On the Design of Inclusive Ubiquitous Access

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***Abstract*—The development towards ubiquitous network access requires innovative solutions to get remote areas included, especially rural areas of developing regions. The challenges include robustness of network components, poor or non-existent power supply and sustainable business models. We argue that large scale user-driven community networks are becoming technically viable to deploy in areas that are short of supply of telecommunication services due to little or no commercial interest. To support this claim, we discuss the design of key network elements and careful power management based on alternative energy sources and storage. We also provide a status report from ongoing field-tests regarding provisioning of broadband network services in Serengeti, Tanzania, and outline briefly our strategy to achieve sustainability. On the technical side, we first discuss an affordable, high-performance, low-effect router based on open source software and standard off-the-shelf hardware offering both copper and fibre links. Our design is capable of forwarding more than 700kpps at 22.3W. The power consumption is considerably less than all alternatives in our comparison. Then we discuss power management and the use of batteries and super-capacitors as backup and storage solutions.**

I. Introduction

In the knowledge society, ubiquitous access to communication networks and services, broadband as well as mobile, is becoming a prerequisite to keep up with your peers, whether you are an individual, an organization or a country, wherever you are based. Broadband networks have also been identified by the UN Broadband Commission [1] as uniquely powerful tools for achieving the Millennium Development Goals. Ubiquitous access is thus a social and economical challenge, not only a technical. There are many areas that are underserved due to the perceived business risks. In most of these areas, there is demand but no supply since the revenue streams are unpredictable and the costs high due to the investments required in infrastructure, such as optical fibre cables, reliable electrical power and a complete commercial supply chain. In developing regions, the risks may also include political components due to unstable policies and under-developed regulatory frameworks.

Even though many rural areas enjoy access to mobile phone networks, few of them provide broadband services due to lack of broadband communication infrastructure. Local broadband communication services are mostly non-existent while Internet access is sometimes provided via narrowband VSATs connections through community access points (telecenters).

Our research is focusing on first mile rather than last mile strategies to bridge the digital divide by stimulating the development of local broadband markets, starting from the end-users. We advocate the creation of local community-driven broadband islands, meaning that the uplink, if it exists, is narrowband, until the necessary upstream infrastructure becomes available. Thanks to the availability of easy-to-use and affordable high-performance standard PC hardware and open source software, large scale user-driven community networks are becoming technically viable to deploy in areas that are short of supply of telecommunication services due to little or no commercial interest. However, there are observations regarding the availability of power supply in rural developing regions [2], [3]. The challenge is therefore not only about minimizing the demand for power to reduce the environment foot print and save costs. It is also about managing the available power to be able to provide services when users need them, whether this is continuously 24/7 or according to a schedule, and to manage backup power storage optimally. As a service provider, you may not have access to any power infrastructure at all or you might have to manage planned rationing schemes, unplanned blackouts, brownouts, destructive transients, etc. Consequently, energy awareness and power management may have to become integrated in the communication systems architecture and even in application systems to allow user-control. Design of low-effect network elements is one approach.

In this paper, we discuss our work on an affordable high-performance, low-effect router based on open source software and carefully selected standard off-the-shelf hardware offering both copper and optical fibre links, and a power management system designed to manage alternative energy sources and storage. The current version of the router is capable of forwarding more than 700kpps at 22.3W. This power consumption is considerably less than all alternatives in our comparison. We also report on ongoing field-tests based on the use of the current version of this router for provisioning of broadband network services in Serengeti, Tanzania [4].

We acknowledge earlier work on software routers such as [5], [6], [7], [8]. However, the context and design goals were different. To our knowledge, none of them considered robustness and low-power consumption as key factors in their designs. In addition, our work considered viable options for power backup and storage using ultra-capacitors.

Our contribution in this paper is in the design of a low-

978-1-4577-1177-0/11/$26.00

cost, low-power infrastructure router based on open source software and selected standard hardware components. Another contribution is on the analysis of the routing performance and power consumption. Even though our design is focusing on the developing world, such a router could as well be deployed in developed regions with a similar traffic demand.

