A Study of the Environmental Impact of Wired and Wireless Local Area Network Access

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Abstract — *This paper presents a life cycle assessment of the energy and emission intensity of wired and wireless local area network access. Following a cradle-to-grave approach, the energy consumed and greenhouse gas emissions in the manufacture of Ethernet switches and WiFi access points (including the extraction of raw materials, component manufacturing, assembly, and transportation) as well as during their actual usage are evaluated. The results show that while the manufacturing stage is responsible for a significant fraction of the overall energy consumption, the usage phase accounts for most of the emissions*[1].

Index Terms — Local area networks, environmental impact, green networks, sustainability.

I. INTRODUCTION

Network access through local area networks (LANs) is ubiquitous in residential, commercial, educational and public places. Among the various available technologies, Ethernet (or IEEE 802.3) and WiFi (or IEEE 802.11) are two of the most popular means for network access. Given the widespread use and popularity of these two local area network access protocols, it is of interest and importance to evaluate the environmental impact of these technologies. This paper investigates two aspects of the sustainability of local area networks by evaluating the energy and emission intensity of WiFi access points and Ethernet switches.

The most common way to use Ethernet is for a user to connect to an Ethernet switch using a cable. On the other hand, WiFi users usually connect (wirelessly) to an access point that serves as a gateway to the network. Ethernet and WiFi network interface cards are also required at the clients to connect to the switches and access points, respectively, and most computing devices either have them built-in or can use them as an add-on device. This paper focuses its attention on the access points for WiFi based networks and the switches for Ethernet based networks, and evaluates the energy it takes to manufacture and operate them, along with the greenhouse gas emissions they are responsible for. In addition, this paper also aims to analyze and identify the stages in the life cycle that have the greatest impact on the environment. The methodology used in paper is also applicable to the client side Ethernet and wireless access cards.

The energy, sustainability and environmental aspects of various Information and Communication Technologies (ICT) have received increasing attention in the recent past [1],[2],[3]. However, to the best of the author's knowledge, the sustainability and environmental impact of WiFi or Ethernet based local area networks has not been adequately addressed. Past research has evaluated the energy intensity of computer manufacturing in terms of the total energy and fossil fuel consumption of desktop computers and cathode ray tube monitors [4]. The life cycle inventory data of various electronic components has been calculated in terms of the energy consumption and atmospheric emissions [5]. Existing literature has evaluated the material and energy consumption of mobile phones [6],[7], as well as the energy consumption of universal mobile telecommunication system (UMTS) and global system for mobile communications (GSM) mobile communication systems [8]. The energy consumption of a WiFi access point has also been evaluated [9]. This paper fills the void in existing literature regarding the energy and emission intensity of local area network access.

This paper uses a Life Cycle Assessment (LCA) method to evaluate the environmental impact of WiFi access points and Ethernet switches. Two popular, commercial-off-the-shelf devices (one access point and one switch) were used as case studies for the LCA. Following a cradle-to-grave approach and detailed inventory analysis, the energy consumption and emissions associated with the manufacturing and operation of the access point and the switch are evaluated.

The rest of the paper is organized as follows. Section II presents an overview of LCA, the datasets used in this paper, and the architecture of WiFi access points and an Ethernet switches. Section III presents the energy and emission intensity analysis of the access point and the switch. Section IV presents a discussion of the results and Section V concludes the paper.

II. BACKGROUND AND RELEVANT CONCEPTS

This section provides an overview of the methodology, concepts and the data sources used in this paper. We also describe the architecture of WiFi access points and Ethernet switches. The complexity of the architecture directly affects the material and component costs as well as the cost of running the device.

A. *Ethernet Swtich*

The IEEE 802.3 Standard [10] specifies the physical (PHY) layer and the medium access control (MAC) at the data link

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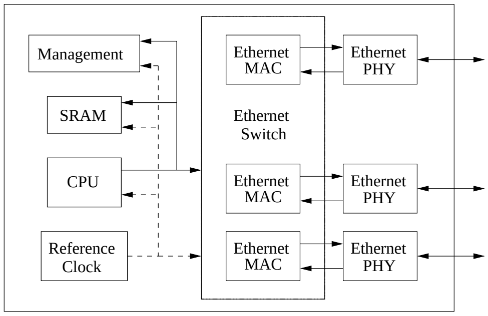

Fig. 1. Simplified block diagram of an Ethernet switch.

layer for wired Ethernet. The data rates supported by Ethernet has evolved from 10 Mbits/s in 1985 (IEEE 802.3a) to 40 Gbits/s in 2010. The basic mode of connections in Ethernet is to use copper or fiber cables to connect computing devices, either directly, or through the use of intermediate hubs, switches and routers. The basic utility of the Ethernet switch is to create a separate collision domain for each switch port, resulting in a considerable improvement over the throughput achievable by using hubs.

