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Service Time Scheduling Method for Wireless Networks Powered by Renewable Energy

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論文題目 **Service Time Scheduling Method for Wireless Networks Powered by Renewable Energy**

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Chapter 1

Introduction

1.1 Background

During the last decade, there have been tremendous growth in communication networks market. The continuously growing demand for mobile phones triggers the rapid expansion of the information and communication technology industry, which comprise the largest network on Earth with over five billion subscribers [1]. Unfortunately, many people still lack this fundamental service. Nearly 95% of the uncovered population live in rural areas without power grid [2]. The primary reason for their lack of service is economic; power is the fundamental cost in any ICT infrastructure deployment, dominating both the capital and operating costs of rural networks. The International Telecommunications Union indicated that 50% of the operating expenditure (OPEX) cost for rural network is power [3]. In addition, the installation of wired backhaul interconnecting base stations such as optical fibre is considerably expensive, thus, there is no incentive for operators to make the large infrastructure investments in poor and rural areas [4]. Moreover, the disruption of power supply and the damage of wired transmission lines due to natural disasters (e.g., earthquake, tsunami, hurricane), leading to the disruption of telecommunication services (e.g., cellular networks, third generation (3G), long term evolution (LTE) services, and Internet infrastructures) have become a big challenge to be addressed in ICT [5–9]. Thus, providing information and communication technology services in rural area with limited power infrastructure, and in areas affected by disasters is a challenging issue which needs to be tackled by researchers and engineers. In order to mitigate the high expenses in the deployment of wired backhaul in rural areas, or to construct disaster zone networks [10–14], researchers have focus on alternate technology, namely the wireless mesh networks. The wireless mesh networks present an attractive choice for these purposes due to their multi-hop wireless communication feature, with a wireless backbone comprising base stations, which provide more bandwidth resources. Hence, wireless mesh networks comes as an alternative to extend network coverage to rural areas. Moreover, such networks can be exploited for fast deployment of an urgently required communication infrastructure to mitigate the collapse in communication due to disasters such as earthquake and hurricane.

However, the base station-based wireless mesh networks technology in rural areas and disaster struck areas still suffers from a major challenge concerning the power supply, with the absence of power grid and the disruption of power supply cable in rural areas and disaster struck areas, respectively. As an alternative, attention has been paid by engineers on diesel battery to power the base stations in rural and disaster struck areas. However, extra infrastructure, such as built road or helicopter, are required to transport the fuel to the base stations [15]. Unfortunately, infrastructure such as built road are often absent or damaged in such area. Meanwhile, the use of helicopter as fuel transportation mean is unaffordable in poor and rural area. Thus, ambient energy sources, namely solar and wind energy, become the ultimate alternative to power the base stations in such areas [16–21]. However, environmentally powered base stations have to deal with the variable behaviour and the uncertainty in the available energy provided by ambient energy sources over time, which results in challenges in developing reliable and energy-efficient communication networks in rural areas and areas damaged by disaster.

1.2 Objectives

The objective of this thesis is to propose a synchronized base stations switching method with an efficient service time scheduling method that considers the variable behavior of ambient sources of energy such as energy harvesting prediction, to provide the maximum possible network service time with the available resources, while guaranteeing fairness in service time allocation over consecutive days. We consider base stations-based wireless mesh networks powered by renewable energy source, photovoltaic cells, to extend communication coverage in rural areas, and to address the issue of communication disruption in disaster struck areas. At the beginning of each day, through beacon messages, base stations share information on their available energy and the energy predicted to be harvested during the following days. Based on this information, we perform a synchronized toggle of base stations, through which we guarantee network coverage simultaneously to all the users in the targeted area. Moreover, in order to perform a fair allocation of network service time per day, we introduce a successive shift window-based approach of size n days, which is updated at the beginning of each day.

We introduce two evaluation metrics, namely, the mean service time deviation and the users' satisfaction ratio, which measures the balance of the distribution of network service time over consecutive days, and the deviation between the allocated daily service time and the minimum daily service time required by users. The mean service time deviation is used to evaluate the fairness in the allocation of network service time per day, meanwhile, the users' satisfaction ratio is used to evaluate the satisfaction of users on the daily service time allocation. Moreover, we analyse the effect of the shift window size n days on the mean service time deviation, and the robustness of the proposed scheme to severe fluctuation in energy harvesting over days.

In order to measure the effectiveness of the proposed method, we evaluate its performance in comparison with the traditional scheme, namely, the dynamic base station switching, which consists of running base stations according to their available energy and the user demand in daily network service time.

1.3 Thesis Structure

The remainder of this thesis is organized as follows.

Chapter 2 provides an overview of wireless base station mesh networks powered by renewable energy. Here, we describe the architecture and investigate the challenges encountered in such networks.

Chapter 3 depicts our considered network model and system assumptions. Moreover, and formulates the problem that needs to be addressed in such networks.

Chapter 4 introduces our proposed method. The method makes use of a successive shift window approach of size n days to guarantee a fair allocation of network service time over consecutive days.

Chapter 5 analyses the effectiveness of our proposal and its robustness to severe harvesting fluctuation, in comparison to existing scheme.

Chapter 6 evaluates the performance of our proposal by using computer-based simulation.

Chapter 7 concludes the thesis.

Chapter 2

Wireless Base Station Mesh Networks Powered by Renewable Energy

In this section, we overview the wireless base station mesh networks powered by renewable energy. With the high expenses in deploying ICT infrastructure such as wired backhaul in rural and developing region, and the eventual damage of Internet transmission line such as optical fibre after the occurrence of a disaster, researchers have diverted attention toward an alternate technology, such as wireless mesh networks comprising base stations. Moreover, in order to power such networks, researchers attention have been on renewable energy alternative from ambient sources, such as sun and wind.

2.1 Overview of Wireless BS Mesh Networks Powered by Renewable Energy

In several remote locations of the world such as Africa, South-east Asia, and Northern Canada, where electrical grids are not available or are unreliable, renewable energy resources such as solar and wind energy seem to be more viable options to reduce the overall network expenditure [15, 22]. Hence, communication network operators in these off-grid sites adopting renewable energy resources could save recur-

Table 2.1: Comparative table of base stations.

