Solar Powered Cellular Base Stations: Current Scenario, Issues and Proposed Solutions

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***Abstract*—The increasing deployment of cellular networks across the globe has brought two issues to the forefront: the energy cost of running these networks and the associated environmental impact. Also, most of the recent growth in cellular networks has been in developing countries, where the unavailability of reliable electricity grids forces operators to use sources like diesel generators for power, which not only increases the operating cost but also contributes to pollution. Cellular base stations powered by renewable energy sources such as solar power have emerged as one of the promising solutions to these issues. This article presents an overview of the state-of-the-art in the design and deployment of solar powered cellular base stations. The article also discusses current challenges in the deployment and operation of such base stations and some of the proposed solutions.**

I. Introduction

With more than six billion subscribers, the cellular networking and communications industry is growing rapidly. To support this growth in the subscriber base, cellular operators have expanded their coverage and capacity by deploying additional network infrastructure. This in turn has increased the energy consumption of cellular networks and their contribution to greenhouse gas emissions. With more than three million base stations (BSs) worldwide, cellular networks currently contribute to around 3% of the worldwide energy consumption and 2% of carbon emissions [1]. Also, it is predicted that the carbon emissions of information and communication technologies (ICT) will increase from 170 metric-tons in 2014 to 235 metric-tons by 2020. This increase in the power consumption and carbon footprint of cellular networks has led to various initiatives for "green" solutions from telecom providers, government agencies and researchers.

One of the key components of a cellular network is the base station. BSs are categorized according to their power consumption in descending order as: macro, micro, mini and femto. Among these, macro base stations are the primary ones in terms of deployment and have power consumption ranging from 0.5 to 2 kW. BSs consume around 60% of the overall power consumption in cellular networks. Thus one of the most promising solutions for green cellular networks is BSs that are powered by solar energy. Base stations that are powered by energy harvested from solar radiation not only reduce the carbon footprint of cellular networks, they can also be implemented with lower capital cost as compared to those using grid or conventional sources of energy [2].

There is a second factor driving the interest in solar powered base stations. In the recent past, the bulk of the growth in the deployment of cellular base stations has been in parts of the world such as Africa and Asia where the penetration of cellular communication is still low. Unfortunately, many of these regions lack reliable grid connectivity and telecom operators are thus forced to use conventional sources such as diesel to power the base stations, leading to higher operating costs and emissions. For example, studies indicate that of the 4,00,000 base stations in India, more than 70% face power cuts for more than 8 hours a day. As a result, the telecom industry in India consumes more than 2 billion liters of diesel per year, spending around US$ 1.4 billion and producing more than 5 metric-tons of carbon dioxide [3].

Current estimates suggest that there are 3,20,100 off-grid (i.e. without any grid connectivity) and 7,01,000 bad-grid (i.e. connected to a grid supply with frequent power outages, loss of phase, or fluctuating voltages) BSs in the world [4]. The off-grid and bad-grid BSs are predicted to grow by 22% and 13% by the year 2020, respectively. Around 80% of these would be installed in African and Asian countries. It is noteworthy that although many of the countries in these regions have poor grid connectivity, they are rich in terms of solar resources. Consequently, solar powered BSs are a viable and attractive option in these regions.

This article presents a technical overview of solar powered BSs including the current state-of-the-art and a discussion on the issues and technical challenges surrounding their adoption and deployment by telecom operators. The article also provides an overview of the components of solar powered BSs, highlights the advantages of solar powered BSs over traditional BSs, and presents a case study of current deployment of solar powered BSs in Ghana.

II. Motivating Factors for Solar Powered BS's

This section presents the various advantages and other factors that have motivated the increasing deployment of solar powered base stations.

1. **Cost savings:** Although solar powered BSs have a high CAPEX (capital expenditure), the OPEX (operating expenditure) is much smaller, leading to cost savings on the long run. The bulk of the savings in the OPEX comes from the cost of energy, specially in areas where network operators have to rely on diesel generators. The OPEX for solar powered BSs primarily comprises of the cost of replacing the batteries (required every 3-8 years based on the battery usage pattern).
2. **Greener operation:** The use of a renewable energy source implies that there are no harmful emissions during the operational stage.

Fig. 1. Worldwide deployment status of solar powered base stations at the end of 2014 [4]. The number in the circles indicate the number of solar powered BSs in a particular country.

