SolarMesh - Energy-Efficient, Autonomous Wireless Networks for Developing Countries

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Abstract. This paper presents the research and development activities within "**SolarMesh** - Energy-Efficient, Autonomous, Wide-Area Wireless Voice and Data Network", a R&D project funded by the German Federal Ministry of Education and Research. The project, bringing together expertise from academia and industry in Germany, is specifically dedicated to develop reliable wireless communications infrastructure for rural areas in developing countries, such as in sub-Saharan Africa. Wireless mesh networks based on IEEE 802.11 Wireless LAN technology combined with intelligent functions for self-configuration and self-adaptation can provide affordable ICT infrastructure for access and backhaul operation while at the same time offering carrier-grade QoS for voice and data services. Moreover, the paper outlines how the SolarMesh network operates independently from (potentially unreliable) local energy grids using autarkic energy supply (solar power) and implementing energy-aware routing and handover functions.

Keywords: wireless mesh networks, communications infrastructure for rural areas, autarkic energy supply, situation-aware network management, self-adaptation.

1 Introduction

Today, information and communication technology (ICT) infrastructure (both operator equipment and consumer electronics), besides being very costly, is generally developed according to needs and requirements of urban areas in developed countries. In rural areas and even more so in developing countries (except for the big cities), we encounter completely different conditions and deployment environments and significant financial restrictions. Therefore, the most feasible approach is to conceptually and technically adapt, extend, and improve existing equipment so that it better reflects the needs of thinly populated regions in developing countries. The SolarMesh project, a consortium funded by the German Ministry of Education and Research, consisting of two research institutions and three companies, develops such an autonomous, resource-efficient, easily deployable and maintainable system, as presented in this work. The remainder of the

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paper is structured as follows: The next two subsections briefly describe the motivation and objectives of the SolarMesh project. Section 2 provides an overview of related work, Section 3 outlines the system concept of SolarMesh. According research challenges are presented in Section 4 whereas Section 5 discusses expected results. The paper concludes with a summary and description of future work in Section 6.

1.1 Motivation

From an overall perspective, the SolarMesh project is motivated by a lack of affordable connectivity that at least supplies basic bandwidth and QoS levels for rural areas in both developing and developed countries. More specifically, the project aims at resolving the following problems:

- **Opening Up for New Markets**
  Billions of people in rural areas and developing regions do not have satisfactory access to the Internet or other telecommunication services. Tapping this demand offers a significant market and business potential.
- **Technological Challenges**
  The lack of reliable energy supply, large coverage areas in thinly populated regions, scarce availability of technically trained personnel, as well as extremely harsh climate conditions are some of the difficulties faced when deploying and operating a large-scale wireless mesh network. Hardware and software have to be designed accordingly:
  - **Autarkic energy supply**
    Due to limited or unreliable energy supply, SolarMesh network nodes exploit solar power from panels attached to the nodes. However, this self-reliance comes at the cost of potential outages due to the limited storage capabilities.
  - **Wireless backhaul network**
    Similar to solar energy supply providing independence from the local energy grid, a wireless backhaul network guarantees an autonomous operation of high capacity backbone links, independent from existing wired infrastructure. However, spectrum usage has to be reconciliated with local authorities and organizations in order to avoid interference from other radio systems.
- **Compatability and Future Proofness**
  Accelerating progress in mobile communications technologies will lead to new terminal generations and increasing requirements w.r.t. to QoS. Considerable investments, especially in rural areas, can only be justified if scalable and extensible communications systems support these trends. In Africa, the current majority of GSM terminals will (sooner or later) be replaced by more sophisticated terminals disposing of several air interfaces, e.g. smartphones. Therefore, the SolarMesh architecture incorporates advanced WLAN access points, thus making the system future-proof in an affordable manner.

- **Economic Cooperation and Development Issues**
  In many developing countries, communication networks are the only means for accessing information. Hence, investments into these infrastructures will have direct consequences on the quality of medical services, education, interaction with governmental agencies, and diversity of opinion.