A simplified block diagram of an Ethernet switch is shown in Figure 1 [11]. The switch has functional blocks for the MAC and PHY layers of the IEEE 802.3 protocol, a switch fabric and an associated scheduler, and a control unit. The Ethernet MAC and PHY functional blocks are responsible for transmitting and receiving Ethernet frames, address checking, cyclic redundancy checking (CRC) and carrier sense multiple access with collision detection (CSMA/CD). The switch maintains a table with known MAC addresses and the ports they are on. Depending on the manufacturer, the memory for storing this table might be the on same chip as the switch fabric, or on a separate chip. Vendors also add different levels of manageability into switches. While a low-end switch may not have any manageability, managed switches have functional blocks for collecting traffic related statistics, and managing and troubleshooting connections. Finally, some switches may also have layer 3 functionalities.

For the case study reported in this paper, an Ethernet switch with 5 ports, capable of data rates up to 100 Mbits/s was used. The switch under consideration has a single integrated circuit (IC) that does the switching and management functions and there is no separate memory chip for storing the routing table. The switch also has an IC for DC-to-DC conversion. There is single clock for the entire device. The switch also has indicator light emitting diodes (LEDs) to indicate the status of each port as well as the switch.

B. *WiFi Access Point*

The IEEE 802.11 standard [12] covers both the physical and the medium access control layers of wireless networks. The standard specifies that a network can be configured in two different ways: infrastructure and ad-hoc. In the infrastructure mode, an access point is typically connected using an Ethernet (IEEE 802.3) link to a wired network and all wireless nodes communicate with this network through the access point. On the other hand, in an ad-hoc network the computers are brought together to form a network dynamically. The focus of this paper is on infrastructure networks that are based on the use of access points.

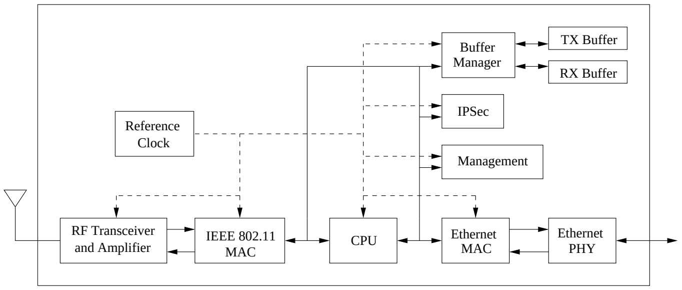

Fig. 2. Simplified block disgram of a WiFi access point.

A simplified block diagram of a WiFi access point is shown in Figure 2 [13]. The access points have functional blocks for the MAC and PHY layers of both IEEE 802.11 and 802.3 protocols, transmit and receive buffers that are controlled by a buffer manager, units for management and Internet Protocol Security (IPSec), and a control unit. The access point communicates with the wired network using the Ethernet MAC and PHY functional blocks. These two blocks are responsible for transmitting and receiving Ethernet frames, address checking, CRC, and CSMA/CD based medium access. The received frames and the frames to be transmitted are stored in pre-allocated transmit and receive buffers. Depending on the exact architecture of the access point, the Ethernet MAC functional block and the central processing unit (CPU) are also responsible for checksum calculation, and insertion and deletion of Transport Control Protocol/Internet Protocol (TCP/IP) headers. The radio frequency (RF) transceiver and amplifier carry out the IEEE 802.11 PHY operations and its functionality is analogous to that of the Ethernet PHY functional block. Similarly, the functionality of the IEEE 802.11 and Ethernet MAC functional blocks are similar, except that the IEEE 802.11 MAC is based on CSMA with collision avoidance (CSMA/CA). The management functional block is responsible for allowing administrators to setup, repair and maintain the access point while the IPSec functional block authenticates and encrypts the IP packets.

For this paper’s case study, the WiFi access point used has two antennas and also includes a 5-port Ethernet hub (a typical configuration for many popular access points). The access point under consideration uses two memory chips: a 256MB double data rate synchronous dynamic random access memory (DDR SDRAM) and a 8MB flash memory. The access point also uses two separate ICs for the Ethernet switch and the IEEE 802.11 router. In addition, three different clocks are used: one by the Ethernet functional blocks, one by the IEEE 802.11 MAC and one by the IEEE 802.11 PHY.

