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Techno-Economics of Small Cell Networks: The AWARE Project

Peter Reichl, Ivan Gojmerac, Dominique Barth, Mariem Krichen, Johanne Cohen, Olivier Marcé, Werner Wiedermann

Abstract—**The rapidly growing bandwidth demand for mobile internet and mobile broadband applications is currently triggering the development of novel approaches to increase the capacity of the macro infrastructure of current mobile networks. Among the available options, increasing the spatial density of mobile sites is of specific interest, while at the same time the resulting new paradigm of user-provided small cell networks requires to redefine the traditional roles and relationships of network operators and end customers to a large extent. The COMET/CELTIC project AWARE (Aggregation of Wireless Access Resources) addresses corresponding open issues from a dedicated techno-economic perspective. This paper outlines the basic approach taken by AWARE, describes the resulting "prosumer" model and surveys the results of related game-theoretic analysis.**

Index Terms—**Small Cell Networks, Macro Offloading, Prosumer Models, Evolutionary Game Theory, Nash Equilibrium, Distributed Learning Algorithms, Potential Games**

I. Introduction and Background

While conviction is largely spreading in the research community that bandwidth problems in the core are practically solved by now, wireless access is still widely considered a source of major concern, especially if it comes to the huge success of current and future mobile internet and mobile broadband applications. In order to be able to provide sufficient bandwidth for enabling a satisfying Quality-of-Service (QoS) and Quality-of-Experience (QoE) for the underlying services, mobile network operators have started to investigate various ideas for increasing the capacity of the macro network infrastructure. In this context, the three most important approaches include

- acquiring additional spectrum,
- increasing the spectral efficiency, and
- increasing the spatial density of sites.

While the first option depends heavily on the appropriate spectrum refarming (which is a process largely out of control of the operators), the second option is already followed within the evolution from UMTS over HSPA to LTE and beyond.

Being a real alternative to the current technological mainstream, third option not only allows for precise offload in spatial regions with high overall bandwidth request, but at the same time provides clear advantages in terms of lowering the environmental footprint, due to reduced power consumption. Finally, also economies of scale effects deserve attention, leading to lower base station unit prices. However, this option is also associated with several stumbling blocks: first of all, it is difficult and expensive to increase the density of macro base stations, especially in urban areas. At the same time, most users today use their "mobile internet" mostly within their homes or in their office premises, i.e. in indoor scenarios which do not include true mobility.

In this paper, we focus therefore on recent ideas on creating small cell networks by placing base stations directly into the home or the office of an end user, while using the already existing cheap public Internet access (DSL, cable etc.) for backhauling, i.e. for connecting the base station to the core network. The resulting technical and socio-economic challenges of such User Provided Small Cell (UPSC) networks are at the heart of the research project which is introduced and surveyed in Section 2. Section 3 discusses the resulting role change for the end user, who at the same time acts as consumer and producer of mobile network services. In Section 4, we describe a model for sharing Femto access and survey results from related game theoretic analysis, before Section 5 draws some conclusions and provides an outlook on current and future work.

II. Project AWARE: Small Cell Networks for Macro Offloading

In general, we may distinguish two fundamentally different ways for creating small cell networks, which could easily be termed as the "Net Heads" vs the "Bell Heads" approach, respectively:

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- *IEEE 802.11 Wi-Fi a/b/g/n*: The very popular and widespread WLAN technology is almost ubiquitously available today, and is based on OFDM which allows for high maximum link bit-rates and simple radio resource management (RRM) mechanisms. Its flat architecture is easy to deploy, however hard to administrate. Beyond the well-known compatibility problems (even for Wi-Fi certified devices), especially the lack of real access to SIM-based AAA is considered a veritable drawback.
- *3GPP UMTS and LTE Femto Cells*: In contrast to Wi-Fi which operates in the free ISM band, Femto base stations are bound to use licensed spectrum. To this end, UMTS technology is based on WCDMA with HSDPA+ providing up to 84 Mbit/s (Rel 9), while high latency is still considered the main problem. In contrast, LTE is based on OFDMA with more than 300 Mbit/s maximum downlink bit-rate, relying on a flat all-IP architecture in the packet core. Moreover, LTE provides a very flexible RRM due to the assignment of sub-carriers. Note that for both UMTS and LTE, the operator controls RRM and AAA, and thus is in a position to enforce QoS.

