QoE-Based Flow Admission Control in Small Cell Networks

Adlen Ksentini, *Senior Member, IEEE*, Tarik Taleb, *Senior Member, IEEE*, and Khaled B. Letaif, *Fellow, IEEE*

***Abstract*—An important requirement on 5G mobile systems is to accommodate massive numbers of wireless devices and users. Heterogeneous networks are expected to play a crucial role in meeting this requirement. In this vein, small cells are expected to become an integral part of these heterogeneous networks. However, their success would not last longer unless they offer services at a quality similar to that currently ensured by the macro cellular networks. Mitigating congestion of the backhaul links to small cell networks is a crucial factor. With this regard, this paper proposes an admission control that makes decisions to redirect IP flows, fully or partially, to the macro or small cell networks, or to reject the incoming flows. The decision mechanism is based on predictions of users' Quality of Experience (QoE). It is modeled as a Markov decision process (MDP), whereby the aim is to derive the optimal policy (i.e. reject or accept flows in the macro or the small cell) that maximizes users' QoE. Through computer simulations, we evaluate the performance of the proposed admission control and compare it against a random policy decision. We also numerically illustrate its optimal policies in different scenarios under different traffic load conditions.**

***Index Terms*—Small cells, LTE, QoE, admission control, 5G, and Markov decision process.**

I. INTRODUCTION

5G SYSTEMS are required to ensure high data rates everywhere while supporting massive numbers of wireless devices. In this regard, extension to higher frequencies, complementing lower frequencies, for extreme capacity and data rates in dense areas is seen as a vital key technology area for 5G. Moreover, one of the main challenges of the upcoming 5G networks is to accommodate the high demand of data raised from the increasing number of devices. In this vein, deploying small cells should be considered with high interest to overcome this issue. 5G networks would deploy densely self-organizing low-cost and low power small base-stations. Small cells will play an important role in this context. They are indeed gaining ground at a tremendous pace, offering numerous benefits, most importantly better indoor coverage (e.g., in shopping malls and large enterprises), increased peak bit rate in low coverage areas and ultimately improved communication reliability over a wide service area including outdoor and indoor. They also represent an efficient solution to selectively offload IP traffic (e.g., YouTube traffic), above all without any manual interventions of users (i.e., unlike WiFi networks that usually require users' consent), to avoid congestion at the relevant macro network [1], [2].

When a user is in an indoor environment, small cells connect the User Equipment (UE) to a mobile operator's core network through an entity called H(e)NB (Home e-Node B) gateway, using fixed broadband access networks (e.g., broadband Digital Subscriber Line (DSL), cable, or Fiber To The Home (FTTH) technology) as backhaul. The wide acceptance of small cells among the general consumers would not last longer unless they offer mobile connectivity services at a quality similar to that currently ensured by the macro cellular networks. This quality of mobile services provided at small cells does not depend only on the radio link quality from the UEs to the small cells, but to a large extend, on the level of congestion on the backhaul links to the small cell networks. Mitigating congestion of these backhaul links is therefore of vital importance. Indeed, it is crucial to avoid situations whereby a potential number of users simultaneously connect to a small cell network (e.g., in a residential area) whilst the communication path, in the backhaul (e.g., to the same DSL Access Multiplexer (DSLAM), to the H(e)NB gateway, or to other relevant potential nodes) is congested or is about to get severely congested. Such situations would result in downgrading the Quality of Service (QoS) and ultimately the Quality of Experience (QoE) of all users connecting to the small cell network [3], [4]. As a remedy to this issue, in this paper, we devise an agile admission control mechanism that anticipates QoS/QoE degradation and proactively defines policies for admitting UEs handing-in from the macro network to the small cell network. It also enables IP flow mobility between small cell and macro networks. An abridged version of this admission control mechanism has been introduced in [5]. In this paper, we extend the work by providing an analytical model to the admission control mechanism based on Markov Decision Process (MDP). The ultimate objective of the proposed model is to derive the optimal policy (i.e., reject or accept flows in the macro or the small cell) which maximizes users' QoE under different load scenarios (low and high load user traffic). The contribution of this work is two fold. Firstly, we provide an admission control mechanism that anticipates users' QoE degradation by steering traffic between macro and small cells or rejecting it if the overall users' QoE falls under a predefined threshold. Secondly, we introduce a MDP-based

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A. Ksentini is with the EURECOM, Sophia-Antipolis, France (e-mail: aksentini@ieee.org).

T. Taleb is with Sejong University, Seoul, Korea, and Aalto University, Espoo, Finland (e-mail: talebtarik@ieee.org).

K. B. Letaif is with Hong Kong University of Science and Technnology, Hong Kong City, Hong Kong (e-mail: eekhamed@ee.ust.hk).

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model in order to derive the optimal policy to be used by the admission control mechanism. Besides, we show the optimal policy construction for several traffic load configurations. To the best knowledge of the authors, this work is the first that considers users' QoE as the main metric to steer traffic in a macro/small cells network.

The remainder of this paper is structured as follows. Section II highlights some research work pertaining to small cell communications. The admission control approach, briefly proposed in [5] and dubbed hereunder as Qo^2BAC, is detailed in Section III. Section IV models the proposed admission control as a MDP process. The analytical discussion of the proposed admission control is made in Section V. The paper concludes in Section VI.

II. RELATED WORK

Regarding small cell networks, several research works have been conducted in the recent literature. Many of them have dealt with mobility management issues, and that is in both the Open Subscriber Group (OSG) case and the Close Subscriber Group (CSG) case [6], [7]. Solutions to this issue were in the form of predicting the user movement, comparing the small cells that have been visited to those stored in the local cache, and then selecting the ones that a user should more likely connect to [8]. Again to support mobility between macro and small cells networks, the work in [9] proposes a mobility management scheme based on QoS, traffic type (e.g., real time vs. non-real time), and UE's speed considering three velocity ranges, namely low, medium, and high.