C. *Life Cycle Assessment*

Life cycle assessment is a well-established tool for the study and quantification of the environmental impact of process, products, and activities. As the name suggests, the

TABLE I

PARTS INVENTORY OF THE WIFI ACCESS POINT (SM: SURFACE MOUNTED, HM: HOLE MOUNTED, BNC: BAYONET NEILL-CONCELMAN)

Component	Quantity	Weight (g)	Area (mm^2)	Material (Wh/g)	Component cost		Emission (g-CO$_2$/g)	Source(s)	Energy Intensity (Wh)	Emission (g-CO$_2$)
					(Wh/g)	(Wh/mm^2)				
Access Point										
SM resistors	121	0.54	-	3.53	95.99	-	2.71	[15],[16]	53.74	1.46
SM capacitors	188	2.72	-	6.28	109.86	-	1.29	[15],[16]	315.90	3.51
SM inductors	15	0.42	-	5.80	48.00	-	2.70	[15],[16]	22.60	1.13
HM capacitors	5	4.14	-	31.50	11.88	-	13.22	[15],[16]	179.59	54.73
HM inductors	7	10.12	-	18.50	6.51	-	6.64	[15],[16]	253.10	67.20
ICs	18	4.63	520.20	98.32	24.11	40.27	28.57	[15],[16]	21515.31	132.28
Diodes	17	1.53	-	386.59		-	56.86	[15]	591.48	87.00
LED housing	8	1.64	-	22.5	0.86	-	1.86	[15],[16]	38.31	3.05
PWB	1	82.36	21957.75	0.03	-	0.34	0.02	[15],[16]	8124.37	439.16
Connectors	4	25.80	-	22.70	6.51	-	3.50	[15]	753.62	90.30
Screws	3	2.00	-	14.85	7.78	-	1.78	[15]	45.26	3.56
Aluminum cover	1	1.76	-	16.10	0.75	-	17.06	[15],[16]	29.66	30.03
BNC connectors	2	55.32	-	19.79	5.08	-	10.18	[15]	1375.81	563.16
Cables	2	59.68	-	12.02	0.83	-	5.59	[15]	766.89	333.61
Clock crystals	3	1.11	-	18.50	6.51	-	6.64	[6],[15]	27.76	7.37
Plastic casing	1	207.50	-	22.50	0.86	-	1.86	[15],[16]	4847.20	385.95
Antennas										
Cables	2	59.68	-	12.02	0.83	-	5.59	[15]	40.47	17.61
BNC connectors	2	28.51	-	19.79	5.08	-	10.18	[15]	709.04	290.23
Plastic casing	2	28.34	-	22.50	0.86	-	1.86	[15],[16]	622.02	52.71
Packaging										
Paper	5	22.00	-	1.67	0.83	-	0.85	[15]	55.00	18.70
Cardboard	2	237.00	-	15.92	1.33	-	0.33	[15]	4088.25	78.21
Plastic	4	31.00	-	22.50	0.86	-	1.86	[15],[16]	724.16	57.66
Pins	2	0.07	-	14.85	7.78	-	1.78	[15],[16]	1.58	0.13
Total									45304.66	2718.75

analysis covers the entire life cycle of a product, starting from the extraction of raw materials, manufacturing, transport, use (including re-use and maintenance), and final disposal (including recycling). The methodology followed by LCA of a product involves four stages: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation [14]. The first stage in LCA defines the system under study. This stage establishes the system boundaries, and defines the inputs and outputs of the system. The second stage quantifies the material and energy use of the product, and uses it to quantify the overall burden on the environmental. The environmental burden may be defined in terms of resource and energy consumption, air and water emissions, and solid waste. The third stage aggregates the metrics related to the environmental burden into a number of impact categories and evaluates their potential environmental impact. This stage considers specific environmental effects (for example, global warming) and aggregates the environmental burdens as per their contribution to these effects. The final stage in the LCA methodology isolates the stages in the life cycle that have the most impact, does sensitivity analysis, and identifies and recommends possibilities for performance improvement. The methodology for LCA is still under evolution and the exact details of the steps of the LCA are usually adapted for the specific product or process under consideration.

D. Data Sources

This paper primarily uses the LCA database developed by the Center for Environmental Assessment of Product and Material Systems at the Chalmers University of Technology in Göteborg, Sweden [15]. The database was initiated by a joint research forum comprising of thirteen industrial corporations and Chalmers University of Technology. The database was first released in 1998 and currently contains more than 500 data sets that have been documented and quality reviewed. The database lists the energy and material inputs and outputs associated with the production of various materials, components, assembly, and transportation systems. Three impact assessment models are provided in the database: EPS (Environmental Priority Services), EDIP (Environmental Design of Industrial Products), and Eco-Indicator. The database also provides a simple impact assessment calculator where the environmental impact of each dataset can be calculated based on the three assessment methods mentioned above.