1.2 Objectives

Based on the motivation described in the previous section, the project has identified five key objectives that will guide the development of the wireless mesh network:

1. **High-performing, Adaptive and Extensible System Architecture**
   The overall architecture will be developed in a way that technologies beyond those considered in the project (WLAN IEEE 802.11 and GSM) can be integrated easily. This holds particularly true for those alternative radio technologies reducing costs, energy consumption, or access barriers. Therefore, the integration of GSM as an additional access technology is motivated by three reasons: GSM terminals are relatively affordable, their energy consumption is comparably low, and, finally, they are very common in (rural) Africa. Moreover, many services, including governmental services, merely rely on SMS signalling. However, the termination of the GSM connection already takes place in the access points in order to avoid expensive GERAN infrastructure.
2. **Development of a Mesh Network Based on Autarkic Energy Supply**
   Energy supply of the mesh nodes is based on regenerative sources (solar power). Hence, all components (hardware, software, backbone and air interface) and mechanisms (routing, scheduling, handover, radio transmission) have to be optimized taking into account fluctuating power availability and limited energy storage capacities. The partners will develop according advanced energy-aware methods for network control.
3. **Advanced Auto-Configuration Capabilities**
   Deployment and start up of the mesh network will not necessarily require technically trained personnel. Individual nodes as well as the network as a whole will configure mostly autonomously and adapted to their respective deployment area.
4. **Advanced Self-adaptation Capabilities**
   Besides considering energy efficiency as a main factor, network management and load balancing have to support a large-area mesh network with time-variant topology and dynamically changing traffic load. Availability of individual nodes will be significantly reduced due to limited energy resources, extreme weather conditions (high temperatures, strong rain, sand storms), and maintenance work. The network will have to cope with these characteristics in an autonomous and signalling-efficient manner.

5. **Implementation of Efficient Handover und Routing Mechanisms** Handover and routing processes will be optimized and executed in a situation-aware manner to facilitate mobility support for the user and multi-KPI (key performance indicator) network management for the operator. For the latter, this allows for both control and prediction of power consumption, radio link availibility, and load distribution in the network. The user will benefit from seamless connectivity, independent of service and radio technology.

2 Related Work

Carrier-grade wireless mesh networks generally have been subject to former research projects. In EU FP7 CARMEN [5], a wireless mesh infrastructure has been developed that abstracts from different link layer technologies by the usage of IEEE 802.21. The design of the infrastructure and the routing mechanisms provides different QoS classes.

Generally, system-level models optimize the overall system performance w.r.t. a chosen set of parameters [2], [8]. When including energy consumption, transmission power is an important factor. Accordingly, current energy models particularly optimize network topology (i.e. the location of BTSs). Energy consumption is modeled based on path loss ($\frac{1}{d^n}$, where d denotes the distance between transmitter and receiver and n depends on the environments of the considered system), with additional consideration of large-scale fading using log-normal distributions as well as small-scale fading using Rayleigh distributions, e.g. [7] and [9].

For wireless ad-hoc networks deploying nodes running with regenerative energy sources (e.g. solar power for countries of sub-Saharan Africa), routing protocols also play an important role in energy consumption [3]. Several energy-aware routing algorithms have been developed that take the characteristics of regenerative energy supplies and the referring outage situations into consideration. In [1], an energy-aware routing within the scope of wireless mesh networks based on a WLAN architecture is mapped to an assignment problem and solved by a generic algorithm. In [6], the general relation between energy consumption and throughput in the scope of WLAN infrastructures is given. Frequently, total energy consumption is modeled in a linear way, using metrics for consumed energy per information unit routed, such as "energy per bit", or "energy per packet". Obviously, these linear models do not properly reflect energy consumed due to unsuccessful attempts to acquire the channel (media contention), messages lost due to collision, bit errors, or loss of wireless connectivity [4].

3 System Concept

The following section describes the main system concept of SolarMesh. It depicts an introduction to the overall system architecture, the auto-configuration and self-adaptation mechanisms and finally to the handover and routing mechanisms that are implemented.

3.1 System Architecture

Several SolarMesh nodes create a wireless, autonomous meshed backhaul network based on IEEE 802.11 wireless technology, as depicted in Fig. 1. The mesh network has three tasks: Providing connectivity to the external core network, offering heterogeneous wireless access to user terminals and, most importantly, serving as a wireless backhaul network within a particular area, thus replacing wired infrastructure. The first one is realized by several gateway connections to the core network and the Internet, whereas the second one is provided by utilizing commonly used Wide Area Network (WAN) technologies, e.g. GSM (in order to take advantage of the cheap off-the-shelf user devices) or Wireless LAN (thus exploiting its affordable network components). Backhaul connectivity is solely based on IEEE 802.11, incorporating mechanisms for carrier-grade QoS; i.e. different services and the accordingly required QoS classes are supported by the overall SolarMesh architecture, namely best-effort and delay-sensitive VoIP services.

