How to Design an Energy Efficient Fiber-Wireless Network

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Abstract

We analyze the energy consumption of current in-building networks and show that new network designs employing fiber-wireless Technologies could lead to significant energy savings in future high-speed networks.

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1. Introduction

Current in-building networks are generally designed to meet capacity, performance, and installation cost requirements without considering their energy consumption (EC). Statistics show [1] that the Internet usage in North America increases at a sustained rate of 40% p.a. Although today’s communications networks consume only a small fraction of the total world-wide EC (i.e. ~1-2% [2]), this is expected to change significantly in the near future. Both the number of network users and the bandwidth consumption per user are growing much faster than the aggregated total world-wide EC [2]. It is predicated that by 2025, communications networks will consume almost two orders of magnitude more than what they do today [2] unless new more energy efficient networking technologies are developed and deployed.

Therefore, new network implementation technologies are needed in order to address the energy challenge. In this paper, we investigate the energy consumption of current in-building networks (IBN) beyond data centers [3]. We build on the analysis of the power consumption of a typical office building IT network (OBI) and of a typical residential network in [4] and show that new network implementation approaches employing fiber-wireless technologies could lead to significant energy savings in future high-speed communications. Figure 1 shows our estimate of the EC of all in-building networks in USA. We see that focusing only on data centers’ energy efficiency is not sufficient to solve the problem of EC of in-building networks - residential and office buildings must be addressed as well.

Figure 2 shows that the EC of in-building networks in the U.S. alone is higher than the EC of both global optical transport and of the core and metro area networks worldwide.

2. Goals and Methodology

Our main goal is to understand the energy consumption of current IBNs (including network architecture design and implementation) and to find more energy-efficient alternatives. An important “boundary condition” is that these alternatives should not introduce performance degradations. We aim at achieving higher network performance with less energy. To achieve these goals, we model and analyze network components, network architectures and network protocols, and use simulations to evaluate the energy consumption of various networking technologies. We also conducted experimental measurements on actual networks and used the measurement data in our statistical analyzes.

3. Current and Near-Future IBNs: Office and Residential

Office Buildings: In Ref [4], we describe a typical OBIT which is also illustrated in Figure 3. We analyzed how energy is consumed in an OBIT [4]. The MDF and IDFs consume a large percentage of energy, about 14% and 39%, respectively, in large OBITs during the day. In small OBITs, the MDF consumes 74% during the day. NICs consume a considerable amount of energy in large OBITs, about 43%; this is even more than the MDFs’ consumption. This is due to the large number of users in large OBITs. Since small office buildings have fewer users, their NICs do not consume as much energy as those in large office buildings.

Residential Buildings: Today’s or near-future typical residential networks consist of an ONT and a WAP, which are usually connected using a coaxial cable or an Ethernet cable. WAPs can be wired to some user devices in residential unit using copper Ethernet, and connected to others wirelessly. A general illustration of today’s residential network is given in Figure 4. The power consumption distribution of today’s residential network is given in Figure 5; there is no sleep mode mechanism in current WAPs.
4. Possible Avenues to Greener IBNs:

In this section, we discuss how network implementations of IBNs (residential and OBIT) can be made more energy efficient. The discussion is based on network elements’ models we designed to evaluate the power consumption of wired and wireless technologies. We’ve integrated these models into network models to explore the advantages of various options including (a) energy efficient components; (b) smaller wireless cells; (c) use of Optical Ethernet instead of Copper Ethernet; (d) Radio-over-Fiber (RoF) and (e) more energy efficient protocols.

4.1. Energy-efficient components: Customer Premises Equipment (CPE) provides interconnectivity between the in-home optical/wireless network and the access network, as shown in Figure 6. When optical to electrical to optical (OEO) regeneration is performed at the CPE, it is possible to use plastic optical fiber to interconnect the CPE, WAPs and terminal equivalent plugs, while keeping the protocol transparent. The proposed CPE architecture where OEO regeneration is employed is illustrated in Figure 7.

