Applied Mathematical Modelling 40 (2016) 5123–5138

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

On the economic sustainability of supplying bandwidth policies in multi-layer wireless cognitive networks

G. Aloi[a], L. Grandinetti[a,*], P. Pace[a], O. Pisacane[b]

[a] Department of Informatics, Modeling, Electronics and System Engineering (DIMES), Universitá della Calabria, Rende, CS, Italy
[b] Faculty of Engineering, Universitá degli Studi e-Campus, Novedrate, CO, Italy

ARTICLE INFO

Article history:
Received 6 November 2013
Revised 7 October 2015
Accepted 11 December 2015
Available online 30 December 2015

Keywords:
PM inventory management
NewsVendor model
Wireless cognitive networks
Resource sharing
Pricing
Incentive engineering

ABSTRACT

Nowadays, advanced inventory management policies guarantee cost reductions and higher service levels, making them very attractive for modern and challenging communication scenarios such as those related to *Multi-layer Wireless Cognitive Networks* (MWCNs). In these systems, the radio resources can be considered extremely perishable "commodities" with a short-term lifetime. After describing the latest state of the art on this topic, the novelty of the paper is in being the first to adapt the *NewsVendor* model from *Logistics* in order to guarantee a cost-effective bandwidth provisioning in MWCNs. Then, we study the economic sustainability of the proposed approach compared to the one based on the adaptive period inventory management policy, already presented in the literature. Numerical results show that the *NewsVendor* model outperforms the adaptive period inventory management policy in all the cases under investigation. It provides decision makers with more stable supply solutions by taking into consideration both the randomness of the bandwidth requirements and its short-term lifetime. In addition, it also improves both the total profit and user satisfaction levels.

1. Introduction

Inventory management plays a significant role in providing an organization with cost savings and higher service levels. According to the features of a given system, the set of the most suitable inventory management policies is initially identified. Then, the most appropriate one is selected by performing an accurate performance analysis. This policy is chosen in order to guarantee a more reactive system especially during peak times and therefore, it also takes under control both *overstocking* cases (in which an organization has more resources than it really needs) and *out of stock* cases (in which an organization cannot satisfy customer demands). To solve problems of resource provisioning in wireless telecommunication networks, typical approaches used in logistics are reported in several literature studies (see Section 2); however, these kinds of approach have not been extended yet to the specific case of *Multi-layer Wireless Cognitive Networks* (MWCN). In this context, since radio resources must be bought, used or resold only in short time periods, bandwidth resources should be treated as extremely perishable goods with a short-term lifetime over each wireless link. For this reason, bandwidth provisioning strategies need to be designed accurately because over-supplied or unused resources can turn into a cost or a loss of revenue. To the best of our knowledge, the work described in [1] is still the only existing contribution in which an adaptive

* Corresponding author. Tel.: +39 3351244747.
E-mail addresses: gianluca.aloi@unical.it (G. Aloi), lucio.grandinetti@unical.it, lugran@unical.it (L. Grandinetti), ppace@dimes.unical.it (P. Pace), ornella.pisacane@uniecampus.it (O. Pisacane).

http://dx.doi.org/10.1016/j.apm.2015.12.036
S0307-904X(15)00848-3/

period-based *Inventory Management* policy (IM, for short) is applied to handle the bandwidth provisioning issue in MWCNs. In this work, the effectiveness of typical IM policies applied to MWCNs is verified by proposing an innovative *NewsVendor* model for bandwidth provisioning. Therefore, addressing the challenging telecommunication scenario detailed in Section 3, the main contributions of this interdisciplinary work can be summarized as in the following:

- A detailed literary overview on both the inventory management policies and the telecommunication networks with a particular focus on the *Cognitive Paradigm*;
- The definition of an inventory management policy based on a *NewsVendor* model (NV, for short) to effectively support bandwidth provisioning in MWCNs;
- The study of the economic sustainability of NV compared to IM;
- A detailed sensitivity analysis on the main input parameters, i.e., the total number of users and their distribution between the *Delay Sensitive* and the *Loss Sensitive* classes.

It is worth remarking that the interdisciplinary nature of this work is mainly due to the need also to include aspects related to the bandwidth forecast, as do the analyzed solution approaches. The remainder of this paper is organized as follows: Section 2 overviews the literature on two layers, from a general point of view, the inventory policies are analyzed with reference to the case of short-term lifetime goods while from a specific point of view, some applications of these methods to telecommunication scenarios are described; Section 3 summarizes the major aspects of the MWCN under examination together with its main modules; Section 4 focuses attention on the two bandwidth supply modules, whose performances are then compared and analyzed in Section 5 with reference to specific metrics introduced in Section 5.2; finally, Section 6 concludes the paper signaling new directions for future research.

2. Related works

In this Section, we aim to provide the readers with a literature review that covers the aspects related to both inventory management techniques in general and applied to telecommunication scenarios. Moreover, some scientific contributions with reference to wireless cognitive networks are also described.

2.1. Scientific contributions to inventory management

Effective inventory management is a critical but essential issue to handle customer demands efficiently and achieve worthwhile cost savings [2]. Many literary contributions have analyzed inventory management from different points of view and especially with reference to logistic applications. In [3], for instance, a two-stage supply chain is analyzed with reference to both inventory management and goods transport; in [4], an optimization model is proposed for minimizing production, inventory and delivery costs. Moreover, some mathematical models take into consideration stochastic customer requirements and, in some cases, stochastic lot size-dependent lead times.

However, uncertainty has not to be considered as the only challenging issue to address. In fact, products can also present a very short-term lifetime (i.e., perishable goods). In these cases, inventory management policies have to take into account that the quantities available in a certain period may no longer be available in the next. Therefore, the related mathematical models have to include perishability [5] by considering a fixed and loose shelf-life (i.e., with and without a best-before-date). In the literature, some methods of integrating perishability into mathematical models are proposed: in [6] for maximizing the expected revenue; in [7] with the aim of analyzing the effects due to product perishability on, among the other things, the average inventory level in a two-echelon supply chain and, finally, in [8] for determining a best order-up-to-level and review interval policy for a fixed-life perishable product.

Traditionally, in the literature, the *NewsVendor* model is used for handling perishability. For a review on this topic, the readers are referred to [9] and [10]. In [11], for instance, the authors apply this model for managing a supply chain with one manufacturer and one retailer. Furthermore, the model is also applied in cases in which the objective function presents two risk parameters with reference to the risk-averse and the risk-taking behavior of the inventory manager [12]. The work proposed in [13] describes a methodology to examine the multi-product *NewsVendor* problem with two constraints and they also propose a solution approach with the aim of determining the optimal batch size for each product. Moreover, their solution approach does not depend on the specific probability distribution function used for modeling product demands.

Together with perishability, the *NewsVendor* model is also applied in cases in which customer demands are stochastic (usually, normally distributed). In [14], for instance, a supplier selection problem is analyzed in which the set of suppliers is characterized by different yields and prices. In addition, the demands are assumed to be stochastic. The authors also propose a mathematical model with the aim of maximizing the buyer's profit. Finally, they design a solution method that combines the active set method with a Newton search procedure. In [15], two NewsVendor-type products with disparate costs and prices are described while two fuzzy models for the NewsVendor problem in an uncertain environment are proposed in [16] under the hypothesis of stochastic demand.

The significant advantages of such a model are also analyzed by integrating it with other inventory models [17]. In the very recent work proposed in [18], the authors aim to maximize the retailer's profits through price discounts in a two-stage supply chain. For this purpose, the proposed model takes into account, among the other things, price elasticity of the