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Queueing Models For Energy-Efficient Communication Protocols In Wireless Networks

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Abstract

Energy consumption in wireless networks is a growing concern due to rising connectivity demands. Queueing models, grounded in queueing theory, offer a powerful approach to developing energy-efficient communication protocols. This article explores how these models optimize mobile communications by analyzing queue dynamics, including arrival rates, service disciplines, and service times. A balance between responsiveness and energy efficiency can be achieved by integrating queueing models into protocol design. Practical applications, such as in sensor and mobile networks, highlight their effectiveness. Future directions involve incorporating machine learning and advanced network architectures, reinforcing the role of queueing models in enhancing performance and sustainability in wireless communications.

Introduction

Wireless networks play a crucial role as the backbone of modern communication systems, supporting a wide range of devices and applications. However, the rapid increase in connectivity has led to a corresponding rise in energy consumption, creating an urgent need for energy-efficient communication strategies. Researchers are exploring integrated queueing models as a solution, leveraging their ability to balance performance and energy savings in complex wireless environments. As modern wireless communication expands through personal devices and the Internet of Things (IoT), energy efficiency becomes increasingly vital. Traditional communication protocols, though reliable, often struggle to combine real-time responsiveness with energy-saving requirements, particularly for battery-powered devices. This challenge has prompted growing interest in queueing models as a means to enhance communication protocol design.

The use of queueing models in analyzing energy-efficient communication protocols begins with understanding key concepts from queueing theory, such as stochastic arrival and service rates. These models are particularly suited to address the dynamic behaviour of wireless systems, offering a systematic and mathematical framework for analyzing network performance. By applying queueing theory, researchers can design protocols that effectively manage data flow while minimizing energy use. This approach lays the groundwork for developing sustainable and integrated wireless communication systems that meet the growing demands of connectivity without compromising energy efficiency.

The Basics Of Queueing Theory

Queueing theory, as a branch of applied mathematics, provides a systematic and mathematical analysis of the behaviour of waiting lines which are referred to as queues in various systems. It has been applied in many fields such as telecommunication, computer science, transport, health care and manufacturing to mention but a few where there are entities that queue for services. However, to appreciate its significance in wireless communication it is good to develop a basic appreciation of queueing theory. This entails looking into basic notions like queues, service disciplines, and the performance indicators of the system; it stresses the importance of these notions in modelling stochastic arrival and service processes as a preparation for application to wireless networks.

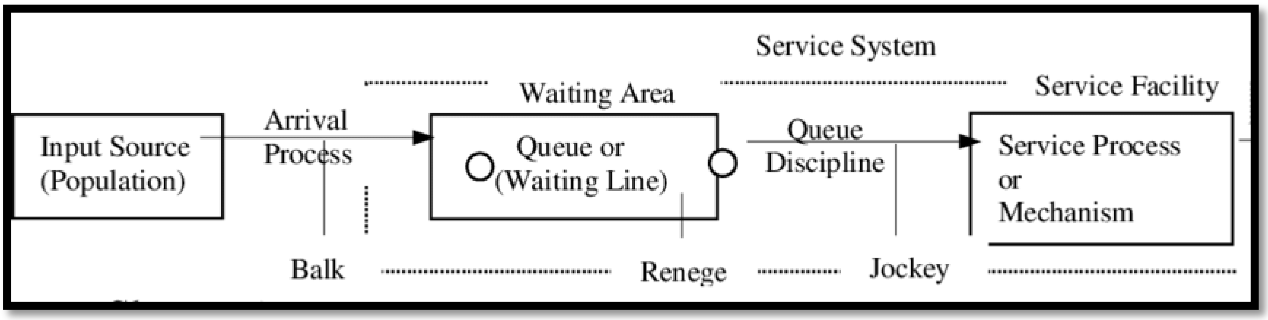

Fig 1: Queueing Theory Concept

Thus one of the main goals of the queueing theory is to understand and model the fundamental trade-off between service time and the cost of waiting. Through the analysis of these queue dynamics, it is possible for researchers to be able to simulate and coordinate various systems resulting in better throughput, shorter waiting times and overutilization of resources. This understanding forms the basis of the queueing theory that has relevance in handling issues to do with waiting for lines and service provision and therefore can be applied usefully in enhancing various systems including wireless communications.

Key Concepts

1. **Arrival Process (λ):** The average number of entities that arrive at the queue per unit time for service, that is arrival rate. In many applications, this arrival process is stochastic or random meaning that, the time between two arrivals is probabilistically determined.