![Figure 7: Proposed CPE architecture](image)

We investigated the power consumption of the access/in-house network, shown in Figure 8, when OEO regeneration is employed at the CPE. VCSEL array is used for transmission and a PIN-type photodiode, a transimpedance amplifier (TIA) and a limiting amplifier (LIA) is used for the reception. We used VCSEL arrays since they consume less power than DFB arrays; since the distance between the CPE and the WAP/plug is short, there is enough power budget to use VCSELS at the CPE. We analyzed the power consumption of the overall access and in-home network. The results are given in Figure 9 using the following assumptions: Each WAP is on 30% of the time and is in sleep mode for the rest of the time. There are 2 WAPs using 802.11n and 2 plugs for wired connectivity, each one operating at 1 Gbps peak data rate.

4.2. Fiber optics instead of copper: As described in Section 2, most wired connections in today’s OBITs are copper Ethernet links. Can optical networking save energy compared to a copper-based infrastructure? A good comparison can be made with commercially available chips that support both copper and optical 1Gbps Ethernet. Such a typical PHY/MAC chip consumes about 1.45 W for copper medium and about 0.55 W for optics medium [5]. However, an optical transceiver is separately needed which adds up another 0.5W [6]. From the foregoing, optical Ethernet can be ~28% more energy-efficient than Electrical Ethernet at 1 Gbps. In fact, optical Ethernet is expected to be significantly more energy-efficient at higher network throughput (e.g. 10 Gbps), because optical fiber transmission has much better data-rate scalability for the same system energy. In addition, optical Ethernet has a much longer reach than copper Ethernet (i.e. 550m for optical [7] compared to just 90m for copper Ethernet [8] at 1 Gbps), which could be exploited to reduce the number of the switching nodes in large-scale deployments. Therefore, by combining all these attributes, optical fiber-based networking solutions can achieve significant energy savings, while offering better network performance.

4.3. Wireless technologies and wireless transmission distance: We compare a single-input single-output (SISO) and a multiple-input multiple-output (MIMO) system with two spatial streams operating at 2.4 GHz and analyze the effects of wireless transmission distance on energy consumption (EC) per bit. We assume a Rayleigh fading channel and the simplified path loss model. Both systems target an average bit error rate (BER) of 10^-3 at the same bit-rate assuming a fixed modulation format. Minimum required transmit power scales with path loss. Power consumption of PA depends on transmit power and its efficiency parameters. We assume that other front-end circuits consume 400mW in SISO and 700mW in MIMO. The back-end of both systems includes signal processing circuits and other digital circuits for PHY. Figure 10 shows the EC per bit as function of wireless transmission distance in MIMO and SISO systems with different modulation formats. We see that the SISO system consumes 34%-42% less energy per bit than the MIMO system with 64QAM modulation due to the fact that SISO system requires fewer circuits and lower transmit energy. The price paid for that advantage is more bandwidth. At lower operating frequencies, bandwidth is severely limited, making MIMO an attractive way for increasing wireless system capacity. However, as Figure 10 shows, MIMO may not be the most energy efficient way towards higher wireless system throughput. MM-wave systems including 60 GHz wireless, which boast of large amounts of license-free spectrum may be the most promising energy-efficient gateway to ultra-high wireless system capacity [9].

4.4. Smaller wireless cells: Figure 10 shows that lower energy per bit is required to bridge short wireless transmission distances for the same modulation format or data throughput. This is due to the higher wireless path-loss for longer transmission distances. Nevertheless, the non-linear variation of the EC per bit with respect to the transmission distance suggests the possibility of an interesting avenue for optimizing system-wide wireless energy consumption. For instance, a BPSK-modulated SISO system has a relatively constant EC per bit of ~18nJ/bit over the first 10 m but quickly rises to ~28 nJ/bit over the next 10m up to 20m. This behavior
suggests an inherent advantage for deploying smaller cells. To investigate this phenomenon further, we modeled the total energy consumption per bit of a 100m×100m wireless coverage area. We fixed the total wireless capacity at 360 Mbps, using a SISO-based wireless system operating at 2.4 GHz. We then split this wireless capacity of several radio cells, using two different system configurations namely distributed back-end with RF front-end (e. g. self-contained WAP) and centralized back-end with distributed front-end (e. g. distributed antenna system). The results are presented in Figure 11, which shows that centralizing and sharing the back-end could save energy wireless delivering the same wireless capacity as a complete distributed system. In addition, using smaller cells could be more energy efficient. This analysis considers the energy consumption of the wireless part of the system. However, in order to determine the total system energy consumption, it is necessary to include the energy consumption of the backhaul as well. In that case it is expected that the backhaul will dominate the total energy consumption for very small cell sizes owing to the large number of wired connections to the WAPs or antennas that would be required. Therefore, this result suggests the existence of an optimal cell size for minimum EC per bit – which may depend on the actual parameters of the deployed system. Further investigation is required to fully understand this behavior.

