Real-World Energy Measurements of a Wireless Mesh Network

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Abstract. Over the past several years the topics of energy consumption and energy harvesting have gained significant importance as a means for improved operation of wireless sensor and mesh networks. Energy-awareness of operation is especially relevant for application scenarios from the domain of environmental monitoring in hard to access areas. In this work we reflect upon our experiences with a real-world deployment of a wireless mesh network. In particular, a comprehensive study on energy measurements collected over several weeks during the summer and the winter period in a network deployment in the Swiss Alps is presented. Energy performance is monitored and analysed for three system components, namely, mesh node, battery and solar panel module. Our findings cover a number of aspects of energy consumption, including the amount of load consumed by a mesh node, the amount of load harvested by a solar panel module, and the dependencies between these two. With our work we aim to shed some light on energy-aware network operation and to help both users and developers in the planning and deployment of a new wireless (mesh) network for environmental research.

Keywords: Wireless mesh networks · Real-world deployments · Energy measurements · Harvesting and consumption · Energy efficiency

1 Introduction

Technical advances in recent decades have led to availability of a wide range of reasonably priced sensors for hydro-meteorological, or generally any other type of systems for environment monitoring. Still, the wide spread-deployment of such systems depends on the costs for data-transfer and maintenance, especially for sensor networks placed in remote or hardly accessible sites. To tackle the connectivity issue, current research combines (wireless) sensor networks with wireless mesh networks to obtain a more optimized system solution. In particular, a wireless mesh network is used to connect separate sensor networks with

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e.g. a monitoring platform, or as a scalable backbone for sensor-to-sensor communication by connecting the separate sensor networks associated to each mesh node.

As more and more outdoor applications require long-lasting, highly energy-efficient, and in fact continuously-working mesh networks running on battery-powered mesh nodes, research on multiple aspects of energy consumption becomes critical. One often taken path by researchers is developing solutions to decrease the energy cost of operation of, e.g., energy-aware routing protocol, algorithms to improve communication schemes, etc. While we acknowledge the importance of this research, we argue that it is of utmost importance to study the problems of energy provisioning as well. Running on batteries is an excellent solution for node independence but unfortunately faces the issue of possible battery depletion. Leaving aside convenience, change of the battery is not feasible for difficult to access deployments, as the one we address in this paper. Therefore, the problem of energy harvesting and energy consumption plays an increasingly important role.

The choice of an appropriate energy harvesting strategy mainly depends on the expected lifetime of the deployed network, the actual energy consumption of the nodes and the physical requirements towards the node design. Although there are several studies that consider energy consumption by wireless sensor or mesh nodes, to the best of our knowledge, none of them conducts investigations in on-site deployed network. In this paper we aim to bridge the gap by offering analysis of a large amount of energy-related measurement data, collected in a real-world wireless mesh network.

The real-world wireless mesh network, referred to as A^4-Mesh[1], was designed and deployed in the Swiss Alps to serve the needs of distant hydro-meteorological monitoring in remote locations. Its purpose is to provide researchers with secure access to their measurements of interest, irrespective of the location. To this extent, the mesh network should support communication to the sensing devices at all times, irrespectively of whether to collect measurement data or to send control commands. To ensure constant availability of the mesh backbone we rely on solar energy.

Our contribution in this paper focuses on providing feedback on the energy-related operation of a wireless mesh network in a real-world deployment. Both energy consumption and energy provisioning are considered. In particular, we conduct measurements to monitor and analyse the energy behaviour of the wireless mesh network from three different perspectives, namely, the mesh node, the battery and the renewable energy source (solar panel module in our case). We believe that our findings can provide an important basis to help researchers and other interested parties in the planning and deployment phase of a wireless mesh network supporting environmental monitoring.