Both approaches are equally shaping the research work performed in the CELTIC/COMET project AWARE (Aggregation of Wireless Access Resources), running in 2010 and 2011 as a two-year application-oriented research project at FTW Telecommunications Research Center Vienna in collaboration with A1 Telekom Austria, Alcatel-Lucent Austria together with Alcatel-Lucent Bell Labs France, and Université de Versailles St Quentin. The main target of AWARE is to explore, in a technology independent manner, the ways in which a shared infrastructure can be consolidated enough to meet the requirements for offering reliable services to its users.

While the motivation for deploying UPSCs is quite straightforward for the operator, due to their potential for OPEX reduction by offloading the (still) quite expensive macro network infrastructure, the dense (almost ideal) utilization of the acquired frequency spectrum, and the "outsourcing" of base station energy and backhauling costs to the end user, the motivation of potential end users is not as clear. Therefore, as an indispensable prerequisite for developing suitable incentive and business models, AWARE uses additionally an interdisciplinary approach to describe and investigate the role change of the end user towards a so-called "prosumer", i.e. an entity which at the same time consumes and produces mobile network services.

In order to determine the general feasibility of a UPSC infrastructure, AWARE has performed some comprehensive urban Wi-Fi measurement campaigns as described in [1] and [2]. The main goal of these studies was to determine the current density of 2.4 GHz Wi-Fi installments, the degree to which the spectrum is over-croweded, and the actual signal levels as well as the aggregated coverage ratio streets of a typical urban environment. To this end, a quadratic section of size 0.25 km² has been selected in the 2nd district of the inner city of Vienna, Austria, exhibiting typical building and population characteristics and density. Using an iPhone-based measurement device, all streets in the selected zone have been exhaustively walked along, recording all measurable IEEE 802.11 beacon frames which are used by Wi-Fi access points to announce themselves with a typical repetition rate of 10 frames per second. Simultaneously, all recorded signal strengths have been tagged with their GPS location (sampling rate 0.1/sec).

From the measurement results which are described and discussed in detail in [1] and [2], we may conclude that the density of observed Wi-Fi access points is surprisingly high already today (in total, we counted 1166 unique MAC addresses in beacons spread over the entire area of 0.25 km², which essentially boils down to seeing one *new* device every 5 meters while walking on the streets)[1]. Together with the relatively high average signal strength of indoor Wi-Fi access points in the streets, this altogether would allow achieving an 80-90% coverage in outdoor urban environments by aggregating less than 10% of the available indoor Wi-Fi access points.

This measured density motivates the interest for UPSC: even if with no additional cell deployed, the radio resource is already there. However, the unmanaged deployment leads to the situation where the high density and the lack of RRM prevent a efficient communication. This is one of the challenges that need to be addressed for UPSC success.

It is worth to be noted that this result can be extrapolated to 3G Femto Cells as well. Indeed, the main parameters to be considered are the emitting power, that is between 50 and 100mw depending of the regulation both for femto base station and Wi-Fi Access Point; and the used frequency band is 2.4GHz, which is close to the main planned frequency for LTE (2.6GHz), or even UMTS (2.1GHz).

III. Prosumer Models for Small Cell Scenarios

The idea of network customers sharing part of their bandwidth with other customers is by far not new and has first been realized for the case of sharing WiFi connections. Here, among the most well-known examples there is the one of FON, which has been founded in 2005 and originally represented a club with three different types of members: (1) a so-called *Linus* is offering WiFi access for free and therefore is entitled for free roaming at any other FON members' access points, (2) a so-called *Bill* is receiving 50% of the revenues generated from any FON user connecting to his WiFi network and purchasing a FON pass, but is not entitled to free roaming, while (3) an *Alien* does not own a WiFi access point but is connecting to those of other FON members (and has to pay for it by purchasing FON passes). In 2007, the definition of a *Bill* has been refined such that also this category is entitled to free roaming at other FON access points (thus blurring the boundary to the *Linus* category), while still receiving 50% of the revenues from connecting FON members[2].

[1] In fact, we believe that our measurements underestimate the *real density* by a factor of 2-3, taking into account additional access points located in rooms with windows towards inner courtyards or on higher floors.

[2] See http://www.fon.com for further details.