3. **Simpler maintenance:** BSs powered by diesel generators have greater maintenance requirements as well as the need to regularly refill the fuel for the generators. In comparison, solar powered BSs have lower maintenance needs and such sites can easily be unmanned.
4. **Greater disaster resistance:** Unlike solar powered BSs, traditional grid connected BSs fail in the case of extended grid failure. For example, during the 2011 earthquake and tsumani in Japan, more than 6,700 cellular BSs experienced outages.
5. **Government regulations and subsidies:** Many countries currently offer subsidies for promoting the use of solar power. In addition, some governments are making it mandatory for telecom operators to have a certain fraction of their BSs powered by renewable energy (e.g. in India).
6. **New base stations with low power consumption:** Large macro base stations have high power consumption, and hence require large solar panels, thereby making solar powered solutions impractical. However, recent technological advances have resulted in macro BSs that consume around 500-800 W and smaller BSs that consume around 50-120 W, making solar powered BSs a practical alternative to traditional BSs.

III. Key Components of Solar Powered BSs

A solar powered BS typically consists of PV panels, batteries, an integrated power unit, and the load. This section describes these components.

A. Photovoltaic panels

Photovoltaic panels are arrays of solar PV cells to convert the solar energy to electricity, thus providing the power to run the base station and to charge the batteries. Photovoltaic panels are given a direct current (DC) rating based on the power that they can generate when the solar power available on panels is 1 kW/m^2. A 1 kW PV panel is typically 5 m^2 in area and the lifetime of a typical PV panel is more than 25 years [2]. There are various factors which affect the power produced by a PV panel include: (i) DC rating of the PV panel, (ii) geographic location or solar irradiation profile of the site, (iii) tilt of the PV panel, and (iv) the DC-AC loss factor.

The current cost of PV panels is around US$ 1000 for a PV panel with DC rating of 1 kW. Currently PV cells based on mono and poly-crystalline silicon are common in large scale applications and they have an efficiency of around 14-19%. The next generation high concentration solar cells (e.g. based on germanium, gallium arsenide and gallium indium phosphide have been shown to reach efficiencies of around 40%.

B. Batteries

Solar powered BSs are equipped with batteries to power them during periods without sufficient solar power, such as nights and bad weather periods. The batteries are charged during the day with the excess energy produced by the solar panels. The cost of batteries forms a significant part of the overall cost of a solar powered BS and thus their lifetime is of critical importance.

The lifetime of a battery depends on the conditions in which it operates, with the depth of discharge (DOD) during each diurnal charge-discharge cycle playing a dominant role. The DOD refers to the percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity. A typical lead-acid battery with a DOD of 60% has an expected lifetime of 1000 charge-discharge cycles (called cycles to failure). In contrast, increasing the DOD to 90% decreases the expected lifetime to 500 charge-discharge cycles. Thus the permissible DOD is one of the important features to be considered in deciding the battery bank capacity of the BS.

Various battery types used in cellular BSs and their salient features are listed in Table I [5]. Among the existing battery

TABLE I
BATTERY TECHNOLOGIES [5]

Battery Type	Cost ($/kWh)	Efficiency (%)	Max. DOD (%)	No. of cycles (at Max. DOD)	Energy density (Wh/kg)	Self-discharge (%/month)
Lead-acid (conventional)	110-140	75-85	70	500-1000	30	1.5-5
Lead-acid (FLA-VRLA)	140-340	80-90	80	1200-1800	30	1.5-5
Nickel-Cadmium	400-900	70-80	100	1500-3000	50	5-20
Nickel Metal Hydride	800-1200	65-70	100	600-900	80	10-25
Lithium-Polymer	950-1650	90-100	80	600	100-150	2-5
Lithium-Ion	1000-1700	95-100	80	1500-3000	90-150	1-5

technologies, lead-acid batteries are the most popular for solar powered BSs because of their lower cost and reliability. A major disadvantage of lead-acid batteries is that their disposal is not environmental friendly.

C. Integrated Power Unit

The power requirements of a BS include the load offered by the transceiver equipment, cooling, and other miscellaneous loads (e.g. lights). The power supply to these loads as well as the conversion and storage of the harvested solar energy is managed by the integrated power unit (IPU). The IPU in a solar powered BS typically consists of DC-DC and DC-AC power converters, battery charger, charge level monitors and regulators, and a power management unit. The power management unit controls the charging of the batteries and the supply of power to the loads. The DC-DC converters are used to supply power to the transceiver equipment and store the power from the solar panels in the batteries, while the DC-AC converters supply power to the AC loads such as the cooling equipment. The battery charge regulator monitors the battery state and disconnects them from the system when the overall charge goes below a specified DOD (generally 50-80%).