The majority of the per unit energy cost values used in this paper were obtained from the LCA database developed by Chalmers University of Technology [15]. The energy and emissions associated with the production of various raw materials was obtained from data originally generated by the Dutch environmental consultant Pré (using the Eco-Indicator impact assessment model), that was further developed [16].

TABLE II

PARTS INVENTORY OF THE POWER SUPPLY (SM: SURFACE MOUNTED, HM: HOLE MOUNTED)

Power Supply										
Component	Quantity	Weight (g)	Area (mm^2)	Material (Wh/g)	Component cost		Emission ($g\text{-}CO_2/g$)	Source(s)	Energy Intensity (Wh)	Emission ($g\text{-}CO_2$)
					(Wh/g)	(Wh/mm^2)				
SM resistors	16	0.14	-	3.53	95.99	-	2.71	[15],[16]	13.93	0.38
SM capacitors	5	0.05	-	6.28	109.86	-	1.29	[15],[16]	5.81	0.06
HM resistors	1	0.54	-	6.15	5.16	-	4.43	[15],[16]	6.10	2.39
HM capacitors	4	10.29	-	31.50	11.88	-	13.22	[15],[16]	446.38	136.03
HM inductors	3	21.41	-	18.50	6.51	-	6.64	[15],[16]	535.48	142.16
ICs	2	0.57	39.10	98.32	24.11	40.27	28.57	[15],[16]	1644.43	16.29
Transistors	3	3.72	22.64	178.52	24.11	23.13	48.41	[6],[15]	1277.45	180.09
Diodes	3	0.25	-	386.59		-	56.86	[15]	96.65	14.72
PWB	1	-	2479.00	0.03	-	0.34	0.02	[15],[16]	917.23	49.58
Fuses	1	0.27	-	18.50	6.51	-	6.64	[15]	6.75	1.79
Screws	2	0.85	-	14.85	7.78	-	1.78	[15]	19.42	1.51
Heat sink	2	6.59	-	16.10	0.75	-	17.06	[15],[16]	111.04	112.43
Foam	3	1.60	-	0.32	28.16	-	1.18	[15]	45.57	1.89
Cable	2	30.13	-	12.02	0.83	-	5.59	[15]	387.17	168.43
Plastic casing	1	37.00	-	22.50	0.86	-	1.86	[15],[16]	864.32	68.82
Plug pins	2	2.00	-	15.92	5.08	-	10.18	[15],[16]	42.00	20.36
Total									6419.55	916.93

For any component for which data was not explicitly available (e.g. surface mounted inductors), data corresponding to "other electronic components" from the LCA database was used [15]. Finally, the material and component costs for diodes are combined in a single entry, as given in the LCA database [15].

III. ENERGY AND EMISSION INTENSITY OF LOCAL AREA NETWORK ACCESS

This section presents a LCA based study to evaluate the energy consumption and greenhouse gas emissions of WiFi access points and Ethernet switches. We first present the overall methodology and then present the details of the study.

A. *Methodology*

The objective of this paper is to quantify the energy and emission intensity of local area network access. An additional objective is to isolate the major sources of environmental burden and identify areas for possible improvement. To accomplish these objectives, a LCA of an Ethernet base station and a WiFi access point is performed.

The system boundary of the LCA presented in this paper includes the entire life cycle of the switch and the base station. This includes the pre-manufacturing steps (raw material extraction and production), manufacturing of parts and components, product assembly, transportation, use, and disposal. The inputs to the system consist of the materials and energy required for manufacturing, transporting, and operating the devices. The outputs of the system consist of the product (the switch and the access point), emissions, waste, and energy released into the environment. A detailed list of the parts and components that are used to manufacture the switch and the access point is created for the inventory analysis. In order to create the parts inventory, both the devices under study were disassembled and their individual components were counted, measured (for dimensions), and weighed. LCA data (primarily from the database at Chalmers University of Technology) is then used on the parts inventory for the impact assessment.

For the WiFi access point and Ethernet switch chosen for the case study, the life-cycle of the two devices is divided into two phases: manufacture and use. It is assumed that at the end of the use phase, the access point and the switch are discarded and not recycled. While this assumption is pessimistic, it is not unrealistic since recent statistics show that only 13.6% of electronic waste is recycled in the USA and the rest ends up in landfills or incinerators [17].

