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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

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aforementioned works have considered the different velocity effect of the modelled mobility cases which is a typical case in smart-city setups.

2.3. Hybrid HetNet modelling

A cellular network of a macrocell and several femtocells are considered in [20]. The authors present a detailed queuing model of the system. The system is modelled using an M/M/1 queue and the Matrix Geometric Method is used to solve the network model. The performance of the system is then analyzed in terms of average system delay and power savings. Similar to the study mentioned in [20], the authors in [21] analyze performance characteristics of a finite capacity femtocell network in terms of a number of quality of service (QoS) parameters such as average packet delay, packet blocking probability, and utilization for different buffer sizes. The system is modelled as an M/M/1/K queue and the results presented show that the mentioned quality of service parameters are highly dependent on traffic intensity as well as buffer size.

Integration of femtocell technology with the current macrocells helps cellular operators to reduce the traffic loads of macrocells and consequently to minimize blocking probability [22]. In [22], an adaptive call admission control (CAC) policy together with the concept of adaptive reserved channel is presented to fulfill QoS requirements for handover traffic. Based on queuing theory and Markov chains, a teletraffic model is presented to evaluate and analyze the QoS metrics in terms of the blocking probability of new calls and failure probability of handover requests in the integrated femtocell/macrocell networks.

A 2-tier cellular heterogeneous network (HetNet) of macro and femto cells is considered in [23,24]. A two-dimensional finite state Markov chain representing queue size and data rate of a mobile user is developed in [23] and the average packet delay of the user is determined as a function of traffic arrival rate. Numerical results and results obtained by simulation reveal that, minimum packet delay is achieved by finding suitable femtocell density using the proposed model. In [24], performance analysis of two-tier femtocell networks with partially open channels is studied and a Markov chain model is presented to analyze performance metrics such as user blocking probability in a macrocell and the blocking probabilities of femtocell and macrocell users in a macrocell. Moreover, energy and spectrum efficiency models of the system are proposed. Simulation results indicate that the number of femtocell users, the number of femtocells in a macrocell, as well as the number of open or closed channels in a femtocell are key factors on the performance of the two-tier femtocell networks. Also, the number of femtocells to deploy in a macrocell can be determined based on the results obtained from the energy efficiency model.

One of the key issues in deployment of integrated femtocell/macrocell networks is mobility management which is studied in [25]. A Markov chain model is used for the queuing analysis of femtocell and macrocell layers of the integrated system. The authors also propose an algorithm to create a neighbor cell list with optimal number of cells for handover. Numerical and simulation results show the importance of mobility management in the deployment of dense femtocellular networks.

In this study, unlike the studies in the literature, an analytical modelling approach is presented which is capable of considering various workloads, ranges, mobility related issues, as well as availability of channels in femtocell infrastructure. To the best of our knowledge this is the first two dimensional modelling attempt with exact solution and high accuracy as well as efficacy. Our modelling approach can be quite useful in discovering the operational space of various femtocell configurations. Femtocell systems with channel failures [32,33] or with partially open channels [24] can be considered for traditional performance measures as well as the expected value of energy consumed together with channel availabilities by using our approach.

2.4. The contributions

In studies similar to the ones presented in [7,8,11–13], performance measures of the system under study are investigated with the assumption of static users, and mobility as one of the most important issues in performance evaluation of wireless networks [16] is not taken into account. Please note that ignoring the mobile users which may leave the system not because they have received service successfully, but instead due to mobility, can cause misleading QoS measurements. Although, the works presented in studies such as [14–19] investigated performance measures of the system by considering mobility of the mobile users, none of them have considered the effect of different velocity of the mobile users on the system performance. This is an important issue in any HetNet setup because mobile users with higher velocity will perform handover to the neighboring cells in a shorter time period compared to the mobile users with lower velocity. Therefore, although there are similar studies considering queuing related issues of similar wireless communication systems, in this study, we considered users which can leave the system while accommodated in the queue due to mobility. Furthermore, for a more realistic presentation, different velocities of mobile users are considered and their effect on the performance characteristics of the system such as MQL, throughput, and response time are investigated.

The works presented in [20–25] consider HetNets consisting of macrocell and femtocells which is similar to our system under study. In [20] a simple M/M/1 model is employed to represent the transmission of data traffic in femtocell networks. A single channel wireless communication system is used as model. The server considered may be available at a given time or may be on vacation. In order to solve the resulting two dimensional Markov process matrix geometric method is employed which is the main competitor to spectral expansion solution employed in this study. Apart from reducing the number of channels to one, Kumar et al. [20] also overlooks the potential unavailability of the channels. In other words the fault tolerant nature of wireless communication systems is not considered. Therefore even for modelling single channel communication systems, the results presented for performance evaluation (average response time is presented), which is an essential part for QoS of femtocells are optimistic. Instead, in our study the models presented can consider single or multi-channel systems in presence of channel unavailability. Therefore, comparing the QoS together with energy efficiency of femtocell systems is performed in a much more realistic way.

In [21] an M/M/1/K queue model is used to represent the transmission of data to a femtocell access point in uplink. Unlike our model, the model employed in [21] limits the system to have only one channel and ignores the potential unavailability of the channel which is quite common in wireless communication systems [34]. Similarly in [22–25] potential unavailability of the channels is not considered in performance evaluation of the HetNet of macrocell and femtocells which makes the results unrealistic since wireless communication systems are tend to be prone to failures due to many different factors such as hardware, software, human error, or a combination of these factors as discussed in [30,31].

In [32,33] channel failures are discussed as one of different sources that can lead to handover failures in HetNets. Using our approach, these systems can be used to analyze various performance measures such as MQL, throughput, and response time as well as expected value of energy consumption in presence of channel failures. Therefore, our contributions can be summarized as follows:

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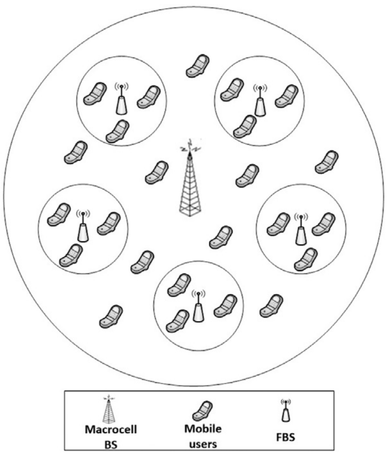

Fig. 1. A typical network of a macrocell and a set of femtocells.

- An analytical approach is presented by considering different traffic loads, ranges, mobility, as well as channel availability in femtocell infrastructure.
- While considering mobility related issues, the effect of velocity of mobile users on the performance of the system is investigated by categorizing the state of mobile users into low, medium, and high mobile states.
- To the best of our knowledge this study is the first two dimensional modelling attempt of femtocell infrastructure where the effects of mobility and the fault tolerant nature are considered with exact solution, high accuracy, and efficacy.
- Our approach can be used by other femtocell systems with channel failures [32,33] or with partially open channels [24] to investigate traditional performance measures of wireless communication systems such as MQL, throughput, and response time.

The following table further summarizes the comparisons between various studies.

