,z_N\right) \\ &\quad \times \widetilde{S}_{i-N+1}\left[\sum_{j=1}^{N}\lambda_j(1-z_j)\right]\tilde{H}\left(\sum_{j=1}^{N}\lambda_j(1-z_j)\right), \quad l = \overline{0,N-1} \end{aligned}$$

and system (2) transforms to:

$$\begin{aligned} f_{i+1}(j) &= u_i\left[I_{\{i=j\}}f_i(j) + \lambda_j b_i f_i(i) + \lambda_j s_{i+1}\right] \\ &\quad + (1-u_i)u_{i-1}\left[\lambda_j(s_{i+1}+\beta) + I_{\{i-1=j\}}f_{i-1}(j) + \lambda_j b_{i-1}f_{i-1}(i-1) + \lambda_j s_{i+1}\right] + \ldots \\ &\quad + (1-u_1)\cdots(1-u_N)\left[I_{\{i-N=j\}}f_{i-N}(j) + \lambda_j b_{i-N}f_{i-N}(i-N)\right], \quad i,j = \overline{1,N}. \end{aligned}$$

As in the case of ordinary cyclic polling, the mean waiting times for the system with adaptive polling are determined as $W_i = \frac{(1+\rho_i)f_i(i,i)}{2\lambda_i^2 C}$, $i = \overline{1,N}$, where the second moments $f_i(j,k)$, $i,j,k = \overline{1,N}$ are computed as a solution to a system of linear equations obtained by differentiating the PGFs $G_i(\mathbf{z})$, $i = \overline{1,N}$. The case of exhaustive queue service is considered similarly [25].

In [30], a polling model with time-limited queue service, describing data transmission in IEEE 802.11e HCCA networks, is investigated. It is shown that the PGF $\omega_i(\mathbf{z})$ for the number of customers in the system at the moments of service completion in queue Q_i is expressed through the PGF $\bar{\omega}_i(\mathbf{z})$ for the number of customers in the system at the moments of polling queue Q_i as follows:

$$\omega_i(\mathbf{z}) = \frac{\gamma\tilde{B}_i\left(\sum_{k=1}^{N}\lambda_k(1-z_k)\right)}{z_i - \tilde{B}_i\left(\sum_{k=1}^{N}\lambda_k(1-z_k)\right)}\left[\bar{\omega}_{i-1}(\mathbf{z})\tilde{S}_i\left(\sum_{k=1}^{N}\lambda_k(1-z_k)\right) - \bar{\omega}_i(\mathbf{z})\right], \quad i = \overline{1,N}$$

where γ is a known constant determined by the mean cycle time C and the total arrival intensity into the system. The PGFs $\bar{\omega}_i(\mathbf{z})$, $i = \overline{1,N}$ are found from functional equations numerically using the Fourier transform. The LST $W_i(s)$ of the waiting time in queue Q_i satisfies the relation

$$W_i(s) = N_i(1-s/\lambda_i)/\tilde{B}_i(s), \quad i = \overline{1,N},$$

where $N_i(s)$ is the PGF for the number of customers in queue Q_i at service completion moments, computed as $N_i(z) = \omega_i(1, \ldots, 1, z_i, 1, \ldots, 1)/\omega_i(\mathbf{1})$.

Reference [31] also considers the application of a large-scale polling system with branching-type service disciplines to modeling the BACnet (Building Automation and Control Networks) protocol for building automation and control networks. Branching-type disciplines are defined as follows. If at some embedded moment, e.g. an arbitrary queue Q_i polling moment, its length is k_i then each of these k_i customers during the Q_i service time is replaced by some random number of customers having PGF $h_i(\mathbf{z})$. As shown in [32], polling systems with branching-type disciplines allow for exact analysis of performance characteristics whereas service disciplines not possessing this property typically necessitate approximate analytical methods.

Branching-type disciplines include, for example, the gated discipline with

$$h_i(z_1, \ldots, z_N) = \tilde{B}_i\left(\sum_{k=1}^{N} \lambda_k(1 - z_k)\right), \quad i = \overline{1, N}$$

and the exhaustive discipline with $h_i(z_1, \ldots, z_N) = \tilde{\theta}_i\left(\sum_{k=1}^{N} \lambda_k(1 - z_k)\right)$, $i = \overline{1, N}$, where the function $\tilde{\theta}(s)$ is defined by the functional relation (3). Limited disciplines, however, do not belong to this class, and systems with such disciplines require the development of approximate methods.