In [4], this model has been adapted to the case of Femto cell owners sharing their 3G/LTE bandwidth with other customers who altogether form a "Femto club" in analogy to the FON club described above. However, note that in this case also the Mobile Operator (MO) has to be integrated into the model, due to the fact that Femto cells are bound to use licensed spectrum. Hence, sharing Femto access is assumed to be a service proposed by the MO to its customers, who are divided into two classes: the Service Provider Customers (SPC) who are owners of Femto cell access which they have contracted with a MO, and the Service Requester Customers (SRC) who are using a mobile device and request using the access points of one or more SPCs being in reach. Note that users can act as SPC and/or SRC at the same time, thus justifying the notion of "prosumers" for this specific user role.

A more in-depth characterization of SPCs reveals that they may share their access either for direct economic reasons (i.e. for generating some revenue which then is shared with the MO), or simply for securing free roaming for themselves at other Femto access points while possessing a Femto cell first and foremost for satisfying their own QoS needs at home. These two cases are direct analogies to the *Bill* and *Linus* categories already known from the FON model. Furthermore, we characterize an SPC by two parameters: his *sensitivity for revenue gain*, denoted by $\mu \in [0;1]$, and his *sensitivity for own QoS* $\Gamma \in [0;1]$. Note that we assume both parameters to be dual, i.e. $\mu + \Gamma = 1$.

Similarly, an SRC can be characterized as an MO customer on the move who needs satisfying QoS at a reasonable price. Again, this allows a differentiation into two basic categories: while SRCs who are interested in free roaming need being registered as either a *Bill* or a *Linus*, the second category consists of MO customers who do not have Femto access at home and have to pay for roaming, thus closely resembling the case of *Aliens*. In this case, the MO is supposed to receive the entire revenue if the SPC is a *Linus*, while the revenue is shared if the SPC is a *Bill*. We characterize an SRC again by two dual parameters, i.e. his *QoS sensitivity* α and his *price sensitivity* β, with $\alpha + \beta = 1$. Mobility of the SRCs is not considered, however it is assumed that an SRC has some regular connection behavior in terms of time slots and QoS needs.

Let us consider now one single SPC together with several SRCs requesting bandwidth from the SPC. In order to maintain a balanced trade-off between preserving his own interest and his willingness to share bandwidth, the SPC is assumed to fix a split of his bandwidth into two classes: class 1 which is exclusively reserved for bandwidth sharing with SRCs, and class 2 which in general is offered to the SRCs as well, however their usage may be preempted by the SPC at any time in case the latter needs bandwidth to satisfy his own QoS needs (hence, in class 2 the interest of the SPC is prior to SRC requests). Finally, we assume that there is a Token Based Accounting System [3] in use where a trusted central entity provides tokens which can be mutually collected and/or spent by the SPC and the SRCs to enable the exchange of services.

IV. GAME-THEORETIC ANALYSIS

Generalizing [4], in this section we describe two approaches to model the problem of sharing wireless access from a game-theoretic perspective, and summarize related results.

A. SRC Competition

Suppose there are N SPCs X_j, $j = 1 \dots N$, each of whom willing to share a total bandwidth B_j which is split into two classes such that the bandwidth in class 1 equals $(1-\psi_j)B_j$ and the bandwidth in class 2 equals $\psi_j B_j$, $0 \le \psi_j \le 1$. SPC X_j is characterized by a fixed preemption probability δ_j for class 2 bandwidth due to own QoS needs of X_j, which can be interpreted as a reduction of expected QoS of bandwidth allocated to the SRCs. Consequently, class 1 and class 2 bandwidth follow (potentially different) tariffs/charging functions which are fixed by the Mobile Operator (MO).

Moreover, assume there are n SRCs Y_i, $i = 1 \dots n$, each of them requiring bandwidth b_i in order to satisfy their QoS needs[3]. Depending on the profile (α_i,β_i) of SRC Y_i, a lower and an upper limit m_i and M_i, resp., for i's request for class 1 bandwidth is determined, which can be translated into lower and upper limits $\hat{m}_i$ and $\hat{M}_i$ for class 2 bandwidth by taking into account the preemption probability δ_j. To further simplify the scenario, let us assume for the moment that each SRC submits a bandwidth request to no more than one SPC. Then, the strategy space for SRC Y_i is made up of all pairs of intervals $([m_{ij}; M_{ij}], [\hat{m}_{ij}; \hat{M}_{ij}])$ of requests for class 1 or class 2 bandwidth directed to SPC X_j with $m_{ij}, M_{ij} \in [m_i; M_i]$, $m_{ij} < M_{ij}$, and $\hat{m}_{ij}, \hat{M}_{ij} \in [\hat{m}_i; \hat{M}_i]$, $\hat{m}_{ij} < \hat{M}_{ij}$, respectively.