3. System model

This section presents the proposed model for the performance evaluation of a cellular HetNet composed of a macrocell and femtocells. As a result of explosive growth in the number of connected devices, mobile data traffic, and energy consumption as well as huge arrival rates from static/mobile users in the current mobile HetNet, deployment and availability of femtocells in the buildings and roads of smart-cities will provide better coverage and capacity to mobile users. In this paper, the system is similar to system considered in [23–25]. As shown in Fig. 1, a set of femtocells are deployed within the coverage area of a macorcell. The system is modelled as a queuing system where the servers are subject to failures, and the requests in the system may leave due to the mobility of the stations as shown in Fig. 2. Please note that we are not considering any kind of interference and there are no failures associated with the macrocell (Table 1).

Table 1
Summary of the related works.

References	MQL	Throughput (γ)	Response Time	Channel Failure	Mobility	Energy
[7,8]	X					X
[11]	X			X		
[13,20]						X
[14,15,17]	X				X	
[18,19]	X				X	
[22,23,25]					X	
[24]					X	X

Table 2
Summary of symbols.

Symbols	Definition
r	Radius of the femtocell
V	Velocity of the mobile users
P	Perimeter of the femtocell
A	Area of the femtocell
N	Total number of channels in the cell
W	Queue capacity of the cell
L	Maximum number of requests in the cell
σ	Total arrival rate of requests in the cell
μ	Total service rate of completed request departures in the cell
μ_{cd}	Mean service rate of handover requests in the cell
ξ	Failure rate of a server
η	Mean repair rate of a failed server

The parameters used in this model are summarized in Table 2. There are N identical channels available in each femtocell. Requests are assumed to arrive independently following Poisson distribution similar to the studies in [14,35–38]. When all the channels are busy, the requests begin to queue up within the buffer of size W. However, no more than L = W + N requests are allowed in the system simultaneously where N requests are served using N available channels and the remaining can only handover to a neighboring cell due to mobility. The queuing strategy is assumed to be First Come First Served (FCFS). Mobile users may move to neighboring cells while they are either in the queue or being served

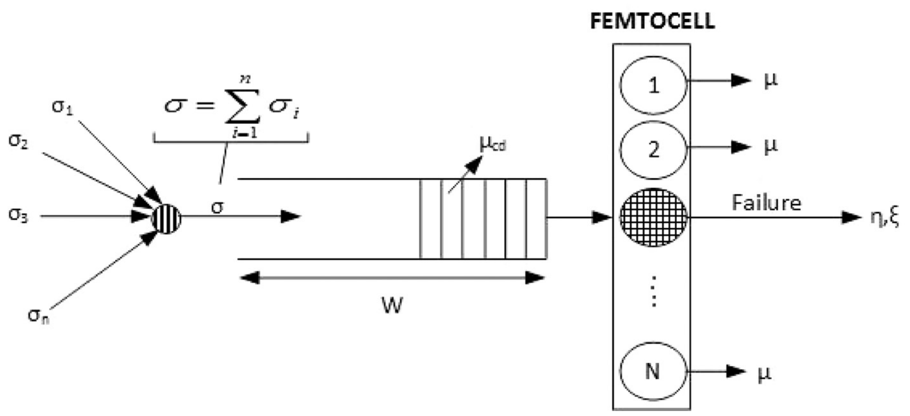

Fig. 2. The queuing system considered with failures and repairs.

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in the system. However, wireless communication systems may encounter failures due to many different reasons such as software, hardware, human error, or a combination of these reasons [30,31]. These failures and unavailability of a channel may degrade the performance of such systems [16]. It is assumed that the down time of each channel is also exponentially distributed, and the average rate for a channel to become available again is called as repair time. In the literature for simplifying the shape of the coverage area, some studies assume hexagon coverage [22,23,25]. In this study, macrocell coverage area is circular with radius R and each macrocell is served by a BS placed at the center. The femtocells which are deployed within the coverage area of a macrocell are assumed to be circular with radius r and are served by FBSs.

3.1. Queuing system

The proposed system is modelled as a queuing system. As mentioned earlier, users may attempt to use their mobile devices such as smartphones, iPads, etc. to use the email system, take part in video conferencing, download music or videos, or use many other applications while they are in shopping malls or driving over the city road of smart-cities. These requests of mobile users can be placed into a queue and served using FCFS strategy. Similar to [14,35–37], arrivals to the system are assumed to follow a Poisson distribution with rate σ, and service time of the servers is exponentially distributed with rate μ. It is a common phenomenon in a mobile HetNet in smart-cities that mobile users may move to neighboring cells of the network due to mobility while they are either in the queue or being served in the system. The service rate due to mobility is denoted by μ_{cd}. Failures may also occur in the system. The failure rate of the channels is exponentially distributed and is denoted by ξ [16,35,39]. Following a failure, the failed channel (server) stays down for an exponentially distributed amount of time with mean rate $1/\eta$. Fig. 2 represents the queuing system under study.

3.2. Service rate due to mobility

The dwell time of a mobile user is the time that the mobile node spends in a given system. For a mobile station in the femtocell, let us define the dwell time as T_{cd} which is exponentially distributed with mean $1/\mu_{cd}$. Following studies such as [19,40,41] it is possible to compute μ_{cd} as follows:

$$\mu_{cd} = \frac{E[v]P}{\pi A} \tag{1}$$

$E[v]$ is the average velocity of the mobile user, and P, A are the length of the perimeter of the femtocell and area of the femtocell respectively.

3.3. Energy consumption model

In this section, we analyze energy consumption in HetNet BS of a femtocell by using the concept of queuing theory based on practical parameters and LTE-specific values. By Shannon's capacity formula, the achievable transmission rate, T_R, of FBSs in bit-per-second under a given transmit power, P_T, and system bandwidth, B, is simply [42]:

$$T_R = B\log_2\left(1 + \frac{P_T}{BN_0}\right) \tag{2}$$

Where N_0 stands for Additive White Gaussian Noise (AWGN) power spectral density. Values for the parameters used in Eq. (2) are given in Table 3 adopted from [43–48].

Based on a hardware model presented in [46], total power consumption, P_{el}, of a FBS can be formulated as follows.

$$P_{el/femto} = P_{el/mp} + P_{el/FPGA} + P_{el/trans} + P_{el/amp} \tag{3}$$

Table 3
FBS parameters and power consumption components.

Parameter/component	Description	Value
B (Hz)	Bandwidth of femtocell	5 * 10^6
N_0 (W/Hz)	AWGN noise density	4 * 10^{-21}
P_T (W)	Transmit power	0.02
$P_{el/mp}$ (W)	Power consumption of the microprocessor	3.2
$P_{el/FPGA}$ (W)	Power consumption of the FPGA	4.7
$P_{el/trans}$ (W)	Power consumption of the transmitter	1.7
$P_{el/amp}$ (W)	Power consumption of the power amplifier	2.4

where $P_{el/mp}$, $P_{el/FPGA}$, $P_{el/trans}$, and $P_{el/amp}$ are power consumption (in W) of, the microprocessor, the FPGA (Field-Programmable Gate Array), the transmitter, and the power amplifier respectively. The values for the parameters can be found in Table 3.

By dividing Eq. (2) by total power consumption of the FBS (P_{el}), in Eq. (3), we will obtain bit-per-joule energy consumption unit which is the achievable rate for a unit of energy consumption [49]. Based on [50], our Maximum Transmission Unit (MTU) is assumed to be 1368 bytes. Therefore, by dividing MTU by the bit-per-joule energy consumption unit, E_{pp} which is the energy consumption for each transmitted packet is calculated for FBSs. Expected energy consumption $E(x)$ is then calculated as follows:

$$E(x) = \sum_{i=1}^{N} P_i.i.\mu.E_{pp} \tag{4}$$

Where P_i, i, μ, and E_{pp} are the probability of having i channels available (sum of all probabilities in columns of Fig. 3), number of available channels, service rate, and energy consumption for each transmitted packet respectively.

