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Modelling green HetNets in dynamic ultra large-scale applications: A case-study for femtocells in smart-cities

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ABSTRACT

In recent years, with the rapid increase in the number of mobile connected devices and data traffic, mobile operators have been trying to find solutions to provide better coverage and capacity for mobile users. In this respect, deployment of femtocells is a promising solution. This paper presents performability analysis of femtocells. Unlike the existing studies, the potential reduction of the service capacity due to failures are considered as well as various performance metrics such as throughput, mean queue length, response time, and energy consumption. In other words, the femtocells are modelled as fault tolerant wireless communication systems, considering factors such as mobility of the mobile users, multiple channels for the femtocells, and failure/repair behaviour of the channels for more realistic performance measures. A typical scenario is considered for smart-city applications as case study where a set of femtocells are deployed within the coverage area of a macrocell. The numerical results presented show the accuracy of the proposed model as an abstraction of a femtocell system. The results also reveal that the computational efficiency of the analytical model is significantly better than simulation.

1. Introduction

Recently, heterogeneous wireless technologies have been developed rapidly to support different Radio Access Technologies (RATs) such as GSM, UMTS, HSPA, LTE, LTE-Advanced, WiMAX, WLAN, etc. in order to connect mobile users to the internet. The next generation of wireless networks has already found its way into a part of a mobile user's daily life who prefers to have ubiquitous internet connection. Nowadays, as a result of rapid development in technology, mobile devices such as smartphones, iPads, tablets, etc. are easy to use which enable people to connect to the internet anytime and anywhere. In other words the mobile users indeed expect high quality service from the infrastructure.

According to Cisco's Global Visual Networking Index (VNI) [1], global mobile data traffic will experience 8-fold growth from 2015 to 2020. It is also predicted that the number of mobile connected devices will be 11.6 billion by 2020 which will exceed the world's population at that time [1].Therefore, mobile operators have been trying to find solutions to satisfy mobile users in terms of coverage and capacity as well as to handle the drastic increase in mobile data traffic.

Current mobile Heterogeneous Networks (HetNets) experience explosive growth in usage and energy consumption. This growth has been driven by the proliferation of smart devices and energy-hungry mobile applications (e.g., online social networks, video streaming, and online gaming). One promising solution for cellular operators in this regard is deployment of femtocells [2]. A femtocell is a cell which provides cellular coverage and is served using a Femtocell Base Station (FBS), also called Home Base Stations (HBSs) which are short-range and low-power Base Stations (BSs) typically deployed in indoor environments for enhanced reception of voice and data traffic [3,4]. Deployment of femtocells will also reduce the need for adding expensive macro BS towers which is another key advantage of femtocells [3]. Recently, FBSs have been used by many mobile operators in outdoor deployments in rural and heavily populated areas and in scenarios such as the one in public transportation vehicles presented in [5]. Mobile Femtocells will become more prominent in the near future to offer better mobile coverage and capacity onboard. On top of that, femtocells can also be used to aggregate mobile traffic load and relay to the macrocells or to other access networks. However, this would cause extensive amounts of energy consumption and significant energy amounts can be wasted unless a reasonable load balance is applied between the deployed femtocells which are typically planned to serve huge numbers of static/mobile users in a smart-city paradigm [6]. This

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would not be achieved without a realistic case study analysis and an accurate analytical model that can predict the system performance in a smart-city setup.

In this paper, a multi-tier wireless cellular HetNet consisting of a macrocell and several femtocells is considered as a case study towards more green future HetNets. Detailed analysis of the system is given for the mobile users based on queuing theory concepts. Numerical results are obtained using the spectral expansion solution approach. The results are then analyzed and elaborated in terms of the performance characteristics of the system such as throughput, mean queue length, response time, as well as energy consumption. The analytical model and solution approach has also been validated through the results obtained from discrete event simulations.

The rest of this paper is organized as follows. Related work is outlined in Section 2. The system model and the analytical solution approach are presented inSections 3 and 4, respectively. In Section 5, the numerical and simulation results are presented for a case study about mobile users under femtocell coverage in smart-cities, and finally, Section 6 concludes this paper.

