A Performance Study of Next Generation Cellular Networks with Base Stations Channels Vacations

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Abstract—The aim of this paper is to give a detailed modeling and performance analysis of Small Cell wireless Networks considering the limited number of mobiles served in each cell and different vacation schemes of the base stations channels, using the Generalized Stochastic Petri nets formalism. Hence, we show how this high level formalism allows a simple construction of detailed and compact models for such networks by considering single and multiple independent vacations of channels or all the base station in the case of synchronous vacations. In addition, we develop the formulas of the main stationary performance measures. Through numerical examples, we discuss the impact of channels number of the base station, vacation rate and vacation scheme on the network performances.

Index Terms—Next Generation Cellular Networks; Generalized Stochastic Petri nets; Modeling; Channels Vacation schemes; Performance measures.

I. Introduction

The traditional cellular network paradigm of colossal macro base stations and large cells were never conceived to serve the demands of today’s mobile broadband users and applications. As this demand for mobile data delivery continues to grow, existing wireless networks are quickly reaching their physical limit and become congested, requiring their migration to ever more efficient wireless standards.

The Small Cell Networks (SCNs) [1], [2] represent a novel networking paradigm and the most promising solution to the growing data consumption need, based on the idea of re-architecting broadband networks to employ much smaller cells sizes which facilitate better spectral efficiency, simply through improved spectral re-use. These networks are founded on a very dense deployment of short-range, low-power, and low-cost base stations operating in conjunction with the main macro-cellular network infrastructure. A general truth is the lower transmission power of a base station, the less costly and the smaller cells size. This creates an additional win-win scenario.

Small cells can be used to provide in-building and outdoor wireless services. They provide a small radio footprint, which coverage range is from 10 meters within urban and in-building locations to 2 km for a rural location, compared to a mobile macrocell which might have a wide range of a few kilometers.

Mobile operators use SCNs to extend their service coverage, and/or increase network capacity, especially for high-density urban deployments. Another advantage is that they allow offloading traffic during peak times and provide high data rates and dedicated capacity to homes, enterprises, or urban hotspots. Moreover, these networks encompass a broad variety of technologies including LTE (Long Term Evolution) and WiMax.

The performance analysis of these next-generation networks has been recently considered in some works [3], [4]. The objective of our paper is to present the modeling and performance evaluation of small cell wireless networks, taking into account the vacations of the base station channels and the limited number of mobiles (or customers) served in each cell.

Systems with servers vacations have been usually analyzed using vacation queueing models theory where the idle time of servers can be used for other secondary jobs. Many applications in manufacturing, computer and communications are based on these models in which processors, besides doing their primary functions, do considerable testing and maintenance to mainly preserve a well use of the system and to provide high reliability. These periods may be regarded as server vacations. Surveys on vacation models, results and applications have been reported by Tian and Zhang [5] and recently by Ke and al. [6].

These vacation queueing models can be classified according to the number of servers (single or multiple servers) and the vacation mechanism, which is characterized by the vacation startup rules and vacation termination rules. A wide class of schemes for governing the vacation mechanism, have been discussed in the literature, namely the multiple vacation policy [7], [8], [9] and the single vacation...
policy [9], [10]. Other studies have considered synchronous
vacations of some servers [11], [10] or all servers of the
station (station vacation).

The main reason for the growing interests in vacation
models during the past decade, is because they can realisti-
cally represent several service/manufacturing systems and
computer/telecommunication networks. However, all these
works on multi-server vacation queueing models, assume
that the customers source is infinite and are based on
queueing theory.

In this study, we propose the applicability of another
mathematical formalism, namely the Generalized Stochas-
tic Petri nets (GSPNs) for modeling and performance eval-
uation of a next-generation Cellular Network divided into
small cells, where each of them is served by a base station
having a number of channels subject to vacations. To this
end, we consider different vacation schemes, namely the
single and multiple independent vacations of channels or
all the base station (synchronous vacations).