[1] A^4-Mesh project and its currently ongoing extension aims at developing a completely functional wireless mesh infrastructure including support for authentication and authorization, accounting, and auditing. For more information, please visit project's website https://a4-mesh.unibe.ch/

The remainder of the paper is organized as follows. Section 2 gives an overview of recent work regarding the deployment of wireless mesh networks, hardware and software approaches to tackle the problem of energy efficiency. Section 3 discusses the design and realisation of the wireless mesh network. Section 4 presents the energy monitoring setup and our findings on energy harvesting and energy consumption in the deployed wireless mesh network. Finally, Sect. 5 summarizes the paper and outlines several interesting problems for further research.

2 Related Work

Wireless mesh networks (WMNs) have been subject to intensive research for several years. This is mainly due to the fact that WMNs imply both the ad-hoc and the traditional infrastructure model of access networks, offering more flexibility but also posing various new challenges for researchers and developers. A comprehensive review on the main research challenges in wireless mesh networks is provided in [1,2], and the most recent one in [3].

Generally, a WMN consists of wireless mesh nodes, which can operate as hosts but also as routers, being in this way access point for the mesh clients. The mesh nodes are typically fully functional computers with tailored embedded operating systems so as to match hardware resource constraints. The mesh clients are often laptops, cell phones or other wireless devices, through which various measurement devices such as sensors can be connected. Single-hop as well as multi-hop modus operandi is supported. The flexibility of mesh nodes in forming a network makes them appropriate choice to form the communication backbone for a large range of application scenarios, including environmental and habitat monitoring, safety surveillance and many others.

First outdoor applications of WNMs have been reported in e.g. [4] for serving local flood warning system and in [5] for facilitating sensor data collection for ecological researchers in a natural reserve. Other applications concern applying wireless mesh networks for safety surveillance in industry or public environments, tactical support for the military, as well as many public and commercial service networking scenarios. An extensive overview of these can be found in [1]. Although each of these scenarios poses various research challenges in terms of routing, connectivity or data processing, in this paper we are more interested in the aspect of energy-operation.

Energy-aware design for wireless mesh networks has been studied from many angles. In the context of the project SolarMESH [6], the potential of powering 802.11-based mesh networks using solar power and rechargeable batteries has been examined. In particular, the problem of lower power operation at the network layer is addressed by the authors. Then, from the perspective of provisioning each node with a solar panel and battery combination that is sufficient to prevent node outage for the duration of the deployment, one could refer to [7,8]. Related to it, the resource allocation and outage control for solar-powered WLAN mesh networks is considered in [9].

Furthermore, in [10] authors propose a context-aware energy management system for network nodes that are energy-self-sufficient. Moreover, a battery-aware scheme for energy efficient coverage and routing is proposed in [11]. In addition an energy model for network coding-enabled WMN, based on the IEEE 802.11 technology, is studied in [12]. Lastly, in [13] authors investigate the energy consumption behavior, though from a perspective of a wireless network interface in an ad hoc networking environment. However, to the best of our knowledge, no study attempts to determine the energy generation and the energy consumption of a real-world wireless mesh network, nor it, in that way, focuses on the energy-aware approach to the deployment of a new wireless (mesh) network. Our paper makes this attempt by measuring and analysing a large amount of energy-related measurement data of a real-world wireless mesh network.

3 WMN Supporting Environmental Research

Deployment of a real-world wireless network requires careful design and meticulous consideration of various aspects related to its way of operation, communication, tooling, etc. Failing to do so can lead to poor or even erroneous network performance. Accordingly, the deployment of the A^4-Mesh network has proceeded in steps, considering system purpose, deployment environment, and technology solutions.

3.1 WMN Deployment Scenario

The application scenario, supported by the A^4-Mesh network, considers an hydro-meteorological monitoring network in the field that should be remotely accessible by researchers at university laboratories. The monitoring network consists of different measurement devices (i.e., sensors) located at various remote sites. From the researchers' perspective it is very desirable and highly convenient to access the devices directly from the campus site, ensuring in this way data transfer at frequent intervals as well as the possibility of remote control, which both reduce the risk of data loss. Hence, a large amount of data, produced by the sensors, needs to be transferred to the university campus, preferably in near real-time. Moreover, a control channel to the sensor network should be supported as well.