2. **Service Process (μ):** The number of entities that are treated in a unit of time. Similar to the case with arrival, the service process is most commonly represented through a stochastic process.
3. **Queue Length (L):** The total number of entities which is present in the queue at a given time. It is necessary to be aware of the length of queues and how to control them in order to achieve performance improvements in the system.
4. **Service Rate**: This is the average time that is required to serve a customer which is represented by the symbol $1/\mu$. It denotes the chance of a system to attend to one or many other entities within a given timeframe.
5. **Utilization (ρ):** Meaning the rate at which customers arrive at the service facility divided by the rate at which customers are served ($\rho = \lambda/ \mu$). It shows just how optimally or otherwise the capacity of the system is being utilized. Hence any utilization greater than 1 is suggestive of congestion.
6. **Queueing Models**: These models define the nature of the behaviour of queues based on certain assumptions. Basic examples are of course the M/M/1 model (which is the mathematical model for describing the behaviour of a single server queue with Markovian arrival processes and Markovian time to service) and models like the M/M/c queue, M/G/1 queue and M/M/c queue which are more complex than the earlier one.
7. **Queue Discipline**: The On-simulator rules specified the order of serving of the entities. Some of the types of disciplines include; First In First Out (FIFO), Last In First Out (LIFO), and Priority queueing.

The Arrival Process (λ) is, therefore, the rate at which customers or other forms of entities wander to join a line of service with another same type in a stochastic manner. In a like manner, the Service Process (μ) refers to the probability of the flow of entities through the system per time-unit, or the rate of serving or processing of entities, which is usually stochastic in the model. The Queue Length (L) defines the number of entities in the queue at any point in time which is quite important while improving organizational performance. The Service Rate is defined as the number of entities a system can address per unit of time, which is equal to the inverse of the mean service time($1/\mu$). Utilization (ρ), which is obtained by dividing the arrival rate by the service rate ($\rho = \lambda / \mu$) indicates the efficiency to which the system's capacity is used. When the ratio is more than 1, chances are that there is congestion prevailing in the health facility. These are the Queueing Models: The basic model is M/M/1 (Markovian arrival process, Markovian service time, single server) and the other models include M/M/c (multiple identical servers) and M/G/1 (general service distribution). Queue Discipline is the way that entities in a queue are provided services and there are common forms including FCFS, LCFS and Priority Queueing. Identifying these elements is very important especially when dealing with the issues of controlling and facilitating the functionality of queues in different systems. Queueing theory has wide-ranging applications across various fields, including telecommunications for managing call centres and optimizing network performance, computer systems for resource allocation and system optimization, transportation for analyzing traffic flow and improving service efficiency at checkpoints, healthcare for managing patient flow in hospitals, and manufacturing for optimizing production lines. A solid understanding of the fundamentals of queueing theory equips individuals with the tools to model and optimize systems involving waiting lines and service processes, enabling effective solutions to complex real-world challenges