	Micro BSs	**Macro BSs**
Power consumption and user traffic dependence	Highly dependent	Quasi-independent
Location	Building roof	Ground
Rural area	Absent	Present
Energy harvesting capability	Small scale	Large scale
Communication range	Short range	Long range

rent costs, since they are cheaper to maintain. One obvious way to save more power is to turn off portions of the network for a period of time (typically at night). This is common in rural and developing regions [3]. Recently, a program called "Green Power for Mobile" to use renewable energy resources for base stations in rural areas has been started by telecommunication industries in developing regions, including MTN Uganda and Zain, united under the Global Systems for Mobile communications Association (GSMA) [23]. This program is meant to aid the mobile industry to deploy solar and wind technologies to power new and existing off-grid base stations in developing countries. On the other hand, researchers have focus on developing disasters resilient regional platform wireless mesh networks such as NerveNet [24]. NerveNet is a regional wireless access platform comprising base stations powered by renewable energy sources, and in which multiple service providers provide their own services with shared use of the network, enabling a range of context-aware services. It acts like a human nervous system which enable a reliable and managed wireless mesh network.

Table 2.2: Descriptive table of existing solution approach.

	User cooperation	**Dynamic BSs switching**
Network topology	Wireless mesh	Wireless mesh
Power consumption Load	BSs & users	BSs
Harvesting prediction	Not considered	Not considered
Daily service time allocation	unbalanced	unbalanced

2.2 Challenges encountered by Wireless BS Mesh Network Powered by Renewable Energy

However, although renewable energy from ambient sources is attractive, it still suffers from significantly higher variability as compared to conventional energy sources. Several researches have been conducted on renewable energy-power base stations to mitigate the variability of energy resources over time. Green Communications in Cellular Networks via User Cooperation was first introduced in [25], and has been shown that not only it increases the data rate, but also it is robust to channel variations. However, despite these advantages, energy efficiency issues of user cooperation render this paradigm unappealing in wireless mobile networks. The reason is, increased rate of one user comes at the price of the energy consumed by another user acting as a relay. The limited battery life time of mobile users in a mobile network leads to selfish users who do not have incentive to cooperate. Recently, authors have proposed the idea of dynamic base stations switching. In [26], Zhou *et al* propose a complementary method to coordinate the ON/OFF toggle of base stations. This scheme takes in consideration the energy availability of each base station and the trend of the users traffic and users daily service time demand at each base station at a given time, allowing in that respect base stations to be switched OFF when there is low energy availability and low users demand. The above mentioned scheme can be summarized in Table 2.2.

As depicted in Table 2.1, smaller base stations (micro BSs) are often located at the roof of building, thus are often directly connected to power source of the building, and sometime equipped with small scale energy harvesting module. Meanwhile, bigger base stations (macro BSs) are located at specific area on the ground well aroused by sun or wind, therefore, they are equipped with large scale energy harvesting module and are more robust to disaster in comparison to micro BSs. The long communication range of macro BSs make them suitable to be deployed in rural area. Moreover, due to the difference in power consumption model of smaller base stations which highly depends on traffic load, and of bigger base stations which power consumption model is quasi independent of traffic load, such traffic based schemes could be reduce to method depending only on energy availability and the daily trend of users demand in regions such as rural areas and disaster struck areas, where smaller base stations are either non-existent or damaged. However, as mentioned in Table 2.2, such schemes fail to consider efficient use of the available renewable energy resources, such as eventual harvesting prediction, thus, can not provide reliable communication service with fair daily service time allocation under environment subject to fluctuation in amounts and rates of energy available over time.

In our work, we address and mitigate these issues by proposing a synchronization method of base stations in wireless mesh networks, that takes into consideration their renewable energy harvesting and prediction capabilities, and the daily trend of the users demand to provide a stable and reliable communication services with fair service time allocation over consecutive days.

2.3 Summary

In this chapter, we took an overview of wireless mesh networks comprising base stations powered by renewable energy. Although such networks aim to extend communication service in area without power grid, such as rural regions and disaster struck areas, an adequate and efficient utilization of available renewable energy subject to fluctuation over time is still needed. In the next chapter, we will introduce our system model and formulate the problem that needs to be solved.

Chapter 3

System Model and Problem Formulation

3.1 System Model

In this section, we describe our considered network model. With the development of information and communications technology, communication networks rely on various scales base stations, namely, pico/micro base stations, installed on buildings, thus easily damaged by disaster or non-existent in rural areas, and bigger (macro) base stations, located in specific area and equipped with renewable energy modules, namely, photovoltaic cells and small wind turbines. Thus, bigger base stations are more resilient to disasters. Moreover, bigger base stations are equipped with technology enabling wireless communication between macro base stations over a long distance range through the wireless backhaul [27]. It is assumed in this research that pico or micro base stations are non-functional in disaster struck area, and non-existent in rural areas. Meanwhile, as depicted in Fig. 3.1, every macro base station is equipped with a photovoltaic cell and are able to forward their traffic to neighbouring macro base station through the wireless backhaul.