In the A^4-Mesh network we propose to use a wireless mesh network as the communication backbone. It is a common form of WMN, where each mesh node relays data for other mesh nodes (a typical adhoc networking paradigm) and only few mesh nodes can additionally act as routers, becoming Internet gateways. The wireless mesh nodes interconnect their corresponding hydro-meteorological sensor(s) to the university campus network through the wireless mesh gateway. Hence, the deployed A^4-Mesh network successfully serves the purpose of a communication infrastructure for environmental monitoring, giving researchers low-cost broadband network access. Figure 1 shows the network setup with the distance of each wireless link and the locations of the connected environmental monitoring stations.

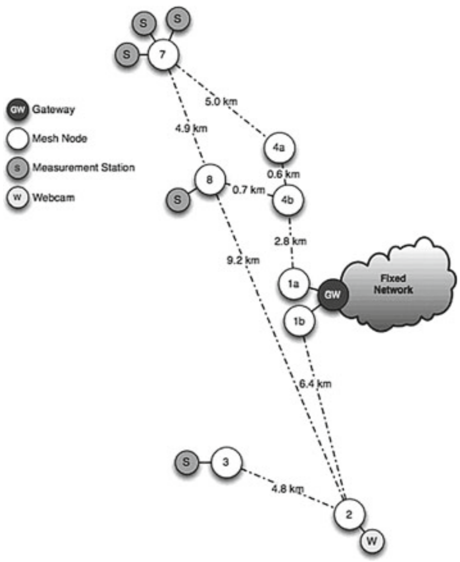

Fig. 1. Wireless mesh network deployed for support to environmental research.

The A^4-Mesh network is deployed in the Swiss Alps, in the Valais region. Figure 1 shows the network setup, used in our measurements, with the distance of each wireless link and the locations of the connected environmental monitoring stations. Node 1 serves as a gateway to the fixed network and thus carries the traffic between the mesh nodes and the Internet. The first link from node 1 is directed to a relay station (node 2) in Vercorin at the opposite hill slope, where a webcam is located. The second link from node 1 connects to nodes 4a and 4b in Cry d'Er. Node 3 connects to the gateway through node 2. Clients, i.e. measurements stations, connect to the mesh nodes using wireless or wired links.

The region where the wireless mesh network is deployed (in the Valais region of the Swiss Alps) has extreme weather conditions with a lot of snow in the winter, requiring mesh nodes that are specifically built for these conditions, i.e. durable cases, self-contained power supply, etc. The latter is especially important and should be able to provide energy to the node at any time. We chose for a solar panel module accompanied by batteries powerful enough to bridge periods of poor sunlight during the long winter period. The panels should be at least 3 meters above the ground to prevent them from being covered by snow. The initial and the final installation of one of the wireless mesh nodes are shown in Fig. 2.

In order to allow for easy access to the A^4-Mesh network, special care was taken regarding the seamless integration of authorisation and authentication functionality into the organization's own authentication and authorisation infrastructure (AAI). In our particular case an existing AAI Shibboleth-based federation, namely, SWITCHaai was used [14]. SWITCHaai is operated by SWITCH,

Fig. 2. Initial and final installation setup of a wireless mesh node for support to environmental research.

the Swiss National Research and Education Network operator, and offers convenient access to academic resources through a single 'virtual ID'.

3.2 WMN Design and Realisation

In current wireless networks, the design of wireless mesh nodes differentiates between two main building blocks, namely, the computer and the wireless hardware. The computer is composed of all those components that are generic to any networking platform and provide the main processing operations required to support the networking process. On the contrary, the wireless hardware refers to the components of the node specific to the wireless transmission process. This includes the wireless cards and other RF components that might be used on the node. Figure 3 shows a block diagram of our wireless mesh node design. It consists of two main system boards, on the left and right side, and one additional backup board in the middle with support for cellular connectivity. The specific

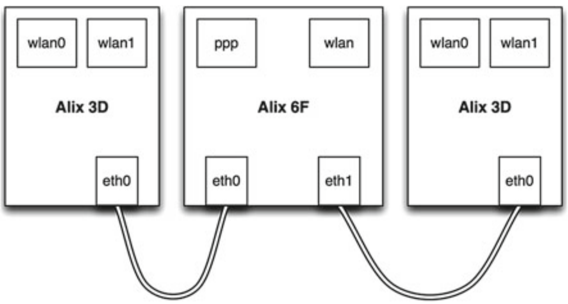

Fig. 3. A block diagram of the wireless mesh node design.