Please note that the modeling approach presented combines the fault tolerant nature of wireless communication systems with the energy models presented in [46–50]. These energy models are combined with state probabilities computed by analyzing the two dimensional Markov chain representation of the system. Furthermore, the mobility of the mobile users is also embedded into the two dimensional Markov chain considered. Eq. (4) shows that, by considering the state probabilities together with the energy consumed in each state, it is possible to derive a mean value for the energy consumed by the system considered. To the best of our knowledge, this is the first time detailed queuing, availability (fault tolerance), and energy efficiency related measures are considered together, which allows us to perform more realistic evaluations by taking QoS in terms of performance, reliability as well as energy efficiency into account.

4. The green HetNet model for steady-state probabilities

In smart-cities, cellular network plays a significant role to support connectivity anytime and anywhere. Future cellular networks are expected to be heterogeneous networks (HetNets) which are defined as a combination of macrocells and small cells such as femtocells [51]. FBSs can be deployed in streets, shopping malls, bus stations, airport, etc. in smart-cities to provide better coverage and capacity to mobile users. It is possible to use two dimensional Markov processes on a finite lattice strip in order to represent an abstraction for the interactions considered in modelling the systems under study. The state diagram for the queuing system considered is shown in Fig. 3.

A pair of integer valued state variables, $I(t)$ and $J(t)$, can be used to describe the state of the system at time t, where $I(t)$ represents the number of channels available, and $J(t)$ specifies the number of requests present at time t. We can assume the minimum value of $I(t)$ is 0, and the maximum is N representing the maximum number of servers in the system. For the state variable

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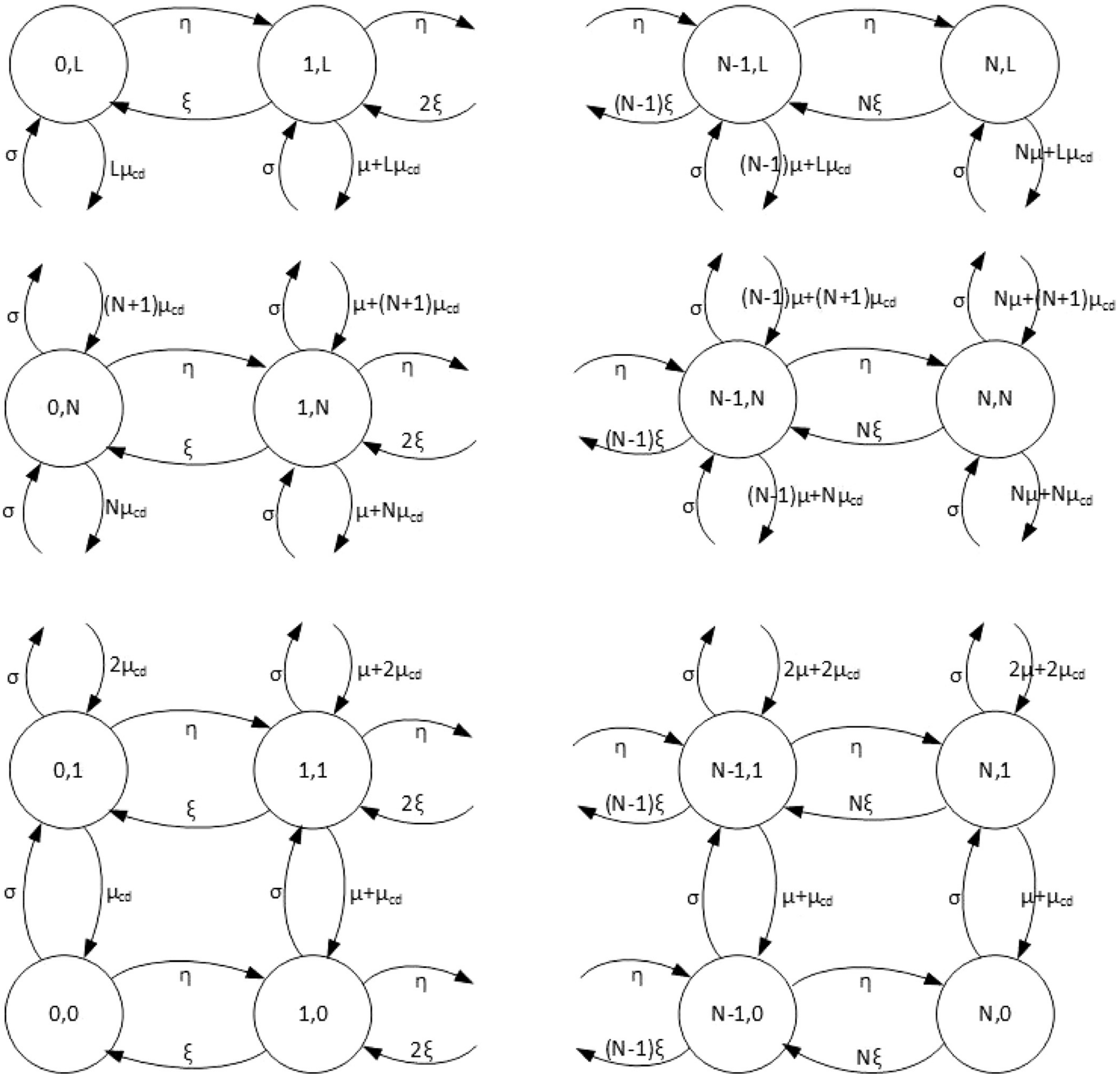

Fig. 3. The stage diagram of the queuing system.

$J(t)$, the minimum value is 0 and it can take values from 0 to L which is the total number of requests in the system at time t, including the one(s) in service. The Markov process is denoted by $Z = \{[I(t), J(t)]; t \geq 0\}$ and is used for performance evaluation of the system under study. We assume that Z is irreducible with a state space of $\{0, 1, \ldots, N\} \times \{0, 1, \ldots, L\}$. It is also assumed that the number of servers, $I(t)$, is represented in the lateral or horizontal direction and the total number of requests, $J(t)$, is represented in the vertical direction of a finite lattice strip. The possible transitions of the model Z are purely lateral transitions from state (i, j) to state (k, j), one-step upward transitions from state (i, j) to state $(k, j+1)$, and one-step downward transitions from state (i, j) to state $(k, j-1)$. In this study spectral expansion approach is employed where A is the matrix of purely lateral transitions with zeros on the main diagonal, and one-step upward and one-step downward transitions are represented in matrices B and C respectively. The parameters representing transitions rates and their positions in these matrices are used to specify the state transitions. For example, having η at position (0,1) shows that there is a transition possible from the state with zero available channels to state with one channel with rate η. Similarly the σ on the main diagonal of the matrix B shows the one step upward transitions with new packet arrivals, and the diagonal of matrix C shows the departures caused by service completion and/or mobility of the stations. The specificities of LTE are incorporated through the correct use of the system parameters within the matrices. Similar to studies in [13–15,19,30], the generic model representing the state transitions can be used with various system specific parameters as provided in Tables 3 and 4. In spectral expansion method, it is assumed that the process has a threshold, M, $(M \geq 1)$ which has an integer value [11,15,18] such that the transition rate matrices, A, B, and C, do not depend on j for $j \geq M$. However, in our system the transi-

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Table 4
Summary of the evaluation parameters.