The rest of the paper is organized as follows: First, we
give the mathematical model describing the cells of the
network. In Section 3, after a brief recall on the GSPNs
formalism basis notions, we present the models describing
Small Cell Wireless Networks with multiple and single
vacations of channels or all the base station. In section 4,
we give computational formulas for evaluating stationary
exact performance measures of these models. Then, based
on numerical examples, we validate the proposed models
with respect to the case without vacations and we discuss
the effect of the network parameters on performances.
Finally, we summarize the main contribution of this work
and we give direction of future developments.

II. Model description

In this paper, we consider a Small Cell Wireless Network
where the supported area is divided into small cells, with
a finite number of mobiles (or customers) $N$ in each cell
and a base station that consists of $c$ ($c \geq 1$) identical and
parallel channels potentially available. Each customer is
considered as idle or busy and each channel can be idle
(available), on service or on vacation.

Free customers generate the so called quasi-random in-
put of calls with rate $\lambda$. These requests are assigned to
channels randomly and without any priority order. If one
of the channels is idle at the moment of the arrival of a
call, then the customer starts being served immediately.
Service times are assumed to be independent identically-
distributed random variables, whose distribution is expo-
nential with parameter $\mu$. After service completion, the
channel becomes idle. Otherwise, if all channels are busy or
on vacation at the moment of a request arrival, the request
is put in a queue until a channel becomes available.

On the other hand, we assume that each channel of
the base station may take an individual or synchronous
vacation and may be used for other secondary jobs such as
testing and preventive maintenance to preserve the sanity
of the network and to provide high reliability and quality of
service. The vacation times are assumed to be independent
and exponentially distributed with rate $\theta$.

Several vacation schemes have been proposed in the liter-
ature. They can be partitioned into two classes: multiple
vacations, where a server returning from a vacation finds
the system empty, goes for another vacation and continu-
ous to do so until it finds waiting customers, and single
vacations, where after a busy period ends, the server goes
on only one vacation. If the system is still empty when it
returns, it stays and waits for a customer to arrive.

Moreover, we consider in this work the independent va-
cations of channels and the synchronous vacations of all
the base station channels. The first case corresponds to
systems where servers operate independently and so their
vacation periods are independent. In the the synchronous
case, the whole station has to be treated as a single entity
during the vacation periods.

III. GSPN Models of Small Cell Networks with
Channels Vacations

A Generalized stochastic Petri net (GSPN) [12] is built
using two kinds of objects: places (represented by cir-
cles), that substantiate resources and transitions that are
partitioned into two different classes: timed transitions
(represented by rectangles) which describe the execution
of time consuming activities and immediate transitions
(represented by thin bars), that have priority over timed
transitions and fire in zero time once they are enabled. The
system state is described by means of markings. A marking
of a Petri net is a mapping $M : P \rightarrow IN$, which specifies
the number of tokens in each place of the network. The
initial marking $M_0$ describes the initial state of the system.
The dynamic behavior of a GSPN results from the firing
of transitions yielding other markings than $M_0$.

In the following, we present the GSPN models describing
small cells in wireless networks with different vacation
schemes.

A. GSPN model of SCNs with independent multiple vaca-
tions of channels

In Fig. 1, the place $Cus._Free$ contains the free or poten-
tial customers (or mobiles). The place $Cus._Wait$ contains
the customers waiting for service. The place $Cus._Ser$ con-
tains the customers in service. The place $Ser._Idle$ repre-
sents the idle channels. Initially, it contains $S$ tokens as all
channels are available and the place $Ser._Vac$ contains the
channels that are on vacation. Hence, the initial marking
of the net is: $M_0 = [M(Cus._Free), M(Cus._Wait),$
The firing of the transition Arrivals represents the generation of a mobile request. It has an infinite server semantics, because all potential mobiles are able to generate requests for service. When the place Cus.Wait contains at least one waiting mobile, and the place Ser.Idle at least one idle channel, the immediate transition X fires and a token is deposited in Cus.Ser, which represents a mobile in service. When the timed transition Service fires, the mobile under service returns to the idle state and the channel becomes available to serve another mobile. This transition has also infinite server semantics, because the channels can work simultaneously.