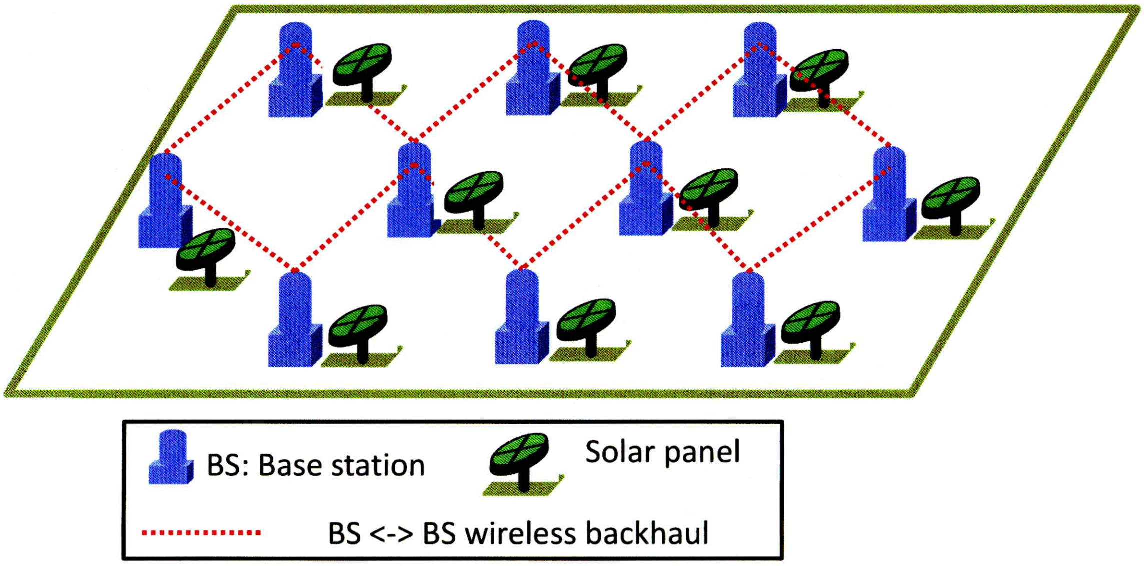

Figure 3.1: Wireless BS Mesh Network Powered by Renewable Energy

3.2 Problem Formulation

In disaster struck areas and rural areas without power grid, not electrified, and with population unable to write or read, the key issue needed to be tackled by researchers lies in providing reliable communication network services enabling real time application such as voice call, while efficiently making use of the available resources. Such an issue can be seen as two sub problems:

- *Shortage of energy supply or absence of power grid:*

  In developing regions,namely South Asia and sub-Saharan Africa, most of the rural areas are off-grid, and often are not electrified. Meanwhile, in disaster struck areas, base stations are assumed to be connected via cables to power distribution centers, which are connected to a power plan. Thus, a damage to any of these power distribution facilities caused by a disaster will lead to a disruption of energy supply from power distribution centers to base stations. The shortage of energy supply and / or the absence of power grid can be addressed by making use of renewable energy harvesting module at each base station.

- *Absence of wired backhaul or disruption of wired communication line:*

  The expenses in deploying wired backhaul such as optical fibers makes it impossible to be deployed in rural areas in developing countries. Moreover, due to the low income of population in these areas, there is no incentive for operators to make large investments in deploying wired backhaul in such areas. Meanwhile, in disaster struck areas, base stations are assumed to be connected to the Internet Service Provider (ISP) through cables and fibers, which is connected to power distribution center via power cable. Therefore, a damage to the power distribution facilities or to the ISP will lead to communication service interruption in the concerned area. Thus, assuming wireless communication between neighbouring base stations [28], communication network services can be provided by forwarding the network traffic from a base station to neighbouring base station through a wireless mesh topology.

The above mentioned problems are linked and could be addressed with a wireless mesh network comprising renewable energy powered base stations, and an efficient use of available energy resources at each base station, taking into consideration both the energy harvesting and prediction capabilities, and their fluctuation over time and per base station.

To the best of our knowledge, no solution has been provided so far that allows an efficient use of the renewable energy unit at base station to provide reliable communication services with a fair allocation of network service over consecutive days. In this paper, based on renewable energy harvesting and prediction capabilities at base stations, and the daily trend of users network service time demand, we propose a method to provide reliable communication service enabling real time application such as voice call to users in rural areas of developing countries and in areas affected by disaster, while guaranteeing fairness in the daily allocation of network service time.

3.3 Summary

In this chapter, we depicted the various problems that occur in extending communication services in rural areas and in areas affecter by natural disasters. These problems comprise the absence of wired backhaul and the absence of power grid. In the next section, we describe our proposed solution.

Chapter 4

Envisioned Solution: Successive Shift Window-Based Daily Service Time Allocation

In this section, we present our envisioned method. In order to provide reliable and stable communication network services enabling real time application such as voice call in rural areas, and in areas struck by disaster and subject to power outage, we propose a synchronization-based scheduling method that takes into consideration renewable energy harvesting and prediction capabilities at base stations, the fluctuation in amounts and rates of energy available over time, and the daily trend of user demand.

4.1 Objectives

The objective of our proposed scheme it to perform an efficient synchronized base stations (BSs) ON/OFF toggle through which, we determine the energy allocation for each day to provide the maximum possible network service time over a given season or period of N days, while ensuring relatively equal service time over consecutive days. However, we face some challenges on the available information, such as the possible harvesting prediction of only n days, $n \ll N$, and the occurrence of eventual error in the prediction of the energy harvesting. To mitigate the above

Table 4.1: List of notations used in the paper.

Notation	**Definition**
BS	Base station
P_{act}	Energy consumed by a BS per hour when active
H_A^i	Energy available at BS A at the beginning of day i
B^*	BS with the lowest amount of energy to be harvested
n	shift window size
ϵ	Prediction error
S	seasonal parameter
α_i	adjustment parameter for the energy allocated to day i
α_{i-opt}	optimum adjustment parameter for day i
Ω_i	Upper bound of the daily service time requested by users
β	Decrease ratio

mentioned challenges, we make use of a successive shift window optimization process, where the window is of size n days and is updated at the beginning of each day.

Moreover, our successive shift window optimization process enables us to guarantee the fairness in network service time allocation over consecutive days. Here, given a day i, the shift window size n is the number of days still which the harvesting prediction is possible. In order to provide communication network services enabling real time application such as voice call, all macro base stations are set ON at the same time. Moreover, it is worth mentioning that the energy consumption of a macro base station is almost independent on the traffic load [29, 30]. Therefore, the power consumption of a macro base station is assumed to be quasi-dependent on time.

