Bandwidth and Consumption Controller Algorithms for Solar-powered Base Stations

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***Abstract*—Solar power is a promising source of energy to use for base stations in mobile networks in order to make telecommunication systems environmentally friendly. Solar energy is an economic and ecological source to supply mobile base stations, although its efficiency is depending on geographical location and the continuously changing weather conditions. In this paper new methods are introduced to calibrate solar cells and improve the availability of base stations by controlling consumption and energy storage. The developed power management algorithms can help to improve reliability of mobile services and provide acceptable quality of services for the customers.**

Keywords-mobile; 3G/4G; solar energy; green networks

I. Introduction

Solar power is becoming a promising source of energy for telecommunication systems in places where conventional electricity is unavailable or impractical [1], for example rural areas with limited access to the electricity grid. Solar power is available in almost every location, so base stations can be deployed far away from the electricity grid. By exploiting solar power to run mobile base stations will not only allow operators to reduce their operation costs, but also allow deeper penetration of mobile networks to inaccessible areas. The increasing popularity of high bandwidth mobile services is also a motivation to connect people living in or traveling to remotely located rural areas. According to a forecast from In-Stat [2], over 230,000 cellular base stations in developing countries will be solar-powered or wind-powered by 2014.

As the world's telecommunication networks are extended and upgraded, rural communication services are becoming more and more important. Without central electricity connection, a standalone power system is required in rural areas to provide energy for the operation. The deployed standalone power system must be cost effective, simple to maintain, and reliable.

Solar energy can be used not only from practical reasons, but from ecological motivations, too. The energy consumption of the Internet is becoming a key issue and more and more activities and projects are studying how to reduce the energy waste. Information and communication technologies are estimated to be responsible for a significant fraction of the world power consumption, ranging between 2% and 10% [3], and contributes an increasing share to global green house gas emissions accounting for over 2% already in 2007 [4]. Energy efficiency of telecom networks is not just a necessary contribution towards the fight against global warming, but with the rapidly rising prices of energy, it is becoming also a financial opportunity. Numerous work [5][6] was presented to prove that significant energy savings can be achieved by accurately turning off nodes and links, e.g. during off-peak time. Solar-powered sites have very low environmental impact and also have the advantage of very low maintenance needs, with a technical lifetime of even 20 years. These sites are much more reliable than diesel generator powered systems. Using solar base stations instead of diesel generators powered ones, at least 35 tons of CO_2 and 13,000 liters of fuel are expected to be saved per year [7].

Some operators are already deployed base stations exclusively with solar energy source [8]. The operated system is programmed to keep the station working independently and without supply up to 5 days, in case of fog or snow. The station does not need any special maintenance or investment, except the change of used batteries once every 5 to 7 years.

Solar power is generated using the photovoltaic properties of semi-conductors to convert light energy into electricity. Manufacturing costs for solar cells have been declining by 3-5% per year in recent years, leading to growth capped only by silicon supply issues. The global adoption of solar is becoming a commercially viable technology, due to falling costs and growing reliability of solar equipments. The cost effective solar energy is an economical source to be adapted to mobile telecommunications environment, however new operation challenges must be solved.

The rest of this paper is organized as follows. The background of solar-powered mobile telecommunication systems and power consumption models are presented in Section II. In Section III. the proposed consumption and bandwidth controller algorithms are introduced. The obtained performance results are presented in Section IV. The summary of the paper and the conclusions can be found in the last section.