D. Configurations for Solar Powered BSs

Depending on the availability of grid or other power sources, a BS may be powered solely or partially by solar energy. The following configurations are common for solar powered BSs:

1) **Solar stand alone:** The BS is powered solely by solar power and the batteries.
2) **Grid-connected:** The BS is powered by energy harvested from PV panels, but in case it falls short, power from grid is used.
3) **Solar-diesel:** The BS is powered by solar energy, but in cases of prolonged bad weather periods, diesel generators are used to meet the power the BS.
4) **Hybrid:** Such a configuration can include a combination of PV arrays, grid power, diesel generators and other renewable sources such as wind energy to power the BS.

IV. CURRENT DEPLOYMENT EFFORTS

As of 2014, estimates suggest that there are roughly 42,951 solar powered base stations across the globe and Figure 1 shows their distribution across various countries [4]. Examples of ongoing deployment efforts include:

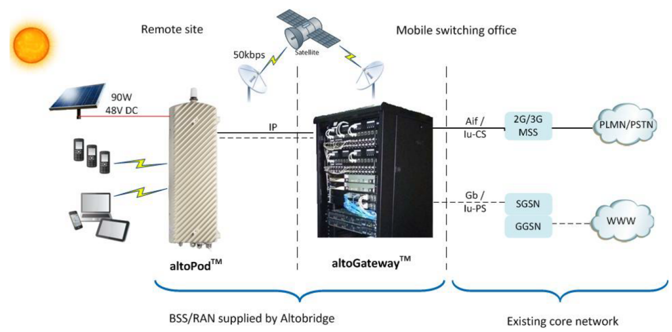

Fig. 2. Network architecture based on Altobridge hardware [7].

- Zong Pakistan: Zong is a telecom service provider in Pakistan that has deployed more that 400 solar powered base stations, primarily in remote and mountainous areas that do not have grid connectivity.
- Project Oryx: This is an initiative by the telecom provider Orange and covers various parts of Asia, Middle East and Africa [6]. By the end of June 2011, around 1165 solar BSs were deployed in 17 countries under this project, mainly in Africa.
- Bhutan Telecom Limited (BTL): BTL has partnered with Vihaan Networks Limited (VNL), an India based telecom equipment manufacturer, to provide cellular connectivity to remote regions of Bhutan that lack infrastructure and have difficult terrain.
- Telkomsel: Telkomsel is the leading telecom operator in Indonesia and by 2012 had 234 BSs powered by solar energy. In addition to smaller BSs, Telekomsel has also deployed solar powered macro BSs.

A. Case Study

To provide a more comprehensive description of a practical deployment scenario, we now present a case study of the initial deployment of solar powered based stations in rural Ghana by the telecom provider Tigo Ghana.

In 2012, 60% of the land area and 20% of the population (5 million people) of Ghana had no mobile coverage. The

TABLE II
ALTOBRIDGE ALTOPOD SPECIFICATIONS [7]

Feature	2G	3G
Frequency Band	GSM 850/900/1800/1900 MHz	UMTS 2100 MHz
Capacity	2 TRX (FR/AMR-HR)	16 sessions (voice or data)
RF power output	+40 dBm (10W)	+40 dBm (10W)
Receiver sensitivity	-108 dBm at 2% BER	-121 dBm at 0.1% BER for 12 kbps
Data throughput	GPRS/EDGE	HSPA (14 Mbps downlink, 5.8 Mbps uplink)
Input volatge	-48V DC	-48V DC
Average power	90 W	90 W
Operating temperature	-30 to + 55 deg C	-30 to + 55 deg C
Cooling	Passive cooling	Passive cooling

primary reasons for the lack of network access in these areas are: (i) the lack of necessary infrastructure such as reliable grid power and (ii) too low average revenue per user (ARPU) to justify the deployment costs. As an initial step to providing network connectivity in these regions, in 2012, Tigo Ghana partnered with network solutions provider K-NET and telecom equipment manufacturer Altobridge to deploy 10 solar powered base stations. The base stations from Altobridge optimize capacity for rural environments and have substantially lower power consumption than conventional systems. In particular, the deployed BSs use compression techniques so that voice calls require rates of 4 kbps (compared to 14 kbps in conventional systems) and each cell site has an average power consumption of 90 W (compared to 130 W or more). The BSs use satellites for backhaul, have a coverage range of 10 km, and capacity for up to 1500 subscribers. The lowering of costs brought about by the design optimizations has the capability to bring in a return on investment for the operator in less than 24 months, assuming 600 subscribers with APRU of $4 per month. Table II shows some of the specifications of the solar powered base stations used in this project and the network architecture is shown in Figure 2. Currently there are plans to expand to 300 additional sites, some of which have already been implemented.