The paper is organized as follows: Background information on the community networks and the reference implementation is discussed in section 2 while section 3 discuss the requirements and design goals for rural developing regions. software router components and their relation to performance and power consumption are discussed in section 4, router design is presented in the same section. The performance and power consumption test results are presented in section 5. Section 6 is devoted to discussion and conclusions.

II. Background

Rural and remote areas in the developing world are faced with the following challenges among others, leading to communication isolation:

- Low population density, and low per capita income due to the low-tech level of economic activities mainly based on agriculture and fishing.
- Scarcity or absence of basic infrastructures, such as electricity, water and access roads, and lack of adequately educated and trained technicians.
- Underdeveloped social services, such as healthcare and education, that could work as anchor customers attracting the necessary investments.

The commercial actors consequently see low revenues, high costs and high risks. They will not take lead. To speed things up, there is also need to start from the other end: to establish local broadband communication networks between end-users on a community level. Learning from history, this is how the global telephone network was built in the 19th and 20th century.

A. Community Network

In areas, where demand is larger than supply due to high perceived risks, local consumer groups can reduce the risks by cooperating to demonstrate viable innovative technical solutions and business models in the form of community networks [9], [10]. Many community network initiatives in the developing world are conceived and managed by an individual or a group of entrepreneurs coming together loosely organized or creating a non-governmental organization (NGO) [11], [12]. The required initial investments and operating costs are usually covered by donations and/or voluntary contributions of manpower and equipment.

These networks are usually a hybrid of technologies: wireless connectivity (WiFi) is popular due to the availability of license-free spectrum, low cost and ease to deploy equipments; fibre is coming up as another option, mainly available via utility companies. As the complexity and demand for capacity in such networks increase, so does the need for more scalable and structured networks, leading to introduction of more advanced routers and wired networks.

B. ICT for Rural Development Project in Tanzania

The Information and Communication Technology (ICT) for Rural Development (ICT4RD) project in Tanzania [13] is designed with a goal to create a model for building and sustaining broadband communication networks in rural areas.The project is funded by the Swedish International Development Agency (SIDA)[1] and executed through a partnership between the Tanzania Commission of Science and Technology (COSTECH)[2]; Dar es Salaam Institute of Technology (DIT)[3], Tanzania; and Royal Institute of Technology (KTH)[4], Sweden.

ICT4RD aim at building local communication networks that will create the broadband users. Hence, its strategy is on facilitating basic public services (education, health and local government) to attract public funds (investment in terms of subsidy, donations, grants or soft loans) for the establishments of the network (Capital Expenditure - CAPEX), but stimulating demand in all stakeholders by delivering a variety of services to attract all sorts of users who will contribute to the running costs (Operational Expenditure - OPEX).

To reduce investment costs, ICT4RD advocate sharing of resources and use of existing communication infrastructures wherever possible. Also, the use of robust, high-performance, low-cost off-the-shelf PC hardware and free open source software components to facilitate the design of powerful local broadband communication infrastructures. The project has two running pilots in Tanzania where the low-power router was deployed in November 2010.

III. Requirements and Design Goals

Most manufacturers of carrier grade network equipment are controlled by the business models of their customers, the large commercial operators, and focused on the development of complex and expensive proprietary technical solutions for extreme traffic volumes and quality of service requirements. This means that most of the core network equipment is power-hungry and dependent on electricity supplied via the power grid. The equipment is designed without consideration to power consumption and to the robustness required in sparsely populated areas. There is a need for certified “community grade” technologies complementing the “carrier grade” class network equipment to be used in community broadband networks in under-served areas.

Due to the socio-economic conditions in under-served areas, the design goals of any technical solution should aim at:

1) Low Cost: A need to lower the cost of ownership due to the low purchasing power of those areas.
2) Low Power: National power grid is not available in all places (not reliable when available), devices should be able to run on alternative energies.

