Context Management in Energy-efficient Radio Access Networks

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***Abstract*—Base stations have been identified to be the most power consuming part in current mobile networks. Since their power profile only depends to a small fraction on the actual traffic load, putting some base stations in sleep mode has been identified as a solution to scale the network power consumption with the actual load.**

This paper presents a new system architecture based on the paradigm of "cell on-demand", which is currently studied in the Beyond Cellular Green Generation (BCG^2) project of the GreenTouch consortium. We first outline the key characteristics of the new system architecture, then, we present a framework for position information processing in order to predict the channel quality between a user and a set of switched-off base stations that can potentially be activated by the system to serve the user.

Experimental evaluation on a small scale testbed shows the viability of the proposed framework by achieving estimation errors of 20%.

I. Introduction

In the last few years, the huge increase in the mobile data demand is stressing operator networks, which need to upgrade the capacity provided to the users. This network evolution requires to expand the current radio access networks by deploying additional base stations. Besides CAPEX considerations, operational costs are becoming an issue to be carefully addressed. It is well-known that last-hop devices are particularly energy-hungry, as their energy consumption can reach more than the 80% of the total energy in the entire access network. This motivated a fairly amount of research in the field of Green Wireless Networking where the main aim is to develop devices, design protocols and plan strategies that include energy efficiency aspects in the normal network operation.

The research community has immediately tackled the issue of energy efficiency in communications and has produced in short time interesting models and solutions to cope with it [1]–[3]. Currently investigated upgrades in the technologies and components of base station equipments allow to reduce the power consumption of devices. However, since the possible improvements on the hardware energy efficiency are limited by the baseline power consumption of active base stations, to go further, energy-efficiency solutions have to recur to more holistic approaches.

The ideal energy behavior is a power consumption of the whole system that is linearly dependent on the traffic load, from a very low level with no traffic to a maximum value with full load. Reducing the maximum power consumption is obviously of paramount importance, but it is basically related to advancements in transmission and hardware technologies, not to the network management. Such improvement could be added on top of the ideal energy behavior. The only energy management strategies able to achieve an energy profile of the network that is proportional to the traffic load are system-level strategies, which can switch-off unused base stations while preserving the performance of the whole network.

Unfortunately, there is a hard constraint in the traditional cellular architecture that prevents from achieving this ideal behavior and, broadly speaking, reaching very large reductions of energy consumption. The fundamental concept of the cellular access architecture is the full coverage of the service area in order to guarantee that users located at any point can request a channel and access the network at any time. Moreover, the network layout is strongly influenced by the traffic distribution. In low traffic density scenarios, cell dimensioning is usually driven by the full-coverage constraint, this leads to sparse base stations where the overlap among cell areas is minimum, just enough to permit mobility procedures. In areas with high traffic loads, instead, base stations are deployed more densely in order to increase the capacity per unit area. This leads to scenarios with high coverage redundancy. It is straightforward to see that energy saving strategies in traditional cellular networks allow only to exploit the switch-off of redundant base stations in dense scenarios when the current traffic load is low. Studies in the field show that achievable energy savings in the current cellular architecture are in the range of 20%-40% [2], [3], depending on the considered traffic profiles and network layouts, because a non-negligible part of the network can never be switched off even if there is no active user. This "switch-off" saving may even reduce (in percentage) with the massive use of small cells. Indeed, the envisioned deployment strategy will provide high capacity with limited coverage overlap, leaving little flexibility, since basically all cells are essential for guaranteeing full coverage.

As a consequence, the ideal behavior of a network energy consumption proportional to the actual load cannot be achieved with the current scenario. A paradigm shift is required in order to completely reshape the structure of the network and enable new ways of providing energy-efficient ubiquitous wireless access.

II. Going beyond traditional Green Networking

A new cellular network paradigm is proposed in "Beyond Green Cellular Generation" (BCG^2) Project within the GreenTouch Consortium.

The idea of the approach originates from the consideration that there is no need of much information in order to provide ubiquitous connectivity. Basically, one has only to provide a signaling service to allow users to request a channel, when it is desired, and, in opposite direction, to enable mobile paging. This has led to consider an architecture where signaling and data networks are separated.

The separation provides better energy-efficiency management because of two important advantages. First, radio interfaces for the signaling network can be designed for long-range low-rate transmissions, thus increasing their energy efficiency since they can be designed on a specific target and not on the current data and signaling mix. Second, base stations for the data networks can be switched off when there are not users with active data session under their coverage. As soon as a user activates, he can request the service to a signaling base stations and the system will provide connectivity by switching on a proper data base station.