As stated earlier, assuring acceptable QoS over IP backhaul is of vital importance for small cell networks, especially for delay-sensitive traffic. This becomes an issue; mainly when the mobile network and the fixed broadband network are independently operated. One solution to this problem is by implementing admission control mechanisms at small cells. In [10], *Olariu el. al.* propose an admission control and resource allocation mechanism to avoid resource overloading and VoIP (Voice over IP) quality degradation at DSLAMs to support small cell communications. In this admission control, the VoIP quality measurements are made at the HeNB GW and the call admission decisions are made based on measurements taken from actual ongoing VoIP calls considering a modified variant of the ITU-T's E-Model algorithm. Based on jitter and delays, the E-Model algorithm derives in real time user perceived QoE in terms of Mean Opinion Score (MOS). VoIP calls are accepted if the average MOS is higher than 3.9, and are rejected if the MOS is less than 3.8. Besides using heuristic policies to implement admission control, the proposed mechanism is dedicated only to VoIP applications. In [11], a handover management scheme along with an admission control mechanism in high-dense small cell networks is introduced. The admission/rejection decisions are made by an entity connected with small cells. The authors differentiate three cases of admission control decisions: (i) for new calls; (ii) for calls originally connected with the macro network; (iii) and for calls originally connected to the small cell network. To implement this admission control mechanism, two thresholds (T_1 and T_2, $T_1 < T_2$) are defined, which represent SINR (Signal Noise Ratio) of the target small cell. For the first case, the new flows are admitted in the small cell if SINR is higher than T_2. Otherwise, the flow is directed to the macro network. For the case of flows originally connected to the macro network, they are directed to the small cell network if SINR is higher than T_2. Finally, when the flows originally connected to the small cell network detects that SINR is falling down, they get connected to the macro network if no other small cell is available. However, if there is another available small cell and SINR is higher than T_2, they are then directed to that small cell. If SINR is less than T_1, the flows are connected to the macro network. Similar to [10], the admission decision mechanisms are based on heuristics. In [12] and [13], *Le et. al.* formulate the admission control mechanism as a Semi Markov Decision Process (SMDP). The admission control process is distributed and is locally implemented by each access point (macro and small cells). The SMDP process allows deriving an optimal policy to accept or reject a flow at the cell level. To solve the SMDP process, the authors use linear programming, whereby the objective function is to minimize the sum of the overall blocking probability. There is no redirection (i.e., forced handover or flow mobility) between macro and small cell networks. Furthermore, the objective function used in the SMDP process considers only the blocking probability and does not consider users' QoE. In [5], the authors presented a mechanism that i) predicts and assesses the variation of QoS metrics in the future such as network load/congestion indications, ii) predicts and assesses the impact of QoS variation on users' QoE, iii) and based on these two predictions, defines policies for admitting UEs into small cell network or macro network, which maximize the new flow's QoE and minimize the degradation of the overall QoE for admitted flows in both networks. Similar to [10] and [11], the decisions are based on simple heuristic. To address this issue, we propose in this paper the use of a MDP model to derive the optimal policies for admission decisions, which complements the framework introduced in [5].

III. QO^{2}BAC: PROPOSED QOS/QOE-BASED ADMISSION CONTROL

A. QoS/QoE Profile Creation

In this section, we describe the QoS/QoE predictions-based admission control, proposed in [5], which defines the basis of the MDP model presented in this paper. The interested reader is referred to [5] for further details on the proposed QoS/QoE predictions-based admission control framework. The focus of this present paper is on how to derive admission decisions.

A typical small cell network deployment is shown in Fig. 1. The shown network architecture comprises a number of small cells, covering multiple households/small offices in a wide residential area or forming an enterprise or a hotspot small cell network (e.g., shopping mall). The multiple small cells are provided by the same mobile network operator and connected through the same DSLAM (or another node relevant to the used fixed access technology) to the mobile operators core network via (optionally) a security gateway and a H(e)NB gateway. Whilst the figure shows the case of a single mobile operator network operating small cells and utilizing the fixed broadband networks DSLAM, the DSLAM can be also shared

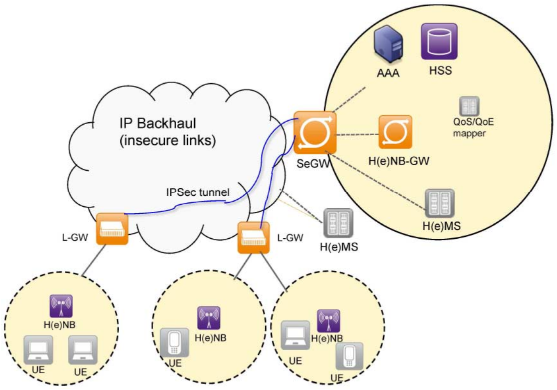


Fig. 1. A typical small cell network deployment.

by small cells operated by different mobile operators. In this case, DSLAMs are assumed to have the capacity to individually identify the different mobile operators using one or more suitable methods. It is also assumed that each individual mobile operator has a Service Level Agreement (SLA) with the ISP (Internet Service Provider) indicating the maximum resources dedicated for the mobile operator at each DSLAM. Intuitively, it is for the benefit of the operator to minimize the cost incurred with the dedicated resources booking without compromising the service quality for its users. In this vein, ensuring good QoS for users may deceptively appear simple by increasing the backhaul capacity, e.g., on busiest sites, i.e., by having the mobile network operator overprovision the dedicated resources (e.g., maximum bandwidth) at DSLAMs or other relevant nodes through well-defined SLAs with the relevant ISP. However, resource overprovisioning is certainly not a cost-efficient solution mainly in developing markets where wireless is amazingly less expensive than cable or DSL [4]. Above all, it is only a short term solution as no matter how powerful the backhaul is, it will be always limited in capacity. Furthermore, the update of SLA does not frequently happen. Therefore, in case more resources become required to avoid congestion and to ensure acceptable QoS, and till a new SLA is established according to which more resources are allocated to a mobile operator, users may perceive frequently poor QoS.

The problem that we solved in [5] is as depicted in Fig. 2. A mobile user enters an area serviced by a small cell network and also covered by the mobile operators macro network. In case a link along the path from the small cells (or the DSLAM or other relevant node) to the H(e)NB GW (or to another relevant point of mobile traffic concentration) is congested or is about to get congested, if the user handovers from the mobile operators macro network to the small cell network, the service quality may get downgraded. Furthermore, due to the handover of the new user to the small cell network, the quality of services received by other existing users may get also downgraded, or worse enough, aggravated. As mentioned before, the proposed framework in [5] is based on three components: i) predicting and assessing the variation of QoS metrics in the future such as network load/congestion indications, ii) predicting and assessing the impact of QoS variation on users QoE, iii), defining policies for admitting UEs into small cell network or macro network.

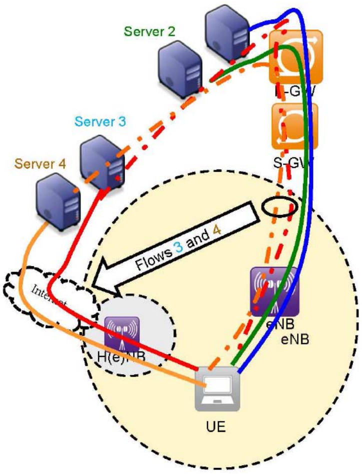


Fig. 2. Admission control based handover and IP flow mobility between macro and small cell networks.