[1] www.sida.se
[2] www.costech.or.tz
[3] www.dit.ac.tz
[4] www.kth.se

3) Modular Design: To meet the hybrid nature of technology choices as well as to adapt the demand (market) growth related to increase in ICT awareness.
4) Robust: To accommodate lack of skilled personnel and the harsh environments such as frequent power outages.

IV. Actual Design and Deployment

In this section, we will discuss the design and deployment of the key element in our proposed solutions in detail, an affordable high-performance, low-effect router based on open source software and carefully selected standard off-the-shelf hardware including network interface cards supporting both copper and optical fibre links, and a power management system designed to manage alternative energy sources and storage.

A. Router Components

Following are the major components in a software based router using off-the-shelf hardware:

1) Motherboard and System Buses
2) Central Processing Unit (CPU)
3) Random Access Memory (RAM)
4) Network interface Card (NIC)

The way a router work is that every packet had to traverse the system bus twice, on arrival via incoming interface (when it is stored into the memory before being processed), and later when it is moved to the outgoing interface; the CPU has to process each individual packet passing through the router; and memory is shared between all network interfaces. The availability of advanced motherboards designed for multiprocessors and fast buses facilitates the design of high-performance software-based routers. In the following subsections, we discuss individual components that directly contribute to the processing capacity and power consumption.

1) Motherboard and System Buses: Motherboard is the heart of a PC-based router. It is basically the interconnection circuit to all components: the CPU, RAM, NIC and System Bus. Whether directly or indirectly, the motherboard connects to everything in a PC. Therefore, availability of expansion slot(s) and the I/O bus architecture are very important, as they allow network cards to be added and affect the speed with which data is transferred between the network card and the CPU.

The System Bus (Peripheral Component Interconnect (PCI)) [18] is designed to efficiently transfer the contents of large blocks of contiguous memory locations between the peripherals and the RAM, without requiring CPU intervention.

2) CPU: CPU is the central component. All packets are processed by the CPU, making it a potential bottleneck especially when processing small size packets. To make them faster, current CPUs are designed as multi-core to facilitate multiprocessing. However, the amount of performance gained by the use of a multi-core processor depends on the software algorithms and implementation. In particular, the gains can be realized by running the multiple cores simultaneously. Authors in [7] observed that the architecture and specifications of the CPU highly affect the routing performance of a software router.

3) RAM: Nowadays memory is not a problem in software routers as its capacity has increased tremendously. However, Egi, N. et. el. [8] noted that for high end system, forwarding performance is limited by memory latency, caused by the design of the PC layout in general.

4) NIC: The network interface card provides the required ports for interconnecting different types of links. Thus, its hardware specifications and driver capabilities affect the performance of the router. Additional pluggable modules are available for connecting different media such as copper or fibre links on the same NIC.

The interfaces receives packets from the physical layer and transfers them into the hosts memory and vice-versa via Direct Memory Access (DMA) operations.

B. Software Selection

The work started by selecting the software to use because it highly affects the selection of hardware components, due to hardware compatibility issues and availability of drivers. For operating system, we chose Bifrost/Linux distribution [19] which has a very small footprint and is optimized for routing, focusing on infrastructure networks. Like any Linux, it can run on any standard x86-based, PC hardware.

C. Hardware Selection and Assembly

The router has gone through three iterations now to improve its performance and power consumption: the first iteration was presented at [20], the second iteration has been deployed on site in Tanzania [4] while the third iteration is still being tested in the lab. In this section we will discuss the “deployed” version and the current “lab” version. All router components are summarized in Table I. It should be noted that this was the best configuration in terms of cost, performance and power consumption combination during the time of writing. We believe that future advancement in individual components discussed above might affect our choice. The router is also known as MinNE which stands for Minimal Network Element.