The firing of transition Y represents the event that a channel is starting a vacation, since there is no waiting mobile left to be served and the firing of transition Vacation represents the end of the vacation period. As this moment, if no mobiles are waiting in the place Cus.Wait, the channel will immediately take another vacation which corresponds to the exhaustive service scheme.

B. GSPN model of SCNs with independent single vacations of channels

In the previous model with multiple vacations, at the end of a service or a vacation period, all the channels return to the idle state represented by the place Ser.Idle. However, in the model with single vacations given in Fig. 2, at a service completion, a token is put in the place Ser.Idle1 which contains the channels having served at least one mobile, since their last vacation period. So, they can serve other waiting mobiles from the place Cus.Wait if any. Otherwise, if the cell is empty, they can take individual vacation (firing of transition Y). However, at the end of the vacation period, the channel joins immediately the place Ser.Idle2 which contains the channels having not yet served any mobile, since their last vacation. Hence, these channels are unable to take another vacation, even if the cell is empty, because between two vacations of the same channel, it should treat at least one mobile. Thus, the channels of Ser.Idle2 must be served at least one mobile after the firing of the immediate transition Z, to join the place Ser.Idle1, where they can start another single vacation. In this model, a channel from Ser.Idle1 starts serving a waiting mobile, if and only if the place Ser.Idle2 is empty. The advantage of this scheme is that all channels participate in servicing. Hence, we avoid situations where some channels don’t stop servicing and so, are much more used than others. Hence, applying this scheme, the network should be more reliable.

C. GSPN models of SCNs with synchronous vacations

In the models with synchronous vacations of all base station channels, as soon as the system is empty and all channels of the base station are idle, they take a vacation simultaneously and they also return to the operational state at the same time, when the vacation is completed. So, a synchronous vacation is a group vacation for all channels. During this amount of time, the channels are unavailable to further requests arrivals to the system. This phenomenon can occur in practice, for example, when all the channels of the base station are run by a single operator which could be subject to random failures or maintenance tasks. In such situations, the whole base station has to be treated as a single entity during the vacation period.

The GSPN modeling a small cell with synchronous multiple vacations of the base station, is the same as the
model given in Fig. 1, in which the multiplicity of the arcs connecting the place \( \text{Ser}_-\text{Idle} \) to transition \( Y \), \( Y \) to the place \( \text{Ser}_-\text{Vac}, \text{Ser}_-\text{Vac} \) to the transition \( \text{Vacation} \) and the transition \( \text{Vacation} \) to place \( \text{Ser}_-\text{Idle} \) equals \( S \) (rather that 1), because the \( S \) channels of the base station take a vacation and return from vacation together. So, the immediate transition \( Y \) fires only when the place \( \text{Ser}_-\text{Idle} \) contains \( S \) idle channels, and there is no token in place \( \text{Cus}_-\text{Wait} \), which is the condition that no request is waiting to be served. The firing of transition \( Y \) will move \( S \) tokens in the place \( \text{Ser}_-\text{Vac} \), which represents the begin of the base station vacation. At the end of this period (after a mean delay of \( 1/\theta \)), \( S \) tokens corresponding to the \( S \) channels will be deposited in \( \text{Ser}_-\text{Idle} \). In this case, the service semantics of the transition \( \text{Vacation} \) is single server semantics, because the base station is a single unit. Hence, the symbol \# could be omitted.

Similarly, the GSPN modeling a small cell with synchronous single vacations of the base station, is the same as the model given in Fig. 2, in which the multiplicity of the arcs connecting the place \( \text{Ser}_-\text{Idle}1 \) to transition \( Y \), \( Y \) to the place \( \text{Ser}_-\text{Vac}, \text{Ser}_-\text{Vac} \) to the transition \( \text{Vacation} \) and the transition \( \text{Vacation} \) to place \( \text{Ser}_-\text{Idle}2 \) equals \( S \) (rather that 1), because the \( S \) channels of the base station begin and finish the vacation together and at the same time.