QoE is assessed in the form of a metric that indicates average user satisfaction level (i.e., MOS). Information on user satisfaction is collected explicitly from users when they handout from the small cell network. Users that are requested to score their satisfaction level can be selected, randomly or following a defined logic: only users that received a particular service/application type, video; only users that have been connecting to the small cell network for a time exceeding a specific threshold; only users that have been having active bearers with specific QoS Class Identifier (QCI) when connected to the small cell network; only users that belong to a specific Closed Subscriber Group (CSG); only users with bearers with specific DiffServ Code Point; only users with an Aggregate Maximum Bit Rate (AMBR) satisfying a specific condition; etc. Users may be given incentives for scoring the service. Satisfaction levels can be collected, from a randomly selected group of users, for instance using Short Message Service (SMS), through a web portal, or through a dedicated application. Incentives could be given to users that scored their service satisfaction levels. It should be noted that for many mobile operators, using small cells for data offload, providing mobile services, or other purposes is still a new service or "yet to be launched" service and operators may then want to evaluate the satisfaction of their customers at an initial phase of the service to assess and ensure an adequate deployment of resources.

In the envisioned architecture depicted in Fig. 1, a new entity, called QoS/QoE mapper, is collocated with the DSLAM. In case of an enterprise network or a shopping mall, it can be collocated at the gateway of the enterprise local network to the ISP network. This QoS/QoE mapper can be also collocated with the H(e)NB GW or at another appropriate location. It can be a physically independent and new node or a function at an existing node. The QoS/QoE mapper is in charge of monitoring the bandwidth variation of the link between the small cell network and the operators H(e)NB gateway, using one or more suitable bandwidth probing techniques [17]. The link bandwidth may vary during different periods of a day. For instance, the link may be heavily accessed during the day and not so much at night. To inflict these variations, the QoS/QoE mapper develops

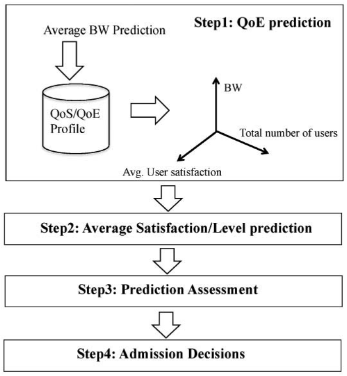


Fig. 3. Major steps behind the proposed admission control mechanism.

a statistical profile over time of the link bandwidth variation. This statistical profile is constantly updated over a long period of time, in the order of days or weeks. This statistical profile is referred to as link bandwidth profile. The QoS/QoE mapper also keeps track of another statistical profile, called QoS/QoE profile hereunder, whereby QoE in terms of the satisfaction level of users, averaged over a short and predetermined period of time T, is mapped to QoS in terms of average link utilization and total number of users connected to the small cell network during the time period T. The QoS/QoE profile is constantly updated through learning.

In the proposed mechanism, small cells and macro cells periodically receive admission control policies from the corresponding QoS/QoE mapper using a dedicated interface and using preconfigured logic to interpret and enforce them. These policies are determined by the QoS/QoE mapper based on the QoS and QoE predicted for the upcoming time period. Following these policies, for example, the handover of a UE into the small cell network is admitted if acceptable customer satisfaction level/QoE is foreseen. Otherwise, the user will be requested to stay connected to the macro network. Fig. 3 depicts the major steps behind our proposed admission control. Decisions on the admission control policies to be sent to macro cells and small cells are run periodically. If the satisfaction level is predicted to be low, the QoS/QoE mapper defines an admission control policy that shall be enforced at the macro cell network or the small cell network, to ultimately increase the satisfaction level to an acceptable value. Whereas step 2 and 3 are well detailed in [5], the main objective of this paper is to formulate an optimal model for step 4.

B. Admission Control Policy Model

1) MDP: Having described some details of the proposed admission control, we now direct our focus to its modeling as an MDP process. The notations used in this paper follow those described in [18]. The envisioned model is based on the use case of Fig. 2, whereby a mobile operator has to decide which network (i.e., small cell network or macro network) the UE needs to attach to in order to maximize its QoE and to minimize the degradation of the overall QoE of admitted flows. We recall that the QoS/QoE mapper, defined above, specifies the admission decision policy. Using the QoS and QoE prediction procedures, the QoS/QoE mapper is aware of the QoE experienced by users in each network type. Furthermore, it is able to assess the impact of adding one new flow to each network type on QoE, by predicting the users' QoE at $(t+1)$ given the current time is (t). In order to retrieve an optimal policy for deciding where to admit a UE with a traffic k, we define a Continuous Time Markov Decision Process (CTMDP) that associates to each state an action, corresponding transition probabilities, and rewards. Let s_t be the process describing the evolution of the system state and S denote the state space. We denote by $A = (a_1, a_2, a_3)$ the vector describing the actions available to the QoS/QoE mapper at each epoch (i.e., arrival or departure of a new UE). Action a_3 is used if the UE is accepted into the small cell network, while action a_2 is used if the UE is accepted into the macro network. Action a_1 refers to the case when the UE is rejected. As will be detailed later, depending on the current state, the set of available actions is different. Let Q_m^k and Q_f^k denote the predicted average QoE if a new UE with a traffic of type k is admitted into the macro network or the small cell network, respectively. This information is available at the QoS/QoE mapper, which constantly tracks the users' satisfaction values. We assume that there are k types of traffic associated to a UE. The state space can be written as:

$$s = \left(n_m^0, \ldots, n_m^k, n_f^0, \ldots, n_f^k, b\right) \tag{1}$$

where n_m^k represents the number of UEs with traffic type k admitted into the macro network cell, n_f^k denotes the number of UEs with traffic type k admitted into the small cell network, and b is a binary value. The QoS/QoE mapper observes the current state s of the network and associates a set of possible actions A_s to it, taken upon arrival to it from the previous state. For a given action a, an instantaneous reward $r(s, s', a)$ is associated to this transition from state s to another state s'. The corresponding formal representation of the CTMDP process is as follows:

$$\left(S, A, (A_s, s \in S), q\left(s' \middle| s, a\right), r\left(s, s', a\right)\right)$$

For particular states, the set of possible actions A reduces to a subset A_s.

A policy P associates an action $a(s|P)$ to a state s. Let Q be the transition matrix, with $q(s|s')$ being the transition rate between states s and s' in S. The transition rates of the controlled process $q(s'|s, a)$ can be derived as follows:

- The transitions due to the arrival of a new UE.
- The transition due to mobility of a user between different regions of the cell, served by the macro base station or by the small cell.
- The transition due to the departure of a UE, e.g., due to the end of the application/session.

It is worth noting that transitions due to the departure of a UE or to the mobility of a user have the same impact on the system. Indeed, our aim is to find the optimal policy when a new UE comes to a region (i.e., due to mobility or the launch of a new session) covered by both macro and small cells. Indeed, if a UE is connected to a small cell and moves to an area covered only by the macro network, there is no need for admission control. The UE is automatically admitted in the macro network.

Meanwhile, the case of a UE being connected to a macro cell and moving to a region covered by both macro and small cells is considered as a new user arrival. The QoS/QoE mapper can thus ask the UE to redirect its IP flows to the small cell if this one offers better QoE or the overall QoE could be improved.