V. CHALLENGES AND PROPOSED SOLUTIONS

This section lists some of the current technical as well as non-technical challenges that stand in the way of widespread deployment of solar powers BSs. We also review some of the proposed solutions to addresses these issues.

A. Economic Challenges

1) High CAPEX: Though on the long run solar powered BSs are more economical due to lower OPEX, the initial installation cost is considerably higher. However, technical advances such as more efficient and cheaper solar panels have decreased the CAPEX/TCO (total cost of ownership) ratio by around 40% between 2009 and 2013. Also, government initiatives such as subsidies given in various countries for the use of renewable energy is effectively reducing the CAPEX and motivating operators to switch to solar powered BSs.

2) Market Forces: Increasingly, the industry's attitude towards green technologies is changing due to the awareness of environmental issues. In addition, some governments (e.g. India) are enacting rules making it mandatory for telecom operators to consider green energy. The market dynamics have also changed with the emergence of an increasing number of companies specializing in developing technologies for renewable energy based, off-grid base stations (e.g. Flexenclosure, VNL, Altobridge).

3) Large BSs: For base stations whose power consumption is more than 3 kW, solar power is currently not an attractive option due to the large PV panel dimensions required. For example, powering a macro BS with power consumption of 3 kW would require an area of around 180 m^2 for the PV panels. However, larger BSs can still be cost effective, e.g. in the presence of government subsidies, though the payback period is still high (7-10 years).

B. Geographical Limitations

1) Regions with Poor Solar Insolation: Solar powered BSs are not very attractive options for regions with poor solar insolation. However, in such regions solar power may be used in conjunction with the grid to power the BSs.

2) Urban Deployments: PV panels should ideally be installed in open areas where shadows from obstructions due to buildings or trees can be avoided. Such sites may be difficult and expensive to procure in urban areas.

3) Long Stretches of Bad Weather: In areas that are prone to frequent and prolonged periods of bad weather with accompanying cloud cover, the required size of the battery banks is very large. This not only increases the CAPEX, but also increases the possibility of outages during these periods.

C. Resource Provisioning and Deployment

1) Resource Provisioning: The successful deployment of a solar powered BS requires meticulous planning to determine the appropriate dimensioning of the PV panels and backup batteries [6], [8]. While over-dimensioning leads to higher than necessary CAPEX, under-dimensioning can lead to frequent outages, thus dissatisfying the customers. A general dimensioning process is presented in [9], which considers a stand-alone solar powered BS at a site for which the solar insolation

TABLE III
OPTIMAL CONFIGURATION FOR VARIOUS OUTAGE PROBABILITIES

Location	PV	n_b	L_{Bat}	CAPEX ($)	OPEX ($)	Total ($)
			$\alpha = .25\%$			
Jaipur	9.5	19	5.76	14820	13158	27978
Kolkata	14	20	5.98	19600	13136	32736
			$\alpha = .5\%$			
Jaipur	8.5	18	5.21	13540	14302	27842
Kolkata	12	21	5.92	17880	13964	31844

data is either available from sources such as NREL [10], or synthetically generated. The resource dimensioning problem seeks to determine the cost optimal PV panel and battery size while satisfying a desired threshold on the power outage probability (i.e. the probability that the battery runs out of power). Let PV_w be the PV panel size and let n_b denote the number of batteries powering the BS. The battery lifetime and power outage probability for a given choice of PV_w and n_b are first obtained by simulations using the hourly weather data traces and the hourly traffic demand. Towards this end, the battery DOD in the charging-discharging cycle for each day of the operational period of T years is noted. The entire range of DOD is split into N regions, and the number of cycles corresponding to each DOD region is counted. The battery lifetime, L_{Bat} is then given by

$$L_{Bat} = T/(\sum_{i=1}^{N} \frac{Z_i}{CTF_i}), \quad (1)$$

where Z_i is the number of cycles with DOD in region i, and CTF_i is the cycles to failure corresponding to region i. The total number of batteries (N_{Bat}) required over the desired time period T is given by

$$N_{Bat} = n_b(T/L_{Bat}) \quad (2)$$

The cost optimization problem is expressed as

$$\begin{aligned} \text{Minimize:} \quad & N_{Bat}C_B + PV_wC_{PV} \\ \text{Subject to:} \quad & O < \alpha \end{aligned}$$

where C_B is the capital cost of one battery and C_{PV} is the cost of PV panel per kW, O is the outage probability, and α is the operator's desired limit on the outage probability.