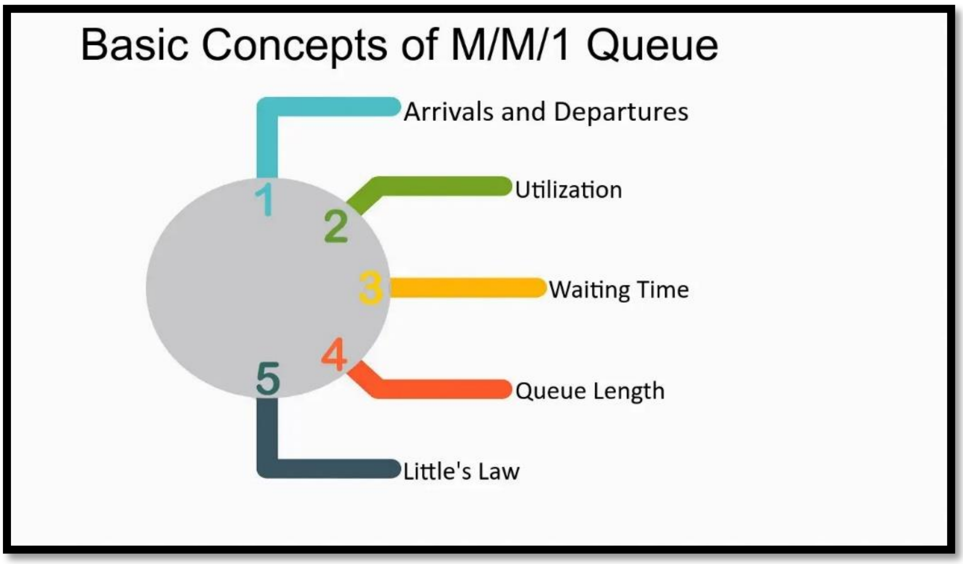

Fig 2: Basic Concepts of M/M/1 Queue

Energy-Efficient Communication Protocols

Traditional wireless communication protocols were not originally designed with energy-efficient devices in mind. As wireless connectivity becomes increasingly integral to modern society, especially in low-power applications like IoT sensors and mobile devices, the need for energy-aware communication protocols has become critical. The queueing theory offers a promising approach to addressing this challenge by enabling the development of communication protocols that strike a balance between performance and power consumption. By studying the behaviour of queues within wireless networks, researchers can fine-tune variables such as transmission intervals and sleep mode durations to reduce energy usage while maintaining acceptable levels of responsiveness. Key considerations include optimizing energy consumption through efficient transmission strategies, extending transmission intervals to reduce idle power usage, and integrating sleep modes to minimize active operation time. Adaptive protocols that respond to network conditions and environmental factors can further improve efficiency by dynamically adjusting transmission parameters, thus avoiding unnecessary energy expenditure.

Queueing models play a pivotal role in the design of energy-efficient communication systems by analyzing how data packets are scheduled for transmission. These models help optimize queue structures, allowing systems to manage traffic in a way that conserves energy without sacrificing performance. For instance, in battery-sensitive environments such as sensor networks, protocols can be tailored to prioritize energy efficiency over latency. Queueing theory also supports the development of protocols that can adapt to varying network loads and stochastic traffic patterns, making them well-suited for the dynamic nature of wireless networks. Real-world applications have demonstrated that queueing-based approaches can significantly extend battery life and maintain data quality, even in power-constrained settings. Despite the inherent complexity of modelling such dynamic systems, the deterministic and probabilistic tools offered by queueing theory remain essential for creating sustainable, energy-aware communication protocols in next-generation wireless networks.

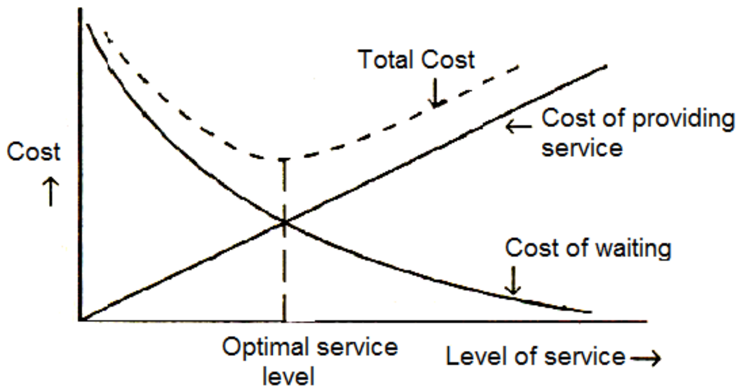

Fig 3: Optimisation of Cost

Implementing Wireless Network

Despite, the use of queueing models in the design of energy-efficient communication protocols for wireless networks is faced with certain challenges. Wireless environments continuously go through changes, as does the condition of a network, and this is a challenge that requires simpler models than organic structures. In this case, we relate the considerations of the inherent difficulties and propose new approaches that will help to achieve greater accuracy of the models in the context of queues.

Stochastic Nature of Wireless Networks:

***Challenge*:** Wireless networks present themselves as stochastic environments with packet arriving, transmission time and channel quality. The intricate nature of these dynamics creates difficulties in capturing the model of the interactions within the network.

***Solution*:** Accept the stochasticity by using high-level probabilistic methods. For understanding the randomness of arrival and service it is possible to use Markovian models like M/M/1 and M/M/c. Thus, by including stochastic components in these models, researchers can better reproduce the real-world variability of wireless communication.

Dynamic Network Conditions

***Challenge*:** Wireless communication networks are characterized by variations and fluctuations in topological characteristics, interferences and traffic intensity. Challenging in modelling these variations is the fact that conditions are not always static; therefore, mere models may not work.

***Solution*:** Implement new generating models of adaptive queueing theory which allows for altering of parameters by the network conditions. Learnt parameters may be introduced where the use of reconditioning and real-life data can be integrated into machine learning algorithms. This adaptive approach helps to improve the model's ability in case of changing environments of the network as well.

