Tag Counting and Monitoring in Large-Scale RFID Systems

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Theoretical Foundations and Algorithm Design

Springer

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ISBN 978-3-319-91991-1 ISBN 978-3-319-91992-8 (eBook)
https://doi.org/10.1007/978-3-319-91992-8

Library of Congress Control Number: 2018942220

Printed on acid-free paper

This Springer imprint is published by the registered company Springer International Publishing AG part of Springer Nature.
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Radio frequency identification (RFID) technology has been experiencing ever-increasing deployment in a wide range of various applications, such as inventory control and supply chain management. In this book, we present systematic research on a number of research problems related to tag counting and monitoring, one of the most fundamental components in RFID systems, particularly when the system scales. These problems are simple to state and intuitively understandable, while of both fundamental and practical importance, and require nontrivial efforts to solve. Specifically, we address the following problems ranging from theoretical modelling and analysis to practical algorithm design and optimisation:

- Stability analysis of the Frame Slotted Aloha (FSA) protocol, the *de facto* standard in RFID tag counting and identification,
- Tag population estimation in dynamic RFID systems,
- Missing tag event detection in the presence of unexpected tags,
- Missing tag event detection in multiple-group multiple-region RFID systems.

In the book, we adopt a research and exposition line from theoretical modelling and analysis to practical algorithm design and optimisation.

To lay the theoretical foundations for the design and optimisation of tag counting and monitoring algorithms, we start by investigating the stability of FSA. Technically, we model the system backlog as a Markov chain with its states being backlog size at the beginning of each frame. The main objective is mathematically translated to analyse the ergodicity of the Markov chain and derive its properties in different regions including the instability region. By employing drift analysis, we derive the closed-form conditions for the stability of FSA and find the stability region maximiser. We also mathematically demonstrate the existence of transience of the backlog Markov chain, which characterises system behaviour in the instability region.

We then establish a generic framework of stable and accurate tag population estimation schemes based on Kalman filter for both static and dynamic RFID systems. Specifically, we model the dynamics of RFID systems as discrete stochastic processes and leverage the techniques in extended Kalman filter (EKF) and cumulative sum control chart (CUSUM) to estimate tag population for both static and dynamic systems. By employing Lyapunov drift analysis, we mathematically characterise the performance of our framework in terms of estimation accuracy and convergence speed by deriving the closed-form conditions on the design parameters under which our scheme can stabilise around the real population size with bounded relative estimation error that tends to zero with exponential convergence rate.

We further proceed to addressing the problem of missing tag detection, one of the most important RFID applications. Different to existing works in this field, we focus on two unexplored while fundamentally important scenarios, missing tag detection in the presence of unexpected tags and in multiple-group multiple-region RFID systems. In the first scenario, we develop a two-phase Bloom filter-based missing tag detection protocol (BMTD). The proposed BMTD exploits Bloom filter in sequence to first deactivate the unexpected tags and then test the membership of the expected tags, thus dampening the interference from the unexpected tags and considerably reducing the detection time. To minimise the detection time of BMTD while achieving the required reliability, we perform theoretical analysis and optimisation on configuring the protocol parameters. In the second scenario, we formulate and study a new missing tag detection problem, arising in multiple-group multiple-region RFID systems, where a mobile reader needs to detect whether there is any missing event for each group of tags. The objective is to devise missing tag detection protocols with minimum execution time while meeting the detection reliability requirement for each group. We develop a suite of three missing tag detection protocols, each decreasing the execution time compared to its predecessor by incorporating an improved version of the Bloom filter design and parameter tuning. By sequentially analysing the developed protocols, we gradually iron out an optimum detection protocol that works in practice.

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