WIRELESS WORLD
RESEARCH FORUM

Energy-Efficient Wireless Mesh Networks

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Abstract—**This paper outlines the objectives of a recently formed research group at Meraka Institute. We consider application of wireles mesh networks in rural infrastructure-defficient parts of the African continent where nodes operate on batteries. As a result energy consumption must be minimized while achieving high throughput and low delay. In this context, we are engaged in various projects to design transmission stratergy to minimize the total energy consumption.**

We apply known modeling methods to model the proposed solutions, then simulate the network using known network simulators such as NS-2 and adapt our established WMN testbed for usage in infrastructure-deficient areas such as rural areas in Africa.

Index Terms—**Energy efficient design, Wireless Mesh networks, Network Protocols**

I. Introduction

The objectives of this research group are the application and adaptation of existing wireless local area networks, especially those based on 802.11 standard, for the energy-efficient wireless mesh network (EE-WMN) architectures, protocols and controls. In addition to the WMN regular features of self-organization and self-configuration, the EE-WMN routers monitor and replenish their energy sources using a host of alternative and renewable energy schemes, and factor in, the remaining energy in their routing decisions.

WMNs have emerged recently as an adaptation of the existing wireless networks with the objectives of extending coverage range, provision of non-line-of-sight connectivity for users without direct line-of-sight links, provision of flexible network architecture that is easy to deploy and configure, and can support and can provide a wide range of network services. They share the characteristics of self-organization and self-healing with mobile ad hoc networks (MANET). In MANET, each node generate its own traffic as well as route traffic generated by other nodes. In WMNs, nodes are either mesh routers or mesh clients, where mesh clients are ordinary WLAN clients and mesh routers are wireless access points with mesh capabilities. Mesh routers cooperatively form a multi-hop network that enable communication between mesh clients and can be connected to point of presence points to provide broadband access to other existing networks such as the Internet. Figure 1, illustrates communication between client A and client B through in a WMN. For the rest of the document we will use mesh nodes to refer to the access points in a WMN.

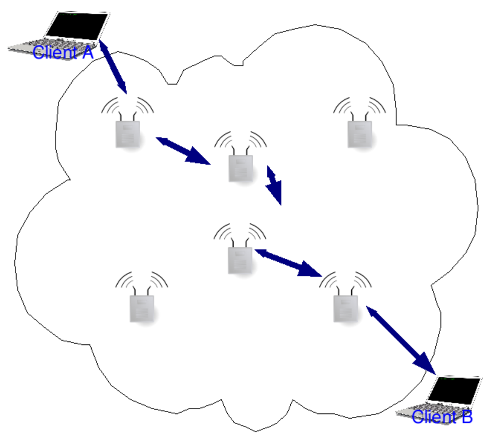

Figure 1: Routing in a WMN

The ease at which WMNs can be set-up has lead to several community WMNs being set-up in many cities across the world. They are receiving attention as a possible access technology for currently undeserved rural areas. The nodes in these community WMNs typically consists of off-the-shelf 802.11 routers with a mesh routing protocol software and a roof mounted antenna.

The nodes automatically form a multi-hop mesh network.

The increasing number of publications and press articles on WMNs have raised the awareness and increased the expectations of policy makers on their potential benefits to the Information society. The formation of standardization task groups such 802.11 task group "s", that is developing a flexible and extensible standard for WMNs based on 802.11, are also highlighting the growing interest in the technology.

The current trends in WMNs research and standardization efforts has been on optimizing multi-hop protocols to increase the scalability and channel capacity. We embrace the community network based philosophy and envisage the practical deployment of WMNs in energy-constraint rural areas in Africa, the nodes therefore will be required to be energy-efficient. Our research focus is therefore on the energy-efficiency operation of the mesh nodes, this is summarized in Figure 2.

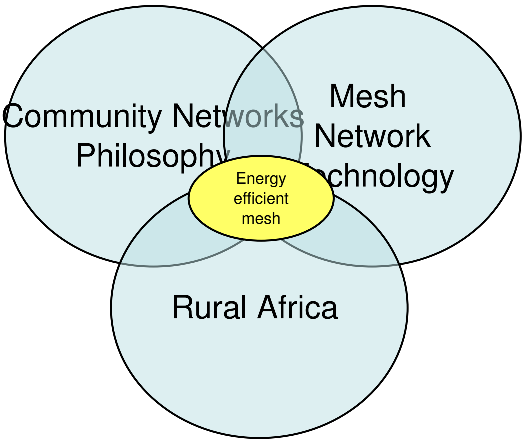

Figure 2: Community Network Philosophy

This paper outlines the long-term objectives and the strategies of our research group. It is structured as follows. Section 2 gives a brief overview of The application domain, rural Africa characteristics that drive our research focus. The current research in WMNs and standardization efforts on WMNs. are presented in section 3. Section 4 outlines the projects that we are undertaking to reach our objectives. Section 5 describes the methodology. Finally section 6 presents collaborative structure and concluding remarks.