The rest of this section elaborates on the inventory analysis and impact assessment of the LCA. The energy and emissions in the various steps of the manufacturing process and the actual use are enumerated and listed to calculate the overall energy and emission intensity of local area network access.

B. *Energy and Emissions During Manufacture*

The manufacturing process for a WiFi access point or an Ethernet switch consists of the following steps, each of which contributes to the energy and emission intensity:

- *Raw material extraction and processing:* The first step in the manufacturing process is the extraction, processing and refining of raw materials that are required for the manufacturing of the various components that constitute the two devices. For electronic and computing devices, while precious metals constitute only a small percentage of the overall device weight, the energy needed to extract and refine them is typically far larger than that required for other materials.
- *Component manufacturing:* In this step the raw materials are used to manufacture the individual components inside an access point or switch. The electronic components needed by an access point or switch can be classified as either passive (such as resistors and capacitors) or active (such as semiconductor chips),

TABLE III

PARTS INVENTORY OF THE ETHERNET SWITCH (SM: SURFACE MOUNTED, HM: HOLE MOUNTED)

Component	Quantity	Weight (g)	Area (mm^2)	Material (Wh/g)	Component cost		Emission ($g\text{-}CO_2/g$)	Source(s)	Energy Intensity (Wh)	Emission ($g\text{-}CO_2$)
					(Wh/g)	(Wh/mm^2)				
Switch										
SM resistors	54	0.49	-	3.53	95.99	-	2.71	[15],[16]	48.77	1.33
SM capacitors	52	0.41	-	6.28	109.86	-	1.29	[15],[16]	47.62	0.53
SM inductors	4	0.31	-	5.80	48.00	-	2.70	[15],[16]	16.68	0.84
HM capacitors	6	3.68	-	31.50	11.88	-	13.22	[15],[16]	159.64	48.65
HM inductors	4	8.45	-	18.50	6.51	-	6.64	[15],[16]	211.33	56.11
ICs	2	1.66	121.30	98.32	24.11	40.27	28.57	[15],[16]	5087.99	47.43
Diodes	8	0.33	-	386.59		-	56.86	[15]	127.58	18.76
PWB	1	26.47	7055.00	0.03	-	0.34	0.02	[15],[16]	2610.35	141.10
Connectors	3	24.07	-	22.70	6.51	-	3.50	[15]	703.09	84.25
Screws	3	2.00	-	14.85	7.78	-	1.78	[15]	45.26	3.56
Heat sink	1	2.24	-	16.10	0.75	-	17.06	[15],[16]	37.74	38.21
Grips	4	0.21	-	0.32	28.16	-	1.18	[15]	5.98	0.25
Cable	2	170.08	-	12.02	0.83	-	5.59	[15]	2185.53	950.75
Clock crystals	1	0.42	-	18.50	6.51	-	6.64	[6],[15]	10.50	2.79
Plastic casing	1	27.00	-	22.50	0.86	-	1.86	[15],[16]	630.72	50.22
Metal casing	1	115.50	-	15.92	5.08	-	10.18	[15],[16]	2425.50	1175.79
Packaging										
Paper	3	42.00	-	1.67	0.83	-	0.85	[15]	105.00	35.70
Cardboard	2	199.00	-	15.92	1.33	-	0.33	[15]	3432.75	65.67
Plastic	3	9.50	-	22.50	0.86	-	1.86	[15],[16]	221.92	17.67
Pins	2	0.06	-	14.85	7.78	-	1.78	[15],[16]	1.36	0.11
				Total					18115.31	2739.72

each having different energy intensities. In addition, there are a number of other components such as connectors, cables, switches etc..

- *Assembly:* The assembly phase starts with the soldering of the electronic components on a printed wiring board (PWB). All other components such as antennas and casing are then assembled and the product is tested. The major sources of energy consumption in this phase are the electricity required for lighting, air conditioning and machinery, usually in that order [6].
- *Packaging and transportation:* The energy consumed for packaging and transportation is primarily dependent on the weight and dimensions of the product, the distance traveled, and the means of transportation. The transportation stage includes cargo vessels (from Asia to North America in the context of the case study) as well as trucks (from cargo terminals to distribution points). Details of the assumptions and calculations related to the packaging and transportation are listed in the Appendix.

To evaluate the energy intensity of each stage of the manufacturing process, first a detailed inventory analysis to evaluate the weight (or surface area in case of semiconductor devices and printed wiring boards) of the various components that constitute the access point and the switch was conducted. Then, existing databases were used to evaluate the energy and emission intensity of each component in each stage of the manufacturing process.