We assume that the arrival rate of UEs with traffic i follows a Poisson law with intensity λ_i and that the sojourn time in the system is exponentially distributed with a mean $\frac{1}{\mu}$. These two assumptions are made due to the facts that i) voice call durations are usually modeled using an exponential distribution and ii) for video streaming applications, μ is equal to $\frac{\delta}{R}$, whereby δ and R denote the file size, (which is exponentially distributed [19]) and the download data rate (which is considered constant for the sake of simplicity), respectively. By construction, we define a policy as a function of the actual state. The decision of accepting a UE/flow in a small cell or in the macro network is thus taken by observing only the actual state. Since this process is Markovian (i.e., the arrival rate is Poisson and the sojourn time is exponential), the controlled process is then also Markovian. In order to resolve this MDP system, we use an equivalent Discrete Time Markov Decision Process (DTMDP) for the mentioned CTMDP to find the optimal policy. We particularly consider a DTMDP process with a finite state space S. For each $s \in S$, we denote by A_s the finite set of allowed actions in that state. This DTMDP process can be found by uniformization and discretization of the initial process as follows [18]:

- When all the transition rates in matrix Q are bounded, the sojourn times in all states are exponential with bounded parameters $q(s|s,a)$. Therefore, a $sup_{(s \in S, a \in A_s)} q(s|s,a)$ exists and there is a constant value c such as:

  $$sup_{(s \in S, a \in A_s)} [1 - p(s,a)] q(s|s,a) \leq c < \infty$$

  where $p(s|s,a)$ denotes the probabilities of staying in the same state after the next event.

We can thus define an equivalent uniformized process with state-independent exponential sojourn times with parameter c and transition probabilities:

$$p(s'|s,a) = \begin{cases} 1 - \frac{([1-p(s|s)]q(s|s,a))}{c} & s = s' \\ \frac{p(s'|s)q(s'|s,a)}{c} & s \neq s' \end{cases} \tag{2}$$

In the remainder of this section, we use the DTMDP version. For $t \in N$, let s_t, a_t and r_t denote state, action and reward at time t of the DTMDP procedure, respectively. Let $P^a_{(s,s')} = p\left[s_{(t+1)} = s' | s_t = s, s_{(t+1)} = s', a_t = a\right]$ denotes the transition probabilities and $R^a_{(s,s')} = E[r_{(t+1)} | s_t = s, s_{(t+1)} = s', a_t = a]$ denotes the expected reward associated to the transitions. A policy π is mapping between a state and an action and can be denoted as $a_t = \pi(s_t)$, where $t \in N$. Accordingly, a policy $\pi = (\theta_1, \theta_2, \theta_3, \ldots, \theta_N)$ is a sequence of decision rules to be used at all decision epochs. In this paper, we consider only deterministic policies as they are easy to implement [18]. When a new UE arrives at the system, the QoS/QoE mapper decides whether to admit the UE in the small cell using action a_3, to admit the UE in the macro cell using action a_2, or to reject the UE using action a_1. For each transition, a reward is obtained. In case of actions a_3 or a_2, this reward corresponds to the sum of the average QoE (i.e., MOS) predicted in both cells. That is, if a UE with traffic k is accepted into the small cell, the corresponding reward is the average QoE obtained in the small cell (including the arriving UE) and the average QoE in the macro network. In addition, a constant reward is added for each admitted flow, which represents the gain for the network operator when accepting a flow. This reward is obtained as follows:

$$r(s,s',a) = Q^k_m + Q^k_f + Cst \tag{3}$$

Given a discount factor $\gamma \in [0,1)$ and an initial state s, we define the total discounted reward for a policy $\pi = (\theta_1, \theta_2, \theta_3, \ldots, \theta_N)$ as follows:

$$v^\pi_\gamma = \lim_{N \to \infty} E^\pi_\gamma \left\{ \sum_{t=1}^{N} \gamma^{t-1} r_t \right\} = E^\pi_\gamma \left\{ \sum_{t=1}^{\infty} \gamma^{t-1} r_t \right\} \tag{4}$$

It is worth mentioning that the QoE metric is represented by MOS. The MOS value is between 0 and 10; where 10 and 0 represent the highest quality and the poorest quality, respectively. Due to the uniformization of CMTC, $r(s,s',a)$ depends explicitly on the transitions between states. According to [18], the new reward function $r'(s,s',a)$ is obtained as follows:

$$r'(s,s',a) = r(s,s',a) \frac{\alpha + \beta(s,s',a)}{\alpha + c} \tag{5}$$

where $\beta(s,s',a)$ is the transition rate between state s and s' when using action a, and α is a parameter to fix. With the new formulation of the reward function and the uniformization of CMTC, we can use the discounted models as in discrete models to resolve the system [18]. Let $v(s)$ denotes the maximum discounted total reward, given the initial state s. That is, $v(s) = max_{\pi \in \Pi} v^\pi(s)$. From [18], the optimality equations are given by

$$v(s) = max_{\pi \in \Pi} \left\{ r'(s, s'a) + \sum_{s' \in S} \gamma P\left[s'|s,a\right] v(s') \right\} \tag{6}$$

The solutions of the optimality equations correspond to the maximum expected discounted total reward $v(s)$ and the optimal policy $\pi^*(s)$. It is worth mentioning that the optimal policy $\pi^*(s)$ indicates the decision as to which network the UE is to be attached, knowing the state s. There are several algorithms that can be used to resolve the optimization problem given by the above optimality equations. Value iteration and policy iteration are two notable examples.

In the remainder of this section, we show the different steps for deriving the optimal policy for admission control between a small cell network and macro network. For the sake of simplicity, but without loss of generality, we consider the case of UEs using only one traffic type. This traffic represents a video streaming session. We assume that the video sizes are exponentially distributed with a parameter δ. A server is sending each video with a constant bit rate R Kbps. The user arrival rate is following a Poisson process with an intensity λ. The state space is $S = \{n_1, n_2, b\}$, where n_1 denotes the number of accepted UEs in the macro network, n_2 denotes the number of UEs in

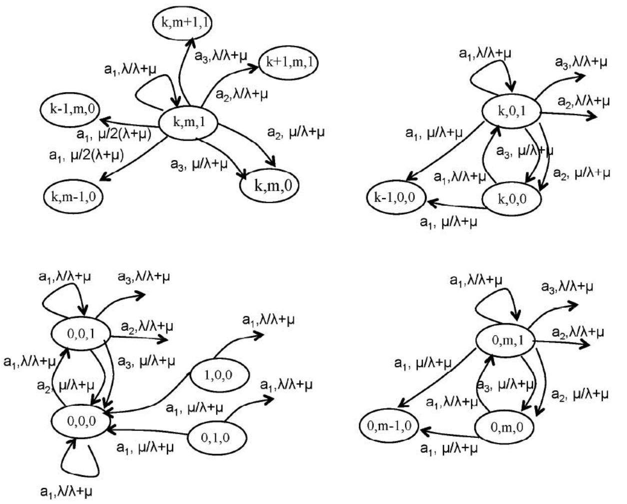


Fig. 4. The MDP scheme for one small cell, one macro network and one traffic class.