### IV. Performance measures

The aim of this section is to derive the formulas of the most important stationary performance indices corresponding to a small cell. As all the proposed models are bounded and the initial marking is a home state, the underlying continuous time Markov chains are ergodic for the different vacation schemes. Hence, the steady-state probability distribution vector \( \pi \) exists and can be obtained as the solution of the linear system of equations \( \pi Q = 0 \) with the normalization condition \( \sum_i \pi_i = 1 \), where \( \pi_i \) denotes the steady-state probability that the process is in state \( M_i \) and \( Q \) is the transition rates matrix. Having the probabilities vector \( \pi \), several stationary performance measures of small cell wireless networks with different vacation schemes can be derived as follows. In these formulas, \( M_i(p) \) denotes the number of tokens in place \( p \) in marking \( M_i \), \( A \) the set of reachable tangible markings, and \( A(t) \) is the set of tangible markings reachable by transition \( t \) and \( E(t) \) is the set of markings where the transition \( t \) is enabled.

- **Mean number of busy channels (\( n_s \))**:
  \[
  n_s = \sum_{i: M_i \in RS} M_i(\text{Cus}_-\text{Ser}).\pi_i
  \]

- **Mean number of waiting requests in a micro cell (\( n_o \))**:
  \[
  n_o = \sum_{i: M_i \in RS} M_i(\text{Cus}_-\text{Wait}).\pi_i
  \]

- **Mean number of channels on vacation (\( n_v \))**:
  \[
  n_v = \sum_{i: M_i \in RS} M_i(\text{Ser}_-\text{Vac}).\pi_i
  \]

- **Mean number of idle channels (\( n_f \))**:
  \[
  n_f = S - (n_s + n_v)
  \]

    \[
    = \sum_{i: M_i \in RS} M_i(\text{Ser}_-\text{Idle}).\pi_i, \quad \text{in multiple vacations}
    \]

    \[
    = \sum_{i: M_i \in RS} M_i(\text{Ser}_-\text{Idle1}) + M_i(\text{Ser}_-\text{Idle2}).\pi_i, \quad \text{in single vacations}
    \]

- **Effective request arrival rate (\( \bar{\lambda} \))**:
  \[
  \bar{\lambda} = \sum_{i: M_i \in E(\text{Arrival})} M_i(\text{Cus}_-\text{Free}).\lambda.\pi_i
  \]

- **Mean rate of vacation (\( \bar{\gamma} \))**:
  \[
  \bar{\gamma} = \sum_{i: M_i \in E(\text{Vacation})} M_i(\text{Ser}_-\text{Vac}).\theta.\pi_i
  \]

- **Utilization of \( c \) channels (\( U_c \))**: \( (1 \leq c \leq S) \)
  \[
  U_c = \sum_{i: M_i(\text{Cus}_-\text{Ser}) \geq c} \pi_i
  \]

- **Vacation of \( c \) channels (\( V_c \))**: \( (1 \leq c \leq S) \)
  \[
  V_c = \sum_{i: M_i(\text{Ser}_-\text{Vac}) \geq c} \pi_i
  \]

- **Availability of \( c \) channels (\( A_c \))**: \( (1 \leq c \leq S) \)
  \[
  A_c = 1 - \sum_{i: M_i(\text{Cus}_-\text{Ser}) + M_i(\text{Ser}_-\text{Vac}) \geq c} \pi_i
  \]

- **Blocking probability of a call (\( B \))** is given in table I

- **Admission probability (\( A \))**:
  \[
  A = 1 - B
  \]

- **Mean mobile request waiting time (\( \bar{W} \))**:
  \[
  \bar{W} = \frac{n_o}{\bar{\lambda}}
  \]