The WiFi access point in the case study (as well as typical commercial access points) can be considered to be made of three parts: the access point itself, the antennas, and the power supply. On the other hand, the Ethernet switch in the case study (and other commercial Ethernet switches) consists of just the switch hardware and the power supply. Both devices use a similar power supply with minor variations. To keep the comparison as even as possible, it is assumed that the same power supply is used for both devices and a generic commercial off the shelf power supply is used in this case study. The list of all components and their weights for the WiFi access point are given in Table I and those for the power supply are given in Table II. Similarly, the list of all components and their weights for the Ethernet switch are given in Table III. Note that the figures for packaging in these tables do not include the corrugated cardboard boxes used for the bulk shipping from the factory to the retail shops. Tables IV and V show the overall figures for the energy and emission intensity for the access point and switch, respectively, and include the material and energy costs during the transportation stages. For the ICs and transistors, the surface area of the silicon wafers (i.e. die size) used inside the chips are also listed (since the LCA database provides the energy intensity in terms of the area). However, since only the external area of an IC is measurable and most data sheets do not provide die size dimensions, this paper assumes that the die area is 40% of the IC area. Typical IC packaging technologies such as chip scale packaging (CSP), ball grid array (BGA), shrink small-outline package (SSOP) and thin-SSOP (TSSOP) have a die size that is between 30-80% of the IC area [18], and this paper uses a conservative estimate in this range. Also, the die size of a power transistor is assumed to be 11.07 mm^2 [19] and that of other discrete transistors is assumed to be 0.5 mm^2 [20].

TABLE IV
OVERALL ENERGY AND EMISSION INTENSITY OF THE WIFI ACCESS POINT. THE VALUES FOR RAW MATERIAL EXTRACTION AND COMPONENT MANUFACTURING STAGES ARE OBTAINED FROM TABLES I AND III

Stage		Weight (g)	Distance (km)	Energy Intensity			Emission Intensity		
				Unit Cost	Source	Energy (Wh)	Unit Cost (g-CO$_2$/g)	Source	Emission (g-CO$_2$)
Materials and components		759.29	-	-	-	24534.86	-	-	3656.65
Assembly		759.29	-	15.90 Wh/g	[6]	12072.71	6.50 g-CO$_2$/g	[6]	4935.39
Transportation: truck	Cardboard	64.51	-	17.25 Wh/g	[15]	1112.80	0.33 g-CO$_2$/g	[15]	21.29
	Transport	823.80	400	0.00061 Wh/g-km	[15]	201.01	0.000161 g-CO$_2$/g-km	[15]	53.05
Transportation: ship		1466.80	20100	0.000056 Wh/g-km	[15]	1651.03	0.0000151 g-CO$_2$/g-km	[15]	445.19
		Total				39572.41			9111.57

C. *Energy and Emissions During Usage*

Measurements were conducted on the WiFi access point under different traffic loads to evaluate the power consumption of an access point in the use phase. The measurements show that the current drawn from the power supply was constant at 150.25 mA at all loads and the supply voltage was 14.78 V. Considering a power supply efficiency of 80% [21], the per day energy consumption of the access point is 66.62 Wh, assuming a typical usage scenario where the access point always stays powered on (e.g. in academic institutions and many residences). Thus the total power intensity of the access point is 24316.30, 48632.60 and 72948.90 Wh for usage lifetimes of one, two and three years, respectively. As of 1999, the CO$_2$ emission intensity of power generation in the USA was 0.61 grams of CO$_2$ per Wh (based on generation from all energy sources) [22]. This implies that the energy usage of the access point resulted in 40.64 g, 14.83 kg, 29.67 kg and 44.50 kg of CO$_2$ emissions over a period of a day, a year, two years and three years, respectively.

Similar measurements conducted on the Ethernet switch show that the current drawn from the power supply was constant at 107.3 mA at all loads and the power supply voltage was 15.07 V. Again, considering a power supply efficiency of 80%, the per day energy consumption of the Ethernet switch is 48.51 Wh, assuming a typical usage scenario where the Ethernet switch always stays powered on. Thus the total power intensity of the Ethernet switch is 17706.15, 35412.30 and 53118.45 Wh for usage lifetimes of one, two and three years, respectively. In terms of the emissions, this energy usage of the Ethernet switch corresponds to 29.59 g, 10.80 kg, 21.60 kg and 32.40 kg of CO$_2$ emission of a period of a day, a year, two years and three years, respectively.