For a polling system with a branching-type discipline, the functional relation (1) for the PGFs $G_i(\mathbf{z})$, $i = \overline{1, N}$ transforms to

$$G_{i+1}(\mathbf{z}) = G_i\left(z_1, z_2, \ldots, z_{i-1}, h_i(\mathbf{z}), z_{i+1}, \ldots, z_N\right) \tilde{S}_{i+1}\left[\sum_{j=1}^{N} \lambda_j(1 - z_j)\right], \quad i = \overline{1, N}$$

which enables the derivation of performance characteristics based on the mean queue lengths at polling moments, obtained by differentiating the above relations.

The LST of the cycle time C is given by

$$\mathbf{E}\left[e^{-uC}\right] = G_1(\tilde{\theta}_1(\gamma_1(\mathbf{u})), \ldots, \tilde{\theta}(\gamma_N(\mathbf{u}))) \prod_{i=1}^{N} \tilde{S}_i(\mathbf{u}),$$

where $\mathbf{u} = (u, \ldots, u)$, $\gamma_N(\mathbf{z}) = z_N$, $\gamma_i(\mathbf{z}) = z_i + \sum_{j=i+1}^{N} \lambda_i(1 - \tilde{\theta}_j(\gamma_j(\mathbf{z})))$, $i = \overline{1, N-1}$.

For service disciplines not belonging to the branching class, such as k-limited service, [31] also proposes a so-called *flexible k-limited* discipline. It is similar to the ordinary k-limited discipline except when the server serves fewer than k customers in a queue. In this case, the server utilizes the unused service capacity to serve the next queue in order. This allows, for example, in the case of a highly asymmetric polling system, to transfer part of the service resource from less loaded queues to more loaded ones, thereby reducing the mean system waiting time.

References [33, 34] explore the possibility of organizing a metropolitan broadband wireless network using a tethered high-altitude long-endurance unmanned aerial platform [35–37]. An IEEE 802.11 PCF base station installed on an Unmanned Aerial Vehicle (UAV) at an altitude of 100–150 m can significantly increase the line-of-sight zone between subscribers and the base station antenna thereby expanding the network's coverage area. References [38, 39] investigate a polling model with retrials, describing the data transmission mechanism in FANET (Flying Ad Hoc Network) — wireless self-organizing networks based on UAVs.

In [40], the case of Markovian polling order is investigated, modeling Carrier-Sense Multiple-Access Collision-Avoidance (CSMA-CA) in IEEE 802.11 networks operating in random access mode. The server visits queues according to a random Markovian polling scheme, described by a stochastic matrix $\mathbf{P} = (p_{i,j})_{i,j=\overline{1,N}}$ and a probability vector $\mathbf{q} = (q_1, \ldots, q_N)$. The vector $\mathbf{q}$ is calculated as the solution of the system $\mathbf{qP} = \mathbf{q}$, $\sum_{i=1}^{N} q_i = 1$.

The queue service discipline can be any branching type as described above. The mean cycle time for queue Q_i is calculated as $C_i = \frac{\sigma}{q_i(1-\rho)}$, where $\sigma = \sum_{j=1}^{N} q_j \sum_{k=1}^{N} p_{j,k}\mathbf{E}[S_{j,k}]$; $S_{j,k}$ is the random variable describing the switchover time between queues Q_j and Q_k, $j,k = \overline{1,N}$.

This case allows application of the PGF method yielding the functional relations similar to (1)

$$q_j G_j(\mathbf{z}) = \sum_{i=1}^{N} p_{i,j} q_i G_i\left(z_1, z_2, \ldots, z_{i-1}, h_i(\mathbf{z}), z_{i+1}, \ldots, z_N\right) \tilde{S}_{i+1}\left[\sum_{j=1}^{N} \lambda_j (1 - z_j)\right], \quad j = \overline{1,N}.$$

The first moments $f_i(j)$, $i,j = \overline{1,N}$ of the queue lengths at the start of polling can be obtained explicitly facilitating the computation of key system performance characteristics.