1) Motherboard/CPU: Since the motherboard is the interconnecting circuit, we started by selecting the motherboard, followed by the NIC, noting that PCI bus and RAM will depend on the architecture of the motherboard. Also, we should note that most low power motherboards come with embedded CPUs. We wanted a motherboard that is an x86 compatible architecture to support Bifrost/Linux operating system, and that could possibly support PCIe to enhance performance.

The CPU on the motherboard should consume low power, support multicore and multiqueue to enhance the performance. Intel Atom family of CPUs seemed to meet our needs. The deployed version has a Supermicro X7SPA-HF motherboard with atom D510 CPU while the lab version has the same motherboard but atom D525 CPU.

TABLE I
COMPLETE SET OF ROUTER COMPONENTS

Component	Deployed Router	Lab Router
Chassis	Supermicro SC502L-200B	Same
DC Power Supply	12V picoPSU	6-34V picoPSU
Motherboard/CPU	Supermicro X7SPA-HF (Dual Core Intel Atom D510 1.66 GHz - Intel ICH9/9R)	Use Atom D525
Bus	1 (x4) PCI-E (in x16 slot)	Same
Onboard Ethernet interface	Dual 10/100/1000 LAN (Intel 82574L)	Same
Memory	SO-DIMM DDR2 2GB 667MHZ	Same
Permanent Storage	USB - Sandisk Cruzer 4 GB	Same
NIC	Interface Masters Niagara 4NE-76-4SFP	Niagara 42084
Cooling	Forced air with fan	Convective with heat sink

2) Network Interface Card: Having chosen the motherboard and CPU, we wanted a card that fit into the motherboard and is modular, meaning that could support copper and optic fibre connections. But also, it should exploit the use of multi-core architecture in CPUs. We have chosen the Interface Masters Niagara 4NE-76-4SFP NIC, based on the Intel 82576 chipset, it supports different types of pluggable transceivers known as small form-factor pluggable (SFP), commercially available. In addition, this board supports Digital Optical Monitoring (DOM) for collecting the physical layer statistics of the optical fibre. The lab version use Niagara 42084 card based on the new Intel 1GE chipset 82580 which requires less power.

3) Main Memory and Media Storage: Our chosen motherboard supports DDR2 400/533 SO-DIMM, up to 2GB. Thus, we use a Kingston 1GB SODIMM RAM as main memory. Since Bifrost/Linux can run from a flash disk, we use a Sandisk Cruzer slice USB 2.0 2GB as media storage.

4) Casing, Cooling and Physical Considerations: We chose a rack mounted casing for the router, as this is the common type of casing used by commercial router products that are placed inside racks or cabinets. The deployed router uses 12V picoPSU and a fan for cooling. To increase options for input power supply and storage, the lab router use a new picoPSU that have a voltage range between 6-34V. To avoid the use of active cooling components such as fans so that we can reduce the demand for power as well as the risk for failures requiring local interventions, the current lab router use heat sinks.

The current design, is shown in Figure 1 with two input options: the main supply or battery. Their performance and power consumption will be discussed in the next section.

D. Storage for Power Backup

We are exploring the use of a battery of ultra-capacitors rather than the currently most frequently used lead acid batteries. Ultra-capacitors have two main advantages: 1) they