Non-Stationary Behavior

***Challenge*:** Most wireless networks display non-stationary characteristics, which implies that the statistical nature of the network changes with time. Most of the existing queueing models have stationary characteristics while the wireless environment is mainly dynamic.

***Solution*:** Use models that will capture the non-stationarity of wireless networks by incorporating time into the model. It may also require dividing time into portions and then tweaking the extensive model parameters correspondingly. Since the conditions prevailing in wireless communication systems change as time goes on, time-varying queueing models provide better modelling.

Heterogeneous Devices And Traffic

***Challenge*:** It is after noticed that many devices with different capabilities and different traffic patterns are in use in wireless networks; thus, the modelling is complicated. Queues can therefore exhibit diverse behaviours depending on the parameters of the devices as well as the kind of interactions they have.

***Solution*:** Extend the queueing models by adding heterogeneity into the system through a classification of the device that is based on the traffic and capability. These models permit the specification of devices of different types with different types of service requirements.

Subsequently, this makes the approach more comprehensive in terms of understanding how energy-efficient protocols could be implemented for different classes of devices.

Validation And Calibration

***Challenge*:** This brings into perspective the need to validate the queueing models in order to ascertain the accuracy of the models. But in order to facilitate the formulation of realistic optimization issues and as input to the wireless communication systems models, the datasets that are required often could be difficult to obtain.

***Solution*:** It is recommended that those kinds of validation and calibration processes should equally incorporate evidential data collected from simulations. On the one hand, simulation enables the experimenters to test many different situations, on the other hand, real data gives the vision of real system performance. This hybrid approach improves the accuracy of the proposed queuing models by synchronising them with the reactivity of the networks.

Scalability

***Challenge*:** Although the current wireless networks are not that large, scalability is an important issue as they tend to expand in size and functionality. As will be evident, conventional queueing theories may not be well-equipped to deal with these higher volumes of devices and data traffic.

***Solution*:** Study queueing models that are relevant to a network with a higher number of nodes that can be expanded to manage a more significant number of nodes of the network. A second approach is to partition and distribute the computational load using parallelism and distribution; thus, scalability remains an issue that the models can handle. These solutions hence outline a general approach modellers can adopt in overcoming the modelling hurdles related to energy-efficient communication protocols in wireless networks with an aim of advancing the development of appropriate queueing models. Thus, these models may work as key in addressing the stochastic, dynamic and heterogeneity of wireless environments to ensure that protocols offer sustainability and optimal performance.

Future Directions

Future directions in the development of energy-efficient communication protocols using queueing models include the integration of machine learning, adaptation to emerging network architectures, multi-objective optimization, and incorporation of edge computing. The seamless integration of machine learning enables dynamic adjustments to communication protocols based on real-time network conditions, enhancing responsiveness and adaptability. With the rise of 5G and future network architectures, queueing models must evolve to address challenges such as increased data rates, reduced latency, and higher device density, ensuring continued relevance. Additionally, incorporating multi-objective optimization allows protocols to balance not only energy efficiency but also latency, reliability, and security, catering to the diverse requirements of various applications. Furthermore, extending queueing models to support edge computing paradigms can significantly reduce latency and energy use by enabling distributed processing closer to the data source. These advancements collectively point toward a more intelligent, adaptable, and efficient wireless communication landscape.

Conclusion

The integration of queueing models into the design of energy-efficient communication protocols marks a significant step toward achieving sustainable wireless networks. As connectivity demands rise, collaboration between queuing theorists and communication engineers becomes essential. This review highlights the theoretical foundations, practical applications, and future possibilities of queueing models in driving energy efficiency in wireless communications. With the emergence of technologies like 5G and the potential of machine learning for dynamic protocol adaptation, the fusion of queueing theory with cutting-edge advancements offers promising avenues for research. Queueing models provide a systematic and mathematical framework to optimize data flow and develop responsive, energy-aware protocols. As modern life grows increasingly connected, the synergy between queueing models and communication strategies becomes a pivotal force in creating a future where seamless wireless communication coexists with energy conservation. This convergence underscores the role of mathematical rigour in addressing energy challenges and establishes a refined framework for balancing data dynamics with energy efficiency. Looking ahead, researchers face both exciting prospects and complex challenges as they explore how machine learning and advanced network architectures can further elevate the performance and sustainability of wireless communication systems. Ultimately, queueing models, positioned at the intersection of theoretical elegance and practical relevance, hold the potential to transform wireless communication into a harmonized blend of responsiveness and energy efficiency, shaping a more sustainable and interconnected digital future.