The mean unconditional queue length L_j for Q_j is computed as:

$$L_j = \sum_{i=1}^{N}\left(\rho_i x_i(j) + \frac{(1-\rho)q_i}{\sigma}\sum_{k=1}^{N} p_{i,k}\mathbf{E}[S_{i,k}] y_{i,k}(j)\right), \quad j = \overline{1,N}$$

where $x_i(j)$ and $y_{i,k}(j)$ are known constants. The article [40] also generalizes the pseudo-conservation law for an arbitrary branching-type service discipline which can be used for system performance optimization

$$\sum_{i=1}^{N} \rho_i W_i = \rho \frac{\sum_{i=1}^{N} \lambda_i b_i^{(2)}}{2(1-\rho)} + \frac{1}{\sigma}\sum_{i=1}^{N} q_i \sum_{k=1}^{N} p_{i,k}\mathbf{E}[S_{i,k}] \sum_{j=1, j\neq i}^{N} f_i(j) b_j$$
$$+ \frac{1}{1-\rho}\sum_{i=1}^{N} \lambda_i \frac{1-\rho_i}{1-h_i(i)} \sum_{k=1}^{N} p_{i,k}\mathbf{E}[S_{i,k}] \sum_{j=1}^{N} b_j h_i(j) + \frac{\rho}{2\sigma}\sum_{i=1}^{N} q_i \sum_{k=1}^{N} p_{i,k}\mathbf{E}[S_{i,k}^2].$$

A model of a priority polling system with three queues and threshold-based service is used in [41] to analyze switching systems operating in Asynchronous Transfer Mode (ATM) for large-scale metropolitan networks, such as the DQDB (Distributed Queue Dual Bus) standard.

A similar application of a polling system with random polling order to describe a multiple access scheme in IEEE 802.16 WiMAX metropolitan networks operating in contention-based access mode is considered in [42]. Reference [43] proposes a multi-level MAC protocol with priority polling for military applications. For a system with three queues and limited service, describing a specific case of a polling system with an adaptive polling mechanism, [44] presents the stability condition.

In conclusion of this section, we note that subsequent versions of the IEEE 802.11 standard have introduced new access mechanisms (e.g., Triggered Uplink Access, TUA) [45, 46], which can also be effectively investigated using stochastic polling models.

4. SYSTEMATIZATION OF WORKS ON THE APPLICATION OF POLLING MODELS IN INTERNET OF THINGS NETWORKS AND 5G/6G CELLULAR NETWORKS

Internet of Things (IoT) networks have seen intensive development in recent years [47–49]. Stochastic polling models can be effectively used to evaluate characteristics and perform comparative analysis of protocols for such networks. Among the works devoted to this type of analysis, the following can be noted.

In [50], a Medium Access Control (MAC) protocol for IoT networks is analyzed using a star-type priority polling model. Such polling allows for separating users with different priorities to reduce delay and ensure fair access service. The model is represented by a system of $N+1$ $M/G/1$-type queues. Queue Q_h has priority over the other N queues and is served by the server according to a gated discipline each time after the service of any other queue is completed. The non-priority queues receive exhaustive service.

The vector describing the number of customers in the queues at the moment of polling Q_i has dimension $N+1$; therefore, the corresponding PGF of stationary probabilities has an additional argument z_h. The functional relations (1) in this case connect the PGFs $G_i(\mathbf{z}, z_h)$ and $G_{ih}(\mathbf{z}, z_h)$ as follows:

$$G_{i+1}(\mathbf{z}, z_h) = G_{ih}\left(\mathbf{z}, \tilde{B}_h\left(\sum_{j=1}^{N}\lambda_j(1-z_j)+\lambda_h(1-z_h)\right)\right), \tag{5}$$

$$G_{ih}(\mathbf{z}, z_h) = G_i\left(z_1,\dots,z_{i-1}, \tilde{\theta}_i\left(\sum_{j=1}^{N}\lambda_j(1-z_j)+\lambda_h(1-z_h)\right), z_{i+1},\dots,z_N, z_h\right)$$
$$\times \tilde{S}_i\left[\sum_{j=1}^{N}\lambda_j(1-z_j)+\lambda_h(1-z_h)\right], \quad i=\overline{1,N}.$$

As shown in Sections 2 and 3, these functional equations allow for the computation of key performance characteristics. Note that here $\tilde{S}_i(s)$ is the LST of the server disconnection time from queue Q_i.

In [51], a neural network algorithm is used to predict and analyze network performance in Wireless Sensor Networks (WSN). The model enables solving priority tasks in the IoT domain. A neural network is constructed to predict system performance. It is demonstrated how the proposed priority scheme helps improve system performance compared to a similar polling system with a single-level priority.