The overall system architecture consists of several nodes, disposing of different functionalities:

- **SMN** (SolarMesh Node) holds the SolarMesh capabilities and embodies a basic interface for other nodes within architecture. The main task of the SMNs is to build up the mesh backhaul network and to forward the user- and control-plane traffic w.r.t. the QoS requirements among the SMNs (to the target sink).
- **SMGW** (SolarMesh Gateway) constitutes the gateway of the wireless backhaul network to the external backbone networks via Global Area Networks (GANs), e.g. a satellite link.
- **SMAP** (SolarMesh Access Point) provides the wireless access interface to the user terminals. It is equipped with at least one radio interface dedicated to the user terminal access, which do not carry the backhaul traffic. Available access technologies are IEEE 802.11 and GSM.
- **SMC** (SolarMesh Coordinator) performs cluster-wide, centralized decisions within a cluster of SMNs. The task of the SMCs is to consider both cluster- and network-wide optimization goals for radio planning, energy-aware node and link configuration, capacity management or handover decisions

Besides a comprehensive modeling of the system for simulation purpose, a future testbed will be set up with IEEE 802.11 based *meshnode IV* modules by saxnet GmbH which will be used to deploy the SolarMesh backhaul network. To realize the GSM-based access network, SMAPs will be extended with additional *USRP 2* from Ettus LLC controlled by *openBTS* and an *Asterisk PBX* software.

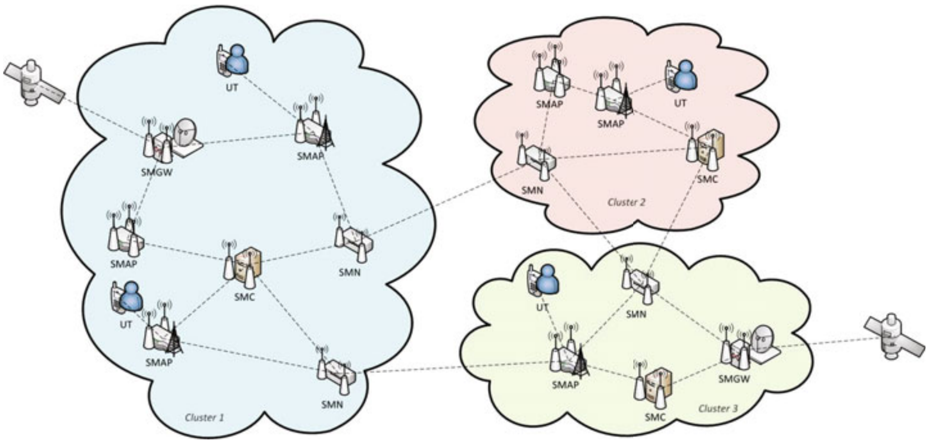

Fig. 1. Overview of System Concept

3.2 Auto-Configuration and Self-adaptation

One of the main characteristics of SolarMesh is the ability of auto-configuration and self-adaptation, as shown in Fig. 2. This is realized by an autonomous topology detection and configuration of the deployed SMNs. They are grouped into clusters in order to decrease the overall singaling effort and to perform local, i.e. cluster-wide, optimization concerning routing and handover decisions. Within a cluster, a SMC is determined that is responsible for the cluster-wide decisions and optimizations. Hence, a SMC can decide to switch off a SMN due to low utilization of the according SMN or its low energy status, e.g. caused by an almost empty buffer battery and, simultaneously, no energy supply by solar panels. As a result, the network topology is reconfigured and the traffic of the considered SMN is dynamically re-routed via other routes. SMNs are able to modify transmission power, modulation and coding schemes, respectively, as well as provided QoS in an autonomous way.

Target access points for the user terminals are selected depending on the load situation on the target SMAPs, the capabilities of the user terminals and the SMAPs and the QoS that has been requested by the user terminal.

3.3 Efficient Handover and Routing Mechanisms

The handover and routing decisions are primarily based on mobility, load situation, energy situation within the SMNs and the provided and requested QoS parameters. Mobility-based handovers are triggered by the local SMNs whereas the remaining handover decisions are performed by the SMCs in order to allow for a cluster-wide or global optimization. Both horizontal, i.e. within the same radio technology, and vertical, i.e. across different radio networks, handovers

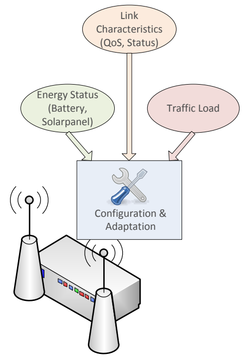

Fig. 2. Auto-Configuration and Self-Adaptation Functionalities of a SMC Node

can be performed. For each end-to-end connection, the most efficient path w.r.t. energy status or load situation is selected.

4 Research Challenges

Within SolarMesh, several research challenges need to be tackled which will be described in the following section.