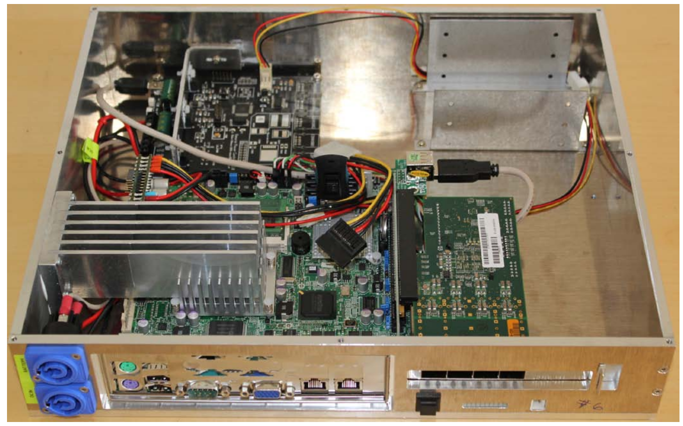

Fig. 1. Internal view of the casing with the components

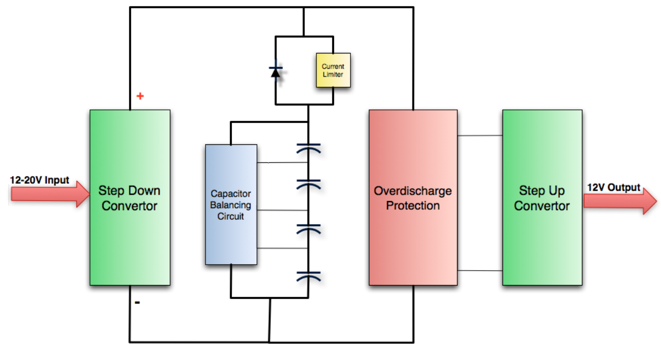

Fig. 2. Overall structure of the Energy Module

can better withstand the high operating temperatures observed in rural developing regions. 2) They are less sensitive to deep discharging cycles compared to lead-acid batteries.

The backup design has been changing as well to reflect the changes in the router design as follows:

1) Backup based on the 12V picoPSU: To achieve the required 12V to power the router, our setup involved 4 Maxwell BCAP 1500F ultra-capacitors [14], each with operating voltage up to 2.7V, arranged in series to form a battery providing up to 10.8V. This setup necessitated the use of a DC-to-DC step-down converter to provide the correct voltage for charging. To protect the ultra-capacitors from over-voltage during charging, a balancing circuit was designed to equally balance the charge on each of the 4 capacitors and to protect them from overcharging. Another DC-to-DC step-up converter was needed to provide the correct voltage to the router. The energy setup diagram is given in Figure 2.

2) Backup based on the 6-34V picoPSU: To increase the efficiency of the power supply, a new version is being tested involving 16 Maxwell BCAP 3000F ultra-capacitors, each with operating voltage up to 2.7V. The capacitors are arranged in two parallel banks each of eight capacitors in series, thus forming a battery providing up to 21.6V. The whole setup provide a backup of 2 hours. at 22W. The actual assembly is shown in Figure 3.

A printed circuit board has been designed for the balancing

Fig. 3. Final Capacitors Design

circuits. The new router design also includes an integrated power management module performing monitoring and control of charge voltages and currents, facilitating graceful shutdown and wakeup of the router depending on availability of power, and monitoring of temperature sensors on a one-wire bus. This is still work in progress.

V. Results and Analysis

In this section, we present lab tests as well as on-field recorded measurements and observations of our router and the power management. The tools used to measure router performance and power consumption include pktgen[5], a stand alone version of the power management module mentioned in the previous section and a DC power meter (Doc Wattson R102). Unless stated otherwise, the measurements in this section refer to the deployed router.

A. Router Performance

In the lab test, we used two different setup options to test the performance and power consumptions of the router as follows:

1) Using only the dual 1GE RJ45 ports on the motherboard.
2) an external quad 1GE SFP port NIC supporting both fiber and copper links.

The first setup is useful in situations where there is neither a need for extra ports nor for higher performance while the later case is useful in situations where there is different link media (fiber), or need for higher performance or more ports.