the small cell network, and b is a binary value, where $b = 0$ if there is a UE departure and $b = 1$ if there is a traffic arrival. The system is in state (n_1, n_2,0) if there are n_1 UEs in the macro network and n_2 UEs in the small cell network and no new UE arrivals. We observe this state when a transition corresponds to a UE departure. In such state, the only available action is a_1. In state (n_1, n_2,1), the QoS/QoE mapper has to decide on whether to accept the arriving UE into the macro cell through action a_2, to accept the arriving UE into the small cell network using action a_3 or to reject the UE with action a_1. Fig. 4 shows the possible transition probabilities, and the transition rate for the case of a UE with one traffic type. We can clearly deduce the transition rate as follows:

$$\beta(s, s', a) = \begin{cases} \lambda & if\ \ s = 0, s' = 0\ and\ b = \{0, 1\} \\ \lambda + \mu & if\ \ s = 0, s' = 0 \\ & and\ \ b = 1\ or\ s > 0\ and\ s' > 0 \end{cases} \tag{7}$$

Intuitively, when there is no UE in the system ($b = 0$ or $b = 1$ and the chosen action is a_1), the next decision epoch occurs upon arrival of a new UE at the system (following an exponential distribution with parameter λ). In any other state, the next decision epoch happens when a UE arrives at the system or leaves the system (i.e., due to service completion or mobility). Denoting by T_a the time until the next arrival and by T_s the time until the next service completion, the time of the next decision epoch is then $T = min(T_a, T_s)$. We deduce the distribution of T as follows:

$$\begin{aligned} P(T > t) &= P(min(T_a, T_s) > t) \\ &= P(T_a > t, T_s > t) \\ &= P(T_a > t) * P(T_s > t) \\ &= e^{-\lambda t} * e^{-\mu t} \\ &= e^{-(\lambda+\mu)t} \end{aligned} \tag{8}$$

Therefore, T is also following an exponential distribution with parameter $(\lambda + \mu)$. Accordingly, the transition probabilities are defined as follows:

$$p(j|s, a) = \begin{cases} 1 - \frac{\lambda}{\lambda+\mu} & j = s, a = \{a_1, a_2\} \\ 1 - \frac{\mu}{\lambda+\mu} & j = s, a = \{a_3, a_4\} \\ \frac{\lambda}{\lambda+\mu} & j = (k, m+1, 1), s = (k, m, 1), a = \{a_3, \} \\ & or\ j = (k+1, m, 1), s = (k, m, 1), a = \{a_2\} \\ & or\ j = (k, m, 1), a = \{a_1\}, b = \{0, 1\} \\ \frac{\mu}{\lambda+\mu} & j = (0, m-1, b), \\ & s = (0, m, 0), a = \{a_1\}, b = \{0, 1\}, m \neq 0 \\ & or\ j = (k, 0, b), s = (k-1, 0, 0), a = \{a_1\}, \\ & b = \{0, 1\}, k \neq 0 \\ & or\ j = (k, m, 1), s = (k, m, 0), a = \{a_2, a_3\}, \\ & k \neq 0, m \neq 0 \\ \frac{\mu}{2(\lambda+\mu)} & j = (k, m, 0), s = (k-1, m, 0), a = \{a_1, \}, \\ & k \neq 0, m \neq 0 \\ 0 & Otherwise \end{cases} \tag{9}$$

We observe that when the system is empty, the next decision epoch occurs when the system is in state (0,0,1). If there are k UEs connected to the macro network and m UEs connected to the small cell network, and there is no UE arrival or a UE has been rejected, the next decision epoch is either $(k, m, 1)$, $(k-1, m, 0)$, or $(k, m-1, 0)$ depending on whether a new UE arrived or a service has been completed. On the other hand, if there are k UEs connected to the macro network and m UEs connected to the small cell network, and a UE arrival has been admitted, the subsequent states are then $(k + 1, m,$1) or (k, m+1,1) depending on whether the UE has been accepted into the macro network or into the small cell network. The transition probability due to the arrival of a UE is $P(T_a < T) = \frac{\lambda}{\lambda+\mu}$. Regarding the departure of a UE, we distinguish two cases: (i) there is either no UE being admitted into the macro network or no UE being admitted into the small cell network, therefore $P(T_s < T) = \frac{\mu}{\lambda+\mu}$; (ii) there are k UEs admitted into the macro network and m UEs admitted into the small cell network, therefore $P(T_s < T) = \frac{\mu}{2(\lambda+\mu)}$ as there are two possible next decision epochs with equal probabilities $\frac{1}{2}$, (k−1, m,0) and $(k, m-1, 0)$.

2) Discounted Factor Value: In order to show the meaning of the discounted factor in the proposed model, we assume that the QoE/QoS mapper is executing the MDP admission control algorithm as long as users are coming. As stated before, decision epochs correspond to the instants when a user comes to the network. It is obvious that these epochs are related to the user traffic activity. Usually, the user trafic fluctuates along the day. High trafic is seen during the day, and low traffic (even inexistant) during the night. Therefore, the number of decision epochs during low trafic period may equal to zero. By considering this feature, the traffic arrival process can be modeled as an Interrupted Poisson Process (IPP). Fig. 5 depicts the simple two states Markov chain corresponding to the IPP. In the active state, the user trafic is coming to the network according to a Poisson distribution. The process stays in the active state with a probability α, and moves to the inactive state with the

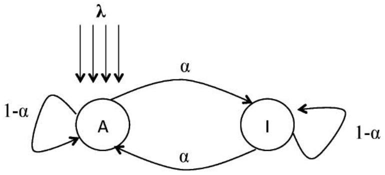


Fig. 5. The IPP Markov Chain.

probability $1-\alpha$. In the inactive state there is no traffic, and then the number of decision epoch is zero. The system remains in this state with the probability $1-\alpha$ and comes back to the active state with the probability α. Since this chain is aperiodic with a finite number of state, the steady distribution exists. We easily obtain the probability distribution as follows:

$$\begin{aligned}\pi_A &= \alpha \\ \pi_I &= 1-\alpha \end{aligned} \tag{10}$$

Accordingly, the probability to be in active state or α can also be interpreted as the discount factor (γ) of the MDP model. Besides fixing the precision of the MDP solution, it will represent the probability that QoS/QoE has to activate the module of admission control.