The general idea of the system is to have data base stations designed for high data rates, flexible and smart. Vice versa, signaling base stations have to guarantee the coverage, therefore, they will be designed to be very energy efficient for low data rates and long-range transmissions. In fact, separating data and signaling is not new in the networking scientific literature, however, in cellular access networks it leads to several interesting technical challenges that arise from the interaction between signaling and data networks [4].

A key component of the new architecture is the resource management. Its task is to select and allocate the resources to properly serve the request issued by each user and, simultaneously, lead the network to a status of minimum energy consumption. In this task, the information about the user, its *context*, is even more fundamental, because every resource allocation decision must be based on it in order to be the most energy-efficient as possible. However, in a scenario where data cells can be activated on-demand, gathering user context information is not trivial.

In current cellular technologies user terminals provide the necessary information to network in order to access the service. In particular, the user terminal issues service requests, via the wireless interface, to the same base station that will serve the requests. This is not longer true in the new architecture with data and signaling separation, thus, richer information is required, a *context* of the service request is required to design a resource selection algorithm for the data network.

The main information to be included in the context is the location of the user terminal in order to identify the potential data base stations that can serve its request. This is not strictly needed in current cellular networks since the base station that accepts the service request is the same that serves it.

However, location may not be sufficient to identify the best serving base station as the quality of the radio channel may be poor due to propagation impairments or, even worse, an estimation may not be available. Indeed, the serving base station could be in a sleep mode and no pilot signal would be available for a channel measurement.

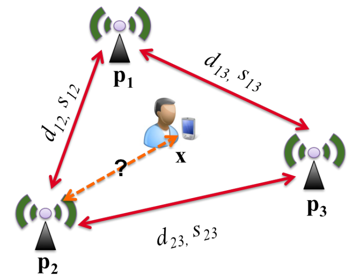

Fig. 1. Position processing scenario.

In addition to user terminal position, the information on the network status is particularly important for the resource management, since the energy consumption caused by the same resource selection depends on the current status of the network resources. The information on the network status basically includes operation modes of base stations, active or sleeping, and the amount of radio resources available for new data sessions. A further piece of information is the list of base stations that can potentially cover a given position. This list can be populated once the signal strenght at the given position has been estimated for all the base stations.

The last type of required context information is on the characteristics of the requested data session and the profile of the user, in terms both of traffic and of mobility. They influence delay, bandwidth and dropping probabilities of the connection used to serve the user.

Based on user and traffic profiles, user position, coverage information, and network status, the resource management system can select the best base station and resources to be activated in order to serve every user at the highest energy efficiency. Among the tasks required to manage these types of information, the possibility to predict the quality of the channel between a base station and a terminal located in a given position is, in our opinion, the one that needs to be investigated first. In the next section, we propose a framework for processing position information in order to create propagation models, thus predict the quality of coverage of a base station at a given point.

III. Problem statement

With reference to Fig. 1, we consider the following problem. Given a mobile terminal located at $\mathbf{x}$, we aim to estimate the Received Signal Strength (RSS) from M base stations in known locations $\mathbf{p}_m, m = 1 \cdots M$. By doing this, the base stations can be ranked in decreasing order of the estimated RSS, and the top one could be selected by the mobile terminal to set up an uplink channel. This problem can be viewed as the inverse problem of the location estimation problem based on RSS measurements which has been widely studied in the past and it is the basis of many today's localization systems

Classical distance-based parametric models, e.g., the Okumura-Hata model, can be used for a first, rough approximation of the received signal strength. However, in order to achieve more accurate estimation, more sophisticated schemes must be implemented. A first approach is to consider the propagation model implicitly, and describing the RSSI at a certain location as a linear combination of the distances from the mobile terminal to all the base stations [6]. In this case the RSSI-to-distance mapping is estimated solely on measurements between base stations (if these are available), thus enabling a zero-configuration setup.