In [52], a new fast polling algorithm for wireless mesh networks in narrowband IoT systems is presented. It is shown that the algorithm significantly minimizes the polling time required by the data collection and management center to receive responses from all remote telemetry devices. In [53], a polling model with two queues and a correlated Batch Markovian Arrival Process (BMAP) input stream is investigated for the design and optimization of high-definition video streaming in IoT networks.

Stochastic polling models can be effectively used for performance evaluation and design of protocols for next-generation 5G/6G cellular networks. The deployment of 5G/6G networks provides a significant expansion of the service range for users, increased network capacity, and higher data transfer speeds compared to previous generations [54]. To achieve high and ultra-high data rates in access and transport segments of next-generation networks, not only traditional centimeter-wave radio channels (up to 6 GHz) but also millimeter-wave channels (up to 100 GHz) with wide bandwidth are utilized [55, 56].

However, considering the propagation characteristics of millimeter waves (short coverage zones), the 3GPP consortium proposed the Integrated Access and Backhaul (IAB) technology [57] which integrates access and backhaul functions within a single network. This technology allows for the creation of a cost-effective network by using inexpensive relay nodes (IAB nodes) instead of fully equipped base stations, which is particularly important for deploying 5G networks along transportation corridors.

In [58], a polling model with two queues is used to analyze the performance of a terminal node in an IAB network. One queue stores data transmitted via the downlink from the parent IAB node, the second stores data transmitted via the uplink from child nodes and user equipment associated with the terminal node. In [59–61], a boundary node is modeled as an $M_K/G_K/1$-type polling system with cyclic polling and instantaneous server switchovers between queues ($s_i = 0$, $i = \overline{1, K}$) except for a period s_0 at the beginning of the cycle which can be interpreted as the connection time to queue Q_1. It is assumed that customers can only arrive at the queues during time s_0 representing a combination of globally-gated and exhaustive service. In this case, the PGF (1) for the number of customers at queue polling moments takes the form

$$G_i(\mathbf{z}) = \tilde{S}\left(\sum_{j=i}^{K}(\lambda_j(1 - z_j))\right), \quad i = \overline{1, K},$$

where $\tilde{S}(w)$ is the LST of the distribution function of the random variable s_0. Subsequently, moments of arbitrary order for the random variables X_i^j, $i, j = \overline{1, K}$, describing the number of customers in queues at polling moments, are obtained explicitly. The LST of the delay time distribution in queue Q_i with an arbitrary service time distribution function has the form

$$\tilde{\Delta}_i(w) = s^i \prod_{j=1}^{i} \frac{1}{s + \lambda_j(1 - \tilde{B}_j(w))}$$

with mean $\Delta_i = \frac{1}{s}\sum_{j=1}^{i}\lambda_j b_j$, $i = \overline{1, K}$.

Polling models have found application in modeling congestion control for SIP servers [62]. SIP (Session Initiation Protocol) is a data transmission protocol that describes a method for establishing and terminating a user communication session in 5G networks. In [62], a scheme for threshold-based control of load generated by non-priority clients is proposed. In [63], the analysis of the SIP server congestion control mechanism is continued by testing various service disciplines. The considered polling model assumes a threshold-based discipline for switching to a priority queue and two service disciplines: exhaustive and gated. It is shown that in some cases, using gated service for the priority queue is preferable.

In conclusion of this section, we also note the article [64] which considers a model with a controlled (dynamic) polling order to achieve the required level of fairness — the system's ability to provide the same quality of service to users in generalized scheduling algorithms in modern wireless networks, and the paper [65] which investigates various polling policies (rules for polling and service) to solve scalability problems of the standard Transmission Control Protocol (TCP).

5. APPLICATION OF STOCHASTIC POLLING MODELS IN TRANSPORTATION AND VEHICULAR TRAFFIC MANAGEMENT AT INTERSECTIONS

The application of polling models in traffic control has an extensive history, detailed in the review [9] published in 2011. The further development of this application area is reflected in a number of later articles. In particular, [66] considers a polling model with random duration of green traffic signals for each direction depending on its traffic load, aiming to minimize waiting time at an intersection. To model automated traffic light control regulating vehicle movement at an intersection, [67, 68] investigates a two-queue polling system with a threshold-type priority for switching the server between queues. The traffic light determines the crossing priority for two directions in a threshold-based manner: when the number of vehicles in any direction reaches a threshold value, the green light turns on for that direction. In [68], a matrix-analytic approach is applied to obtain the key performance characteristics of such a model. A variation of threshold-based strategies for switching the server between queues to regulate intersection traffic is also considered in [7].