Due to his request to SPC X_j, the SRC Y_i is allocated bandwidth $b_{ij} = b_{ij}(m_{ij}, M_{ij})$ (class 1) or $\hat{b}_{ij} = \hat{b}_{ij}(\hat{m}_{ij}, \hat{M}_{ij})$ (class 2). Note that we do not allow to simultaneously assign class 1 and class 2 bandwidths to the same SRC, while it might happen that there is no bandwidth allocated at all, hence in general $b_{ij} \cdot \hat{b}_{ij} = 0$. In the following, however, we restrict our attention to the case where the available shared bandwidth of SRC Y_i is somewhere in between the sum of the lower and the sum of the upper limits of bandwidth requests, i.e.

$$\begin{gathered} \sum_i m_{ij} \le (1-\psi_j) B_j \le \sum_i M_{ij} \qquad \text{and} \\ \sum_i \hat{m}_{ij} \le \psi_j B_j \le \sum_i \hat{M}_{ij} \end{gathered} \tag{1}$$

Then, each SPC starts with allocating the minimum bandwidth requests and then distributes the remaining shared bandwidth in a fair manner. Based on this, the expected utility of an SPC can be described as weighted difference between revenues and reduction of own QoS as follows:

$$\overline{U}_{X_j} = \sum_i \mu\left(C_i(b_i) + C_i(\hat{b}_i)(1-\delta_j)\right) - \Gamma\left(b_i + \hat{b}_i(1-\delta_j)\right) \tag{2}$$

Here, the first bracket corresponds to linear charging func-

[3] In [5], this is illustrated for the case of file transfer applications whose QoS is characterized in terms of download time which easily allows to determine upper and lower limits on the required bandwidth.

tions C_j where in addition class 2 traffic is discounted depending on the preemption probability, while the second term catches the expected reduction of own QoS due to the allocation decisions.

Similarly, the expected utility of SRCs Y_i can be described as expected QoS satisfaction minus cost (charges):

$$\overline{U}_{Y_i} = \alpha_i \cdot (b_i + \hat{b}_i(1-\delta_j)) - \beta_i \cdot \left(C_j(b_i) + C_j(\hat{b}_i)\cdot(1-\delta_j)\right) \quad (3)$$

As described in [4] for an infinitesimally discretized version of the problem with linear tariff functions C_i, each instance of the SRC game admits at least one pure Nash equilibrium. This can be proved by constructing a suitable potential function which is monotonic along the trajectory of a best response dynamic algorithm. In each iteration, one SRC considered as a "strongest strategy player" is prioritized over the other players since serving only this player is better for the SPC rather than serving all the other SRCs. In fact, a strongest player has a strategy that whenever played allows the SPC to have better utility rather than serving all the other SRCs (considering all their strategies combinations). If no strongest player exists, SRCs alliances are considered by merging the strategies of an alliance of k SRCs and thus considering the resulting SRC as a fictive one; then the same process to look for a strongest SRC player is triggered.

B. SPC Game

So far, we have assumed that each SPC has fixed his split of bandwidth into class 1 and class 2 before the competition between the SRCs is starting, and therefore aims at individually maximizing his utility function (2). We will now extend the game and assume to this end that the bandwidth requests of the SRCs are initially fixed, leaving the SPCs with the question of how to optimally determine their split parameters ψ_j, $j = 1\ldots N$ while at the same time attracting as much SRC traffic as possible. Note that SPC X_j has some own QoS needs in the sense that he (probabilistically) requires some bandwidth (for our model, it is sufficient to consider the average such own bandwidth request q_j, $0 \le q_j \le B_j$). As this need can be satisfied only from class 2, this determines the preemption probability δ_j for class 2 bandwidth as

$$\delta_j = \frac{q_j}{\psi_j \cdot B_j} \quad (4)$$

In this way, a game between the N SPCs is constituted, where the SPCs allocate bandwidth to requesting SRC by maximizing an objective function which is composed from the revenue gained by allocating bandwidth to SRCs and the benefit of the bandwidth available for his own QoS needs (described by the corresponding benefit function G_j):