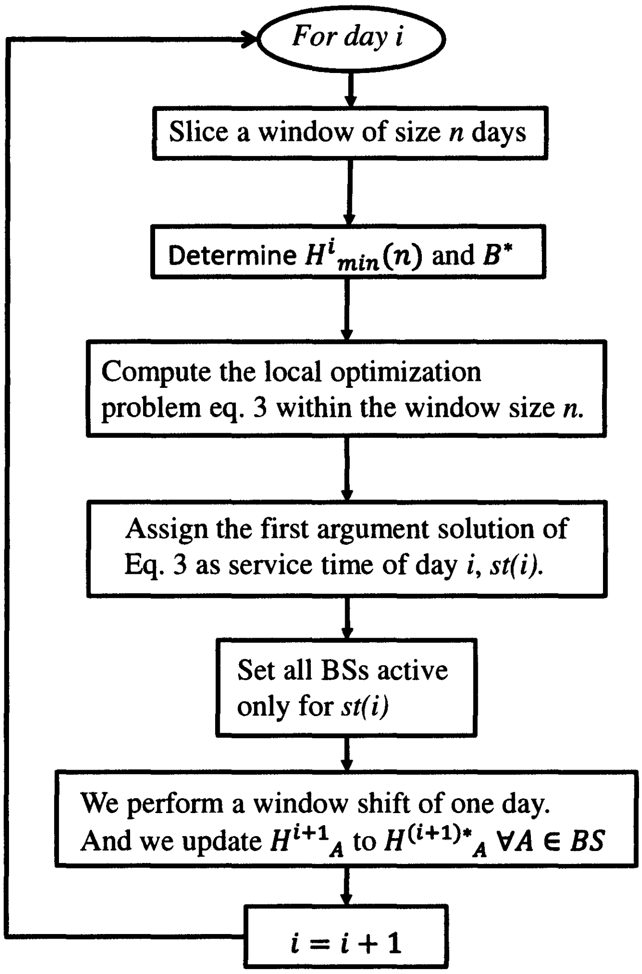

Figure 4.1: Description of the steps of the proposed method.

4.2 Process

Fig.4.1 demonstrates our proposed method, which is executed in time series. The figure shows a number of sequential steps performed at the beginning of each day, which are described in the following. The notations used in these steps are summarized in Table 4.1.

1. In the first step, we define a window of size n days including the current day, and we check the available energy of every base station in the system at the beginning of the current day i, and the energy estimated to be harvested

over the $n-1$ following days. Then, as in Eq. (4.1), we determine $H^i_{min}(n)$, the minimum amount of energy that could be harvested by a base station in the system throughout the window of size n days, and B_i the base station argument of $H^i_{min}(n)$.

$$H^i_{min}(n) = \min_{A \in BS}\left(\sum_{j=i}^{j=i+n-1} H^j_A\right) \tag{4.1}$$

$$B^* = Arg\left\{\min_{A \in BS}\left(\sum_{j=i}^{j=i+n-1} H^j_A\right)\right\} \tag{4.2}$$

2. In the second step, we maximize the total network service time within the window of size n through the following local optimization:

Maximize

$$\frac{1}{P_{act}}\left((H^i_{B^*} + \alpha_i P_{act}) + \sum_{j=i+1}^{n+i-1}\left((1-\epsilon)H^j_{B^*} + \alpha_j P_{act}\right)\right), \tag{4.3}$$

Subject to

$$\alpha_i \leq 0, \quad \alpha_j \leq \max(-\alpha_{j-1}, 0)\ \forall j > i,$$

$$-S \leq \alpha_j \leq S \quad i \leq j \leq i+n-1, \quad \Gamma_j \leq P_{act},$$

$$0 \leq \frac{1}{P_{act}}(H^i_{B^*} + \alpha_i P_{act}) \leq \Omega_i$$

The first and second constraint ensure a considerable small deviation in service time allocation over consecutive days. Where,

$$S = \frac{1}{P_{act}}\frac{H_{max} - H_{min}}{2},$$

represents the seasonal parameter which displays the harvesting difference between the day with the highest harvesting and the day with the lowest harvesting in a given season, with H_{max} and H_{min} corresponding to the maximum harvested and the minimum harvested energy, respectively. Meanwhile the second constraint correspond to the fact that the allocated service time of a given time cannot exit the upper bound of the daily service time requested by users.

3. In the third step, we assign the argument , solution of our local optimization problem as service time of the day i, $st(i)$ as in the following equation.

$$st(i) = \frac{1}{P_{act}}(H^i_{B^*} + \alpha_{i-opt} P_{act}). \tag{4.4}$$

   Where $\frac{1}{P_{act}}(H^i_{B^*} + \alpha_{i-opt} P_{act})$, is the first argument of the solution of our local optimization problem.

4. We then set active all the BSs for exactly $st(i)$. And we set all the BSs to sleep for the rest of the day, mainly during night, when the users demand for communication service is low.

5. At the end of the day, we perform a shift of one day, and we update H^{i+1}_A to $H^{(i+1)*}_A$ $\forall A \in BS$, following eq. 4.3

$$H^{(i+1)*}_A = H^{i+1}_A + \max(H^i_A - st(i), 0) \ \ \forall A \in BS. \tag{4.5}$$

6. Then for the following day, we restart the process and repeat the steps from 1 to 6.

4.3 Summary

In this chapter, we propose a successive shift window-based local optimization approach, which takes in consideration the renewable energy resource available and its harvesting prediction over a given horizon, to fairly allocate the network service time over days. In the following chapter, we perform some analysis to verify the correctness of our proposal.

Chapter 5

Analysis of the Effectiveness of the Proposed Method

In this section, we proof the effectiveness of our proposed method and its robustness to severe fluctuation in energy harvesting from ambient sources, in comparison to existing scheme. Here, our comparison candidate is the dynamic base station switching depict in chapter 2. In order to provide real time application such as voice call simultaneously to all users in the targeted area, we consider a synchronized ON/OFF switching of BSs. Moreover, we assume the upper bound of user daily network service time demand to be the same throughout the targeted area.

5.1 Definition and Description of the Comparison Candidate: Dynamic BSs Switching

The comparison candidate, dynamic BSs switching, can be described as follows:

5.1.1 Input

- *Base stations:*

  Due to the fact that our targeted areas are rural areas and disaster struck area, we consider bigger base stations, namely macro base stations as described in Table 2.1