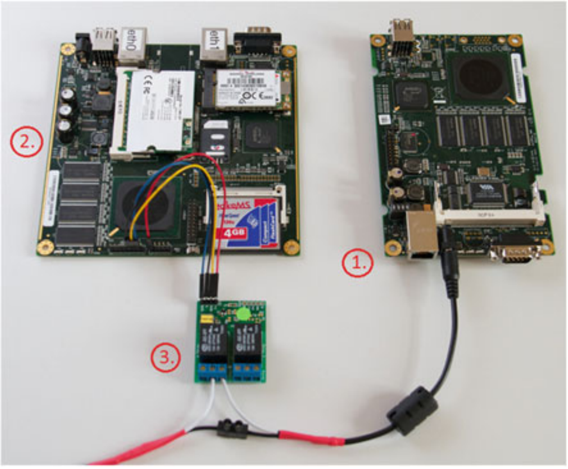

Fig. 4. An example of the main board (1) together with the backup board (2) and the controlling reboot relay (3) of a wireless mesh node used in the deployment of the A^4-Mesh network.

design choice is motivated by the need for remote recovery in case of failure of the mesh node. If an erroneous image is uploaded to a mesh node, we are still able to connect to the backup board through the cellular networks and either reboot the node or upload a new image. Hence, the need to physically access a temporally non-operational node is omitted, reducing maintenance costs of the overall WMN. The use of a backup board additionally improves the node uninterrupted operational lifetime, or at least for nodes covered by cellular networks.

For the realisation of the mesh nodes we selected PC Engines ALIX boards, which are small form factor system boards optimized for wireless routing and network security applications. ALIX.3 series boards are used as the two main system boards while an ALIX.6 series board with support for GSM/UMTS cards is used for the backup board. Figure 4 shows an example of interconnected main system and backup board of a mesh node we used in our deployment. Then, in terms of wireless hardware, the two ALIX.3-series boards have 802.11n radio cards installed in the miniPCI socket. These are used to provide the interconnection link between the mesh nodes. Note that on each main system two cards are installed, supporting in total up to four links per one mesh node. The ALIX.6-series backup board has an 802.11 a/b/g radio card installed in the miniPCI socket, providing wireless connectivity, and an UMTS embedded module of Sierra Wireless AirPrime MC Series.

As the current deployment of the A^4-Mesh wireless mesh network is based on the IEEE 802.11n standard, appropriate antennas are necessary. 802.11n builds on previous 802.11 standards by adding multiple input multiple output (MIMO) technology to improve network throughput. Therefore, we used MIMO 25 dBi Dual Polarization Panel antennas, which are designed for the 5.8 GHz frequency

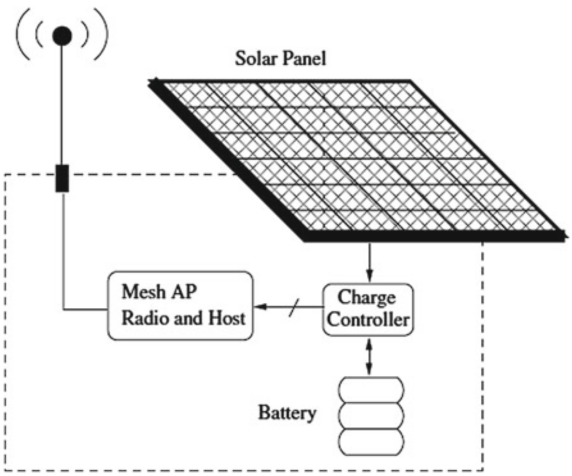

Fig. 5. Schematic of a simple solar panel charger circuit, taken from [7].

range and, at rating of 25 dBi, perfectly suited for our long distance point-to-point communication. Furthermore, the mesh node is connected to a twin relay that works with the standard I2C interface to control and individually reboot up to two connected mesh boards easily and without taking up any ports or MPU resources. Relays are configured to conduct electric current to the connected board when turned off.