$$U_{X_j} = \mu_j \sum_i \left(C_i(b_{ij}) + C_i(\hat{b}_{ij})(1-\delta_j)\right) + \Gamma_j \cdot G_j(\psi_j B_j - \overline{\hat{B}}_j)$$

such that (5)

$$\overline{B}_j := \sum_i b_{ij} \le (1-\psi_j)B_j \quad \text{and} \quad \overline{\hat{B}}_j := \sum_i \hat{b}_{ij} \le \psi_j B_j$$

where $\overline{B}_j$ and $\overline{\hat{B}}_j$ correspond to the total class 1 and class 2 bandwidth allocated to SRCs, resp.

Based on this allocation, the payoff function of Y_i is depending both on the benefit due to the allocated bandwidth and the corresponding cost (payment), hence

$$U_{Y_i} = \alpha_i \cdot G_i(b_{ij} + \hat{b}_{ij}) - \beta_i \cdot \left(C_i(b_{ij}) + C_i(\hat{b}_{ij})\cdot(1-\delta_j)\right) \quad (6)$$

with cost functions C_i (depending e.g. on whether Y_i is a Linus, Bill, or Alien) and benefit functions G_i which are monotonically increasing on the interval $[m_i; M_i]$ with $G_i(m_i) = 0$ and $G_i(M_i) = 1$[4]. As before, bandwidth is charged in a usage dependent way specified by the cost function, while we assume that the charge for class 2 bandwidth additionally is discounted by a factor of $1-\delta_j$, in order to account for the risk of preemption.

There are several typical cases for bandwidth split: if for instance (a) X_j does not have own QoS needs or is revenue sensitive ($\mu_j > 0.5$), he will assign as much bandwidth to class 1 as possible (i.e. requested from the SRCs) in order to maximize profit, while (b) on the other hand, if X_j is QoS sensitive ($\Gamma_j > 0.5$) and needs own bandwidth b_j, he will take care of choosing ψ_j such that his need can be fulfilled, i.e. $\psi_j B_j \ge b_j$. Note that if there is sufficient class 1 bandwidth demand (i.e. more than can be satisfied), this suggests a choice of $\psi_j = 0$ in case (a) and $\psi_j = b_j / B_j$ in case (b), i.e. allocation decisions $\hat{b}_{ij} = 0$ for class 2 requests throughout.

In general, however, SPC X_j will first determine the split parameter ψ_j (and thus also the preemption probability δ_j), then receive the requests from the SRCs, and finally decide about the allocation of class 1 bandwidth to class 1 SRC requests, and of class 2 bandwidth either to class SRC requests or to own needs. For calculating the optimal value for the split parameter ψ_j, suppose for the moment that charges (cost) are proportional (i.e. identical after scaling) to bandwidth, while the benefit functions G_j have linear form (also for the SPC). Rewriting equation (5), in this case we get

$$U_{X_j} = \mu_j\left(\overline{B}_j + (1-\delta_j)\overline{\hat{B}}_j\right) + \Gamma_j(\psi_j B_j - \overline{\hat{B}}_j) \quad (7)$$

We can safely assume that $\overline{B}_j = (1-\psi_j)B_j$ in order to avoid class 1 bandwidth being wasted. Then, using (4), this gives the first order condition

$$\frac{dU_{X_j}}{d\psi_j} = -\mu_j B_j + \mu_j \overline{\hat{B}}_j \cdot \frac{q_j}{B_j \psi_j^2} + \Gamma_j \cdot B_j = 0 \quad (8)$$

Note that (8) has a solution if and only if $\mu_j > \Gamma_j$, i.e. for price sensitive SPCs. In this case,

$$\psi_j^* = \frac{1}{B_j}\sqrt{\frac{\mu_j}{\mu_j - \Gamma_j}\overline{\hat{B}}_j q_j} \quad (9)$$

hence the optimal size of class 2 depends equally on the square roots of the total class 2 allocation to the SRCs and the

[4] Note that recent results on Quality of Experience for file download [6] suggest for instance a logarithmic form for the benefit function.

average own QoS needs of the SPC. If the SPC is QoS sensitive (i.e. $\mu_j < \Gamma_j$), then the left-hand side of (5) is always positive, and hence the optimal $\psi_j^* = 1$ (i.e. no class 1 traffic at all).