The chipset used on the external NIC has multiple RX/TX-rings and queues which can be mapped via Message Signaled Interrupts (MSI) to utilize different CPU-cores of the processor to give an efficient network load sharing. A key function in this process is to distribute a network flows to the same CPU-core to avoid packet reordering. This done by Receiver Side Scaling (RSS) [16] or by some classifier function on the chip. For non-multiqueue capable cards, that is cards with only one RX-ring and one queue connected with an interrupt just to one CPU-core. The recent Receive Packet Steering (RPS) software function within the Linux kernel can be used to distribute network load/flows among other CPU-cores at lower

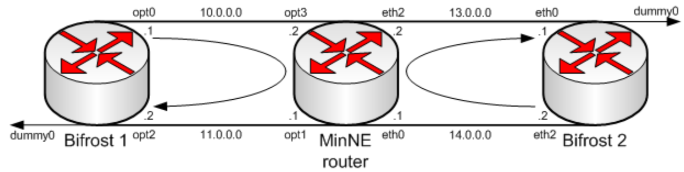

Fig. 4. Overall structure of the Energy Module

TABLE II
Routing Performance and Power Consumption

Component	Deployed	Lab Router
Maximum Throughput (Packet rate)	522 kpps	732 kpps
Maximum Data rate (unidirectional)	984 Mbps	984 Mbps
Power Consumption when idle	22.15 watts	18.40 watts
Power Consumption at full speed	24.75 watts	22.3 watts

performance compared to multiqueue capable cards. Linux has efficient implementation of multiqueue functions in both network device drivers and kernel code.

Using pktgen tool, we generated ten million packets arranged in two queues with five million packets per queue. To accommodate our setup, we applied the pktgen patch[6] on the receiver side. Also, because the Motherboard ports does not support multi-queue, we used the RPS tool to distribute the traffic among the 4 cores on the CPU.

We performed routing performance measurements following the RFC 2544 [21] standard. Figure 4 depicts our test set-up. The sender and receiver (Bifrost 1&2) are high performance machines with the following specifications:- Tyan S7002 Motherboard; Intel E5520 Quad Core 2.27GHz CPU; Intel 82576 NIC; and 3GB Memory. MinNE router (Minimal Network Element) is our device under test.

Both machines were running the latest Bifrost/Linux distribution (v.6.0.1, 32-bit Kernel).

Fig. 5 presents the routing performance using the external NIC, we observe that the router can forward more than 500kpps. Fig. 6 presents routing performance of the Motherboard ports where more than 230kpps are transferred. Note that packets were evenly distributed into all four threads of the CPU as the Motherboard ports does not support multiqueue.

There is no performance measurements on field except the fact that this router has been running for more than four months now without any problem.

B. Power Consumption

The experiment began by setting up just the motherboard without any component attached, measurement recorded. An incremental approach was then used where individual components were added onto the motherboard and power increase was recorded. It should be emphasized that the increase in power consumption does not represent the precise amount drawn by that particular component to make a generalization, however, we believe the readings did provide the precise power

[5]http://www.linuxfoundation.org/collaborate/workgroups/networking/pktgen

[6]http://tslab.ssvl.kth.se/pktgen/

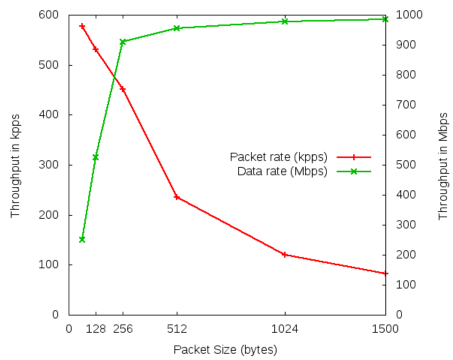

Fig. 5. External NIC Routing Performance

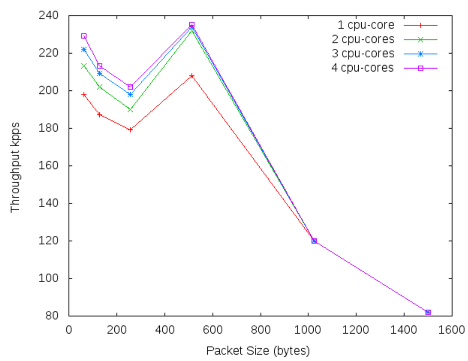

Fig. 6. Motherboard ports Routing Performance (With CPU-cores)