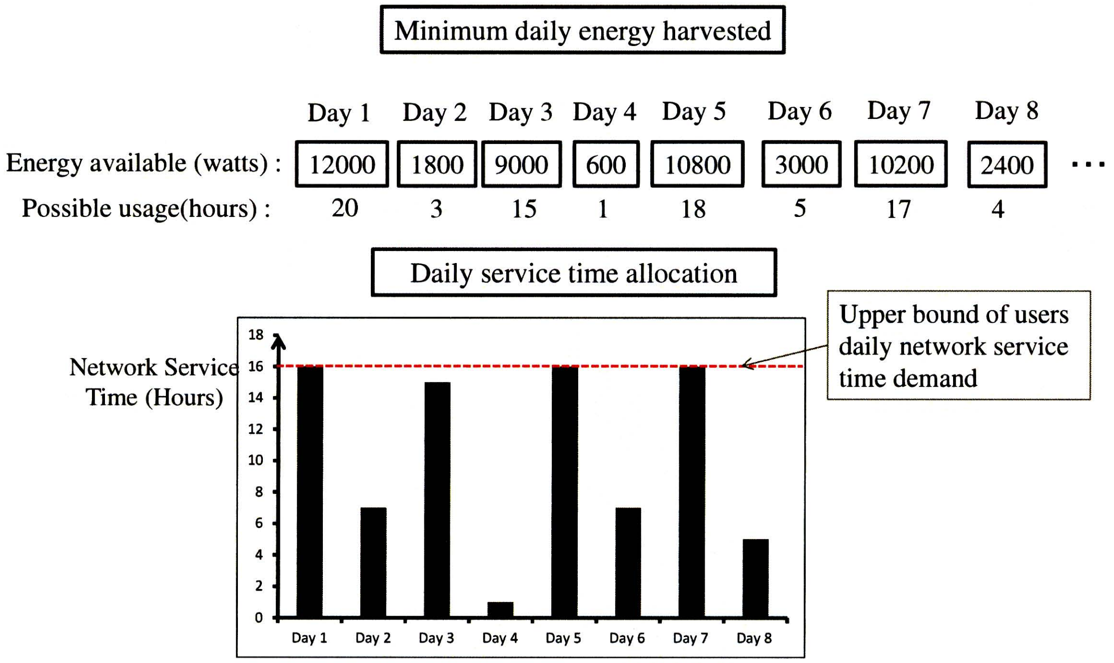

Figure 5.1: Sample service time allocation process of the traditional scheme

- *Users traffic per base station:*

  As described in Table 2.1, the power consumption of macro BSs is quasi-independent of users traffic. Thus, the users traffic is not considered in this case.

- *Upper bound of users daily network service time demand:*

  This parameter is calculated through historical data on the trend of the network service time requested by users of a given area and at a given season. For example, for a given region and a given season, users often request network service from 7:00 in the morning to 22:00 in the night. Thus, the upper bound of users daily network service time is 16 hours.

- *Energy availability of BSs at the beginning of each day*

5.1.2 Method

Based on the energy availability at BSs per day, this method decides the ON/OFF switching scheduling of BSs, through which all BSs are simultaneously set active active, such that the network service time of each day is less or equal to the upper bound of the users daily network service time demand. Thus, result in an allocation of network service time per day for a given season.

Fig. 5.1 depicts a sample service time allocation process of the traditional scheme. Here, the power consumed per base station per hour is set to 600 watts, meanwhile the upper bound of users daily network service time demand is set to 16 hours (from 7:00 to 22:00). For days when the available amount of energy at base station enables a possible usage of more than 16 hours, only 16 hours are allocated as network service time, and the remaining energy is kept and used on the following day.

5.2 Definition of our Evaluation Metrics

In this section, we define the metric used to evaluate our proposal, namely, the users' satisfaction ratio, and the mean time deviation. It is worth mentioning that in this chapter, the analysis are perform only with one evaluation metric, the mean service time deviation.

5.2.1 Users' Satisfaction Ratio

Here, we introduce our first evaluation metric, the user's satisfaction ratio (USR). This metric measures the satisfaction of users on the daily service time allocation, by evaluating the deviation between the allocated daily service time and the minimum service time required by users. Based on the concept of standard deviation in statistical data distribution, we define the users' satisfaction ratio as follow:

$$USR = 1 - \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(1-\chi(i)\right)^2}\ , \tag{5.1}$$

where,

$$\chi(i) = \begin{cases} \frac{st(i)}{\mu} & \text{if } st(i) \leq \mu \\ 1 & \text{otherwise} \end{cases}$$

N represents the number of days of the given season. Meanwhile, $st(i)$ and μ represent the network service time allocate to the day i and the minimum daily service time required by users, respectively.

5.2.2 Mean Service Time Deviation

Here, we introduce the mean service time deviation ($\overline{STD}$), which measures the fairness of the service time allocation over consecutive days. The mean service time deviation is compute as follow:

$$\overline{STD} = \frac{1}{N} \sum_{i=1}^{N} \big(|st(i) - st(i+1)| \big), \tag{5.2}$$

where $st(i)$ and N are the network service time allocate to the day i and the total number of day of the targeted season or period, respectively.

In our analysis, we assume that the energy harvested each day is less or equal to the energy required to satisfy the upper bound of the daily users demand, and gradually decreases with days. Moreover, we assume a constant decreasing ratio, β. For a given day i, the network service time $st(i)$ can be given by eq. 5.3 and eq. 5.5 for the traditional and proposed schemes, respectively.

- Dynamic BS switching approach

$$st(i) = \frac{1}{P_{act}} H^{i}_{min}, \tag{5.3}$$

where H^{i}_{min} is the lowest amount of energy available at any BS at the beginning of day i. Thus, the mean service time deviation can be given as follows:

$$\overline{STD} = \frac{1}{P_{act}} \beta, \tag{5.4}$$

- Proposed scheme

$$st(i+1) = \frac{1}{n * P_{act}} \left\{ \left(\sum_{j=i+1}^{i+n-1} H_{B*}^{j} \right) + |H_{B*}^{i} - st(i)| \right\}, \tag{5.5}$$

where,

$$st(1) = \frac{1}{n * P_{act}} \sum_{j=1}^{n} H_{B*}^{j}.$$

After expansion and simplification, we obtain the following equation:

$$st(i+1) = \frac{1}{P_{act}} \left\{ H_1 - \frac{\beta}{2(n+1)} \psi(i,n) \right\}, \tag{5.6}$$

where,

$$\psi(i,n) = \left(\frac{-1}{n} \right)^{i+1} + \left(\frac{-1}{n} \right)^{i} + n(n+3-2N) - 2N.$$