II. Motivation

Our research focus is motivated by the desire to connect an estimated 450 million rural Africans that are currently without access to broadband ICT infrastructure and services. Today, a small fraction of them has access to radio broadcasts, and voice via mobile cellular telephony. Without broadband access these rural communities are unable to access a wide variety of new ICT applications such as e-government, e-commerce, e-learning, and e-health. Due to relatively low levels of adult literacy access to interactive multimedia services is as important for rural communities as voice connectivity. We are therefore addressing this digital divide by engaging in research and development efforts to develop affordable energy-efficient devices for connectivity to broadband networks.

The term rural is often used in opposition to urban to refer to areas that are located several hundreds of kilometers from the urban centers. For the purpose of this research group we adopted the definition of rural that is used by ITU development bureau. Rural refers to isolated and poorly served areas by telecommunication facilities, where various factors interact to make the establishment of telecommunication services difficult. A rural area may consist of scattered settlements, villages or small towns, and may be located several hundreds of kilometers away from an urban or city center. However, in some cases a suburban area may also be considered as rural.

A rural area exhibits one or more of the following characteristics:

- scarcity or absence of public facilities such as reliable electricity supply, water, access roads and regular transport;
- scarcity of technical personnel;
- difficult topographical conditions, e.g. lakes, rivers, hills, mountains or deserts, which render the construction of wire telecommunication networks very costly;
- severe climatic conditions that make critical demands on the equipment;
- low level of economic activity mainly based on agriculture, fishing, handicrafts, etc.;
- low per capita income;
- underdeveloped social infrastructures (health, education, etc.);
- low population density;
- very high calling rates per telephone line, reflecting the scarcity of telephone service and the fact that large numbers of people rely on a single telephone line.

These characteristics make it difficult to provide public telecommunication services of acceptable quality by traditional means at affordable prices, while also achieving commercial viability for the service provider. Considerable research efforts and developments are therefore required to develop technologies and business models to provide affordable ICT services to rural populations.

The advantages offered by the leading technologies in the provision of broadband access world-wide is the Digital Subscriber Line (DSL) and cable Modem service cannot be enjoyed by rural populations due to unavailability of basic telephony and Cable Television infrastructure. Wireless technologies hold much promise for these areas without existing wired infrastructure.

The advantage offered by mesh networks stems from their ease of installation and maintenance thus they can be deployed even in the absence of highly qualified technical personnel. Because they are multi-hop networks they can be deployed around hills and mountains to provide a non-line-of-sight wireless connectivity. Therefore energy-efficient wireless mesh networks hold most advantage for rural areas.

III. Current Research in WMNs

Researchers in WMN are revisiting the protocol design of existing wireless networks, ad hoc networks and wireless sensor networks from the perspective of WMNs. Akyildiz et. al[1] present a comprehensive survey of the current and open research areas in WMNs across all network protocol layers. We present a brief survey of current research in routing protocols, MAC sub-layer protocols and in radio techniques for increasing capacity and scalability of mesh networks.

A.Routing Protocols

The mobile ad hoc routing protocols are classified as either proactive, reactive or hybrid. The most popular proactive protocol is *Optimized Link Source Protocol (OLSR)*[2]. The most popular reactive protocols are *Ad hoc On Demand Distance Vector (AODV)*[3] and *Dynamic Source Routing (DSR)*[4]. The Internet Engineering Task Force has created MANET working group to standardize IP routing protocol functionality suitable for wireless routing application within both static and dynamic topologies. The group is pursuing proactive protocol, OLSRv2 and reactive protocol, DYMO[5]. DYMO is a simplified combination of AODV and DSR.

B.802.11 MAC Sublayer Protocols

While the current 802.11 routers are routinely deployed for WMNs, the MAC sublayer of 802.11 does not perform well as the number of hops increase in WMN. This has lead to a number studies aimed at designing a MAC that is more suitable for WMNs . A new WMN MAC protocol based on STDMA called 2p protocol[6] has been proposed for long distance rural WMNs. An adaptation of the network layer MANET routing protocols for Data Link (Layer 2) routing, is an ongoing effort[7]. The IEEE 802.11 task group “s” is proposing a hybrid routing protocol, Hybrid Wireless Mesh Protocol (HWMP). The foundation of this protocol is RM-AODV, which is an adaptation of AODV, that work on layer 2 and uses MAC addresses and radio-aware routing metric, instead of hop count. An optional proactive protocols RA-OLSR, which is an layer 2 adaptation of OLSR, has also been proposed[7].