II. Background

Energy management of wireless telecommunication systems are intensively investigated to found solutions for consumption reduction. In case of solar-powered base stations other type of power management methods are required compared to conventional ones, because the access to energy source is limited and not continuous. The solar cell dimensions

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must be determined to produce enough energy for the whole day and supply the base station from stored energy if the sunlight intensity is becoming low. Solar cells are semiconductor devices that convert sunlight into direct current electricity, bypassing thermodynamic cycles and mechanical generators. When light photons of sufficient energy strike a solar cell, they knock electrons free in the silicon crystal structure, forcing them through an external circuit and then returning them to the other side of the solar cell to start the process all over again. Solar is universal and will work virtually anywhere; however, some locations are obviously more suitable than others. Irradiance is a measure of the sun's power available at the earth's surface, with power peaking at about 1,000 watts per square meter (W/m^2). With typical silicone crystalline solar cell efficiencies around 14 to 20 percent [9], about 140 to 200 watts can be generated per square meter of solar cells placed in full sun.

In order to efficiently manage the produced energy, consumption models must be used to estimate the energy requirements of a mobile station. Numerous consumption models [10]–[12] exist to determinate the correlation between the power consumption and the provided bandwidth. In most of the models the power consumption of a micro base station consists of two parts, modeled concurrently. The first part describes the static power consumption, which is consumed without any traffic served. The second part is depending on the load situation.

$$P_{BS} = P_{static} + P_{dynamic} \quad (1)$$

For macrocell stations the power consumption is almost independent of the input load, whereas for microcells, the consumption is highly dependent on the forwarded traffic. The relation of the traffic load and consumption is linear in the referenced models. The proposed consumption and bandwidth controller algorithms are based on the linear model, therefore in this work the consumption (*c*) is determined in function of load (*bw*) by equation (2).

$$c = P_{max} - \frac{P_{max} - P_{min}}{BW_{max} - BW_{min}}\left(BW_{max} - bw\right) \quad (2)$$

The highest bandwidth (BW_{max}) is corresponding to the highest consumption (P_{max}), while the lowest acceptable bandwidth (BW_{min}) needs the lowest power (P_{min}) to provide basic services. If the basic services cannot be served, the base station will be switched to sleep mode.

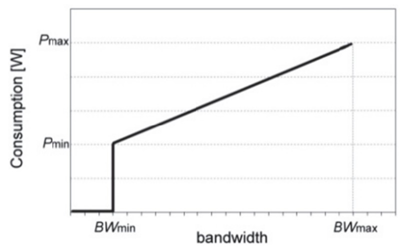

Figure 1. Consumption-bandwidth linear model

The load of a base station is continuously changing according to the number of users connected, user bit rates, the time of the day, etc. Due to the large number of mobile customers, the characteristic of the load can be statistically analyzed. The statistical traffic distribution can also be used to predict the forwarded traffic, therefore the expected consumption of a mobile base station. In this work the network load characteristic (Figure 2.) of a 3G mobile provider was used as a reference.

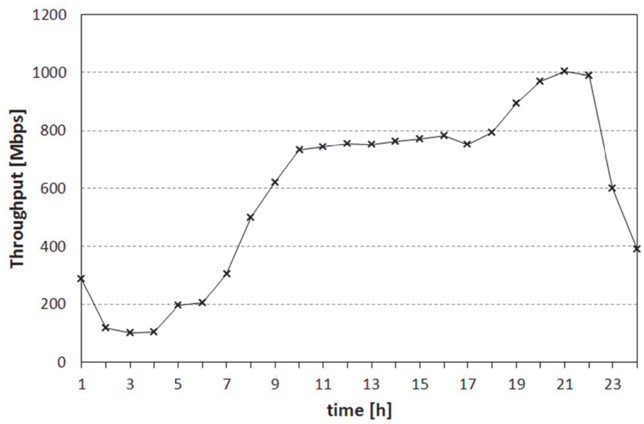

Figure 2. Traffic distribution used as a reference (Vodafone Hungary)

Of course the throughput values are adjusted to describe a single base station load variation; therefore the highest peak of the throughput curve was set to 2Mbps in a UMTS network. As Figure 2. shows the customer load is high during the middle of the day and the highest in the evening. To use solar cells as power source, the energy production must be planned and controlled to store energy in time of the day and utilize the accumulated energy at the end of the day, when the user activity is the highest, but the production is zero.