Thus, the mean service time deviation can be given as follows:

$$\overline{STD} = \frac{\beta}{2P_{act}(N-1)} * \Theta(n), \tag{5.7}$$

where,

$$\Theta(n) = 1 - \left(\frac{-1}{n} \right)^{N-n} - 2n^2 + n \left\{ \left(\frac{-1}{n} \right)^{N-n} + 2N - 3 \right\} + 2N.$$

5.3 Comparison of the Mean Service Time Deviation: Proposal vs Traditional

5.3.1 Impact of the window size n on the daily network service time allocation

In order to evaluate the impact of our window size on the service time allocation over days, we perform a comparison of mean service time deviation obtained through our proposal and the one obtain through the traditional scheme, and compute the difference $(eq.5.5 - eq.5.7)$. It is worth mentioning that the smaller the mean service time deviation, the fair is the daily service time allocation. We obtain the following function:

$$f(n,\beta) = \Delta(\overline{STD}) = \frac{\beta}{2P_{act}(N-1)} * g(n), \tag{5.8}$$

where,

$$g(n) = \frac{1}{n+1}\left\{2n^2 + n\left(1 - \left(\frac{-1}{n}\right)^{N-n}\right) + \left(\frac{-1}{n}\right)^{N-n} - 3\right\}.$$

In realistic environment, $n < N$, thus, $g(n)$ can be given as follow,

$$g(n) = \frac{2n^2 + n - 3}{n+1}.$$

We easily prove by induction that $g(n) > 1$, $\forall n \geq 2$. Thus, we prove that $f_\beta(n) > 0$ $\forall n \geq 2$ which result in our method outperforming the traditional scheme in providing a fair daily service time allocation independently of our window size, with a lower mean service time deviation.

5.3.2 Impact of the harvesting fluctuation on the daily network service time allocation

In order to evaluate the impact of harvesting fluctuation on the service time allocation over days, we consider the function

$$f_n(\beta) = \frac{g(n)}{2P_{act}(N-1)} * \beta.$$

With the fact that

$$g(n) > 1 \ \forall n \geq 2,$$

we easily prove that $f_n(\beta)$ increases linearly with respect of β. Thus, in an environment with severe harvesting fluctuation over days i.e., big value of β, our proposed scheme highly outperforms the traditional scheme.

5.4 Summary

In this chapter, through analysis, we demonstrated the effectiveness of our proposal and its robustness to severe fluctuation in energy harvested over days in comparison to the existing scheme. In the next chapter, we perform computer-based simulation to prove the effectiveness of our proposed scheme and validate the analysis findings.

Chapter 6

Performance Evaluation

In this section, we describe the performance evaluation of our proposed scheme carried out through computer-base simulations. We evaluate the effectiveness of the use of our shift window process on the fairness of the daily service time allocation. Moreover, we evaluate the robustness of our proposal to high fluctuation in energy harvesting over consecutive days. The dynamic BSs switching scheme described in the previous chapter is used as comparison candidate. Furthermore, we evaluate the robustness of our proposed scheme to the occurrence of prediction error. To evaluate the effectiveness of our proposal, we use the evaluation metrics depicted in 5, namely, the mean service time deviation and the user's satisfaction ratio, which evaluate the fairness in the daily allocation of service time, and the deviation between the service time allocated per day and the minimum daily service time required by users, respectively.

6.1 Simulation Settings

The considered simulation parameters are listed in Table 6.1. As shown in Table 6.1, the time to provide communication service is a period of three weeks. We consider a wireless mesh network model of 20 base stations, and we assume all base stations are equipped with photovoltaic cell, and a battery with a capacity of 20 Kwh. We assume that the maximum possible harvesting prediction horizon is one

Table 6.1: Simulation environment.

Parameter	Value
Number of BSs	20
Power consumed per hour (P_{act})	600 watts
Number of considered days (N)	3 weeks (21 days)
Window size (n)	2 to 7 days
Seasonal parameter (S)	10 hours
User demand upper bound	16 hours (6 AM-10 PM)
Minimum service time required (μ)	12h - 16h
Prediction error	0% - 40%

week, thus, our window size varies from 2 to 7 days. moreover, for the simulation, we set the seasonal parameter of 10 hours and the upper bound of the daily service time demand of user to 16 hours (from 6 AM to 10 PM). Meanwhile, we set the initial value of the minimum daily service time required by users to be 75% of the upper bound of their daily demand (i.e., $75\% \times 16h = 12h$)

6.2 Effectiveness of the shift window process on the fairness of the service time allocation

In order to evaluate the effectiveness of our successive shift window approach, we set a random harvesting profile with the existence of sunny, cloudy and rainy days, alternatively. We consider a given period of 3 weeks (21 days). Then, we varied the window size from 2 to 7 days, and we compute the mean service time deviation. Here, we assume a perfect prediction, i.e., $\epsilon = 0$. Fig. 6.1 demonstrates that independently of the value of our window size, our proposed scheme shows a lower mean service time deviation in comparison to the traditional, thus, our proposal enables a fair network service time allocation over consecutive days. Moreover, for