IV. PERFORMANCE EVALUATION

In order to find the correlation between the overall QoE (i.e., MOS) and the number of UEs attached to a cell, we use the Pseudo-Subjective Quality Assessment (PSQA) tool [20]. PSQA is an automatic QoE evaluation tool for multimedia services based on Random Neuronal Network (RNN). It learns the non-linear relationship between parameters impacting the service quality and the users' perceived QoE. Unless otherwise specified, the PSQA version used in the simulations is dedicated to video quality evaluation, whilst the RNN used in the proposed solution concerns all types of services. To estimate the users' QoE in terms of MOS, PSQA takes as input the loss rate and the mean loss burst size observed by the video flow. It is worth noting that we used PSQA in order to emulate the functionality of the QoS/QoE mapper and to predict the overall QoE for varying numbers of UEs. In real-life deployments, PSQA-like approach or other similar learning approaches could be used to assess and predict user's QoE as stated in Section III.

To derive the relation between the number of UEs (NB_{UE}) and the overall QoE for each network type, we conduct some preliminary simulation tests. We considered a video streaming service with a mean file size following a YouTube model (i.e. $\delta = 100$ Mbits). We used the NS3 network simulator to simulate UEs attaching to a radio access network of LTE macro cells and LTE small cells, and accessing a remote video-streaming server. The uplink and downlink physical characteristics of both eNBs and HeNBs are based on the LTE specifications. In our envisioned network architecture, we deliberately set the bottleneck link at the ADSL down link (i.e., link between DSLAM and the small cell network gateway) whereby a link of four Mbps is used. The video server is sending an H.264 video at a rate $R = 364$ kbits/s. In the simulations, we vary the number of UEs in each cell and compute the average QoE (using PSQA) obtained for each population of UEs. The obtained results are as follows:

$$MOS_{smallcell}(NB_{UE}) = \begin{cases} 10 & \text{if } NB_{UE} \le 11 \\ 7.88 & \text{if } NB_{UE} = 12 \\ 4.71 & \text{if } NB_{UE} = 13 \\ 1.7 & \text{if } NB_{UE} = 13 \\ 0.71 & Otherwise \end{cases} \tag{11}$$

$$MOS_{macro}(NB_{UE}) = \begin{cases} 10 & \text{if } NB_{UE} \le 30 \\ 8.21 & \text{if } NB_{UE} = 31 \\ 6.37 & \text{if } NB_{UE} = 32 \\ 4.52 & \text{if } NB_{UE} = 33 \\ 2.58 & \text{if } NB_{UE} = 34 \\ 0.71 & Otherwise \end{cases} \tag{12}$$

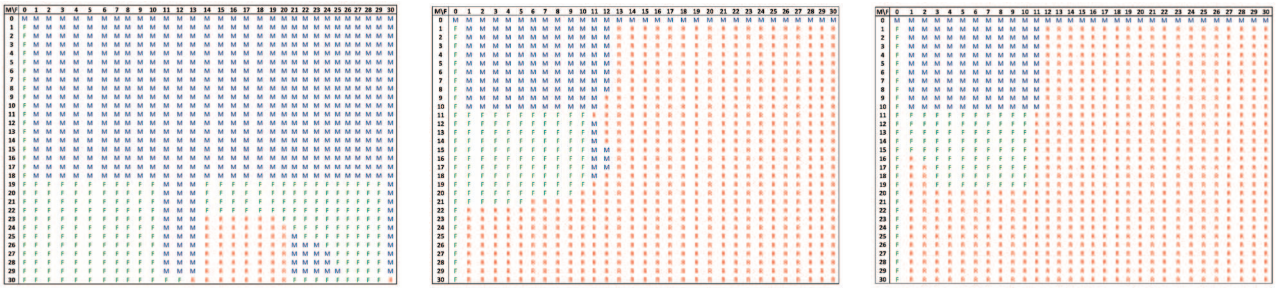
TABLE I
SIMULATION PARAMETERS

Parameter	value
ADSL link rate	4 Mbps
Video stream rate	364 Kbps
α	0.91
γ	0.91

It can be easily observed that the macro network can accept more UEs without degrading the users' QoE. This is intuitive given the fact that the macro network does not suffer from the ADSL bottleneck as in the case of the small cell network. We observe that QoE remains at the maximum when $NB_{UE} < 31$ and $NB_{UE} < 12$ for the macro cell and small cell networks, respectively. After that, the QoE drastically degrades for both networks. Regarding the discounted factor, we fixed the period of time spent in the active period to 22 hours. Since this value depends from the probability to be in this state and the total period of time (for instance 24 hours), then $\alpha = \gamma = 0.91$. Table I summarizes the parameters used in the simulation.

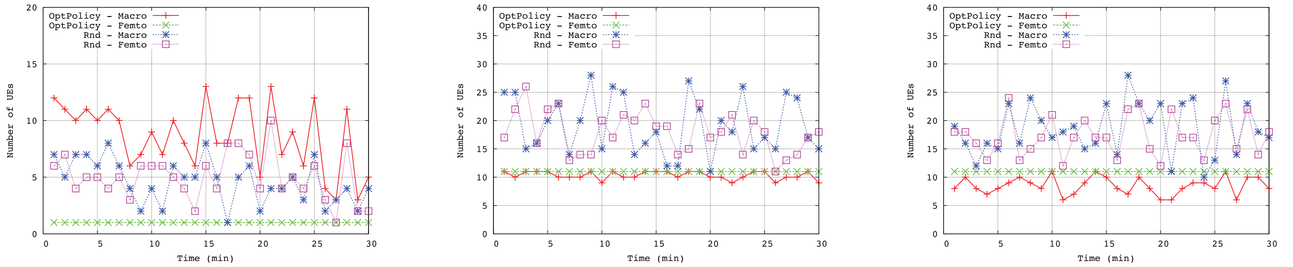
Having derived the relation between the number of UEs and the average perceived QoE (i.e., MOS), we now build the reward function and hence resolve the MDP process in order to obtain the optimal policies for different configurations. For this purpose, a Matlab implementation of the value iteration algorithm [21] is used to derive the optimal policy which satisfies the QoE constraints.

Fig. 6 shows the optimal policy constructions for different configurations of the network traffic. The horizontal axis (i) denotes the number of UEs in the small cell network, while the vertical axis (j) shows the number of UEs in the macro network. The intersection between i and j represents the action (a = R reject UE, a = M accept UE in the macro cell network, and a = F accept the UE in the small cell network) to be taken by the QoS/QoE mapper for an arriving UE, when i UEs are in the small cell network and j UEs are in the macro network. For instance, in Fig. 6(c), (5,5) indicates the action (here accept the UE in the macrocell) to use when there are 5 UEs in the macro network and 5 UEs in the small cell network. For a better readability of the policies, we limited the number of displayed states to 30 UEs in the macro cell network (i.e. $j \le 30$) and 30 UEs in the small cell network (i.e. $i \le 30$).



(a) $\rho = 0.25$ (b) $\rho = 1$ (c) $\rho = 4$

Fig. 6. Optimal policy construction in case of $\rho = 0.25$.



(a) $\rho = 0.25$ (b) $\rho = 1$ (c) $\rho = 4$

Fig. 7. Number of UEs in the macro network and the small cell network.