Component	Value
Femtocell radius	30 m
Mobile user velocity	Low, medium, high
Femtocell transmit power	20 mW
Femtocell transmission bandwidth	5 MHZ
# femtocell channels	8
Expected service rate per hour (μ)	200 (user/hour)
Expected failure rate per hour (ξ)	0.001
Expected rate for down time of channels per hour (η)	0.5

tion rate matrices are always dependent on j, because the requests in the queue may leave the system due to mobility regardless of the number of channels available.

Definition 4.1. A, B and C are square matrices each of size $(N+1) \times (N+1)$. The elements of matrix A depend only on the failure and repair rates of the servers, ξ and η respectively. The transition rate matrices A, B and C are given in the following equations. The matrix C depends on the number of requests in the system for $j = 0, 1, \ldots, L$. Therefore, the threshold M is taken as $M = L$.

$$A = A_j = \begin{pmatrix} 0 & \eta & 0 & 0 & 0 & 0 & 0 & 0 \\ \xi & 0 & \eta & 0 & 0 & 0 & 0 & 0 \\ 0 & 2\xi & 0 & \eta & 0 & 0 & 0 & 0 \\ 0 & 0 & 3\xi & 0 & \ddots & 0 & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 & \ddots & 0 & 0 \\ 0 & 0 & 0 & 0 & \ddots & 0 & \eta & 0 \\ 0 & 0 & 0 & 0 & 0 & (N-1)\xi & 0 & \eta \\ 0 & 0 & 0 & 0 & 0 & 0 & N\xi & 0 \end{pmatrix} \tag{5}$$

$$B = B_j = \begin{pmatrix} \sigma & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \ddots & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \sigma \end{pmatrix} \tag{6}$$

$$C_j = \begin{pmatrix} min(0,j)\mu + j\mu_{cd} & 0 & 0 & 0 & 0 \\ 0 & min(1,j)\mu + j\mu_{cd} & 0 & 0 & 0 \\ 0 & 0 & \ddots & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & min(N,j)\mu + j\mu_{cd} \end{pmatrix} \tag{7}$$

If the number of requests in the system is less than the number of available channels, each request is served using a channel. On the other hand, if the number of requests is greater than the number of available channels (let's say k channels are available at that time), first k requests are served using k available channels and the remaining can only be handed over to a neighboring cell with the service rate μ_{cd}. The spectral expansion solution approach is employed for the steady-state solution. The details of the spectral expansion solution approach can be found in [11,34,52]

Definition 4.2. Following spectral expansion solution, the steady-state probabilities of the states presented in Fig. 3 can be expressed as:

$$P_{i,j} = \lim_{t \longrightarrow \infty} P(I(t) = i, J(t) = j);\ 0 \le i \le N, 0 \le j \le L$$

Theorem 4.1. *It is then possible to obtain all state probabilities in the form of* $P_{i,j} = \sum_{l=0}^{N} (a_l \psi_l(i) \lambda_l^{j-M+1} + b_l \phi_l(i) \beta_l^{L-j}),\ M-1 \le j \le L$

where, λ *and* ψ *are eigenvalues and left-eigenvectors of* $Q(\lambda)$ *respectively, and* ψ *is a row-vector defined as*

$\psi = \psi_0, \psi_1, \ldots, \psi_N, \quad \lambda = \lambda_0, \lambda_1, \ldots, \lambda_N$ *and* $\psi Q(\lambda) = 0;\ |Q(\lambda)| = 0$

β *and* ϕ *are eigenvalues and left-eigenvectors of* $\overline{Q}(\beta)$ *respectively, and* ϕ *is a vector defined as* $\phi = \phi_0, \phi_1, \ldots, \phi_N,\ \beta = \beta_0, \beta_1, \ldots, \beta_N$.

Proof. Let's define certain diagonal matrices of size $(N+1) \times (N+1)$ as follows:

$$D_j^A(i,i) = \sum_{l=0}^{N} A_j(i,l);\ D^A(i,i) = \sum_{l=0}^{N} A(i,l)$$

$$D_j^B(i,i) = \sum_{l=0}^{N} B_j(i,l);\ D^B(i,i) = \sum_{l=0}^{N} B(i,l)$$

$$D_j^C(i,i) = \sum_{l=0}^{N} C_j(i,l);\ D^C(i,i) = \sum_{l=0}^{N} C(i,l)$$

and $Q_0 = B$, $Q_1 = A - D^A - D^B - D^C$, $Q_2 = C$. Then, the state probabilities in a row, can be defined as:

$v_j = (P_{0,j}, P_{1,j}, \ldots, P_{N,j});\ j = 0, 1, \ldots, L$. For $0 \le j \le L$, the balance equations are:

$$v_0[D_0^A + D_0^B] = v_0 A_0 + v_1 C_1 \tag{8}$$

$$v_j[D_j^A + D_j^B + D_j^C] = v_{j-1} B_{j-1} + v_j A_j + v_{j+1} C_{j+1};\ 1 \le j \le M-1 \tag{9}$$

$$v_j[D^A + D^B + D^C] = v_{j-1} B + v_j A + v_{j+1} C;\ M \le j < L \tag{10}$$

$$v_L[D^A + D^C] = v_L B + v_L A \tag{11}$$

The normalisation equation is given as:

$$\sum_{j=0}^{L} v_j e = \sum_{j=0}^{L} \sum_{i=0}^{N} P_{i,j} = 1$$

From Eq. (10)

$$v_j Q_0 + v_{j+1} Q_1 + v_{j+2} Q_2 = 0;\ (M-1) \le j \le (L-2)$$

and the characteristic matrix polynomials can be expressed as [52]:

$$Q(\lambda) = Q_0 + Q_1 \lambda + Q_2 \lambda^2;\ \overline{Q}(\beta) = Q_2 + Q_1 \beta + Q_0 \beta^2$$

where

$$\psi Q(\lambda) = 0;\ |Q(\lambda)| = 0;\ \phi \overline{Q}(\beta) = 0;\ |\overline{Q}(\beta)| = 0$$

Furthermore, $v_j = \sum_{l=0}^{N} (a_l \psi_l \lambda_l^{j-M+1} + b_l \phi_l \beta_l^{L-j}),\ M-1 \le j \le L$

$\lambda_l (l = 0, 1, \ldots, N)$ and $\beta_l (l = 0, 1, \ldots, N)$ are $N+1$ eigenvalues, each that are strictly inside the unit circle , and a_l $(l = 0, 1, \ldots, N)$, $b_l (l = 0, 1, \ldots, N)$ are arbitrary constants which can be scalar or

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Fig. 4. Femtocells serving mobile users in a smart city.

complex-conjugate. v_j vectors can be obtained using the process in [52]. □

The state probabilities can be used to calculate important performance measures such as mean queue length (MQL) and throughput (γ) as well as expected value of energy consumed as explained in Section 3 using the following equations.

$$MQL = \sum_{j=0}^{L} j \sum_{i=0}^{N} P_{i,j} \tag{12}$$

$$\gamma = \sum_{i=0}^{N} i\mu P_{i,j} \tag{13}$$

5. A typical femtocell case study for smart-cities

In smart cities [53,54], femtocells will expand to realize the heterogeneous data exchange paradigms including data centers, ubiquitous devices, personal and environmental monitoring devices connected to mobile users via femtocells both in metropolitan as well as urban areas. Those distributed femtocells will provide a multitude of services to improve the residential experience and quality of living in smart-cities. Femtocells in such settings will be abundant and available on roads and/or deployed in public/private buildings (shopping malls, smart homes, etc.). In such a comprehensive HetNet model, an efficient energy-consumption policy is required [55,56] to motivate the usage of femtocells in serving hundreds of incoming static/mobile users per hour in a green framework. Moreover, the foreseen HetNet model introduces challenges regarding the system's limitations in terms of the available capacity and targeted QoS, given the variety of data that is exchanged. Hence, we visualize a green HetNet-driven femtocell case study for smart-cities that tackles the aforementioned concerns. The scenario considered is shown in Fig. 4.