2. Related work

Modelling telecommunication systems using queuing theory has been popular for many years [7–9]. Different performance metrics such as average number of customers in the system, average utilization, average power consumption of the system, average waiting time in the queue, and throughput are derived from queuing models depending on the system and the objectives of the analysis [7,10]. All these modelling systems can be classified into the following classes; static, dynamic, and hybrid models. For static models, it is assumed that the users are static and mobility related issues are not considered at all. Dynamic models are those with mobile users in the system. In addition, hybrid models consider HetNets consisting of macrocell and femtocells in the system. In static models such as the ones presented in [7,8,11–13], performance measures of the systems have been investigated without considering mobility in the system. Unlike static models, mobility as one of the main issues in performance evaluation of wireless communication systems is investigated in [14–19]. Moreover, cellular HetNets consisting of macrocell and femtocells are studied in [20–25] in order to investigate the performance of the system using the concept of queuing theory as detailed in the following subsections.

2.1. Models with the assumption of static users

In [7], the authors studied the energy consumption of a campus WLAN. A simple approximate queuing model is used to save energy in WLANs by considering sleep modes for Access Points (APs) and activation of APs according to the user demand. Another similar study is presented in [8] where the authors presented a set of algorithms to reduce the energy consumption of a dense WLAN and provide better quality of service to the users. The results presented show that by using sleep modes for the APs, considerable amount of energy can be saved when the number of users connected to the network is small.

An admission control problem for a multi-service LTE radio network is addressed in [12]. The authors propose a model for two resource demanding video services; video conferencing and video on demand. Teletraffic and queuing theories are applied to obtain a recursive algorithm in order to calculate performance measures such as blocking probability and mean bit rate.

The research in [13] analyzes behavior of adaptive modulation and coding (AMC) systems with sleep mode using queuing theory. The authors analyze the energy consumption per packet, the average delay, and the packet loss rate and propose an algorithm to improve energy efficiency. However, the mobility factor, which is a key factor in any smart-city paradigm, was ignored, and this can dramatically affect the estimated system performance in practice.

2.2. Models with mobile users

In [14], an integrated cellular/WLAN system is modelled for highly mobile users using a two-stage open queuing system with guard channel and buffering in order to obtain acceptable levels of quality of service in heterogeneous environments. An exact analytical solution of the system is given using the spectral expansion solution approach that can be useful for vertical handover decision management. A similar approach is used in [15] to model an integrated cellular/WLAN system in order to study performance characteristics of the system such as mean queue length and blocking probability. The system is modelled as a two-stage open queuing network and the exact solution is presented using the spectral expansion solution approach. Simulation is also employed to validate the accuracy of the proposed system. Other similar approaches to model an integrated cellular/WLAN are presented in [18].

One of the main issues in performance evaluation of wireless communication systems is mobility [16]. Due to the importance of mobility, including velocity is always valuable in any cellular system study [14,17,19,26]. For example in [27], the authors classify the velocity of mobile users into low mobile state (0–15 km/h), medium mobile state (15–30 km/h), and high mobile state (above 30 km/h) in order to analyze the effects of mobile users' velocity on the performance of the system. This is because the users with high velocity will cross the coverage area of the neighboring cells and must perform handover in a shorter time period compared to the users with low or medium velocity. For instance, a mobile user with a velocity equal to 1 km/h can experience different handover delay compared to a mobile user with a velocity of 10 km/h in particular scenarios [28,29], where the time factor plays a key role in estimating cost and energy consumption not only for participating users but also for service providers. This introduces the need for a mechanism that can model and predict such cases for more efficient femtocell usage under varying user mobility conditions. Wireless communication systems may experience failure due to different factors such as software, hardware, human error, or a combination of these factors [30,31]. In [16], wireless cellular networks with failure and recovery are modelled using a Markov reward model. An S-channel per cell in homogeneous cellular system and mobility related issues are considered in the system. Performance characteristics of the system such as mean queue length and blocking probability are presented using an analytical model.

In [17], the authors presented a mathematical model for analytical study on complete and partial channel allocation schemes. By employing Markov models which are based on shared channels and using an analytical approach, the results are presented for performance measures such as mean queue length and blocking probability.

Two handoff schemes with and without preemptive priority procedures for integrated wireless mobile networks are proposed and analyzed in [19]. In this study, the service calls are categorized into four different types as originating voice calls, originating data calls, voice handoff request calls, and data handoff request calls. A three-dimensional Markov chain is used to model the system and analyze the system performance in terms of average transmission delay of data calls, blocking probability of originating calls, and forced termination probability of voice handoff requests. The results presented reveal that by increasing the number of reserved channels for handoff request calls, forced termination probability of voice handoff requests can be decreased. However, none of the