To represent the network traffic, we denote by $\rho = \frac{\lambda}{\mu}$ the network load. It represents the ratio between the intensity of the traffic (λ) and the sojourn duration in the system (μ). We considered three values to cover all possible configurations: (i) low load ($\rho = 0.25$); (ii) medium load ($\rho = 1$); and (iii) high load ($\rho = 4$). Regarding the reward model, the constant gain is set to $Cst = 10$, which encourages the system to accept UEs and increase the operator's revenue.

From Figs. (b) and 6(c), we observe that the optimal policy behavior is to reject arriving UEs when the system is reaching states where good QoE can no longer be ensured. We also observe that the frequency of these states is higher in case of $\rho = 4$ than in case of $\rho = 1$. Clearly, the number of states where the system rejects UEs is convex to the traffic load. This is a straightforward observation as the UE arrival rate is higher than the departure rate, a fact that results in overloading the system and hence reducing the overall QoE (i.e., as apparent from the PSQA results). Furthermore, it is also noticeable from Fig. 6(a) that even when the traffic load is relatively low, in some states the system tends to reject UEs. However, the frequency of these states is negligible compared to the precedent cases. The probability to reach these states is significantly low as the number of arriving UEs is lower than the number of UEs leaving the network. In contrast, the probability to reach the states where the system is highly loaded is higher for both cases $\rho = 4$ and $\rho = 1$. Hereunder, we show the impact of using the derived optimal policies on the users' QoE. For this purpose, we simulated the three cases of traffic loads using NS3. As a comparison term, we use a random policy approach without admission control, which admits the arriving UEs uniformly between the macro network and the small cell network. The simulation duration is set to 30 minutes; a duration long enough to ensure a stable simulation environment. UEs are arriving according to a Poisson distribution with a mean of λ per minute. UEs download a video file with an average size following an exponential distribution with a mean of δ. We modify the values of λ and δ in order to obtain the three configurations of ρ (0.25, 1 and 4), which represent the three scenarios of traffic load used in Fig. 6 to derive the optimal policies. We used the same network architecture as the one used for deriving the relation between the number of UEs and users' QoE.

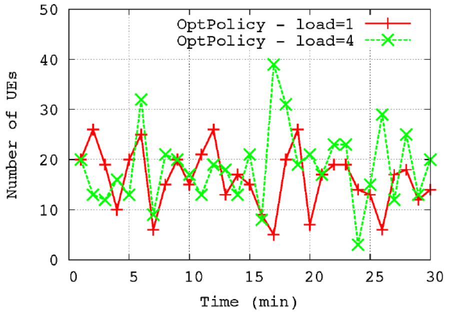
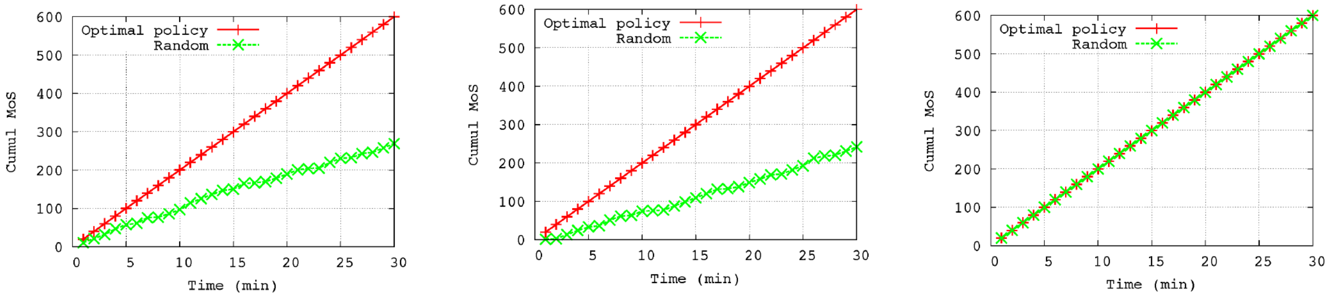


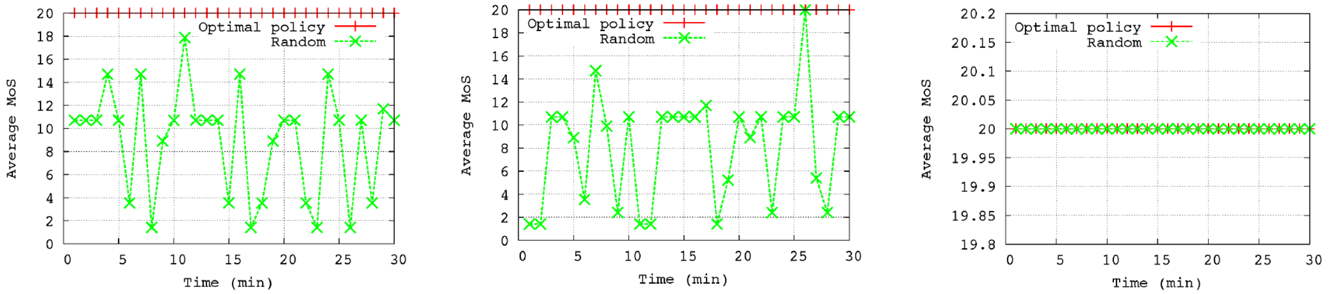
Fig. 8. Number of rejected UEs.

Fig. 7 illustrates the behavior of the optimal policy in distributing the arriving flows between the small cell network and the macro network when using the optimal policy (OptPolicy) as well as the random policy (Rnd) under the three traffic loads. As stated earlier, the random policy uniformly distributes the load on both networks, whereas the optimal policy redirects UEs to either the macro network or to the small cell network according to the constraint of QoE. In both cases of high and medium traffic loads (Figs. 7a and 7b), the optimal policy maintains the number of UEs admitted at the small cell



(a) $\rho = 0.25$ (b) $\rho = 1$ (c) $\rho = 4$

Fig. 9. Cumulated MOS.



(a) $\rho = 0.25$ (b) $\rho = 1$ (c) $\rho = 4$

Fig. 10. Average MOS.

less than 12, as higher numbers of UEs may degrade the average QoE. In case of scenarios with low load (Fig. 7c), the optimal policy attaches most of the arriving UEs to the macro network: only one UE attaches to the small cell. This performance is particularly due to the fact that QoE is not affected when the traffic load is low.

Fig. 8 shows the number of UEs rejected when using the optimal policy. We plot only the cases of high and medium loads, since no UEs were rejected when the traffic load is low. As expected, the number of rejected UEs is higher when the traffic load is high. This follows the optimal policy recommendation, where there are more states rejecting UEs in case of high traffic load. Additionally, throughout the simulations, the QoS/QoE mapper is rejecting UEs in order to maintain good QoE for admitted UEs. This behavior is confirmed in Fig. 9, which presents the cumulated MOS for the three traffic load scenarios. Clearly, regardless the traffic loads, the optimal policy is achieving the highest QoE. Indeed, thanks to its admission control, the system is able to maintain the highest QoE for admitted UEs. It shall be noted that the only case where both policies exhibit the same performance is in the case of low load. This is due to the fact that the number of UEs in the system does not exceed the threshold beyond which QoE degrades (i.e., 11 UEs for small cell network and 30 UEs for macro network). This gain is also noticeable from Fig. 10, which presents the instantaneous average MOS throughout the simulation.