We consider a set of femtocells which are deployed within the coverage area of a macrocell to provide sufficient users' capacity while maintaining adequate QoS in terms of throughput, mean queue length, response time, and energy consumption. Mobile users might be static/mobile and may use their smartphones and energy-hungry mobile applications such as mobile video while they are shopping in the mall or driving over the city roads. Each femtocell has a transmit power of 20 mW and a transmission bandwidth of 5 MHZ. Typically users are assumed to be uniformly distributed in the coverage area of their serving cell. Femtocell radius is considered to be 30 m [57]. The other parameters used in this case study are mainly driven from [27,43,44,57,58], summarized in Table 4.

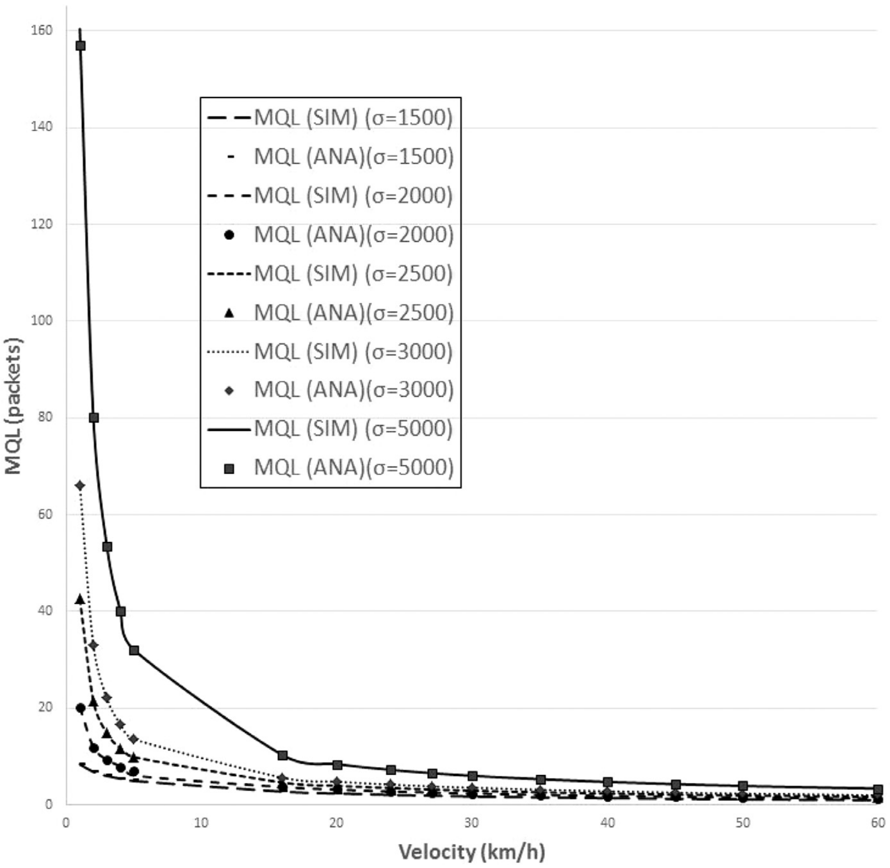

Fig. 5. The effects of velocity of mobile users on MQL.

5.1. *Performance metrics and parameters*

In order to assess our proposed model, we consider the following performance metrics:

- Throughput: is set here as a quality measure. It is the average percentage of transmitted data packets that succeed in reaching the destination reflecting the effect of node heterogeneity in HetNets setup and it is measured in 'packets per hour'.
- Mean Queue Length (MQL): is measured in 'packets' and is defined as the average number of the requests pending in the system, either waiting in the queue or being served.
- Response time: is defined as the time spent by a mobile user from arrival until departure and plays a significant role in performance evaluation since it incorporates all the delays involved for a user request.
- Energy consumption: is defined as the amount of energy consumed by a single FBS based on the requests of mobile users.

These metrics are evaluated while varying the following parameters:

- Arrival rate: The number of arrivals per unit of time is defined as arrival rate. In this study we use different arrival rates to analyze the effect of traffic loads on the performance evaluation of the system. Please note that, for the case study considered, the incoming requests can be originating from within the femtocell, or can be handed over from the macrocell (or other femtocells). Since the superposition of incoming arrival streams would also follow Poisson distribution, and since the model is flexible for various incoming traffic loads, it is assumed that the arrival rate incorporates all these incoming streams. The queuing system is shown in Fig. 2. The arrival rates for the femtocells vary according to the applications. In this study, the order of arrival rates is similar to the measures from previous studies such as [43]. Following this and the number of servers in a femtocell [43] the service rate can be specified as in Table 4.
- Mobile user velocity: As mobility is one of the important issues in deployment of HetNets [25], including velocity is always valuable in performance evaluation of such HetNets [26]. In this study we classify the velocity of mobile users similar to studies such as [27].
  1. Low speed mobile users such as pedestrians and stationary users with the velocity from 0 to 15 km/h.
  2. Medium speed mobile users like those who ride a bike with the velocity from 15 to 30 km/h.
  3. High speed mobile users with the velocity above 30 km/h.

5.2. *Simulation setups*

Simulation modelling is used and the results obtained from discrete event simulations are employed for the validation of the analytical model. The results obtained from the analytical model are presented comparatively with the results from simulation software written in C++ language and validated to simulate the actual system. An event-based scheduling approach is taken into account, which depends on the events and their effects on the system state. A discrete event simulation program has been employed. The simulation program employed is able to incorporate the effects of mobility, as well as channel availabilities unlike the commonly used tools for queuing theory. In other words, the simulation program developed, considers an additional stochastic process for specifying the number of channels at a given time as well as number of requests leaving the system due to mobility. One of the most com-

