Research Statement

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My research interests broadly lie in queueing systems, stochastic modelling, wireless sensor networks (WSNs), Markov decision process (MDP) and game theory. I am highly motivated by the idea that mathematical models can provide powerful insights into the design of telecommunication systems. My focus over the past couple of years has been on reducing the complexities of real systems, isolating the important components, and then develop models that characterise the impact of design decisions on the wireless sensor networks as a whole. I apply analytic models and tools that are traditionally used in the operations research community, in particular stochastic modelling and queueing theory. My research contributes to both performance evaluation and optimal design of WSNs. The main goal is to understand the fundamental performance limits of such networks, and develop efficient, low-complexity, and scalable algorithms for diverse applications of these systems.

I have been working in applied mathematics specifically towards the applications in wireless sensor networks for my dissertation. My research contributes to both performance evaluation and optimal design of WSNs. I used traditional methods in optimization and stochastic modelling to optimize the data collection in WSNs. I will describe the contribution I made toward a better understanding of these problems as well as current and future research.

1 Brief research overview

The problem of battery replacement and disposal is a key impediment to ubiquitous use of WSN. Despite vast improvements in power consumption and ongoing developments in power management, the lifetime of sensor node is largely determined by the energy of on-board batteries as it is expensive if not impossible to replace batteries once the sensors are deployed. To overcome dependency on batteries, many research effort focuses on sensors that extract the necessary energy from ambient energy in the environment. However, external conditions from which the harvesting circuitry draws its energy fluctuate over time, such that the amount of energy that can be harvested fluctuates as well. From a performance evaluation point of view, the harvesting process is an additional source of uncertainty which can greatly affect the performance. Hence, I have worked on developing accurate models of WSNs which can account the random nature of the harvesting process. Broadly speaking, my work can be organised into the following areas.

1.1 Isolated wireless sensor node

The sensor node (SN) is a key component of a WSN which can be modelled as a system of two interacting buffers, i.e. a data buffer to store the collected information and an energy buffer to store the energy harvested from the environment. Each buffer is generally fed by an input process that is typically bursty. While burstiness in data buffers is a well-studied subject, the interaction of two buffers holds interesting questions, for example in terms of optimal control and dimensions. I have developed an analytical model for a static sensor node that assess the interaction between data collection, energy harvesting and energy expenditure. For the data buffer, I have focused on the quality aspects of the information instead of quantity. In particular, I have used the concept of value of information (VoI) which describes the utility (importance) of an information in a application specific context. To understand the fundamental performance of the node, I have analysed the model and obtain the stationary solution for battery levels and VoI. Some interesting properties and detail analysis is available in journal articles [1, 2]. Then I extended the model to capture the uncertainty of energy harvesting more realistically by modelling it as Markov modulated process. The extension also allowed the time correlation for data sensing process and study the trade off between the cost of frequent data collection and timely data delivery. Given the assumptions, exact expressions for the performance metrics of these models were found. In particular, it was revealed that the presence of time correlation in energy harvesting process has major impact on performance. While these models are used for performance analysis, I have also studied a stochastic recursion model with Markov decision process (MDP) [3]. The MDP model allows a balanced design of different objectives, for example, minimising energy consumption or maximising sensed information. I have exploited the special quasi birth-death (QBD) structure of the problem and then used policy iteration algorithm to obtain the optimal transmission policy. The solution reveals that the structure of optimal policy is of threshold type which is very easy to implement in practice.

1.2 Large scale wireless sensor network

The models for single sensor node are only useful in one hop communication application where sensor node interact with the mobile sink only e.g., highway traffic monitoring. The exact expressions for the performance metrics of these models were found, i.e., without relying on approximations. However, once one studies multiple nodes at once in multi-hop communication applications, such an approach is no longer feasible. Indeed, solving Markovian models that involve multiple nodes is computationally challenging due to the well-known state-space-explosion problem, inherent to multidimensional Markov models. Nevertheless, models of complete sensor networks are indispensable to evaluate the impact of different environmental conditions on the performance of the WSN, as well as to evaluate the impact of the network topology. Stochastic scaling techniques have the potential to partially overcome the state-space explosion problem. Scaling techniques like heavy-traffic limits, fluid and diffusion limits, and mean field approximations study the performance of the stochastic systems when some of its parameters are sent to infinity.

I have formulated the large scale WSN with equivalent mean-field model which heavily reduced the computational effort needed to obtain the optimal control of the network. It neglects the behaviour of an individual node by considering the proportion of users in a certain state. Then, I further defined the optimisation problem as the continuous time deterministic one which is then solved using Hamiltonian-Jacobi-Bellman equations. Initially, I have developed a concrete model with three levels of VoI in full detail and analysed its transient behaviour. While analysing the model theoretically, I have discovered some interesting proprieties of the optimal transmission policies such as its bang-bang nature and the threshold structure. Such a policy is very easy to implement in practice for large WSNs. Moreover, I have also validated the mean field approximation through Monte-Carlo simulations by comparing the performance of the random system to that of the mean field limit for original system.