IV. DISCUSSION

The results of the previous two subsections show that the manufacturing stage accounts for a significant portion of the overall energy intensity of both the WiFi access point and the Ethernet switch. Table VI lists the overall energy consumption and emission intensity of the switch and the access point for various device lifetimes. The table also lists the relative contribution of the manufacturing phase to these two metrics. For the WiFi access point in the case study, the energy consumed during manufacturing accounts for 61.9%, 44.9% and 35.2% of the overall energy consumption for product lifetimes of one, two and three years, respectively. On the other hand, the CO$_2$ emissions during manufacturing account for 38.1%, 23.5% and 17.0% of the overall CO$_2$ emissions for product lifetimes of one, two and three years, respectively. The corresponding numbers for the Ethernet switch are 80.1%, 66.8% and 57.2% for the energy consumption and 49.2%, 32.6% and 24.4% for the CO$_2$ emissions.

For both the access point and the switch, the manufacturing phase accounts for a large fraction of the overall energy consumption. On the other hand, the usage phase accounts for a higher fraction of the CO$_2$ emissions for both the devices. While recycling is an option to mitigate the environmental impact of manufacturing, they only recover a fraction of the used raw materials in the components, while assembly and transportation energies are never recovered. Thus, extending the usable lifetime of the access points, for example by upgrades, is an attractive option to reduce the environmental impact of local area networks. Also, since the usage phase contributes most of the CO$_2$ emissions, using cleaner sources of electricity for domestic and office users would lower the emission intensity of local area networks.

During the manufacture stage, the energy consumption for the WiFi access point is about 80% higher than that of the Ethernet switch. However, the CO$_2$ emissions for the WiFi access point during the manufacture stage is only 15% higher than that for the Ethernet switch. This is primarily due to two factors: (i) the access point has a large number of ICs which drive up the energy consumption; (ii) the Ethernet switch used in the case study had a metal casing which increased its CO$_2$ emissions. During the usage stage, the energy consumption as well as CO$_2$ emissions of the WiFi access point is about 37% more than that of the Ethernet switch. This number is specific to the particular choice of the access point and Ethernet switch chosen for the case study. However, in general an Ethernet switch tends to consume lower energy than a corresponding WiFi access point. This is primarily because an Ethernet switch has a smaller number of functionalities compared to a WiFi access point. The larger number of functions supported by WiFi access points also implies that they require more components when they are manufactured. Consequently, the

TABLE V

OVERALL ENERGY AND EMISSION INTENSITY OF THE ETHERNET SWITCH. THE VALUES FOR RAW MATERIAL EXTRACTION AND COMPONENT MANUFACTURING STAGES ARE OBTAINED FROM TABLES II AND III

Stage		**Weight (g)**	**Distance (km)**	**Energy Intensity**			**Emission Intensity**		
				Unit Cost	**Source**	**Energy (Wh)**	**Unit Cost (g-CO$_2$/g)**	**Source**	**Emission (g-CO$_2$)**
Materials and components		932.75	-	-	-	51724.21	-	-	3635.68
Assembly		932.75	-	15.90 Wh/g	[6]	14830.73	6.50 g-CO$_2$/g	[6]	6062.88
Transportation: truck	Cardboard	108.86	-	17.25 Wh/g	[15]	1877.84	0.33 g-CO$_2$/g	[15]	35.92
	Transport	1041.61	400	0.00061 Wh/g-km	[15]	254.15	0.000161 g-C0$_2$/g-km	[15]	67.08
Transportation: ship		2126.68	20100	0.000056 Wh/g-km	[15]	2393.79	0.0000151 g-CO$_2$/g-km	[15]	645.47
		Total				71080.72			10447.03

overall energy and emission intensity of WiFi access points are generally higher than Ethernet switches.

This paper assumed that the devices are discarded at the end of their use phase. A fraction of the devices may be repaired and reused, and some devices may be shipped to countries in Asia and Africa where they may be reused or recycled. While the reuse of devices adds some extra environmental burdens (e.g. due to transportation), overall it serves to reduce the impact associated with the manufacturing of a device. The recycling of electronic devices to reclaim materials is primarily done for metals such as copper and gold [23]. The negative environmental and social impact of such processes (e.g. due to release of toxic pollutants) tends to be high, particularly for unregulated operations that are prevalent in certain countries [23]. The overall benefit of such recycling is an open issue.