To illustrate the system dimensioning results, we consider simulations for a Long Term Evolution (LTE) base station with 10 MHz bandwidth, 3 sectors with 2 transceivers each, and 2×2 Multi Input Multi Output (MIMO) configuration. The BS uses 12 V, 205 Ah flooded lead acid batteries and the batteries are not allowed to discharge below a DOD of 0.7 to avoid degradation. We consider two locations in India: Jaipur and Kolkata, and the solar data for these locations was obtained from the NREL database. Current market rates of US$ 280 for C_B and US$ 1000 for C_{PV} was used for cost calculations. We consider a target operational lifetime of $T = 20$ years.

Figure 3 shows the minimum battery requirement for various PV panel sizes for two values of outage probabilities, and the battery lifetime as a function of the number of batteries for two different PV sizes. Further, the cost optimal configurations are presented in Table III. The results show that there is a significant increase in the number of batteries required for meeting smaller power outage probabilities, specially when the PV panel size is small. Thus there is a tradeoff between the outage probability and the CAPEX. Also, if the battery size is too small, the outage probability cannot be satisfied irrespective of the PV panel size. This is because the battery bank is too small to store the harvested energy even though the PV wattage is high. Finally, the battery lifetime reduces significantly if the battery bank size is reduced since the batteries have to go through deeper charge-discharge cycles. This reduction in the battery life is reflected in increased OPEX.

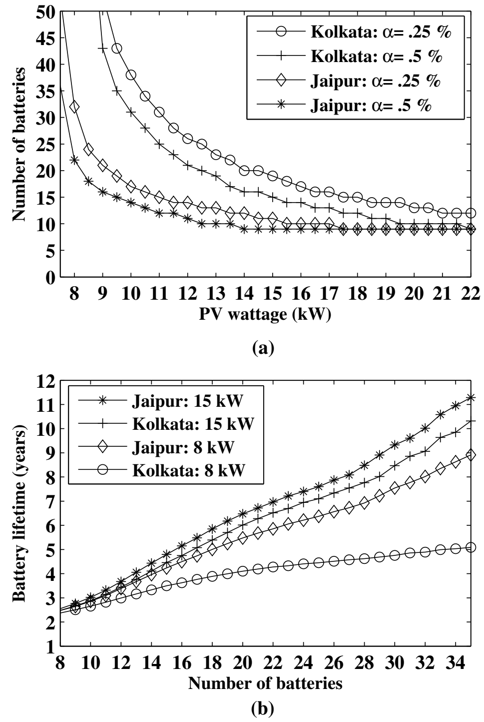

Fig. 3. a) PV wattage vs number of batteries required for two different outage probabilities for Kolkata and Jaipur. b) Battery lifetime for 2 different PV Wattage for two locations.

2) Choosing a Configuration: Section III-D presents the different configurations for solar powered BSs. The choice of a configuration for a given location depends on parameters such as the daily grid-outage period, cost of diesel fuel and generators, location specific solar and wind speed data etc. Based on these information, the overall cost (CAPEX + OPEX) for the different configurations for the desired operational period is computed and the cost-optimal configuration is chosen [3].

3) Deploying Small Cells: Small cells BSs have the advantage of reduced transmitter to mobile terminal (MT) distance, reduced transmit power requirement, higher data rates and low BS power consumption, and are thus an attractive option for increasing network capacity and spectral efficiency. The main challenges associated with deploying small cell BSs is to determine the number of BSs to deploy and their locations. Given the tradeoff between the outage probability and the number of BSs, recent studies have shown that it is preferable to have more small cell BSs with less energy harvesting (EH) resources rather than few BSs with larger EH resources [11]. Due to the complexity of the problem, the required number of small cell BSs is determined keeping in mind only the desired outage probability, with other parameters (like the macro BSs and their location) kept as fixed. The small cell locations are determined by factors such as the spatial distribution of traffic hotspots and solar insolation.

D. Network Management and Resource Allocation

For energy harvesting BSs, the major resources in the network are: the energy harvested by the BSs, the transmission power level at which the BSs choose to operate, and the spectrum available for transmission. Due to the stochastic nature of the traffic intensity and solar insolation, deciding operating strategies for the BSs is a challenging problem. In most cases, weather forecast data and historical traffic models may be required for determining the network's operating conditions. The most widely explored problems in this context aim to minimize the overall energy consumption of the network through a variety of mechanisms. Some of the resource allocation strategies considered in literature are as follows.