C. Distributed Learning Algorithm for SRC

While so far we have been dealing with the existence of Nash equilibria and optimal strategies, we now turn to the question whether there exists a distributed algorithm (i.e. each player has only knowledge about local information) which converges to a pure Nash equilibrium.

To this end, [5] describes a decentralized learning algorithm for Nash equilibria in discrete stochastic multi-person games with incomplete information. Essentially, during each iteration the algorithm updates a probability vector for the available pure strategies. This update is based only on local information, most notably the utility achieved from the most recent allocation decision, together with a learning parameter governing the speed of the learning process (cf. [7]).

This algorithm is applied to a discretized system with utility functions according to equations (2) and (3). Numerical results in [5] confirm that the algorithm converges towards, and does so towards one of the pure NEs previously identified.

As an illustrative example, consider a scenario with three QoS-sensitive SRCs (i.e. $\alpha_i = 1$) and one gain-sensitive SPC (i.e. $\mu_1 = 1$), where each SRC has only 2 strategies, i.e. highest QoS ($s_i^1 = \alpha_i = 1$), and very high QoS ($s_i^2 = \alpha_i - \kappa$); in our example we choose $\kappa = 0.1$. We denote by S_i the set of strategies for SRC i, hence $S_i = \{s_i^1, s_i^2\}$, $i \in \{1,2,3\}$. Then, the set Π^* of pure Nash equilibria can be determined in a straightforward way by analyzing the SRC's utility matrix defined by (3), in our case leading to a total of three NEs:

$$\Pi^* = \{(s_1^1, s_2^2, s_3^2), (s_1^2, s_2^1, s_3^2), (s_1^2, s_2^2, s_3^1)\} \tag{10}$$

The decentralized learning algorithm is applied for 700 iterations. In Figure 1, each point represents the mean over 5 iterations of SRCs strategies probability. Observe that the decentralized learning algorithm converges after 325 iterations to (s_1^2,s_2^2, s_3^1) which is one of the NEs according to (10).

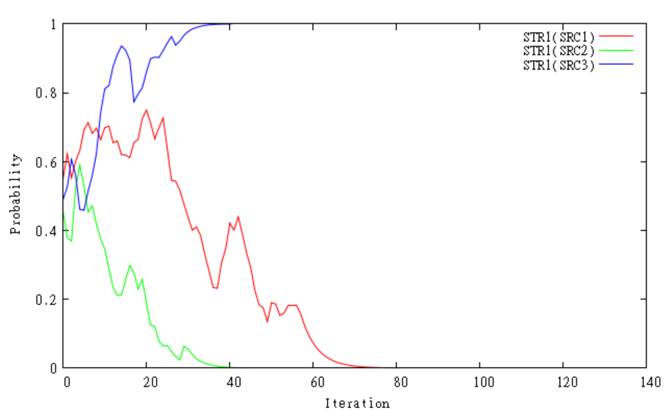

Figure 1: Convergence of distributed learning algorithm

The experiments have been conducted for a number of SRCs between 2 and 8. Table 1 provides an illustration of the resulting average convergence speeds for 60 repeated games each and $N = 1$.

# SRCs	2	3	4	5	6	7
# iterations	248	630	585	1002	1089	1083

Table 1: Convergence speed depending on number of SRCs

V. Conclusions and Further Work

Small cell networks are expected to significantly disburden the future macro infrastructure of mobile operators by facilitating additional user-provided bandwidth. At the same time, they trigger a couple of highly interesting techno-economic questions which form the core issues addressed by the CELTIC/COMET project AWARE running at the Telecommunications Research Center Vienna from 2010-2011.

This paper provides a survey about the main project contents with a clear focus on economic issues. After describing related prosumer models, we use game theoretic methods to provide initial insight into the competition between users providing bandwidth and those requesting it. The existence of corresponding Nash equlibria can be shown, and the efficiency of a distributed learning algorithm is investigated. Further work in the AWARE project is concentrating primarily on the implementation of a prototype as well as an extension of the game theoretic analysis. The prototype focuses on the capacity to seamlessly handoff a data session from 3G to Wi-Fi, with a sufficient control of the QoS to provide expected QoE to customers. This is based on (a) a Media Independent Handover (MIH defined, in IEEE 802.21 standard) system tightly coupled with 3G network, (b) a local measurement of Wi-Fi resources occupancy that is used for triggering the handover procedure efficiently.

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