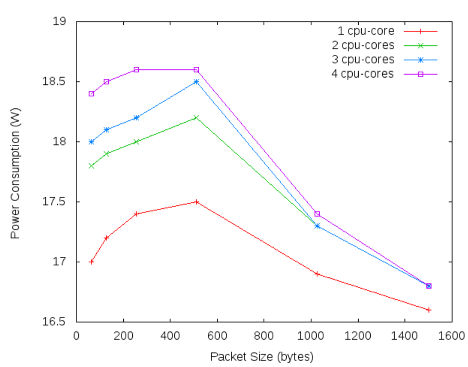

Fig. 7. Power Consumption (with CPU-cores)

consumption of the whole system, and the increase in power is a result of the new component to the system.

In Figure 7, we present the impact of different CPU cores on power consumption. The overall routing performance and power consumption was provided in Table II.

C. Backup System

Current system of 16 capacitors can provide backup energy for a maximum of 2 hours only, providing 22.3W. Apart from this short time to provide backup power, the final product was also very bulky as it was seen in Figure 3, hence some packaging issues. In addition, capacitors are still expensive and not readily available in rural developing regions. Thus, ultra-

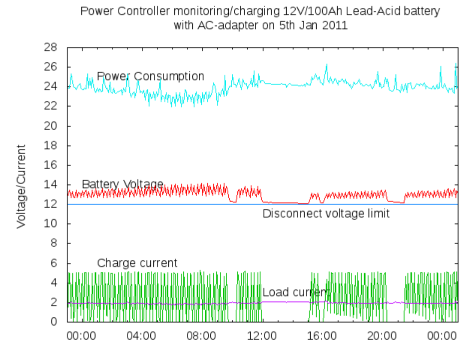

Fig. 8. On Site Power Monitoring and Control: 12V Lead-Acid battery as backup

capacitors were not a better option given that a new battery can offer 12 hours time and are readily available. Therefore, current backup solution in use is lead-acid batteries, continuing with research activities on the ultra-capacitors as future backup solution.

D. Onsite Power Management

The power management system has been running for more than three months. For presentation convenience, Figure 8 presents a one day capture of the power monitoring and control on site. The graph indicates the router's power consumption and load current. The drop in the charge current indicates power fluctuations where the battery is maintaining a steady load current (backup).

VI. Discussion and Conclusion

As observed in Figure 5 and 6, the ports on the external NIC provides very high forwarding capabilities compared to the Motherboard ports. This fact make our design modular, that you add performance capability based on need as well as budget.

Also, to make sure that we have achieved our goal of designing a low power, high performance, affordable router, we wanted to make comparisons with products of similar performance characteristics. However, we could not get all the routers to test for a comparison, instead, we gathered information through vendors websites or fact sheets to get performance and power consumption data. We know this is not the best way to make comparisons, but, we believe the information provided are good enough to paint a rough picture to guide our discussion. The cost information was obtained from the market (equipment resellers). Summary of the comparison is provided in Table III.

Our router design has six ports in total that each can accommodate 1 Gb/s which is comparable to Cisco 7507 router having seven slots accommodating up to 1 Gb/s per slot. The researchers in [17] established that the Cisco 7507 base system consumes approximately 210 Watts.

Future work includes more research on packaging and creating a micro-controller for charge/discharge monitoring of

TABLE III
COMPARISON TO OTHER PRODUCTS

	MinNe	Cisco 2821	Vyatta 2501	Juniper J4350
Power Consumption	23W	54W	345W	350W
Input Voltage	12V	110V to 240V	240V	240V
License	Open Source	Proprietary	Open Source	Proprietary
Performance	723kpps	170kpps	500kpps	225kpps
Cost ($)	1,194	3,282	2,310	3,732

the ultra-capacitor solution as a backup and alternative power storage.

ACKNOWLEDGMENT

The contribution of the MinNE student team making the actual implementation and testing of the prototype [22] in the Communication Systems Design framework (CSD) [23] is gratefully acknowledged.

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