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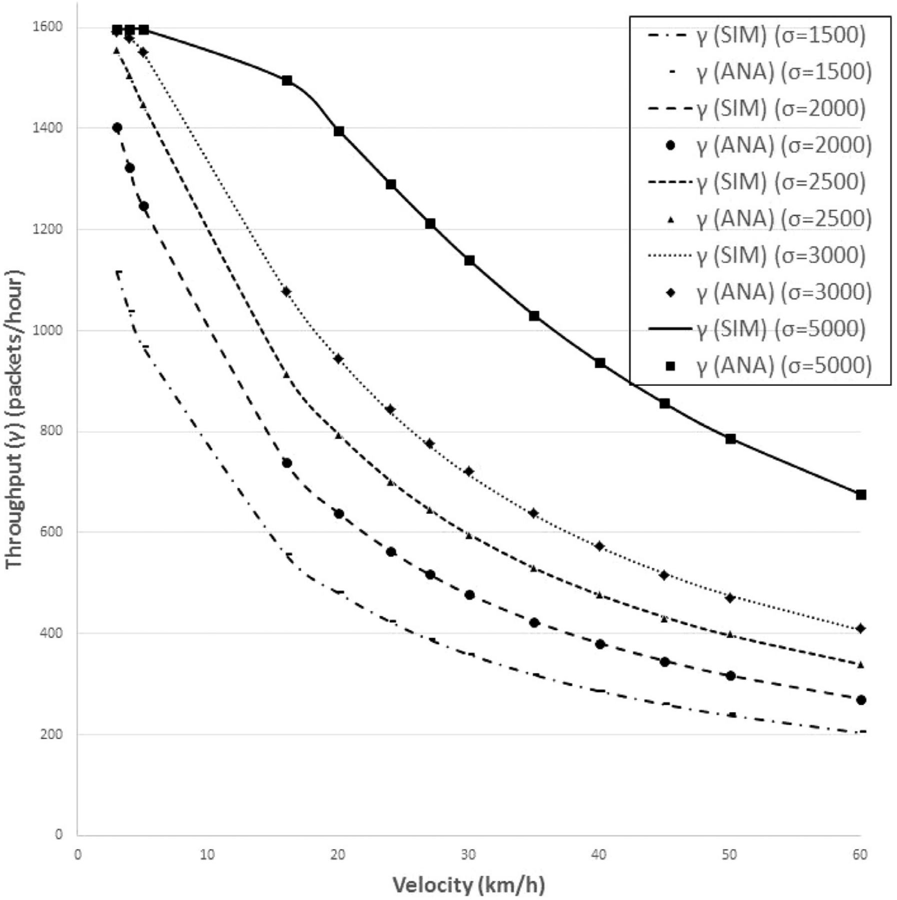

Fig. 6. The effects of velocity of mobile users on throughput.

monly used stopping criterion called relative precision is employed for the simulation, therefore, the simulation is stopped at the first checkpoint when the condition $\delta \leq \delta_{max}$, where δ_{max} is the maximum acceptable value of the relative precision of confidence intervals at the $100(1-\alpha)\%$ significance level, $0 < \delta_{max} < 1$.

The obtained simulation results are within the confidence interval of 5% with a confidence level of 95%, therefore in our simulations, both default values for α and δ are set to 0.05. Please note that the simulation program developed has been validated by using well known queueing theory models ($M/M/1$, $M/M/c$) and results from the literature [11,14,52,59,60].

5.3. Results and discussions

Results obtained for the proposed case study are presented in this section. Based on the arrival rate of users into the femtocell, performance metrics are compared for three different categories named low, medium, and high velocity mobile users. The number of channels allocated to the femtocell are $N = 8$ [43]. It is assumed that the femtocell can accommodate up to 2000 requests simultaneously including the ones in service. Other system parameters used are mainly taken from [27,43,44,57,58].

Fig. 5 shows the effects of velocity of the mobile users on the mean queue length (MQL) for various arrival rates. It is clear from the figure that when the system is congested like in high population density areas such as airports or shopping malls, the mean queue length will also grow as expected. This is because more users request service from the FBS at the same time. As the mobile users move faster in the cell, the MQL decreases. This is due to the fact that the service rate due to mobility, μ_{cd}, is directly proportional to the expected velocity of mobile users [14,19]. Therefore, as the velocity increases, users will leave the cell faster and the MQL will decrease. For example for $\sigma = 5000$ the MQL is approximately equal to 160 at the velocity of 1 km/h. But when the mobile users move faster at the speed of 60 km/h, the MQL is approximately 3.4.

In Fig. 6, the throughput of the system is presented as a function of average velocity of mobile users for different values of arrival rates in the femtocell. The parameters are same as the parameters used in Fig. 5. It is obvious that as arrival rate increases, more requests are served using the available channels in the cell and throughput will increase too. It is also seen that as mobile users move faster in the cell, throughput will decrease. This is because when the velocity increases and mobile users move faster in the cell, they may be moving away from the BS and may leave the cell due to mobility before they are served. Therefore, the number of requests served by the channels will reduce and consequently throughput will decrease as well. Please note that for both Figs. 5 and 6, the simulation results are also presented comparatively for validation. The maximum discrepancy between the analytical results and simulation are 1.83%, and 0.86% for Figs. 5 and 6 respectively which is less than the confidence interval of 5%.

Table 5 presents the results of simulation and analytical models when the stations are not mobile. Parameters used are same as the ones in Figs. 5 and 6; however, the results are presented separately since the order of MQL and throughput increase significantly.

Response Time (RT) plays a significant role in the system performance measures in queuing models [61]. In Fig. 7, the effects of mobile users' velocity on the response time are shown. The parameters used are same as the ones used in Figs. 5 and 6. It can

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Table 5
The effect of congestion for a scenario without mobility (Disc is discrepancy).

σ	MQL SIM	MQL	Disc	γ SIM	γ	Disc	Time SIM	Time
2000	1996.02	1999.34	0.166	1597.12	1573.79	1.46	11975.05	2.016
2500	1998.22	2000.11	0.094	1597.01	1598.90	0.11	12757.94	2.165
3000	1998.86	2000.21	0.067	1597.04	1599.91	0.17	13505.62	2.571
5000	1999.53	2000.54	0.050	1597.02	1599.92	0.18	16519.28	2.825