The whole operation of the mesh nodes is supported by a solar-based power system. Solar energy is harvested by means of a single solar panel per node, i.e., the STM 90 model by SunTechnics with nominal voltage of 18.75 V. The panel is especially appropriate for off-grid solar installations due to its light weight and convenient dimensions. The panel is used to feed the mesh node or to charge the battery. We are using the NPL78-12FR 78 Ah model by Yuasa, which is a sealed lead acid battery. In order to maximise the battery charging state and protect from over-discharge a Maximum Power Point Tracking (MPPT) controller is included, in particular the MorningStar's Sun Saver SS-MPPT-15L model is used. The charging circuit is depicted in Fig. 5.

4 Energy Measurements

Energy measurements were taken over two periods of several weeks each, one in summer and one in winter. In summer, measurements were taken for node 7 and node 8, and in winter for node 3 and node 7 (node 8 had to be replaced in winter for safety of the ski pistes near which it was initially located). Data was collected on the voltage (in Volts) of the solar panel and the battery as well as on the load (in Ah) of the mesh node and the battery. All measurements were taken by programming the SunSaver MPPT charge controller to log measurements data at specified intervals throughout the day and night.

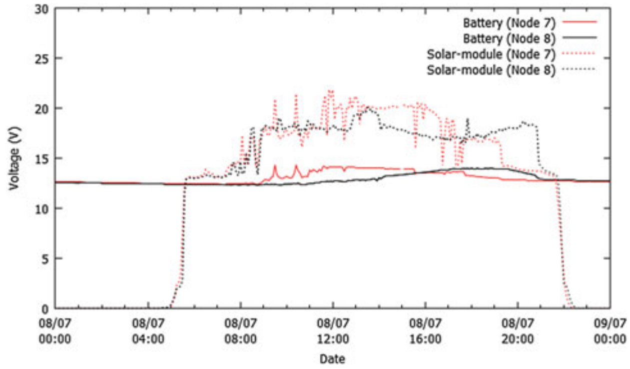

Fig. 6. Measurements of voltage at the battery and the solar panel module of two mesh nodes for an arbitrary summer day taken randomly from the data set.

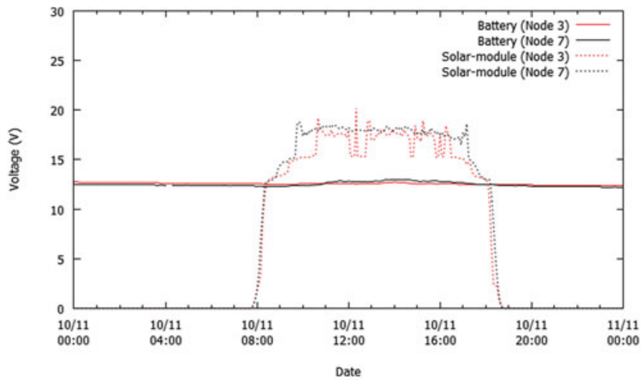

Fig. 7. Measurements of voltage at the battery and the solar panel module of two mesh nodes for an arbitrary winter day taken randomly from the data set.

We begin the discussion with analysing the behaviour of the voltage of both the solar panel and the battery over a single day, taken arbitrary from the data set. The graphs in Figs. 6 and 7 show the results for the summer and winter period, respectively. Although there is variation in the solar panel voltage, significant at times, the average voltage remains high above 15 V in both summer and winter periods, implicating that sufficient node provisioning and battery charging (a 12 V battery charges at about 14 V) can be achieved. The peak fluctuations in the voltage observed during the daytime are primarily due to shadows or clouds, in which cases the battery seamlessly takes over powering the mesh node. Moreover, we observe that the solar panel voltage is influenced not only by the season (higher voltage is recorded in summer) but also by the node location (the daily voltage variations differ per node).