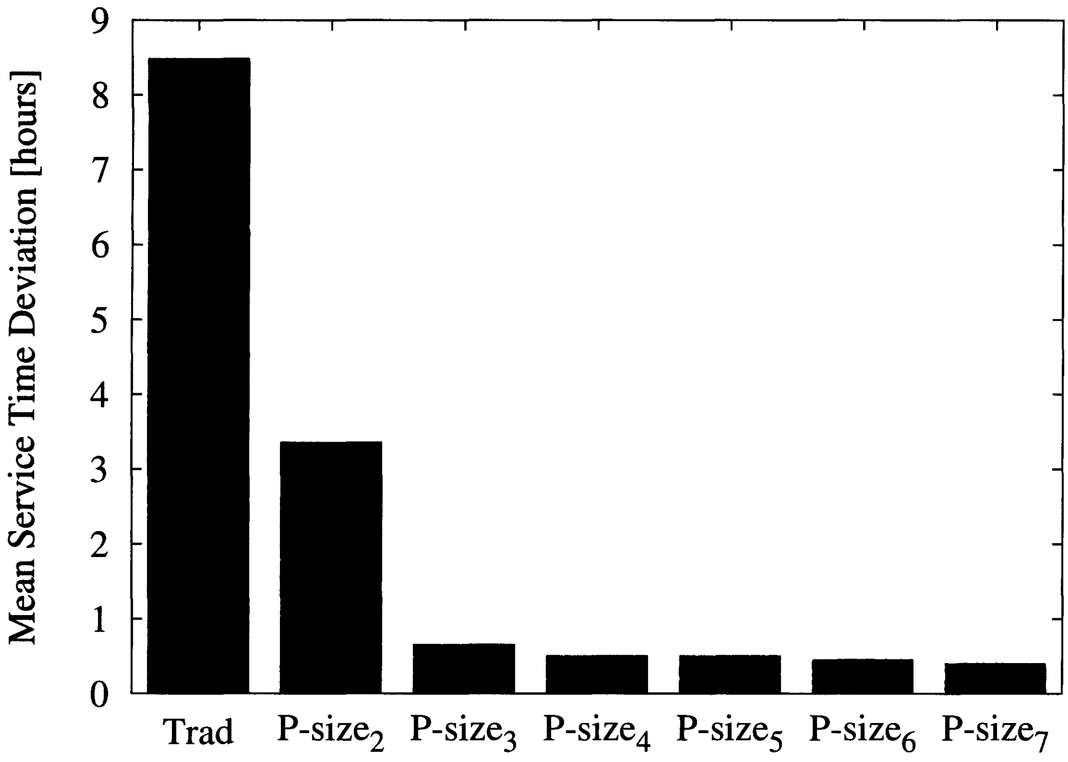

Figure 6.1: Impact of window size n on the daily service time allocation

window sizes greater than 2, our proposal provides network services with relatively equal service time every day.

6.3 Robustness to high fluctuation in energy harvesting

To evaluate the robustness of the proposed scheme to high fluctuation in energy harvesting over days, we considered a similar environment to the previous, with a given period of 3 weeks, and a perfect prediction, i.e., $\epsilon = 0$. We define a random harvesting profile where the minimum harvesting fluctuation is set to β. Then, we vary the value of β from 600 to 6000 watts. We consider windows of size 2, and

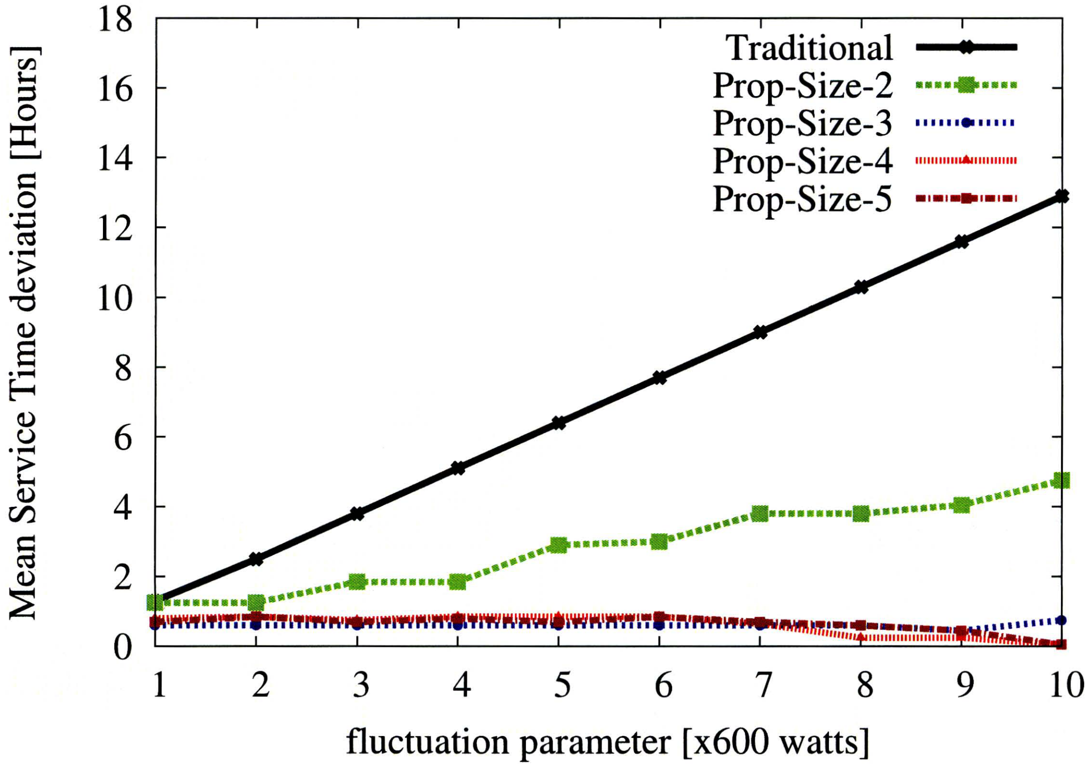

Figure 6.2: Performance on high harvesting fluctuation

3 days, and we compute the mean service time deviation. Fig. 6.2 shows that the increase of the value of β considerably increases the mean service time deviation in the traditional scheme. Meanwhile, in our proposed scheme, for a window size of 2 days, the increase of the value of β slightly increases the mean service time deviation. For a window of size greater or equal to 3 days, we can see that the mean service time deviation is almost not affected by the high fluctuation in harvesting over days. Thus, through our shift window-based approach, we can provide network that guarantee fairness in the daily service time allocation despite the high fluctuation in harvesting that occur in realistic environment.

Moreover, Fig. 6.1 and Fig. 6.2 show that our simulation results verify our analysis findings depicted in chapter 5.