The mobile service must be available continuously, independently from the source of power, thus power management methods must be investigated to avoid the exhaustion of stored energy and provide at least basic services to the customers.

III. Proposed Algorithms

The aim of this work was to propose new algorithms in order to make solar-powered micro base stations in 3G and 4G mobile network more attractive for the providers. The energy production of solar cells is not constant, but depends on numerous factors. The main parameters that influence the amount of produced energy are: solar cell size, solar cell efficiency, angel of inclination, cloud coverage and other atmospheric characteristics.

On the other side, the customers of a mobile provider must be served independently of the weather conditions; therefore energy accumulator must be used as energy buffer. Daytime, the energy production of the solar cells must be higher than the consumption of the mobile station in order to store energy for night time and other low energy productive time periods (e.g. raining, clouds, fog). The capacity of the battery is proportioned to store enough energy to provide minimal services (minimal bandwidth) through 72 hours, assuming it was charged to its maximum capacity. Determination of the solar cell dimensions cannot be done without the knowledge of the consumption of mobile base stations. The consumption can be estimated based on the general user behavior and throughput of the user equipments. The characteristic of the daily traffic of the mobile station can be predicted from the general bandwidth distribution behavior (Figure 2.).

In this paper the linear traffic-consumption model (see eq.(2)) was used to determinate the consumption distribution of a UMTS or LTE base station. The estimated consumption characteristics of a Huaweii BTS3812E [13] UMTS base station and an average LTE e-NodeB [14] without power management algorithms are presented in Figure 3. The consumption values are used as a reference for the proposed algorithm.

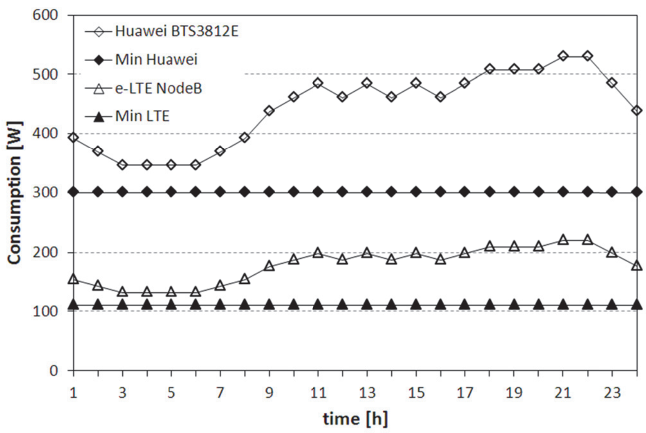

Figure 3. Consumption characteristics

The main concept of the proposed power management algorithms was to control the available bandwidth hereby the consumption of the base station. Using adaptive algorithms, the consumption can be adjusted to the energy production of the solar cell and the stored energy level; however it cannot be forgotten that the minimal services must be always provided.

Several algorithms were developed to control the available bandwidth, hereby the consumption of the mobile base station. The reference of the algorithms was the case when the throughput is not controlled. The surplus of the energy production is stored in the battery if it is not fully charged and the stored energy is utilized without control when the production is low. In the reference case the stored energy in the battery in the i^{th} hour ($e[i]$) can be calculated as follows

$$e[i] = e[i-1] + u[i] - c[i], \tag{3}$$

where $u[i]$ is the energy production and $c[i]$ is the consumption in the i^{th} hour.

The aim of the first proposed algorithm (*Alg1*) is to arrange the stored power of the battery. This simple method will try to provide power to serve mobile users through 72 hour if there is no energy production. If the solar cell does not offer enough energy for the base station, the controller is activated and restricts the power consumption to $c_1[i]=E_{max}/72$. The battery level is changing according to the actual battery level, current production and consumption

$$e[i] = e[i-1] + u[i] - \frac{E_{max}}{72} \tag{4}$$

The allowed bandwidth ($bw_1[i]$) corresponding to the limited consumption can be also determined using the linear consumption-bandwidth relation model.

$$bw_1[i] = BW_{max} + \frac{BW_{max} - BW_{min}}{P_{max} - P_{min}} \left(c_1[i] - P_{max} \right) \tag{5}$$

In equation (5) BW_{max} stands for the achievable bandwidth if the base station is operating on maximum power (P_{max}), while BW_{min} is the lowest acceptable bandwidth to provide basic services. The actual energy level of the battery can be also calculated similarly to (3) by replacing $c[i]$ with $c_1[i]$.