References

1. Shu Li, Jeong Geun Kim, Doo Hee Han and Kye San Lee "A Survey of Energy-Efficient Communication Protocols with QoS Guarantees in Wireless Multimedia Sensor Networks" Sensors (2019) Volume 19 Issue 1 https://doi.org/10.3390/s19010199
2. David Boyle, Roman Kolcun and Eric Yeatman "Energy-Efficient Communication in Wireless Networks" ICT - Energy Concepts for Energy Efficiency and Sustainability 27 September 2016 Published: 22 March 2017 DOI: 10.5772/6598

3. Sandesh Mahamure, Poonam N. Railkar and Parikshit N. Mahalle "Communication Protocol and Queuing Theory-based Modelling for the Internet of Things" Journal of ICT (2016), Vol. 3, 157–176.doi: 10.13052/jicts2245-800X.323
4. Chudzikiewicz, J., Furtak, J., and Zielinski, Z. (2015). "Secure protocol for wireless communication within Internet of Military Things," in IEEE 2015 2ndWorld Forum on Internet of Things (WF-IoT), Milan, 508–513. doi: 10.1109/WF-IoT.2015.7389106
5. Himanshu Mittal and Naresh Sharma "Modeling of Communication Network with Queuing Theory under Fuzzy Environment" Mathematical Statistician and Engineering Applications (2022) Publication Issue: Vol 71 No. 2
6. Bhardwaj, R, Singh, TP: Designing Bulk Arrival Queue Model to an Interdependent Communication System. Prediction and Analytic of Fuzzy, Reliability & Queuing Models. (2018).
7. Jalel Ben-Othman, Bashir Yahya "Energy efficient and QoS based routing protocol for wireless sensor networks" Journal of Parallel and Distributed Computing Volume 70, Issue 8, August 2010, Pages 849-857
8. Giddaluru Madhavia and M.K. Kaushikb "Queuing Methodology Based Power Efficient Routing Protocol for Reliable Data Communications in Manets" Communication Engineering
9. Changzhen Zhang, Jun Yang, Ning Wang "An active queue management for wireless sensor networks with priority scheduling strategy" Journal of Parallel and Distributed Computing Volume 187, May 2024, 104848
10. Sohail Sarang, Goran M. Stojanović, Stevan Stankovski, Željen Trpovski, Micheal Drieberg "Energy-Efficient Asynchronous QoS MAC Protocol for Wireless Sensor Networks" Wireless Communications and Mobile Computing 24 September 2020 https://doi.org/10.1155/2020/8860371
11. Rajagopal Maheswar, Murugan Kathirvelu and Kuppusamy Mohanasundaram "Energy Efficiency in Wireless Networks" Energies Volume 17 Issue 2 10.3390/en17020417
12. Jie Li, Qiyue Li, Yugui Qu, and Baohua Zhao "An Energy-Efficient MAC Protocol Using Dynamic Queue Management for Delay-Tolerant Mobile Sensor Networks" Sensors (Basel). 2011; 11(2): 1847–1864. Published online 2011 Feb 1. doi: 10.3390/s110201847
13. Sławomir Hanczewski, Maciej Stasiak, Joanna Weissenberg "Queueing model of a multi-service system with elastic and adaptive traffic" Computer Networks Volume 147, 24 December 2018, Pages 146-161
14. J.R. Artalejo, T. Phung-Duc "Single server retrial queues with two way communication" Applied Mathematical Modelling Volume 37, Issue 4, 15 February 2013, Pages 1811-1822

15. Sandesh Mahamure, P. Railkar, P. Mahalle "Communication Protocol and Queuing Theory-based Modelling for the Internet of Things" Journal of ICT Standardization DOI:10.13052/JICTS2245-800X.323 Corpus ID: 61870586
16. Christine E. Jones, Krishna M. Sivalingam, Prathima Agrawal & Jyh Cheng Chen "A Survey of Energy Efficient Network Protocols for Wireless Networks" Wireless Networks Published: July 2001 Volume 7, pages 343–358, (2001)
17. Mohammad Z. Siam, Marwan Krunz, Shuguang Cui & Alaa Muqattash "Energy-efficient protocols for wireless networks with adaptive MIMO capabilities" Wireless Networks Published: 10 July 2008 Volume 16, pages 199–212, (2010)
18. Vijay Raghunathan, Saurabh Ganeriwal, ani Srivastava, Curt Schurgers "Energy efficient wireless packet scheduling and fair queuing" ACM Transactions on Embedded Computing Systems (2004) Volume 3, Issue 1 https://doi.org/10.1145/972627.972629