1.3 Underwater wireless sensor network

In contrast to most terrestrial wireless networks, underwater wireless sensor network (UWSNs) widely adopt acoustic communication as its intrinsic properties like low signal interference and large transmission coverage make it more suitable for an underwater environment. Like their terrestrial counterparts, UWSNs adopt multi-hop routing protocols that aim at delivering the harvested data packets to on-surface sink nodes. The design of these routing protocols must account for the energy consumption of the network — battery replacement is considered unfeasible or prohibitively expensive — as well as for common performance indices like the expected end-to-end delay, the packet delivery probability and the network throughput.

I have studied numerically tractable stochastic model to assess the performance of UWSNs. I have developed an algorithm to efficiently calculate various performance indices, including the distribution of the number of hops it takes to send from a point other than the bottom of the network to a surface node, the level dependent energy consumption and the mean end-to-end delay. As the model accounts for the impact of node deployment and the high transmission loss of the acoustic channel, it can be used to understand the behaviour of depth based routing (DBR) protocol at the network level. I have also validated the model by comparing the average performance indices obtained by its analysis with the estimates obtained by a stochastic simulation. The proposed model can be further used for optimisation purposes given the limited computational effort required, in comparison to traditional UWSN simulations.

1.4 Future Research

While I will continue to work on some specific questions in my current areas of research, my vision for the future is to find to the efficient and low-complexity algorithms for large scale wireless networks and make contributions to the fields of networking, control, optimisation, and queueing analysis. Given my strong background in Markov decision process, control optimisation and queueing theory, as well as my rich experience in the modelling and analysis, I believe that my extensive academic preparations have enabled me to pursue many emerging and exciting research areas. Below I would like to describe three research directions that I plan to investigate in future.

1.5 Game theory for energy efficient WSNs

Game theory which is mostly studied in applied economics and sociology, has recenty attracted lot of attention in modern WSNs. It provides analytical tool to model the interaction among the sensor nodes with conflicting interests over limited network resources such as energy or bandwidth. I am planing to model the energy harvesting wireless sensor networks (EH-WSNs) using classical game theoretical approach. The overall aim is to develop the unified model that can improve the use of the harvested energy at the sensor node. Another crucial problem that can be addressed with the model is to optimise the remaining energy of an energy-harvesting sensor node in order to maximise the lifetime of network.

From reliability point of view, wireless links in WSNs are susceptible to catastrophic failures due to eavesdropping, message modification, service denial or intrusions of malicious nodes. The concept of evolutionary game theory can provide the solution to such issues. Ma and Krings [6] already discuss possible applications of evolutionary games in the context of WSN but do not detail possible solutions. Methodologically, this calls for a Markovian description of the dynamics of the evolutionary game and its relation with the replicator dynamics. The replicator dynamics can be interpreted as a fluid limit of the Markov model and it will be interesting to see if the corresponding diffusion limit brings additional insight in the dynamics of the evolutionary game.

1.6 Optimization and Machine learning

My recent work on optimal data collection in wireless networks reveals interesting properties of sensor nodes behaviour. For example, the value of information collected form a isolated sensor node is concave with respect to optimal collection probability. Taking this property under consideration, I plan to invgestigate the large scale WSNs using network flow problem and optimize the sink trajectory in order to collect maximum information. Despite the fact that there exist efficient algorithms for many fundamental problems such as the travelling salesman problem, it is often impossible to adapt these algorithms with additional side constraints without degrading their performance.

It is still challenging to design fast, adaptive and robust control policies in large-scale networks due to high dimension and complexity. The last decade has witnessed crucial breakthroughs in the field of Machine Learning and Data Science. However, most of these techniques have not been adapted made to the mainstream networking research due to their complexity. In future, I plan to work in the emerging interface between networks and machine learning, and design effective control techniques inspired by the advances in Machine Learning.

1.7 Fluid limits and Large Deviation

A fundamental yet challenging problem with critical practical implications concerns control of large scale wireless networks where large number of sensor nodes interact with each other. The primary objective of the network is to design a control policy to optimise some criteria. Control may include influence over rates of arrival and/or service, and routing or scheduling of packets. Except some simple examples, such control problems are quite intractable by classical queueing techniques due to state-space explosion problem, and thus suitable approximation methods are needed. The conversion to a fluid limit offers one way to deal such problems by identifying set of ordinary differential equations (ODE) that captures the essence of the Markov chain in a purely deterministic mode. Whereas a fluid limit filters out any stochasticity from the solutions, it may be desirable to retain a certain amount of uncertainty. This is attained by diffusion models, which quantify the stochastic fluctuations around the deterministic behaviour of the system in the form of a central limit theorem scaling.

Another challenging area is Large deviations theory which constitutes a form of scaling like fluid and diffusion limits, but the question asked is rather how the system can substantially differ from the behaviour exhibited by the fluid model. As it deals with rare events, this is a very useful tool to design systems that are robust to unexpected, unfavourable behaviour. For example, a substantial portion of the network experience low power levels so as to impede the operation of the system. This motivates the explicit study of rare events through large deviations (LD) theory and offer quantitative recommendations to network designers on saving energy in wireless devices

References

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