In the second proposed algorithm (*Alg2*) the bandwidth controller of the mobile base station is based on the actual level of battery. If the battery is full, no restriction to the energy consumption is forced, but if its level is decreasing the consumption must be reduced by limiting the available bandwidth and store energy. The algorithm controls the available bandwidth and consumption if the consumption is higher than the energy production of the solar cell connected to the base station, $c[i]<u[i]$. The actual allowed power consumption ($c_2[i]$) using *Alg2* can be determined as the ratio of the actual reference consumption ($c^*[i]$) and the battery capacity (E_{max}). To provide the basic services, the base station consumption cannot decrease bellow its minimum power requirements (P_{min}).

$$c_2[i] = \max\left(\frac{e[i]}{E_{max}} \cdot c^*[i], P_{min} \right) \tag{6}$$

The third proposed algorithm does not decrease the allowed power consumption significantly if the battery level is high, but the solar energy production is not enough to supply the base station. As the stored energy in the battery is getting low, the bandwidth restriction is becoming continually stricter. In *Alg3* logarithmical function of the battery level is used to control the allowed power of the base station.

$$c_3[i] = \max\left(\log \frac{10 \cdot e[i]}{E_{max}} \cdot c^*[i], P_{min} \right) \tag{7}$$

Assuming that the maximum energy consumption of the base station is the double of the power needed for basic services ($P_{max}=2P_{min}$), the *Alg2* controller will allow only basic services during peak hours if the battery level decreases below 50%. The threshold value can be calculated according to equation (6), where $c^*[i]$ is the reference consumption that cannot exceed P_{max}. In case of *Alg1* the controller will be activated as the battery is not absolutely full, while using *Alg3* the battery level threshold is at 70% if the reference consumption is near P_{max},

The consumption restriction in *Alg3* is depending on the battery level ($e[i]/E_{max}$) and the reference consumption ratio ($c^*[i]/P_{max}$), but cannot decrease below P_{min} according to equation (7). The allowed consumption ratio compared to the reference ($c[i]/c^*[i]$) is depicted in Figure 4.

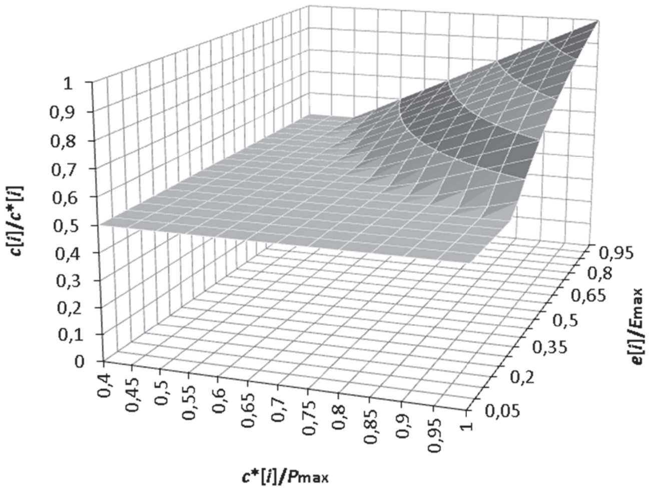

Figure 4. Consumption restriction ratio using *Alg3*

As the figure shows the actual consumption is on the maximum ($c[i]=P_{max}$), only if the battery level is 100% and the reference consumption is also P_{max}. If the battery is fully charged, the algorithm serves the reference bandwidth, without consumption restrictions.