4.1 Autarkic Energy Supply and Energy Efficiency

SolarMesh components will be designed to work in regions with harsh environmental and climate conditions and will cope with unreliable infrastructures, e.g. w.r.t. energy supply or availability of maintenance resources. In order to guarantee a continuous operation mode, nodes need to be equipped with their own energy supply. Power consumption of the SMNs needs to be kept at a minimum aiming at achiving a long operation time. Therefore, an energy management function is required that is capable of reducing power consumption by shutting down certain capabilities. This is handled by an energy management function that employs a detailed energy model of the SMNs. The model takes as input parameters the power consumption of the supported wireless access networks (e.g. IEEE 802.11 and GSM) depending on different modulation modes, supported states of operation as well as state changes. Additionally, the influence of traffic load on the SMNs is considered, which in turn is dependent on the type of the node: SMCs need to handle more control plane traffic than simple SMNs which in turn leads to a higher power consumption. In general, decisions concerning energy management are taken at different hierarchy levels, as depicted in Fig. 3. As an example, modulation schemes for the terminal link can generally be decided at the local node. In contrast, the decision of shutting down an entire node can only be taken at higher levels (cluster or global) since the individual node is not foreseen to have enough information to take that decisions and to assess the consequences.

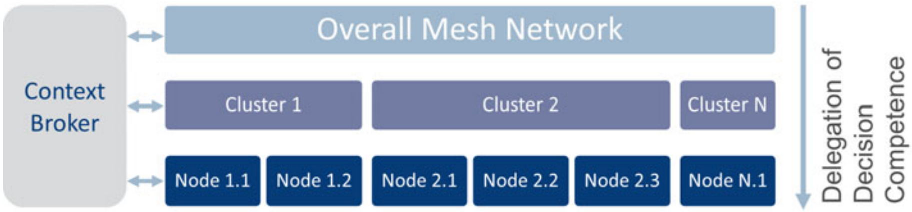

Fig. 3. Network Energy Management Concept

4.2 Network Management

Within the meshed network infrastructure, an advanced network management entity is required in order to perform the required reconfigurations of the constantly changing network topology. This entity has instances at node, cluster, and global level and implements, among others, routing and re-routing mechanisms, handover algorithms, as well as network topology management functionalities. Besides network-side parameters, such as dynamic characteristics of load, traffic situation w.r.t. QoS classes, it takes into consideration mobility and capabilities (such as available air interfaces, display size, or available codecs) of registered UTs.

4.3 Technology Integration

One of the key challenges of SolarMesh is to ensure that the whole infrastructure can be set up and maintained without any or only minimal technical knowledge of the staff (which is a typical situation in rural regions of Africa). This requires sophisticated auto-configuration functionalities of the nodes that guarantee autonomous topology detection and setup of the whole meshed wireless backhaul network over large distances. Another goal is to keep the costs per node at a low level. Finally, the integration of different wireless technologies imposes special requirements on the design of a common network management functionality, i.e. it has to be abstracted from the specific characteristics of indivdual link layer technologies.

5 Expected Results

Within SolarMesh, a wireless mesh infrastructure will be realized that aims to keep the overall deployment and operational costs at a very low level, as required for operation in rural areas of sub-Saharan Africa. The overall system design will be evaluated by a mixed simulation and emulation and will finally be implemented and validated in a testbed environment. Routing and handover decisions will be optimized and accelerated by the usage of context-aware decision functions. Seamless connectivity will be realized by the support of mobility (horizontal and vertical handover) and dynamic routing and re-routing. Due to the usage of the advanced energy management, a significant reduction of the overall power consumption will be realized. Most importantly, the mesh network will rely on and being able to cope with autarkic energy supply solutions, thus gaining independence from locally deployed, potentially unreliable energy grids.

6 Conclusion and Outlook

The paper has outlined the motivation, objectives, research challenges, and the initial system concept of the SolarMesh project. Their relevance for rural regions in developing countries has been demonstrated.

The core **motivation** of the project is the observation of unsatisfying Internet access for rural areas especially in developing countries. Derived from that, the **objective** is to develop a communications infrastructure that considers the special operation requirements of sub-Saharan African countries, thus bringing broadband Internet connectivity to these regions. This includes simple and (semi-)autonomous deployment, operation, and energy supply as well as the use of mesh technology on WLAN basis for cost-efficient access and backhaul network. According **research challenges** hence lie in the areas of autarkic energy supply and energy efficiency, autonomous network management functionalities (including situation-aware routing and handover control), and technology integration (e.g. integration of satellite, GSM, and WLAN).

Future work includes the detailled specification and development of a **system architecture** disposing of hardware and software components that meet the defined requirements. Finally, the system will be validated and evaluated based on simulations and testbed experiments.

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