Some other, straightforward observations for the solar panel are: (1) as it can be expected, as soon as the sun goes down, light stops hitting the solar panel

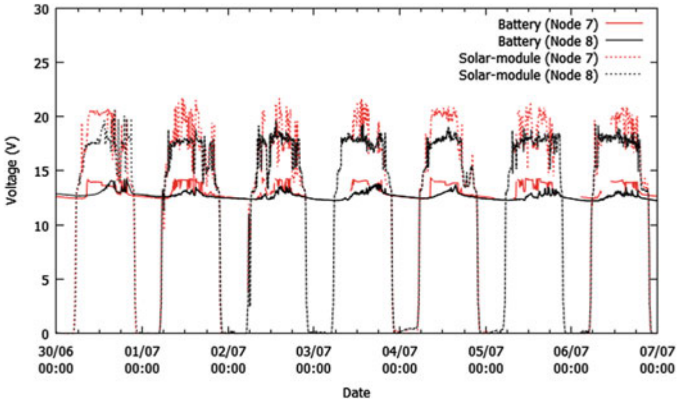

Fig. 8. Measurements of voltage at the battery and the solar panel module of mesh node 8 for one week taken randomly from the data set.

and its voltage drops instantly from a high of above 15 V to a low of 0 V; (2) also intuitive is the longer solar panel activity period in summer due to longed daylight time, e.g., during summer the battery only switches in as a back-up after approximately 9PM until about 7AM (see Fig. 6) while during the winter it does so from about 7PM to 9AM (see Fig. 7). Note that the solar panel generating energy does not necessary mean that the battery is not used at all.

Moving the focus to the battery, its voltage curve appears constant throughout the night when the battery is supplying energy to the mesh node. During daytime there are slight fluctuations in the battery voltage, which is due to the charging of the battery by the solar module. This is especially well visible for the summer period, when one can expect more intensive sunlight. Our observation is further confirmed by looking at a week-long measurement in the summer period as shown in Fig. 8. The figure clearly shows that battery voltage of both nodes can vary considerably over daytime, always above 12 V due to charging, and does so correspondingly due to the variations in the voltage of the solar panel. Moreover, the graphs in Fig. 8 reveal that the voltage values of both the battery and the solar panel module display the same repetitive behaviour during the course of days. During a single day (daytime plus night), the voltage within the mesh node system will be either around 12 V (below which the battery supplies power to the mesh node) or around 18–20 V (when the solar panel module powers the mesh node and recharges the battery). The same measurements but made in winter do not show significant deviations in general behaviour and are omitted here because of space constraints.

The relation between solar panel and battery voltage is well visible in Figs. 9 and 10. The data was collected over a period of few weeks in summer and winter, respectively. We see that the voltage at which the solar panel module produces maximum power in summer is at maximum around 24 V, while in the winter period the voltage reaches a maximum of only around 22 V. At the same time

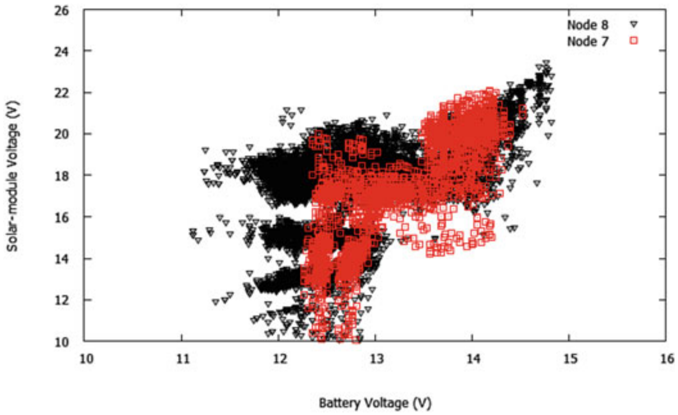

Fig. 9. Relationship between battery and solar panel module voltage. Measurements were taken at two nodes from our real-world wireless mesh network, for a period of few weeks in summer.