IV. OBTAINED RESULTS

The performance of the presented power management algorithms were analyzed by a simulator tool developed in C#. The input parameters of the tool make it possible to configure the base station minimum and maximum consumption values (P_{min}, P_{max}), the reference bandwidth needs, the battery startup level, the solar cell efficiency and dimensions and the range of a random variable that simulates the weather condition changes. In the simulations a Huawei BTS3812E base station for UMTS mobile network was assumed with P_{min}=300W and P_{max}=530W, and an LTE micro cell base station with P_{min}=106W and P_{max}=220W (Figure 3.).

The output of the developed simulator tool is the allowed bandwidths, the corresponding power requirements and the battery levels for every hour during the one week simulation time period.

The energy production of solar cell is influenced by more parameters, like the type, size, efficiency, etc. In the simulation monocrystalline solar cells were assumed with η=17% efficiency. The estimated energy production during a day is presented in Figure 5. The produced energy can be enough to supply an average base station, but it is necessary to store the remaining energy and use it when the production is low.

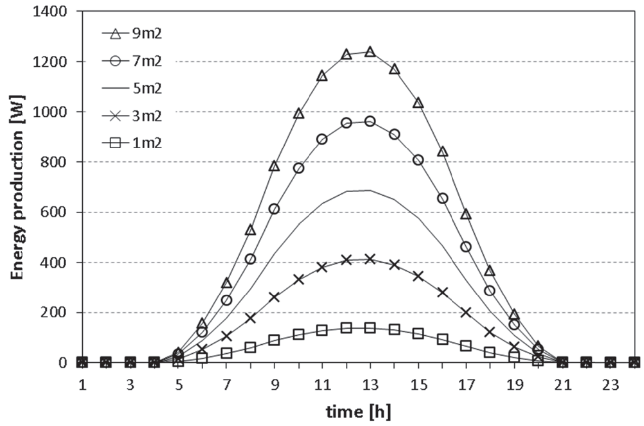

Figure 5. Estimated solar cell energy production

In order to arrange the available energy efficiently the proposed algorithms can be used. Without any power control mechanism the stored energy can be exhausted fast. Assuming that the battery is fully charged (E_{max}=20kWh), the time needed to get exhaust the battery is different depending on the applied power control scheme In case of a 7m^2.solar cell and a Huaweii BTS3812E type base station, the exhausting times are presented in Figure 6.

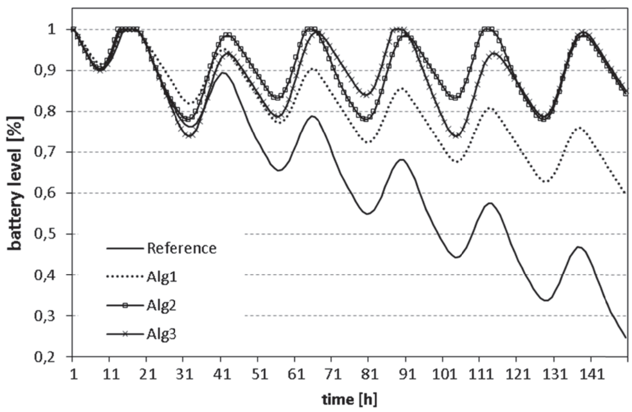

Figure 6. Battery level variations

If all the needs are served without testing the actual battery level (*reference* case), the battery will be flat in few days and only the traffic in the daytime can be served, while during the nights the users will be not able to connect to the network. Using *Alg1*, the consumption is limited, hence the battery exhausting time is longer and the mobile users will be served for longer time. When the battery is becoming empty, the service will be unavailable. In the analyzed scenario the *Reference* and *Alg1* methods are not sustainable because the battery level is definitely decreasing. The other two algorithms (*Alg2*, *Alg3*) are performing better because the battery level is periodically varying but does not decrease below 70%, therefore a reliable service can be provided to the mobile customers. Of course, keeping the battery level higher require stricter restrictions and providing less bandwidth to the users., but the basic traffic needs will be always fulfilled. In the simulations the basic bandwidth that must be available all the time is 144kbps, while the maximum bandwidth is 2Mbps.