Let $\mathbf{S}$ be an $M \times M$ matrix containing the inter-base stations RSS measurements, i.e. $s_{i,j}$ is the RSS at base station i from base station j. Similarly let $\mathbf{D}$ be the inter-distance matrix where each element $d_{i.j} = ||\mathbf{p}_i - \mathbf{p}_j||_2$. While $\mathbf{D}$ is symmetric and has zero diagonal entries, $\mathbf{S}$ is not, as radio links are generally asymmetric. Diagonal entries of $\mathbf{S}$ contain the self-RSS values, which are the only parameters to be estimated (or made equal to P_0). Then, the signal-to-distance model is postulated as:

$$\log(\mathbf{D}) = \mathbf{T}\mathbf{S}, \tag{1}$$

where $\mathbf{T}$ is the signal-to-distance map, usually estimated by means of least squares as

$$\mathbf{T} = \log(\mathbf{D})\mathbf{S}^T(\mathbf{S}\mathbf{S}^T)^{-1} \tag{2}$$

Now, let $\mathbf{d}$ be the M-dimensional terminal to base station vector (i.e. $d_m = ||\mathbf{x}-\mathbf{p}_m||_2$), we can estimate the RSS vector $\hat{\mathbf{s}}_{\mathbf{x}}$ from all the base stations to the mobile terminal in position $\mathbf{x}$ as:

$$\hat{\mathbf{s}}_{\mathbf{x}} = \mathbf{T}^{-1}\log\mathbf{d} \tag{3}$$

This model has the advantage of considering the specific propagation characteristics of the area and it is able to self calibrate without the need of estimating propagation constants like in empirical models. Moreover, that matrix $\mathbf{S}$ can be updated in real time using inter-base stations measurements, giving robustness to the estimation by adapting the model to propagation changes. Moreover, note that the update of matrix $\mathbf{S}$ and the RSS estimation have not to be synchronous, this means that old entries of $\mathbf{S}$ can be used when the corresponding base stations are switched off.

A further approach that includes shadowing/fading/NLOS effects, relies on the construction of a Power Map (PM) [5], which is obtained by observing the RSS measurements $\mathbf{s}_{\mathbf{x}}$ at a terminal in position $\mathbf{x}$. In this case, the (M-dimensional) vector $\mathbf{s}_{\mathbf{x}}$ is called a *fingerprint*. To build the PM, three alternative are possible:

- Collect the fingerprints during an offline phase (e.g. drive test). The measurements to be stored have to be collected from all possible places where the target can be and under various weather conditions at different times in the area under study. This method gives the most accurate database, but it is time consuming and expensive.
- Use the principle of *wardriving*, where the users contribute online to the PM. The idea is that users with positioning capabilities (for instance, GPS) report their position and observations to a database.
- Predict the fingerprints using a model (i.e. Okumura-Hata model or signal-to-distance map).

Now, given that the terminal is in position $\mathbf{x}$, the RSS vector $\mathbf{s}_{\mathbf{x}}$ can be estimated using e.g. a weighted average of the nearest K fingerprints, where the weights are proportional to the distance between the terminal location and the location of the fingerprints, that is

$$\mathbf{s}_{\mathbf{x}} = \sum_{k=1}^{K} w_k \mathbf{s}_k \tag{4}$$

where

$$w_k = \frac{||\mathbf{x} - \mathbf{x}_k||_2^{-2}}{\sum_{k=1}^{K} ||\mathbf{x} - \mathbf{x}_k||_2^{-2}}, \tag{5}$$

and $\mathbf{x}_k$ is the position at which the k-th fingerprint was collected.

IV. Numerical results

In order to have a first evidence of the accuracy achievable by the proposed method, we deployed a testbed in the facilities of a research laboratory. Since we could not use real cellular base station, we applied the estimation algorithm in a wireless sensor network scenario implementing the system in TinyOS environment, an operating system for embedded devices. That shows that, on one hand, both the above-mentioned approaches do not require excessive computational effort, on the other hand, the algorithm is pretty robust and can run also with low-end RF components like sensor boards.

The entire wireless sensor network consists in a set of nodes which exchange beacons to signal its presence, it allows to autonomously set up wireless links and the entire routing topology. A subset of the nodes, typically, all but one, are used as anchor nodes, like base stations, while the other node, which are mobile, behave as user terminals that move around the area. The beacon messages of the anchor nodes, transmitted at the frequency of 4 messages per second, are used by the mobile nodes to measure the real RSS. In addition, every second, each mobile node sends a vector with the RSS measurements from all the anchors and a position ID to an anchor node, e.g., a sink node. The position ID is univocally mapped into a point in the area.

The first set of measurements has bee carried out inside a $25m$ x $10m$ room where students and researchers perform their daily activities. 10 anchor nodes have been installed, equally spaced, along the perimeter of the room, $1.7m$ high from the floor. Static RSS values from all anchors have been estimated at each point of a $30cm$ x $30cm$ grid and compared with the real ground-truth measurement made by a test sensor. The value collected at each point is the results of a temporal average of 30 seconds.