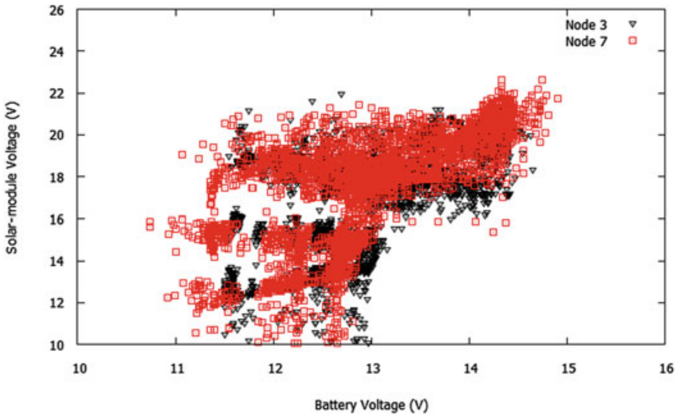

Fig. 10. Relationship between battery and solar panel module voltage. Measurements were taken at two nodes from our real-world wireless mesh network, for a period of few weeks in winter.

lower voltage states are more often reached by the battery voltage in winter, also corresponding to more extensive use of the battery in winter. We also see that as long as the solar panel voltage is above 16 V the battery can charge (its voltage reaches up to 14.5 V), which is in line with the nominal voltage of the panel. It should be noted that delivering charge to the battery at 16 V and delivering enough energy to support the mesh node and battery are not the same. It is possible, as the figures show, that the solar power generates energy but which may not be sufficient to fully recharge the power consumed by the node. Below solar panel voltage of 16 V the battery is mainly discharging with sporadic charges, which are nevertheless not enough to compensate for the discharge. The

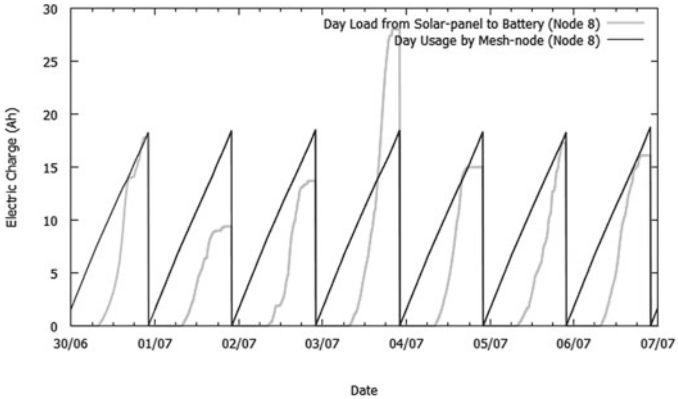

Fig. 11. Battery day load (Ah) along with the mesh node day usage (Ah). Measurements were taken at the mesh node 8 from our real-world wireless mesh network, for a period of one week in summer.

relationship between the battery voltage and the mesh node voltage was also analysed. We observed that they are positively correlated, implying that if one variable increases, the other variable also increases and vice versa. The figures are omitted here because of space constraints.

Along with voltage measurements we also collected data on the electric charge (expressed in Ampere-hours) of the battery and the mesh node. Figure 11 displays the battery day load together with the mesh node day usage for an arbitrary week in summer from the data set. The measurements concern mesh node 8, which is central to the wireless mesh network, see Fig. 1. In addition, Fig. 12 plots the same parameters but for an arbitrary week in the winter period in