As a caveat, it is pointed out there are a number of assumptions made in this paper (e.g. no recycling, power supply efficiency values etc.), which may not be valid in all cases. However, it is fairly straightforward to accommodate alterations. Also, the absence of data in some cases (e.g. manufacturing costs for SM inductors) forced the use of approximations. While such approximations cannot be avoided in the absence of data, since only a small fraction of the components were affected, the errors introduced are not expected to be significant.

V. CONCLUSIONS

This paper presented an LCA based study to evaluate the energy and emission intensity of a WiFi access point and an Ethernet switch over their lifetime. The energy and emissions expended in the manufacturing phase were computed using a detailed inventory analysis and those in the use phase were evaluated experimentally in an operational network. For the devices considered in this paper's study, the results show that manufacturing accounts for 62-80% of the total energy consumption and the remaining 20-38% comes from the use phase, assuming a one year operational lifetime. Similarly, the manufacturing and usage phases account for 38-49% and 51-62% of the total emissions, respectively. For a three year operational lifetime, the energy consumed during the manufacturing phase changes to 35-57% while the emissions during the manufacturing phase changes to 17-24%. The results show that the energy consumed in the manufacturing phase is a significant fraction of the overall energy intensity of both the access point and Ethernet switch. However, the emissions during the use phase dominate the emissions during the manufacturing phase. Mechanisms to increase the overall lifetime of the devices while using cleaner sources of electricity are thus an attractive way to decrease their environmental impact and energy footprint.

APPENDIX

The details of the assumptions related to the packaging and transportation of the devices from the place of manufacture to the place of use are listed in this appendix.

The WiFi access point and the Ethernet switch considered in the case study were both made in China. It is assumed that the two products were manufactured in the Guangzhou province (with a large concentration of electronics industry) and transported using a truck to Hong Kong (150 km), from where it was put in a cargo ship to New York City (20100 km). Finally, the two devices were transported in trucks from New York City to Troy, New York (250 km) where it was purchased and used.

Each device was individually packed (along with instruction manuals, compact disks etc.) at the factory in a cardboard box that is also shrink wrapped in clear plastic. It was assumed that the individual switch and access point packages were put in type EH corrugated cardboard boxes with internal dimensions of 0.91 m x 0.56 m x 0.56 m (36 in x 22 in x 22 in) and external dimensions of 0.93 m x 0.58 m x 0.59 m (36.5 in x 22.75 in x 23.13 in) for bulk transport before being shipped from the factory. The tare weight of the cardboard box was assumed to be 3.48 kg [24]. The dimension of each Ethernet switch and access point after its individual packaging was 24.61 cm x 15.40 cm x 5.87 cm and 27.78 cm x 22.86 cm x 6.99 cm, respectively. Thus each cardboard box for shipping contained 54 switches and 32 access points. The additional shipping weight (due to the cardboard box) per switch and access point was thus 64.51 g and 108.86 g, respectively. Also, it was assumed that a 12.19 m (40 ft) container, with a tare weight of 3750 kg and internal dimensions of 12.12 m x 2.39 m x 2.39 m (39 ft 3 in x 7 ft 10 in x 7 ft 10 in) was used for the overseas shipping [25]. A container can thus hold 108

TABLE VI
ENERGY AND EMISSION INTENSITY FOR VARIOUS LIFETIMES AND THE RELATIVE CONTRIBUTION OF THE MANUFACTURING STAGE (IN PARENTHESIS)

Device	Energy Intensity (KWh)					Emission Intensity (kg-CO$_2$)				
	1 year	2 years	3 years	5 years	10 years	1 year	2 years	3 years	5 years	10 years
Switch	88.79 (80.06%)	106.49 (66.75%)	124.20 (57.23%)	159.61 (44.53%)	248.14 (28.65%)	21.25 (49.17%)	32.05 (32.60%)	42.85 (24.38%)	64.45 (16.21%)	118.45 (8.82%)
Access Point	63.89 (61.94%)	88.21 (44.86%)	112.52 (35.17%)	161.15 (24.56%)	282.74 (14.00%)	23.94 (38.06%)	38.77 (23.50%)	53.60 (17.00%)	83.26 (10.94%)	157.41 (5.79%)

cardboard shipping boxes, thereby carrying 5832 Ethernet switches and 3456 access points per trip. Since a container is reused a large number of times over a period of many years (10 to 15 voyages per year, with a typical lifetime of 10 to 15 years) and recycled at the end [25], the share of the container's manufacturing cost for the transport of a single switch or access point is quite small, and was thus neglected in this study. The additional shipping weight (due to the shipping container) per switch and access point was 643.00 g and 1085.07 g, respectively.

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