Fig. 2 and Fig. 3 shows the cumulative curves of the relative error between the estimated value and the measured one in dBm, respectively, when using the the signal-to-distance map (SDM) and the fingerprinting (FP) approach. The figures show the error distribution when estimating the RSS from the best anchor, the closest, and from the worst anchor, the farthest. We can see that the estimation of the RSS from the worst anchor is much less accurate than the estimation since it is strongly influenced by RSS fluctuation, however, on the perspective of selecting the best base station to serve each user, far away base stations will be selected with small probabilities. Moreover,

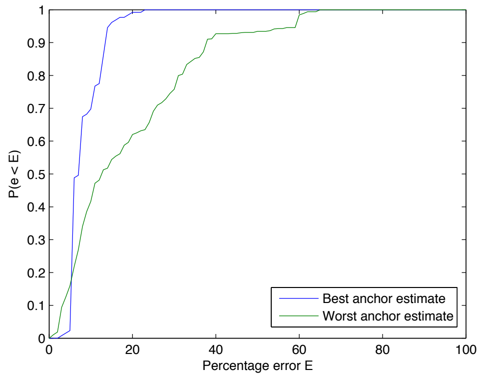

Fig. 2. Cumulative relative error curve using the SDM approach.

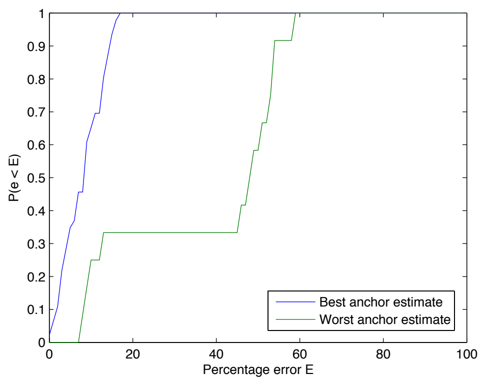

Fig. 3. Cumulative relative error curve using the FP approach.

this opens the algorithm to future improvements, the set of anchors used to estimate the RSS can be filtered by selecting the more reliable candidates.

The curve of the best anchor in Fig. 2 shows the maximum estimation error using the SDM approach is around 20%. Considering Fig. 3, we can note that the FP and SDM perform basically equivalently.

A second testbed has been deployed to evaluate the performance of the system when the RSS of a mobile device must be estimated. The setup consists in 15 anchor sensors located in a $200m^2$ floor. A mobile sensor is moved on a predefined path, a $1m$ step at each second, and it measures RSS from all anchors in its range. This measurements are the ground-truth values to compare with. At the same time, at each point of the path the RSS has been estimated using the SDM approach. Results are shown in Fig. 4, which shows again the cumulative relative error during the entire test. The quality of estimation achieved in this case is again similar to the one obtained by SDM approach in the fixed case.

V. CONCLUSION

The new cellular network architecture proposed in the "Beyond Green Cellular Generation" (BCG^2) Project within the GreenTouch Consortium brings forward the idea of a data and signaling separation to achieve very high energy efficiency in broadband wireless access networks. The energy saving is

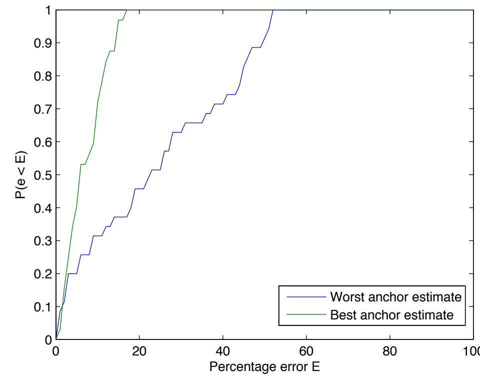

Fig. 4. Cumulative relative error curve using the SDM approach in the mobile case.

mainly obtained by activating data base stations "on-demand" to serve user requests. This leads to the need of estimating the channel quality between a user and switched-off base stations that can potentially be activated by the network to serve the user.

This work presented two approaches to estimate RSS from a set of base stations to a mobile terminal located at a given position: one based on an implicit propagation model, the other on fingerprinting. The two approaches have been implemented in two testbeds that confirmed the viability of proposed solutions, both in static and mobile scenarios. We ran the algorithm on ZigBee nodes inside a laboratory with obstacles and people; considering the quality of RF components and the harshness of the environment, we are confident about the possibility of using the framework in wireless networks with more sophisticated access point devices.

We are currently working towards improving the quality of the prediction framework. A viable approach consists in integrating the proposed approaches in a single system which uses available fingerprints to refine the SDM predictions and, vice versa, relies on SDM when fingerprints are not available. Moreover, real measurements can be exploited to update the fingerprint database.

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