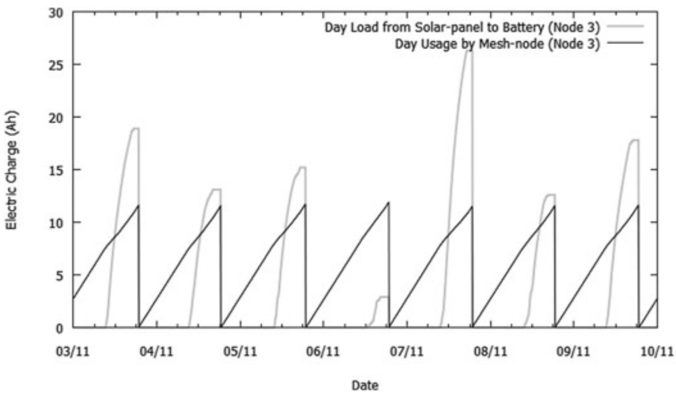

Fig. 12. Battery day load (Ah) along with the mesh node day usage (Ah). Measurements were taken at the mesh node 3 from our real-world wireless mesh network, for a period of one week in winter.

the data set but for the node 3. Monitoring the consumption of node 3 allows us to compare the energy usage between nodes based on their role in the mesh network.

In both figures at first sight it seems that there is lacking data for the battery charge. As the battery day load denotes the battery charging by the solar panel module, we can expect activity only when the panel actually generates charge, which explains the lack of recorded data at the beginning and end of each day when sunlight stops hitting the panel. The case is more extreme in Fig. 12 due to the shorter period of daytime. Moreover, it is interesting to note that the battery day load registers large differences from one day to the next, indicating that, depending on weather conditions, the amount of sunlight reaching the panel may vary considerably. Although sunny days can be used to bring back the battery to full charge and compensate for periods (days) with poor sunlight, one should always consider daylight statistics of potential deployment locations.

Comparing the energy usage of the two mesh nodes shows that node 8 needs more energy (approximately 17 Ah in a day) compared to what node 3 consumes (approximately 12 Ah in a day). The measured data indisputably points out that the mesh node 8 is involved in more intensive inter-node communication using in that way more energy. The impact of the length of the communication link on the required transmit power should also not be neglected, mainly because of higher per-link transmission power. Hence, the design of a wireless mesh network relying on solar energy for its sustainable operation, should take into account the role of each individual node in the overall mesh network as well as the node's location, which affects communication distances but also the amount of usable sunlight.

5 Conclusions and Further Work

In this paper, we have presented a study on energy measurements of a real-world deployment of a wireless mesh network. The measurements were collected over several weeks during the summer and winter period. Although there are several studies that consider various aspects of energy in wireless sensor or mesh nodes, to the best of our knowledge, none of them conducts investigations on energy harvesting and energy consumption in a onsite deployed network. We performed measurements on the mesh nodes but also on the battery and solar panel used to support their operation.

We first analysed the changes in battery and solar panel voltage over a single day or several days. The results revealed that during the span of a single day the voltage either comes at a value of about 14 V, supplied by the battery when the solar panel is not active, or it can reach a maximum voltage value of 24 V (in summer), when the solar panel module powers both the mesh node and recharges the battery. For a period of less sunny weather (in winter) the maximum generated voltage drops to 22 V. Moreover, we observed that during daytime the voltage of the panel may fluctuate, primarily due to shadows or clouds, which results that sometimes during the day the battery seamlessly takes over powering the mesh node. Additionally, we discussed the correlation between the two voltages for a long period of several weeks.

We also presented several results on electric charge from the solar panel module to the battery (i.e. the day load) and the electric charge of the mesh node (i.e. its day usage) during several weeks in both the summer and the winter period. Presented measurements reveal that those nodes that are central (in terms of routing) to the deployed wireless mesh network consume more energy, pointing to a more intensive inter-node communication of that particular mesh node. We hope that our findings can provide an important basis to help researchers and other interested parties in the planning and the development phase of a wireless mesh network supporting environmental monitoring. Besides, we intend to use the current results in the development of a more efficient prediction algorithm for identifying and reducing outages of a solar-power WMN, in that way addressing the power resources in the most efficient and equitable way.

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