In [69], an exact solution for a two-queue polling system with threshold priority is proposed. Simulation results of a polling mechanism at fully autonomous intersections are presented in [70].

Autonomous vehicles approaching an intersection adjust their speed to pass through the intersection while avoiding collisions.

For traffic flows, the assumption of independence of flows moving through an intersection is not realistic; therefore, accounting for the correlated nature of real traffic flows is a highly relevant task. In [71, 72], for a two-queue polling model, the correlated and non-stationary nature of input flows is accounted for using a Markovian Arrival Process (MAP) and a Marked Markovian Arrival Process (MMAP). In [71], two queues of the $MAP/PH/1/N$ type with alternating server service and phase-type service time distribution are considered. The authors provide a detailed analysis of waiting time in the queue, which can serve as a guide for analyzing waiting times in other polling models, not only through their mean values but also in terms of distributions. For example, the LST of the waiting time distribution for customers in the first queue has the form:

$$v_1(s) = \frac{1}{\lambda_1} \sum_{i_1=0}^{N_1-1} \sum_{i_2=0}^{N_2} \Bigg(\boldsymbol{\pi}^{(-1)}(i_1, i_2) \left(I_{M_{-1}} \otimes \hat{D}_1^{(1)} \right) \mathbf{e} v_1^{(-1)}(s, i_1)$$
$$+ \boldsymbol{\pi}^{(-2)}(i_1, i_2) \left(I_{M_{-2}} \otimes \hat{D}_1^{(1)} \right) \mathbf{e} v_1^{(-2)}(s, i_1, i_2)$$
$$+ \sum_{j=1}^{N_1} \boldsymbol{\pi}^{(1)}(j, i_1, i_2) \left(I_{M_1} \otimes \hat{D}_1^{(1)} \right) \mathbf{e} v_1^{(1)}(s, j, i_1, i_2)$$
$$+ \sum_{j=1}^{N_2} \boldsymbol{\pi}^{(2)}(j, i_1, i_2) \left(I_{M_2} \otimes \hat{D}_1^{(1)} \right) \mathbf{e} v_1^{(2)}(s, j, i_1, i_2) \Bigg) + P_1^{(loss)},$$

where $P_1^{(loss)}$ is the loss probability in queue Q_1, $\boldsymbol{\pi}^{(k)}(*)$ are stationary probabilities corresponding to state $(*)$ when the server visits queue Q_k, $v_1^{(k)}(s, *)$ is the LST of the conditional waiting time distribution in queue Q_1 given that the server is in state k and the system is in state $*$, $D_1^{(1)}$ is one of the matrices describing arrivals in the MAP flow.

In conclusion of this section, we also note other applications of polling models in transportation systems. In [73], the application of Radio Frequency Identification (RFID) technology [74] for monitoring the number of vehicles at an intersection to adapt traffic signals to the current traffic situation is investigated. For transportation systems, [75] analyzes the problem of improving priority order delivery without reducing the efficiency of regular order delivery. For this purpose, it is proposed to designate some order-picking machines as priority with exhaustive service discipline, while the others are non-priority with a service limit of one order (1-limited service discipline). In [76], a modification of service disciplines in a polling system describing an order delivery system is proposed to reduce the assembly time for multiple orders for a single customer.

6. APPLICATION OF STOCHASTIC POLLING MODELS IN HEALTHCARE SYSTEMS

Currently, polling system models are actively applied in the field of medical monitoring. For example in [77], a polling system is used to evaluate the performance of wireless body sensor networks which are modern monitoring systems using wireless technologies for disease prediction and diagnosis. The article [78] analyzes a sleep mode scheme in Wireless Body Area Networks (WBAN) based on the IEEE 802.15 standard via a discrete-time polling model with adaptive polling order, assuming the server skips empty queues if they were empty at the previous polling moment.