4.5. Radio-over-fiber (RoF): Today’s OBITs consist of two independent networks: wired and wireless; they are not integrated with each other or optimized for low energy consumption. For instance, WAPs are connected to switches over Ethernet links with copper UTP cables. Even though the end-user is connected to a WAP, the user’s data is processed first by the wireless transceivers and protocol stack of 802.11; then, it is formatted and processed by the 802.3 protocols for transmission over Ethernet cables to the switch. RoF might be an attractive solution since the remote antenna unit can be kept very simple thus minimizing the power consumed by baseband (including) protocol and signal processing. Data can be modulated for wireless transmission in a central location (e.g. in an MDF) and demodulated in the wireless receiver that resides in the end-user’s equipment. This could save additional demodulation and modulation steps at the remote end, and processing of protocol stacks.

4.6. Energy-efficient protocols: To achieve lower power consumption in IBNs, network protocols should be optimized in terms of energy efficiency. For example, bit-interleaving PON [10] protocol is designed for energy efficiency purposes in residential networks. Bits are interleaved at the OLT and the ONT receives only its own bits at a lower rate than the access network rate. In traditional GPON, all downstream traffic is processed at a high clock rate and then the packets whose destination address do not match the OLT’s, are dropped. Typically, about 98% of the whole PON traffic is dropped, resulting in high power consumption for the ONT [10]. However, with the bit-interleaving approach, the packets to be dropped are identified earlier and are not processed, which contributes to power savings. In addition, the low clock rate at the ONT helps to reduce the power consumption when bit-interleaving PON is employed.

The power consumption of bit-interleaving PON ONT and that of XGAPON ONT are compared. In [10], these protocols are implemented using FPGAs and compared in terms of dynamic power consumption of the FPGAs. Since the FPGAs are not optimized for energy efficiency, the static power consumption of the FPGAs (this is the power consumption when it is turned off without any traffic applied) is rather high. Hence, the dynamic power consumption, which is the power consumed when the traffic is applied to the FPGA minus the static power consumption of the FPGA, is a good comparison metric for the two network protocols discussed. It is shown in [10] that the bit-interleaving PON protocol is more energy efficient than the XGAPON protocol even when the two FPGAs are not receiving any traffic and when the sleep mode mechanism is employed to both FPGAs.

5. Summary and Conclusions:

We analyzed today’s residential networks and office building IT networks (OIBTs) and estimated how much energy these networks consume. Networking energy in data centers is less than that of all residential units put together; office building IT networks also consume a significant amount of energy. Reduction of energy consumption of data centers alone will not be sufficient to achieve significant energy savings. The total energy consumption of in-building networks in the U.S. is larger than that of global optical transport and core and metro area networks. To achieve green networking one’s primary focus must be on the in-building networks.

We investigated several options for making In-Building Networks (IBNs) more energy efficient. As we move to higher bitrates, optical links would be more energy efficient. In OIBTs, wireless access networks with cells of optimum size would give significant energy savings. Using components such as VCSEL arrays in residential networks can reduce power consumption. Energy efficient protocols such as bit-interleaving PON protocol in Passive Optical Networks can save a considerable amount of processing energy. RoF can provide seamless integration between wireless and optical transmission and eliminate the need for extra protocol processing and thus may reduce overall energy consumption.

6. Acknowledgements:

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7. References:

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