V. CONCLUSION

In [5], the authors proposed a QoS/QoE-based admission control mechanism for handover and flow mobility decision between macro and small cell networks. The proposed admission control mechanism relies on predictions of users' QoE, deductible from an online neuronal network that learns the relation between user satisfaction and current QoS conditions of a cell. In this paper, we modeled the admission control process as a Markov Decision Process to derive the optimal policy according to the traffic load and the underlying QoE constraints. The performance of the optimal policies obtained by the MDP process are evaluated and com-pared against the case of a random policy. The proposed approach exhibits better performance regardless the traffic load, achieving the highest user QoE.

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Adlen Ksentini (SM'14) received the M.Sc. degree in telecommunication and multimedia networking from the University of Versailles Saint-Quentin-en-Yvelines, Versailles, France, and the Ph.D. degree in computer science from the University of Cergy-Pontoise, Cergy-Pontoise, France, in 2005. He is currently an Associate Professor at the Department of Mobile Communications, EURECOM, Sophia-Antipolis, France. Prior to that, he was an Associate Professor with the University of Rennes1, Rennes, France. He is involved in several national and European projects on QoS and QoE support in future wireless and mobile networks. He has coauthored over 80 technical journal and international conference papers. His research interests include future Internet networks, mobile networks, QoS, QoE, performance evaluation, and multimedia transmission. He is the TPC Chair of the Wireless and Mobile (WMN) Symposium of the IEEE ICC 2016. He was a Guest Editor of *IEEE Wireless Communication Magazine*, *IEEE Communication Magazine*, and two ComSoc MMTC letters. He has been on the Technical Program Committee of major IEEE ComSoc, ICC/Globecom, ICME, WCNC, and PIMRC conferences. He was the recipient of the Best Paper Award from the IEEE ICC 2012 and ACM MSWiM 2005.

Tarik Taleb (S'05–M'05–SM'10) received the B.E. degree (with distinction) in information engineering, the M.Sc. and Ph.D. degrees in information sciences from the Graduate School of Information Sciences (GSIS), Tohoku University, Sendai, Japan, in 2001, 2003, and 2005, respectively. He is currently a Professor with the School of Electrical Engineering, Aalto University, Espoo, Finland. Prior to his current academic position, he was a Senior Researcher and 3GPP Standards Expert with NEC Europe Ltd, Heidelberg, Germany. He was then leading the NEC Europe Labs Team working on RD projects on carrier cloud platforms, an important vision of 5G systems. He was also a Technical Leader of the main work package, Mobile Core Network Cloud, in EU FP7 Mobile Cloud Networking project, coordinating among 9 partners including NEC, France Telecom, British Telecom, Telecom Italia, and Portugal Telecom. Before joining NEC and until March 2009, he was an Assistant Professor with the GSIS, Tohoku University, in a laboratory fully funded by KDDI, the second largest network operator in Japan. From October 2005 to March 2006, he was a Research Fellow with the Intelligent Cosmos Research Institute, Sendai, Japan. His research interests include architectural enhancements to mobile core networks (particularly 3GPPs), mobile cloud networking, network function virtualization, software defined networking, mobile multimedia streaming, inter-vehicular communications, and social media networking. He has been also directly engaged in the development and standardization of the Evolved Packet System as a member of 3GPPs System Architecture Working Group. He is a member of the IEEE Communications Society Standardization Program Development Board. In an attempt to bridge the gap between academia and industry, he founded the "IEEE Workshop on Telecommunications Standards: from Research to Standards," a successful event that was awarded "Best Workshop Award" by the IEEE Communication Society (ComSoC). Based on the success of this workshop, he has also founded and has been the Steering Committee Chair of the IEEE Conference on Standards for Communications and Networking. He is the General Chair of the 2019 edition of the IEEE Wireless Communications and Networking Conference (WCNC19) to be held in Marrakech, Morocco. He is on the Editorial Board of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, the *IEEE Wireless Communications Magazine*, the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, the IEEE COMMUNICATIONS SURVEYS AND TUTORIALS, and a number of Wiley journals. He is serving as the Chair of the Wireless Communications Technical Committee, the largest in IEEE ComSoC. He also served as the Vice Chair of the Satellite and Space Communications Technical Committee of IEEE ComSoc (2006–2010). He has been on the technical program committee of different IEEE conferences, including Globecom, ICC, and WCNC, and chaired some of their symposia. He is an IEEE Communications Society (ComSoc) Distinguished Lecturer. He was the recipient of the 2009 IEEE ComSoc Asia-Pacific Best Young Researcher award (June 2009), the 2008 TELECOM System Technology Award from the Telecommunications Advancement Foundation (March 2008), the 2007 Funai Foundation Science Promotion Award (April 2007), the 2006 IEEE Computer Society Japan Chapter Young Author Award (December 2006), the Niwa Yasujirou Memorial Award (February 2005), and the Young Researcher's Encouragement Award from the Japan chapter of the IEEE Vehicular Technology Society (VTS) (October 2003). Some of his research work have also been awarded best paper awards at prestigious conferences.

Khaled B. Letaief (S'85–M'86–M'90–SM'97–F'03) received the Ph.D. degree from Purdue University, West Lafayette, IN, USA. He is the Chair Professor and Provost of Hamad Bin Khalifa University (HBKU), Qatar, a newly established research-intensive university in Qatar. He has served as the Hong Kong University of Science and Technology (HKUST) Dean of Engineering from 2009 to 2015. Under his leadership, HKUST School of Engineering has not only transformed its education and scope and produced very high caliber scholarship, it has also actively pursued knowledge transfer and societal engagement in broad contexts. It has also dazzled in international rankings. He is a world-renowned leader in wireless communications and networks. In these areas, he has over 500 journal and conference papers and given invited keynote talks as well as courses all over the world. He has made 6 major contributions to IEEE Standards along with 13 patents. He is the founding Editor-in-Chief of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS and was instrumental in organizing many IEEE flagship conferences as well as serving IEEE in many leadership positions, including IEEE ComSoc Vice-President for Technical Activities and IEEE ComSoc Vice-President for Conferences. He is an ISI Highly Cited Researcher and a HKIE Fellow. He was the recipient of the 6 teaching awards and 11 IEEE best paper awards. He was the recipient of the 2007 IEEE Joseph LoCicero Award, 2009 IEEE Marconi Prize Award, 2010 Purdue Outstanding Electrical and Computer Engineer Award, 2011 IEEE Harold Sobol Award, and 2011 IEEE Wireless Communications Technical Committee Recognition Award.