C.Cross-layer Interactions

The performance comparisons of various multi-hop routing protocols which take MAC and physical layer models into consideration reveals that the best performing network layer routing protocol may not result in best performing network overall[8]. Studying the interaction of the protocol layers when designing networks protocols can to optimum solutions[1],[8].

D.Radio Techniques

In terms of radio techniques, the proposed approaches to increasing capacity have included directional and smart antennae, MIMO systems and multi-radio/multi-channel systems. MIMO has become one of the key technologies for the high speed extension of Wi-Fi, as such its advantage for ad hoc wireless networks is receiving a lot of attention from researchers[9],[10],[11]. Studies indicates that multi-radio/multi-channel coupled with well known routing algorithms LQSR and AODV greatly improves the performance of WMNs[12],[13] and as such multi-radio systems are indispensable if WMN were to reach their full potential.

E.Our Contribution

Our research aims to optimize the mesh protocols across all network protocol layers for energy-efficiency. We aim to adapt extensive energy-efficiency models for sensor networks to WMNs. Furthermore we aim to factor in, the remaining energy in each node in the routing and path selection decisions. It is worth noting that the techniques that are considered for increasing the channel capacity for WMNs are also being considered for energy-efficiency[9],[12]. In [12], the energy-efficiency advantage of multi-radio systems have been presented while in [9], MIMO systems have been considered for energy-efficiency in sensor networks. We are therefore studying the energy-efficiency of established and emerging wireless mesh techniques as well as designing new energy-efficient mesh techniques.

IV. Sample Projects

The sources of energy consumption with regard to a network operations, can be classified into two types: communication and computation related with communication dominating the consumption. The computation in the network nodes is chiefly concerned with protocol processing aspects, involving the usage of CPU and memory. The communication involves usage of the transceiver for sending control, route request and response as well as forwarding data packets. We study the energy-efficient aspects of both the communication and computation and attempt to strike a balance between the two.

We present here a sample of the research projects that contribute to the aim of achieving energy-efficient operation in the mesh nodes as well as the entire network. They are classified into three categories; Energy-efficient mesh protocols, Energy-saving architectures for WMNs as well as Dynamic power control.

A.Energy-efficient mesh protocols

The protocol software of chief importance in WMN resides in the network and data link layers of the ISO protocol stack. The main functions of the network layer are routing and congestion control as well as mobility management while the main functions of the data link layer are the establishment of reliable and secure logical link over the unreliable wireless link and allocating space among mesh clients sharing wireless channels. Specific projects include Gateway location energy-aware gateway location protocols, energy-aware computational intelligence routing strategies in WMNs, energy-aware path selection in wireless extended service set.

- **Energy-aware gateway location protocols**: Develop gateway location algorithms to spread the load across various gateway entry points into the mesh network which take into consideration remaining energy in each node.

The first task will involve an in-depth understanding and definition of the routing metrics. The second task will be to study the energy consumption of nodes running ad hoc routing protocols, especially those in consideration for standardization by IETF. The third task will be to develop the model to determine the remaining energy taking into account the energy replenishment rate and energy consumption rate under different network conditions. The final task will use the remaining energy in addition to the typical metrics used to evaluate ad hoc routing protocols that include shortest-hop, shortest delay and locality stability, we evaluate and enhance the routing protocols.

- **Energy-aware computational intelligence routing strategies in WMNs**: Develop a self-organized routing protocol whose major feature will be the synergistic combination of the good attributes of fuzzy set theory and swarm intelligence while observing remaining energy in the mesh nodes.

The first task will involve an in-depth understanding and definition of the routing metrics. The metrics defined in the first task will be used as inputs to the fuzzy decision making algorithm embedded in every node. The second task will involve the development of the stigmergetic communication mechanism for exchanging routing information between routers in energy-conserving manner. This will involve the study of foraging behaviors of Ecoli bacteria and other social organisms associated with mobile food locations. Concepts learnt from this study will be combined with concepts learnt from AntHocNet and BeeAdhoc as we develop an all inclusive mechanism for exchanging routing information. The third task will involve the design of the mechanism for evolving the structure of the fuzzy decision making mechanisms in the routers. In this we hope to propose new frontiers for evolving the fuzzy knowledge base in line with the characteristics of WMNs. In the fourth task, we will combine the swarm intelligence component with the fuzzy component as we develop a hybrid routing protocol for WMNs.