The allowed bandwidth is depending on the allowed consumption determined by the proposed power control algorithms. To analyze the bandwidths, smaller solar cells ($5m^2$) were assumed, to observe how the algorithms perform if the battery is getting empty. The measure bandwidths values are plotted in Figure 7.

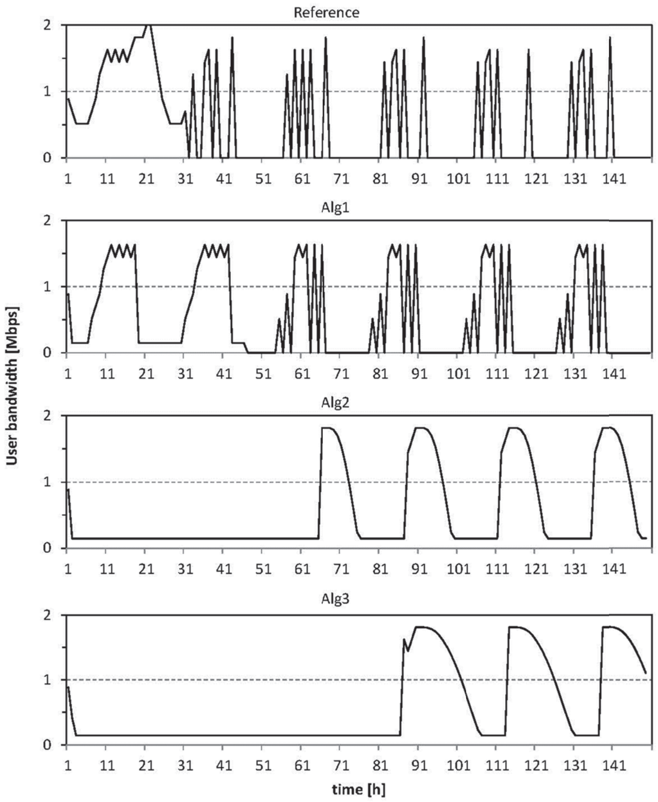

Figure 7. Allowed user bandwidths by the controller algorithms

In the reference case the fully charged battery was emptied within the first 30 hour and the service become available only if enough energy was produced by the solar cells to serve the actual needs. Between the bandwidth pikes the service is unavailable. *Alg1* performs better, but the unavailable periods are also very long. In case of *Alg2* and *Alg3* only basic services (144kbps) are provided while the battery level is not high enough, but if the battery level reaches the threshold the customer needs can be served. The service is not suspended not even during night time, because the battery stores energy to overcome the time periods when no energy is produced.

In the analyzed 150 hour, when the battery was initially charged, the unavailable service time in the reference case was 62%, using *Alg1* it was 48%, while the other control schemes were always providing at least 144kbps. Based on the obtained results, the overall efficiency of the proposed algorithms (*Alg2*, *Alg3*) are significantly better and aids the success of renewable energy sources in mobile communication networks.

V. CONLUSION

Solar energy is a perspective opportunity to supply mobile base stations, which is not only ecologically clean and cost-efficient energy, but can also be used in areas far from infrastructures, in particular from sources of traditional energy. Energy production of solar cells is continuously varying depending on the part of the day, seasons, weather conditions, geographical location, etc. In order to provide reliable services for mobile users, the produced energy utilization must be controlled. The mobile operators are interested to deploy the smallest solar cell needed, but be able to fulfill the customer's requirements.

In this paper power management algorithms were presented in order to extend the availability of network access and offer basic mobile services continuously. The battery level based control algorithms restricts the reachable bandwidth, but decreases the consumption of mobile base station, hence making the power supplement more efficient. Due to economical energy management, the unavailability of the mobile services can be minimized.

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