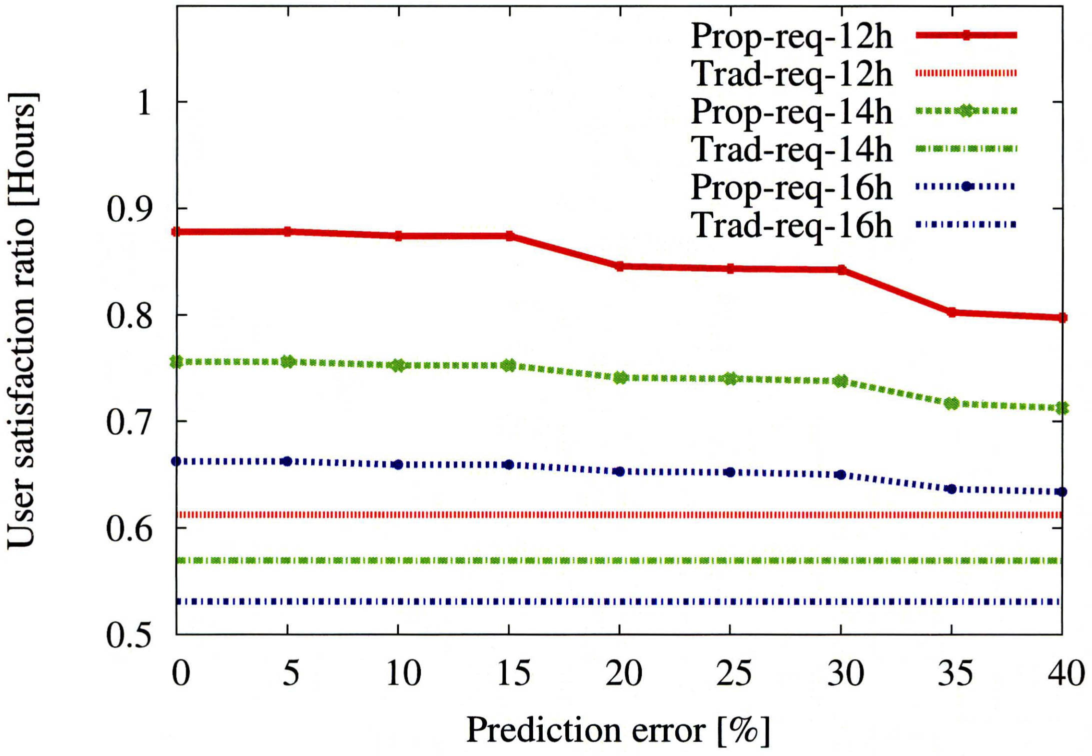

Figure 6.3: Performance on prediction error

6.4 Robustness to the occurrence of prediction error

To evaluate the robustness of the proposed scheme to the occurrence of prediction error in energy harvesting over days, we considered a similar environment to the previous, with a given period of 3 weeks. Here, we fixed our window size to $4days$ and we vary the prediction error, ϵ from 0 to 40%. We set a random harvesting profile with the existence of sunny, cloudy and rainy days, alternatively. Then, we varied the window size from 2 to 7 days, and we compute the users' satisfaction ration, USR. We perform the simulation for 3 different value of the minimum daily service time required by users, 12 $hours$, 14 $hours$, and 16 $hours$, corresponding to

75%, 87, 5%, and 100% of the upper bound of the daily service time demand from users, respectively.

As depicted in Fig. 6.3, despite the occurrence of prediction error in the energy harvesting prediction over days, for the minimum daily time requested by user equal to 12 *hours*, 14 *hours* and 16 *hours*, our proposal ensures a satisfaction of more than 80%, 70%, 62%, respectively. Meanwhile, the traditional method can not a satisfaction ratio greater than 62% for a minimum daily time requested by user greater or equal to 12 *hours*. Fig. 6.3 demonstrates that our proposed scheme can provide a stable network service robust to the occurrence of prediction error.

6.5 Summary

In this chapter, we performed computer-based simulations, we first show the effect of shift window size on mean service time deviation of our proposal, in comparison to existing scheme. Moreover, we show the robustness of our proposed scheme to high fluctuation in energy harvesting, and to the occurrence of prediction error. Furthermore, the simulation results show that by making use of our successive shift window local optimization approach, our method can provide a reliable service, while guaranteeing a fair allocation of network service time over days and ensuring users satisfaction in their daily network service time request within a given period or season.

Chapter 7

Conclusion

In this thesis, we focused on extending communication network services in rural areas without power grid, and quickly responding to network service demands of users in disaster areas, where the power supply and the wired communication lines are damaged. In order to mitigate the high expenses of the wire backhaul, such as fiber, in rural areas of developing countries, and the eventual damage and disruption of wired transmission lines in areas affected by natural disasters, attention has been paid on wireless mesh network composed of base stations. One of the key challenges in wireless mesh network comprising base stations equipped with renewable energy harvesting module in rural region and disaster struck areas is to provide a reliable communication networks, handling real time application such as voice call service, with the available energy resources subject to considerable fluctuation over time.

By making use of a successive shift window-based local optimization approach, we addressed the above mentioned challenge in this paper. We define a new metric, mean service time deviation, that displays the fairness in daily network service time allocation. Through analysis, we prove the effectiveness of our proposal in comparison to the traditional scheme, dynamic base station switching, independently of the size of our shift window. Moreover, we prove the robustness of our proposed scheme to a severe fluctuation in energy harvesting over days. Simulation results show that our proposal outperforms the traditional approach, and can provide the maximum possible network service time within a given season, despite an eventual occurrence of prediction error. Furthermore, our experimental results confirmed our analyses' findings.

The contents of the chapters in this thesis can be summarized as follows.

- •**Chapter 1** The background and objectives of this thesis are introduced.
- •**Chapter 2** In this chapter, we overview the wireless base station mesh network comprising base station powered by renewable energy. We investigate the challenges encountered by such networks.
- •**Chapter 3** In this chapter, we depicted our considered network model and system assumptions. Moreover, we formulated the problem that needs to be addressed in such networks.
- •**Chapter 4** We introduce our proposed method in this chapter. The method makes use of a successive shift window approach of size n days to guarantee a fair allocation of network service time over consecutive days.
- •**Chapter 5** In this chapter, we analyse the effect of our window size n on the effectiveness of our proposal, and its robustness to severe fluctuation in energy harvesting over time, in comparison to existing scheme.
- •**Chapter 6** This chapter shows the performance evaluation that is conducted through computer-based simulation. The results demonstrate that the use of a successive shift window-based approach guarantee a relatively equal network service time over consecutive days. Moreover, the use of our successive shift window approach enable our proposal to be robust to the occurrence of prediction error.

With the achieved results, our proposal can be considered as an efficient service time scheduling that provides reliable communication network services, while mitigating the issue of fluctuation of the behaviour of ambient sources of energy in wireless base station mesh network in disaster struck areas and rural regions in developing countries, where the only available power sources are ambient sources, namely, sun and wind, subject to considerable variation over time.

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