The model considered in [19] describes the initial patient intake process at a medical clinic. Patients are admitted by several nurses, each organizing their own queue of patients, and an on-duty doctor. A patient is directed to the nurse with the shortest queue for examination. Afterward, the doctor admits patients, each time choosing a patient from the longest queue. This scheme involves a combination of two strategies for customer arrival and service: joining an incoming customer to the queue with the shorter length and serving the queue with the larger number of customers by the server. This allows describing the behavior of the corresponding two-queue polling model with a two-dimensional Markov chain where the first component is the length of Q_1, and the second one is the current difference in queue lengths. The Markov chain in this case belongs to the class of quasi birth-and-death processes and has an infinitesimal generator of the form

$$Q = \begin{bmatrix} B_1 & B_0 & 0 & \dots & \dots & \dots \\ B_2 & A_1 & A_0 & 0 & \dots & \dots \\ 0 & A_2 & A_1 & A_0 & 0 & \dots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots \end{bmatrix},$$

where the elements of matrices A_i and B_i are input parameters of the system.

The vector $\mathbf{p}_n$ of stationary state probabilities of the system, corresponding to the number n of customers in queue Q_1 calculated as $\mathbf{p}_n = \mathbf{p}_1 R^{n-1}$, $n \geqslant 1$ where matrix R is the minimal non-negative solution to the matrix equation $A_0 + RA_1 + R^2 A_2 = O$. The vectors $\mathbf{p}_0$ and $\mathbf{p}_1$ are found from the system

$$\mathbf{p}_0 B_1 + \mathbf{p}_1 B_2 = \mathbf{0}, \quad \mathbf{p}_0 B_0 + \mathbf{p}_1 (A_1 + RA_2) = \mathbf{0}, \quad \mathbf{p}_0 \mathbf{e} + \mathbf{p}_1 [I - R]^{-1} \mathbf{e} = 1,$$

where $\mathbf{e} = (1, \dots, 1)$, I is the identity matrix. The mean length of queue Q_1 is calculated as $L_1 = \mathbf{p}_1 [I - R]^{-2} \mathbf{e}$.

In [79], it is proposed to use a polling scheme for scheduling edge computing to adapt scheduling methods for multiple services. An edge server provides services to a hospital information center. The authors consider the problem of maximizing the efficiency of edge server utilization using a star-type priority polling scheme. As in [50], the model has N ordinary queues and one priority queue. All queues receive exhaustive service except Q_h visited by the server each time the server leaves a non-priority queue. The PGFs of the number of customers in queues at polling moments satisfy functional relations similar to (5) where the LST $\tilde{B}_h(s)$ is replaced by $\tilde{\theta}_h(s)$ defined by formula (3).

7. OTHER APPLICATIONS OF POLLING SYSTEMS

Polling systems are also used in other areas not covered in previous sections, such as passive optical networks, robotics, satellite systems, and production processes.

Passive Optical Networks (PON) are a telecommunications technology that uses fiber-optic communication channels to provide users with high-speed Internet access, video, and voice services. The term *passive* stems from the use of passive optical splitters which do not require active components to distribute the optical signal to multiple endpoints. In [80], the issue of the existence of a stationary regime in a multi-server polling system with limited service, modeling the data transmission process in networks based on PON technology, is investigated.

In [81], a scheme for accumulating and servicing customers in polling systems modeling data transmission based on PON technology is proposed. This is the so-called *multi-phase gated* service discipline. A customer arriving at queue Q_i must wait K_i cycles before it is served, $i = \overline{1, N}$. As the authors note, such a multi-phase discipline helps solve the problem of server monopolization by more loaded queues by selecting appropriate values $(K_1, \dots, K_N)$. Despite its complexity, this discipline allows for an exact analysis of the system and explicit derivation of performance characteristics.

The system state at the moment of polling queue Q_1 (start of a cycle) is described by the set of random variables $X_{i,n}^{(k)}$, $k = \overline{1, K_i}$, $i = \overline{1, N}$, $n \geqslant 0$, where $X_{i,n}^{(k)}$ is the number of customers in queue Q_i at phase k at the nth moment of polling queue Q_1. The process $X^{(n)} = \left(X_{1,n}^{(1)}, \ldots, X_{1,n}^{(K_1)}, \ldots, X_{N,n}^{(1)}, \ldots, X_{N,n}^{(K_N)}\right)$, $n \geqslant 0$ is a K-dimensional multi-type branching process with immigration [32], with the PGF for the number of offspring:

$$f(\mathbf{s}) = \left(f^{(1,1)}(\mathbf{s}), \ldots, f^{(1,K_1)}(\mathbf{s}), \ldots, f^{(N,1)}(\mathbf{s}), \ldots, f^{(N,K_N)}(\mathbf{s})\right),$$