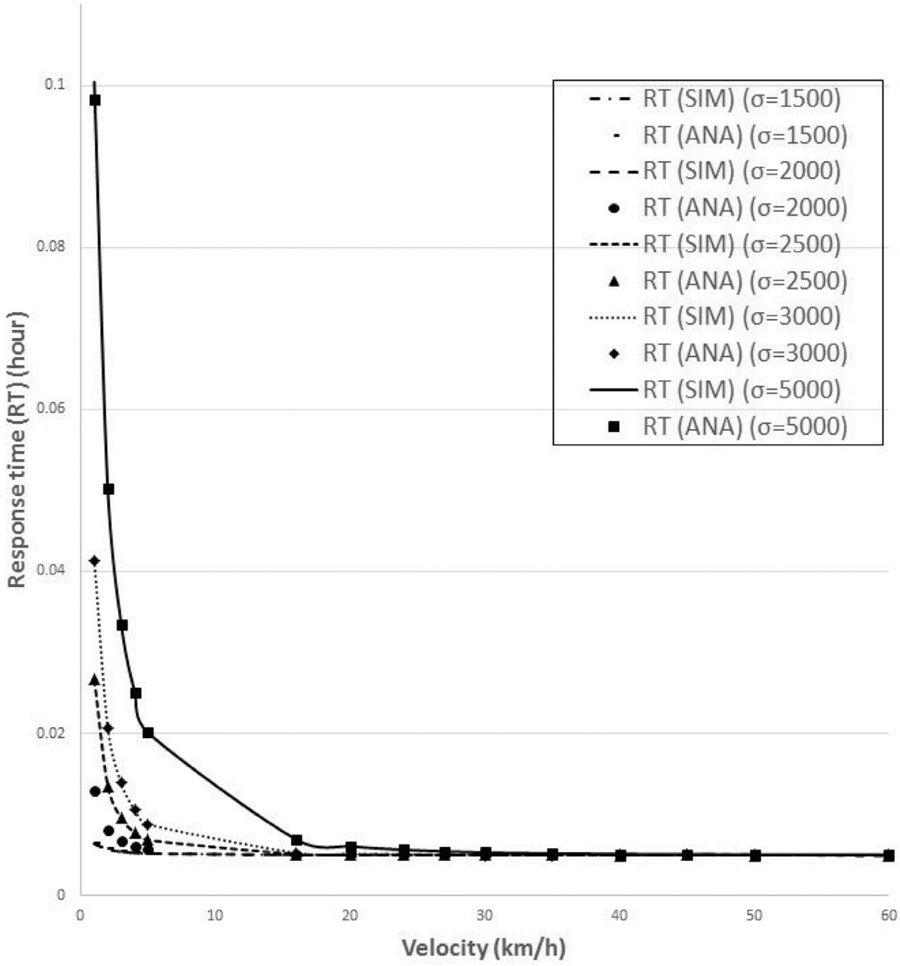

Fig. 7. The effects of velocity of mobile users on response time.

be clearly seen from this figure that for low velocity mobile users (e.g. v = 1 km/h), arrival rate is the most important factor which affects the response time. As velocity of the mobile users increases, it becomes the main factor affecting response time, since the departure of incoming requests becomes significantly higher than the arrival rate. Therefore, for medium and high velocity mobile users (e.g. v $\geq$ 30 km/h) arrival rate does not affect the response time significantly as shown in Fig. 7.

Fig. 8 shows the effects of service rate on response time and expected energy consumption of requests per hour. At $\mu = 100$, expected energy consumption is around 0.53 J per hour. As service rate increases, response time starts decreasing and at the same time more energy is consumed. For instance at $\mu = 1000$, response time is 5.4 s which is 60 times lower than when $\mu = 100$ and expected energy consumption is around 5.3 J which is 10 times higher than when $\mu = 100$. As it is shown in this figure, the optimum configuration for this scenario is obtained around $\mu = 300$ in which the response time is 100.8 s and expected energy consumption is around 1.59 J per hour. Fig. 8 shows that there is a trade-off between energy consumption and the performance of the FBS as expected. The figure also shows that the proposed approach lends itself as an important tool in order to specify the operative space, considering performance as well as energy consumption accurately and effectively.

In order to further emphasize the accuracy and the efficacy of the proposed approach as well as the effects of potential channel failures, Table 6 is presented. Table 6 shows the effects of channel failures on the MQL and throughput. The results were obtained from the simulation and analytical solution approaches by varying σ and channel failure rate, ξ, while keeping μ, μ_{cd}, and η fixed.

Please note that in all the results obtained so far using the simulation and analytical models, we considered expected channel failure rate (ξ) of 0.001 per hour. In order to show the effects of fault tolerant nature of channels, results in Table 6 are presented for cases with different failure rates. Similar to Table 6, Figs. 9 and 10 also show the effect of higher channel failure rates on the MQL,

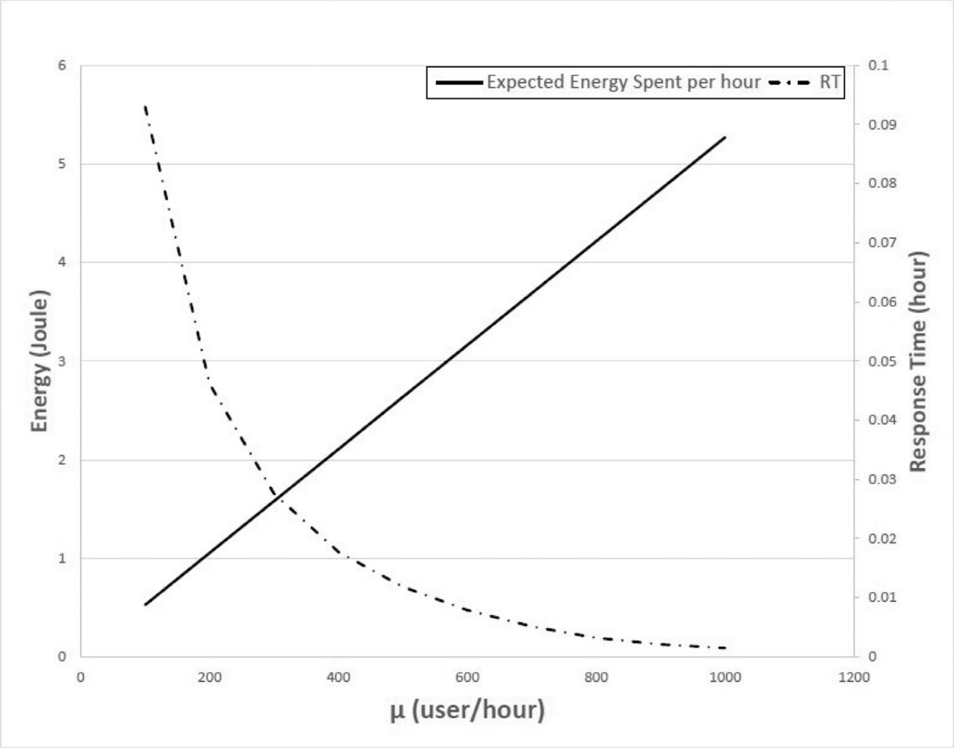

Fig. 8. Response time and energy spent per hour as a function of service rate.

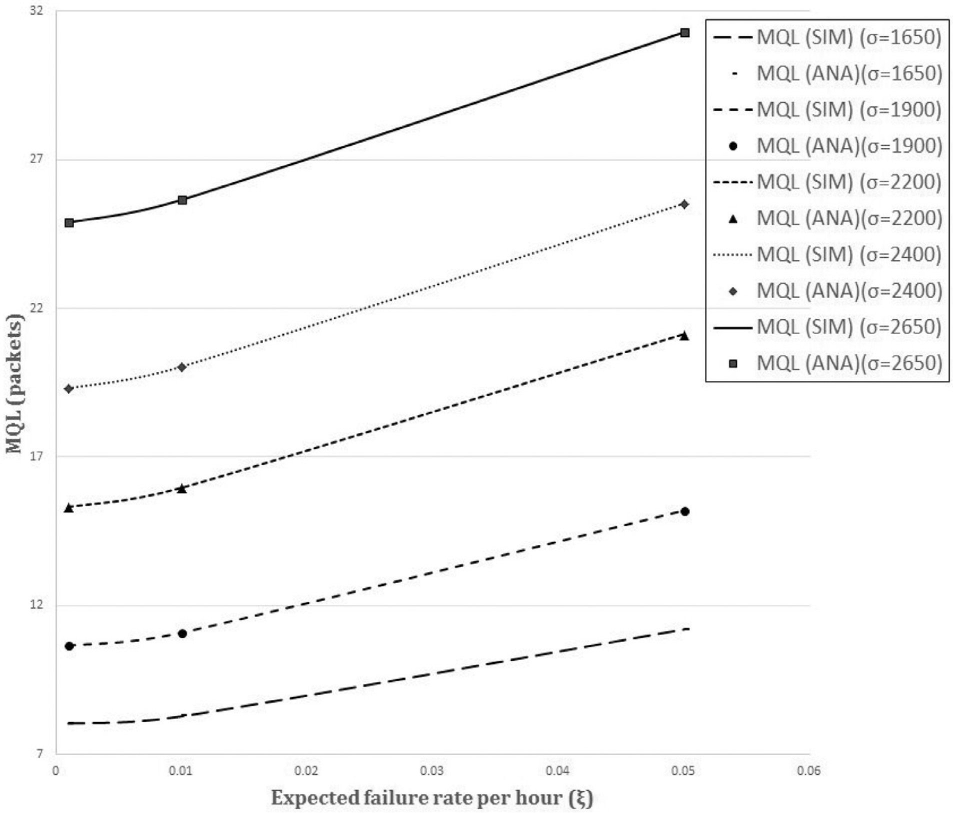

Fig. 9. The effects of channel failures on MQL.