- **Energy-aware path selection in wireless extended service set (ESS)**: Develop a path selection algorithm among access points in a wireless distribution network forming a wireless ESS.

The first task will involve an in-depth understanding and definition of the path selection metrics. Path selection is used instead of routing to make a distinction between routing decision made at the data link layer and those made at network layer. Routing is therefore reserved for decisions made at the network layer. The second task will be to study the energy consumption of nodes running path selection protocols, especially those in consideration for standardization by IEEE. The third task will be to develop the model to determine the remaining energy taking into account the energy replenishment rate and energy consumption rate under different network conditions. The final task will use the remaining energy in addition to the metrics defined in the first task to evaluate the path selection protocols to evaluate and enhance the path selection protocols.

- **Energy-Aware Cross-layer optimization in WMNs**: Joint design optimization for energy efficiency across all layers of the protocol stack as well as the underlying hardware. Since all layers of protocol stack affect the energy consumption and delay for the end-to-end transmission, an efficient system requires a joint design across all these layers.

The first task will involve an in-depth understanding information that should be sent across the layers and how that information should be adapted to. The second task will be to study the interaction between the protocol layer in details and assess possible energy saving mechanism in the communication across layers. The final task will evaluate the cross-layer optimized protocols.

B.Energy-saving architectures for WMNs

Multi-radio, multi-channel architectures have surfaced recently as the architecture that has the potential to increase channel efficiency. Studies indicates that they can improve the performance of WMNs. Another WLAN architecture that is receiving a lot of attention is MIMO, it is considered for increasing the capacity of future WLN. The energy-efficiency of these architecture will be studied.

C.Dynamic power control in WMNs

Power control in wireless ad hoc network is the technique of allowing each node to choose the transmit power level for each packet in a distributed fashion. Most of power control techniques have been reported in several literatures. In particular, topology control for energy-efficiency in wireless ad hoc network is the problem of assigning per-node transmit powers that minimize the maximum transmit power level used in the network, while still maintaining network connectivity. The topology control methods are primarily meant to increase throughput by reducing signal power interference, with associated reduction in energy consumption as a beneficial side effect. The objective of this research is to investigate dynamic power control using graphical model theory for wireless mesh networks.

V. Methodology

In order to analyze the performance of the protocols studied in the research projects mentioned above, simulation environments are extensively used. Currently there is no consensus on the environment to be used. To verify the simulation results, the implementations will be tested on our 49-node, depicted in Figure 3.

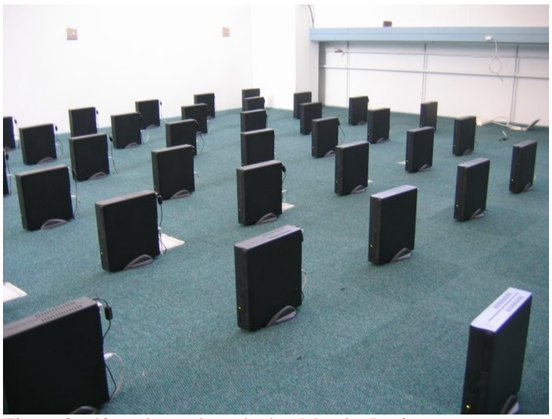

Figure 3.: 49-node mesh testbed at Meraka Institute

VI. Conclusion and way forward

The research group will achieve its objectives through its Human capital development (HCD) programme. HCD programme, along with critical mass R&D and Innovation in ICT, is one of the three objectives of the Meraka Institute. The institute complements and work with higher education institutions (HEIs) to recruit research students to work on its research programs. The institute and the HEIs provide joint supervision and mentoring of the students. The group currently has three PhD students who are currently busy writing their research proposals. Two of the draft proposals served as inputs to specific projects that will be undertaken in the group.

The group aim to exploit its collaboration with local HEIs to recruit more PhD students as well as to recruit post-doctoral researchers. It also aims to establish collaborations with HEIs in order for student and staff exchange and research collaborations.

Acknowledgement

The author would like to thank Kobus Roux, David Johnson, Albert Lysko, Dare Sokoya, Tope Kareem, Clement Nyrenda, Thomas Olwal for the fruitful discussion we had in the formulation of objectives. Special thanks to David Johnson, Clement Nyirenda and Thomas whose Masters and PhD proposals have influenced three of the projects mentioned here.

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