where $\mathbf{s} = \left(s_1^{(1)}, \ldots, s_1^{(K_1)}, \ldots, s_N^{(1)}, \ldots, s_N^{(K_N)}\right)$, and for $i = \overline{1,N}$

$$f^{(i,k)}(\mathbf{s}) = s_i^{(k+1)}, \quad k = \overline{1, K_i - 1},$$
$$f^{(i,K_i)}(\mathbf{s}) = \tilde{B}_i\left(\sum_{j=1}^{i} \lambda_j(1 - s_j^{(1)}) + \sum_{j=i+1}^{N} \lambda_j(1 - f^{(j,1)}(\mathbf{s}))\right),$$

and the PGF of immigration is

$$g(\mathbf{s}) = \prod_{i=1}^{N} \tilde{S}_i\left(\sum_{j=1}^{i} \lambda_j(1 - s_j^{(1)}) + \sum_{j=i+1}^{N} \lambda_j(1 - f^{(j,1)}(\mathbf{s}))\right).$$

The pseudo-conservation law (expression for the weighted sum of mean waiting times in the system) for the multi-phase gated discipline is

$$\sum_{i=1}^{N} \rho_i \mathbf{E}[W_i] = \rho\frac{\rho}{1-\rho}\frac{b^{(2)}}{2b} + \rho\frac{s^{(2)}}{2s} + \frac{s}{2(1-\rho)}\left[\rho^2 - \sum_{i=1}^{N}\rho_i^2\right] + \sum_{i=1}^{N}\mathbf{E}[M_i]$$

where M_i is the mean amount of work remaining in queue Q_i when the server leaves queue Q_i, $b^{(2)} = \sum_{i=1}^{N} \frac{\lambda_i}{\Lambda} b_i^{(2)}$, $b = \sum_{i=1}^{N} \frac{\lambda_i}{\Lambda} b_i$, $\Lambda = \sum_{i=1}^{N} \lambda_i$. For the multi-phase gated discipline, $\mathbf{E}[M_i] = \rho_i((K_i - 1) + \rho_i)\frac{s}{1-\rho}$, $i = \overline{1,N}$.

In [82], another model for data reservation and transmission in PON networks is presented: a polling system with retrials and so-called *glue periods*. Customers arriving at queue Q_i can accumulate in the queue and then receive service only during a so-called glue period, which has a fixed length G_i. Customers arriving outside this period go into orbit and make repeated attempts to join the queue during the glue period. The repeated attempts from the orbit of queue Q_i form a Poisson process with parameter ν_i, $i = \overline{1,N}$.

The PGF for the number of customers in queues at the start of the glue period for queue Q_1 has the explicit form

$$X(\mathbf{z}) = \prod_{m=0}^{\infty} K\left(h_1^{(m)}(\mathbf{z}), h_2^{(m)}(\mathbf{z}), \ldots, h_N^{(m)}(\mathbf{z})\right), \quad i = \overline{1,N},$$

where $h_i^{(0)}(\mathbf{z}) = z_i$, $h_i^{(n)}(\mathbf{z}) = h_i\left(h_i^{(n-1)}(\mathbf{z}), h_2^{(n-1)}(\mathbf{z}), \ldots, h_N^{(i-1)}(\mathbf{z})\right)$, the functions $h_i(\mathbf{z})$, $i = \overline{1,N}$ are defined as

$$h_i(\mathbf{z}) = f_i\left(z_1, \ldots, z_i, h_{i+1}(\mathbf{z}), \ldots, h_N(\mathbf{z})\right),\ i = \overline{1, N-1}, \quad h_N(\mathbf{z}) = f_N(\mathbf{z}),$$

where $f_i(\mathbf{z}) = (1 - e^{-\nu_i G_i})\beta_i(\mathbf{z}) + e^{-\nu_i G_i} z_i$, $\beta_i(\mathbf{z}) = \tilde{B}_i\left(\sum_{j=1}^{N} \lambda_j(1 - z_j)\right)$, $i = \overline{1,N}$.