1) Load Balancing: While operating the BSs, the operator has to take into account the available energy, the expected harvested energy in the near future, and the traffic load at the BSs, with the objective of preventing the BSs from running out of energy or being over-loaded. To ensure continued coverage, BSs may cooperate by dynamically changing the area covered and traffic handled by each BS, in accordance to the energy available at each BS. There are two main techniques for load-balancing among BSs:

Dynamic user association: Since the energy consumption of a BS depends on its traffic load, energy-aware load balancing techniques incorporate the BS traffic load and energy availability in the decision rules for determining which BS a MT would attach itself to. In these strategies, MTs periodically obtain the load and energy information from the BSs in their vicinity and then decide which BS to associate with. However, as MTs associate and direct their traffic at the BSs with higher energy levels, these BSs may experience traffic congestion. Consequently, user association strategies that optimize the energy utilization while avoiding congestion have been proposed [12].

Base station beacon power control: In this approach the BSs either increase or decrease the transmission power of their beacons in order to control the area served by them. This in turn changes the traffic load at the BSs and thus their rate of energy consumption. The problem of optimally controlling the range of the base stations in order to minimize the overall energy consumption, under constraints on the minimum received power at the MTs is NP-hard. Heuristic solutions to the power control problem usually employ greedy algorithms. For example, the algorithm in [13] first obtains the set of BSs with the highest energy depletion rate. For each BS in this set, the beacon power level of each BS is iteratively reduced till the constraint on the minimum received power at the MTs is violated. This process of choosing the BSs and reducing their power continues till no further decrease is possible.

2) BS On/Off Strategies: Switching off BSs is a powerful way of achieving energy savings in a cellular network. Since cellular networks are provisioned for peak-hour traffic, it may be possible to turn off some BSs during off-peak hours while maintaining coverage and quality. Strategies for saving energy by turning off BSs seek to determine the minimum number of BSs required to serve the area, with the desired quality of coverage (e.g. blocking probability, delay) as a constraint. The switching decision may also take into account the energy availability of the BSs. The problem of minimizing the overall energy consumption of a set of BSs, subject to a limit on the load on any BS, is known to be NP-complete [14]. This problem is equivalent to determining the smallest possible set of active BSs subject to the system load constraint. Heuristics for solving this problem center on greedily assigning MTs to BSs with higher loads so that the number of the BSs that have no associated MTs (and thus can be turned off) is maximized.

3) Energy and Spectrum Sharing Among BSs: In any cellular network, the traffic demand and the harvested energy have spatial and stochastic variations which lead to some interesting possibilities regarding resource usage and sharing. To share resources so that outages are minimized or the quality of service (QoS) of users is improved, solar powered BSs may share energy either directly through electrical cables, or indirectly through power-control/load-balancing/spectrum-sharing mechanisms [15]. Energy sharing between BSs may be achieved by two-way energy flows in a smart grid and strategies to develop such sharing mechanisms may be obtained by modeling the system as an energy-trading system. Spectrum sharing in solar powered BSs is motivated by the fact that for a given rate requirement and channel noise (e.g. in an AWGN channel), the transmit power may be reduced by increasing the bandwidth, and vice-versa. The problem of energy and spectrum sharing may also be considered jointly. The sharing strategies may be developed by modeling the system as a convex optimization problem.

4) Coordinated Multipoint (CoMP): In CoMP, BSs cooperate to jointly serve MTs and is particularly useful in combating inter-cell interference (ICI) in dense deployment scenarios, and enhancing network efficiency and overall QoS for users. Implementation of CoMP requires the formation of clusters of transmit points for CoMP transmissions and the allocation of resources to the transmit points. The extent of cooperation and which BSs should cooperate to serve the MTs is decided based on the resources available at the BSs and the decisions are made with the objective to maximize the system performance or to minimize the energy costs. The cluster formation and resource allocation problems are tightly coupled and optimization problems to solve them jointly generally lead to non-convex formulations.

VI. Conclusions

With the growing awareness of environmental issues and the push towards green engineering solutions, solar powered BSs are expected to play a greater role in the future. This article presented an overview of the components of solar powered BSs, the current deployment status, and a case study. We also presented the factors which have motivated their increasing market share along with the currently open problems and their possible solutions.

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