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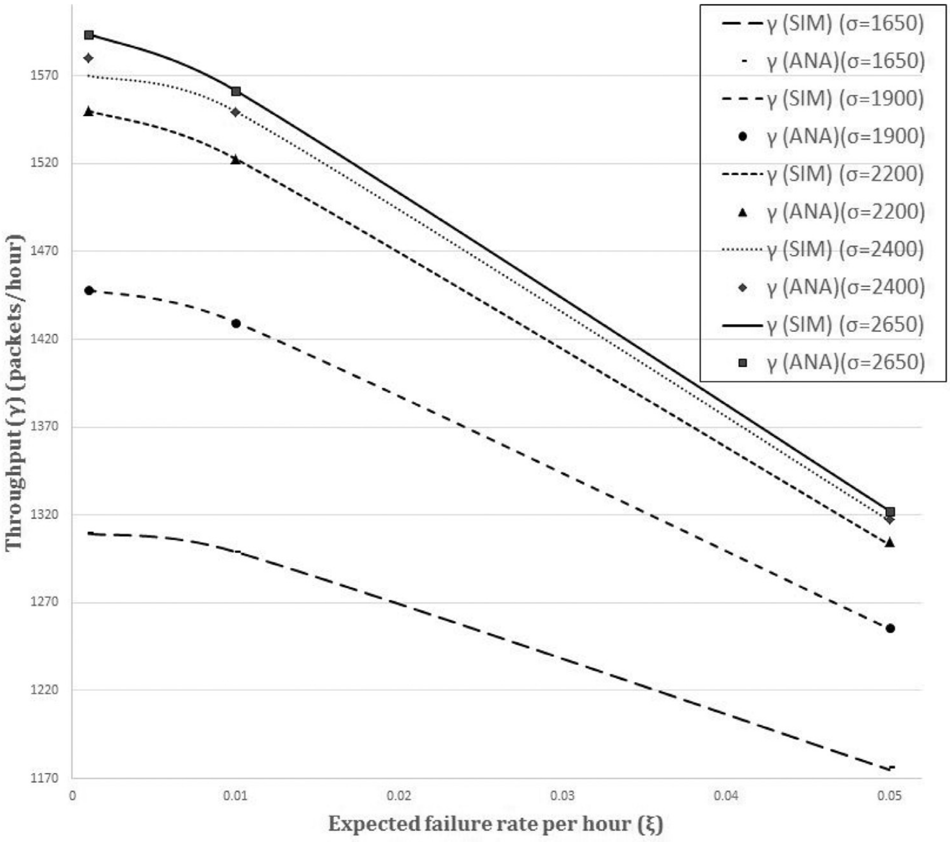

Fig. 10. The effects of channel failures on throughput.

Table 6
The effect of channel failures on MQL and throughput.

σ	MQL SIM	MQL	γ	γ SIM	Time SIM	Time
	$\xi = 0.001$					
1650	8.031	8.033	1309.13	1309.41	2.515	9100.18
1900	10.653	10.654	1447.87	1448.08	2.25	6269.49
2200	15.319	15.323	1549.85	1550.10	2.203	7286.84
2400	19.312	19.316	1580.35	1570.12	2.141	7966.4
2650	24.891	24.893	1593.61	1593.86	2.016	8825.34
	$\xi = 0.01$					
1650	8.2769	8.2765	1298.72	1299.05	2.156	6219.46
1900	11.087	11.089	1429.46	1429.71	0.797	7214.63
2200	15.964	15.965	1522.47	1522.77	0.64	8354.41
2400	20.038	20.043	1549.55	1549.77	0.766	9222.28
2650	25.656	25.655	1561.15	1561.59	0.672	10159.2
	$\xi = 0.05$					
1650	11.172	11.198	1175.85	1175.03	2.687	6154.57
1900	15.181	15.200	1255.69	1255.22	0.641	7120.35
2200	21.101	21.141	1304.47	1303.1	0.672	8269.22
2400	25.515	25.530	1317.12	1316.79	0.718	9068.28
2650	31.286	31.294	1322.22	1322.4	0.657	10093.5

and throughput of the system. The figures clearly show that MQL increases if the failure rate of the system increases, since increased number of users stay in the queue as a result of reduced number of available channels. At the same time, throughput of the system decreases because the number of available service facilities decreases with the increasing failure rates.

The results in Table 6 show that the channel availability can affect the performance of a femtocell system quite significantly especially for high failure rates. The simulation results validate that the results obtained by the analytical approach are accurate. The maximum discrepancies between the analytical model and the simulation are 0.19%, and 0.65% for MQL and throughput values respectively. Table 6 also reveals the efficiency of the new approach in terms of computation time. For instance, in case of $\sigma = 1650$ and $\xi = 0.001$, the execution time for simulation was 9100 s while it was only 2.515 s for the analytical approach to calculate MQL and throughput.

6. Conclusion

In this paper, a hybrid wireless cellular HetNet consisting of a macrocell and several femtocells is considered in smart-cities in presence of failures and recoveries. A new approach is presented for analytically modelling femtocells which are quite popularly deployed in macrocells to support traffic in smart-city environments. With the introduction of Internet of Things (IoT) [62], we believe that the aid of highly available femtocells in such situations for the increasing traffic load will become very important [2].

The results show that traffic load and velocity of mobile users are vital parameters affecting the aforementioned performance metrics, as well as the mean energy consumed by the FBS. Increasing traffic load in the femtocell leads to increases in MQL, throughput, and response time since increased numbers of mobile users request service from the FBSs. However, it is clearly shown by the results that for medium and high velocity mobile users, traffic load does not affect the response time as significantly as the low mobility environment. In this study, unlike the existing ones, the effects of channel failures are also investigated and the results presented in Table 6, Figs. 9, and 10 show the importance of fault tolerance for the systems under consideration.

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The results presented clearly show the accuracy of the analytical approach with maximum discrepancy 1.83% when compared with the simulation results which is less than the confidence interval of the simulation (5%). Furthermore the new approach is an efficient one since it can improve the computation time up to more than 34,000 times compared to the simulation. Such an efficient and accurate method can be quite useful in specifying the operative space for femtocells. For example, as illustrated in numerical results section, the threshold between the response time and mean energy consumption is quite important and an informed decision is essential in order to specify the system parameters in the most appropriate way.

The analytical approach presented is flexible and can be used for the analysis of similar systems with various configurations in future related work.

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