- **Mean mobile request response time (\( \bar{R} \))**:
  \[
  \bar{R} = (n_s + n_o)/\bar{\lambda}
  \]
TABLE I
BLOCKING PROBABILITY OF A CALL (B)

\[
B = \begin{cases}
\sum_{i,M_i \in RS} \sum_{j=1}^{K} j \cdot \lambda \cdot \text{Prob}[M_i(Cus_{Free}) = j \land M_i(Ser_{Idle}) = 0], & \text{in multiple vacations,} \\
\frac{\sum_{i,M_i \in RS} \sum_{j=1}^{K} j \cdot \lambda \cdot \text{Prob}[M_i(Cus_{Free}) = j \land M_i(Ser_{Idle}) = 0 \lor M_i(Ser_{Idle}) = 0]}{\bar{\lambda}}, & \text{in single vacations}
\end{cases}
\]

TABLE II
MEAN RESPONSE TIME WITH N = 50, \( \mu = 1, \theta = 0.5, S = 1 \)

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>0.1</td>
<td>3.107</td>
<td>4.106 910</td>
<td>1.494</td>
<td>1.493 591</td>
</tr>
<tr>
<td>0.3</td>
<td>3.391</td>
<td>3.390 956</td>
<td>2.370</td>
<td>2.370 394</td>
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<tr>
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<td>3.172 213</td>
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<td>4.592 556</td>
<td>4.152</td>
<td>4.152 779</td>
</tr>
<tr>
<td>0.9</td>
<td>6.000</td>
<td>6.000 634</td>
<td>5.718</td>
<td>5.719 074</td>
</tr>
</tbody>
</table>

V. NUMERICAL EXAMPLES

In this section, we consider some numerical results, to validate the proposed models, and also to show the influence of the vacation policies on the performance measures of small cell wireless networks.

The parameter \( \rho = N \lambda / \mu \) represents the largest offered load in the network. Table 1 shows the variation of the mean response time with \( \rho \), for the different vacation schemes, when the base station consists of one channel. From this table, we can see that the numerical results are very close to those obtained by Ibe and Trivedi [13] for single server queues with vacations. On the other hand, in this particular case, the results of the models with channel vacations and base station vacations coincide as can be expected, because the whole base station consists of only one channel.

In Table 2, some experimental results are collected when the channels vacation rate and the station vacation rate are very large. The results were validated by the analytical formulas of finite-source multi-server queueing models \( M/M/S//N \) without vacations. From this table, we can see that the corresponding performance measures are very close to the case without vacation, and to each other with server and station vacation policy, with very high vacation rate. Actually, the derived results are the same up to the 4th decimal digit. Hence, as \( \theta \to \infty \), the channels (or the base station) will eventually take no vacation, since vacation times converge to zero. Therefore, the model will be the corresponding model with no vacation.

We investigate the effects of network parameters and vacation policies on the mean response time as well. Since we deal with multi-server vacation systems, the emphasis we will put on the influence of vacation rate and channels number on the mean response time. On the other hand, we compare performances of the different vacation schemes.

Based on numerical results given in Table 3 and Table 4, a number of observations have been made. First, we see that for the different vacation models, the mean response time decreases as the vacation rate or the channels number increases. From Table 3, we can observe that for systems with a low vacation rate, a little variation of this value has a significant influence on the mean response time. For example, when the vacation rate varies from \( \theta = 0.1 \) to \( \theta = 0.5 \), the decrease of the mean response time approaches 47%. However, when vacations periods become shorter, the decrease of the mean response time is not considerable. Table 3 shows also, that channels vacation schemes give the best performances for low vacation rates. But, when this rate increases, the best performances are given by the synchronous vacation schemes, and particularly by the model with single vacations of station.