The function $K(\mathbf{z})$ is defined as follows:

$$K(\mathbf{z}) = \prod_{i=1}^{N} \sigma_i\left(z_i, \ldots, z_i, h_{i+1}(\mathbf{z}), \ldots, h_N(\mathbf{z})\right) \prod_{i=1}^{N} e^{-G_i D_i(\mathbf{z})}$$

where

$$D_i(\mathbf{z}) = \sum_{j=1}^{i-1} \lambda_j (1 - z_j) + \lambda_i \left(1 - \beta_i \left(z_i, \ldots, z_i, h_{i+1}(\mathbf{z}), \ldots, h_N(\mathbf{z})\right)\right) + \sum_{j=i+1}^{N} \lambda_j \left(1 - h_j(\mathbf{z})\right),$$

$$\sigma_i(\mathbf{z}) = \tilde{S}_i \left(\sum_{j=1}^{N} \lambda_j (1 - z_j) \right).$$

Here, this refers to the LST of the disconnection time from queue Q_i, unlike the main model in Section 2, $i = \overline{1, N}$. In [82], the issue of optimizing the duration of glue periods is also considered.

Wireless Local Area Networks. The authors in [83] analyze a continuous polling system without separate queues, represented by a common two-dimensional waiting area for all customers, where arrivals occur randomly. The system models a Ferry-based Wireless Local Area Network (FWLAN). FWLAN is a concept for a wireless local area network where communication between nodes (users) and the external world or between nodes is possible via a mobile relay — a *ferry*. In such a network, isolated nodes are scattered over a certain area, and direct global communication between them is impossible. The moving relay, traveling along a predetermined cyclic route, communicates with static network nodes (or users) via a wireless communication channel. Mobile base stations are considered in the context of Mobile Ad-Hoc Networks (MANETs), Vehicular Ad-hoc Networks (VANETs), and wireless (static) sensor networks.

Networks-on-Chip. In [84, 85], the case of three-phase gated service is considered as a scheduling algorithm for Medium Access Control (MAC) in a Network-on-Chip (NoC) communication subsystem taking into account the specific features of the two-dimensional interconnection structure.

Energy Saving. In [86], an analysis of a polling system with two queues and time-limited queue service is presented from the perspective of energy consumption. The study primarily focuses on the balance between processor energy consumption in personal computers and their performance for users. It is assumed that in the polling model, the service rate of customers in a queue is not constant but depends on the queue load. This approach allows personal computers to adjust data processing speed and optimize energy consumption depending on the volume of tasks being performed.

Memory Usage Control. The model proposed in [67, 68] has another application — controlling the occupied memory volume in data centers when the data volume on individual disks exceeds a certain limit (threshold), leading to inefficient operation and necessitating memory cleanup.

Robotics. In [87], the use of a polling mechanism for processing environmental and social information received from a robot swarm is described. It is shown that the swarm's ability to adapt to load improves as the number of communication channels between robots decreases, which requires solving the corresponding optimization problem.

Satellite Systems. In [88], a polling model considering time-division duplex communication is investigated for developing a unified control system in global navigation satellite systems to improve data interaction.

Production Processes. In [8], a tandem of two $M/M/1$-type polling systems each having two queues is analyzed. This model represents the aluminum rolling production process. Each production stage is modeled by a polling system which describes the process of sequentially processing different types of alloys.

8. CONCLUSION

This review systematizes new directions of practical application for stochastic polling models based on an analysis of results from numerous articles by domestic and international authors published in recent years. The application of such models for evaluating performance characteristics and designing broadband wireless metropolitan networks, 5G/6G cellular networks, Internet of Things networks, transportation systems, and healthcare systems has been considered. The effectiveness of applying polling models in other areas, including robotics, satellite systems, passive optical networks, and production processes, has been briefly noted. For individual works of theoretical and/or practical interest, the review provides descriptions of original mathematical models of stochastic polling (differing from the main model discussed in Section 2 of the article) and the results of their investigation.

Directions for further development of applied work in the field of stochastic polling have been discussed. These include research on polling models with correlated input flows and generalized Phase-Type (PH) service time distributions, which adequately describe the operation of modern computing systems and networks; the application and development of machine learning methods and the matrix-geometric approach for predicting and evaluating the characteristics of systems with centralized control mechanisms. Additionally, a promising direction for further applied research is modeling new protocols for using multiple frequency channels and serving multiple users, as well as new access mechanisms such as Triggered Uplink Access (TUA).

The presented review summarizes applied research on stochastic polling systems, enables the formulation of new problems, and defines directions for future work in this promising area of queueing theory.

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