From Table 4, we note that the performance difference

TABLE II
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<td>6.000</td>
<td>6.000 634</td>
<td>5.718</td>
<td>5.719 074</td>
</tr>
</tbody>
</table>

TABLE IV
MEAN RESPONSE TIME VERSUS VACATION RATE WITH N = 40, S = 5

<table>
<thead>
<tr>
<th>( \theta )</th>
<th>Independent</th>
<th>Synchronous</th>
<th>Independent</th>
<th>Synchronous</th>
</tr>
</thead>
<tbody>
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<td>( \rho )</td>
<td>multiple</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>1.392 169</td>
<td>3.143 306</td>
<td>2.122 075</td>
<td>3.481 595</td>
</tr>
<tr>
<td>0.3</td>
<td>1.371 122</td>
<td>1.433 241</td>
<td>1.343 080</td>
<td>1.402 029</td>
</tr>
<tr>
<td>0.5</td>
<td>1.342 218</td>
<td>1.035 021</td>
<td>1.099 135</td>
<td>1.066 187</td>
</tr>
<tr>
<td>1</td>
<td>0.912 644</td>
<td>0.761 670</td>
<td>0.865 977</td>
<td>0.738 944</td>
</tr>
<tr>
<td>5</td>
<td>0.677 949</td>
<td>0.597 961</td>
<td>0.629 584</td>
<td>0.600 317</td>
</tr>
<tr>
<td>10</td>
<td>0.639 466</td>
<td>0.597 961</td>
<td>0.618 207</td>
<td>0.595 137</td>
</tr>
</tbody>
</table>

TABLE V
MEAN RESPONSE TIME VERSUS CHANNELS NUMBER WITH N = 40

<table>
<thead>
<tr>
<th>( S )</th>
<th>Independent</th>
<th>Synchronous</th>
<th>Independent</th>
<th>Synchronous</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>multiple</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>14.999 270</td>
<td>14.999 270</td>
<td>14.999 269</td>
<td>14.999 269</td>
</tr>
<tr>
<td>2</td>
<td>5.001 382</td>
<td>5.001 152</td>
<td>5.001 290</td>
<td>5.001 102</td>
</tr>
<tr>
<td>3</td>
<td>1.862 108</td>
<td>1.822 710</td>
<td>1.847 573</td>
<td>1.817 609</td>
</tr>
<tr>
<td>5</td>
<td>0.723 979</td>
<td>0.623 064</td>
<td>0.668 892</td>
<td>0.612 941</td>
</tr>
<tr>
<td>8</td>
<td>0.576 173</td>
<td>0.524 915</td>
<td>0.517 887</td>
<td>0.516 347</td>
</tr>
<tr>
<td>10</td>
<td>0.552 187</td>
<td>0.521 756</td>
<td>0.503 488</td>
<td>0.513 112</td>
</tr>
<tr>
<td>20</td>
<td>0.520 302</td>
<td>0.521 276</td>
<td>0.500 002</td>
<td>0.511 078</td>
</tr>
</tbody>
</table>
among the cells with 1, 2 and 3 channels is significant. Hence, a small change in the number of channels, particularly from 1 to 3, produces a big difference in the mean response time ($\approx -87\%$). However, after a certain value ($S = 3$ in our example), the decrease is not too significant. On the other hand, the multiserver model with synchronous single vacations of station gives the best response time. However, for stations with an important number of channels ($S = 10$ in our example), the model with independent single vacations of channels becomes more interesting in terms of performance.

Finally, these numerical results agree with the intuition that the mean response time is expected to improve as the channels number and the vacation rate increase. In addition, for stations with a reasonable number of channels, to obtain the best response time, the vacation duration should be decreased and apply the synchronous single station vacation scheme.

VI. Conclusion

This paper aims at modeling and studying performances of Small Cell Wireless Networks, taking into account the finite number of mobiles served in a small cell and different vacation schemes of the base station channels. Hence, we showed how the behavior of mobiles with channels vacations can be intuitively described using Generalized Stochastic Petri nets formalism and how several stationary performance measures can be derived.

In conclusion, it is worth noting that our approach based on GSPNs can be further extended to next generation cellular networks with more complex vacation schemes or to networks where channels are subject to breakdowns in addition to their normal vacations.

REFERENCES


