Energy Consumption of Content Distribution from Nano Data Centers versus Centralized Data Centers

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ABSTRACT

Energy consumption of nano data centers has recently been a topic of interest as they emerge as a novel computing and storage platform. We present end-to-end energy consumption models for nano data centers and its centralized counterpart. To assess the energy consumption of nano and centralized data centers, we propose flow-based and time-based energy consumption models for shared and single user network equipment. To evaluate our models, a set of measurements and practical experiments are performed. Our results indicate that nano data centers might lead to energy savings depending on various factors such as location of nano servers, type of access network attached to nano servers, and the ratio of active time to idle time of nano servers. Thus, nano data centers can complement centralized ones and lead to savings energy if certain applications are off-loadable from centralized data centers.

Keywords

Energy consumption, Content distribution, Nano data centers, Centralized data centers, Cloud computing, Measurements

1. INTRODUCTION

A great deal of attention has been paid to the energy consumption of cloud services and data centers in an effort to reduce the energy consumption and carbon footprint of the ICT industry [9, 13]. While a number of different approaches have been applied to improve the energy efficiency within a data center [17, 20], another proposal is to store content in servers which are geographically distributed close to the end-users [21]-[10]. Different strategies have been introduced to distribute content in various parts of the network. One such proposal is to host and distribute the content from end-user premises known as nano data centers [21, 22]. The studies [21, 22] claim this solution is more energy-efficient than sharing videos from centralized data centers. However, other works [11, 8] show the decentralized content distribution consumes more energy than the centralized solution. This difference stems from lack of comprehensive models for the network topology and equipment energy consumption.

To analyze this problem and compare the energy consumption of centralized and nano data centers, we first construct an end-to-end network architecture that includes all equipment required for distributing content from centralized and nano data centers. We then derive comprehensive energy consumption models for content distribution. To do this, we propose a flow-based energy consumption model for shared network equipment and a time-based energy consumption model for single-user network equipment located in the end-user premises.

To estimate the energy consumption of applications distributed from centralized and nano data center based on the developed network and energy models, we study the energy consumption of Wordpress [7] which can host content in servers within centralized data centers or servers in the end-user premises. To construct an energy model of a nano data center we adopt Raspberry Pi's (very small and low power single board computers) [6] as a nano servers and characterize it using packet-level traffic and power consumption measurements. Using the energy models, the energy consumption resulting from requesting data from a nano data center server is compared to that of the same request served from a server within a centralized data center.

In this context, the contributions of this paper are: (a) End-to-end network models for centralized and nano data centers consists of all network equipment are developed; (b) New energy consumption models for shared network elements (flow-based energy model) and single-user network elements (time-based energy model) are proposed; (c) Our network and energy models are applied to an application and a set of power consumption and traffic measurements are performed to obtain realistic results.

Our results indicate that while nano data centers can save energy for some applications by pushing content closer to end-users and decreasing the energy consumption in the transport network, it also can consume more energy (a) when the nano servers are attached to an energy-inefficient access network; or (b) when the idle time of dedicated nano servers is much greater than the active time; or (c) when location of nano serves are very far from the users requesting data. Therefore, the most energy efficient strategy may be a combination of centralized and nano data centers for running applications. By identifying applications best suited for nano data centers and not locating them in centralized data centers, the internal energy consumption of centralized data centers can be improved.

The rest of this paper is organized as follows. The energy consumption models are explained in §2. We present practical experiments and measurements in §3. Energy consumption of centralized and nano data centers is compared in §4. Finally, the paper is concluded in §5.

2. ENERGY CONSUMPTION MODELS

In this section, we describe the energy consumption models for network elements. The models will be used to estimate the energy consumption of accessing data from centralized and nano data centers. The model is based upon calculating the "energy-per-bit" for a given operating condition (that reflects the utilization of the equipment) which is multiplied by the number of bits generated by the service to give the total energy consumption of the service.

To estimate the energy-per-bit of equipment, we categorize network elements into two types: 1) elements that are shared by many users and 2) customer premises equipment (CPE) dedicated to a single user (or few users). For the highly shared equipment we present a "flow-based" energy model and for the single user equipment we present a "time-based" energy model. The energy consumption (energy-per-bit) of each model type is examined separately.

2.1 Shared Network Elements

The cloud service traffic, C_s is only a fraction of the total traffic, C, through a network element within that part of the network that deals with aggregated traffic. For equipment in this part of the network the measure of the energy consumption of the cloud service is based upon proportional allocation of the elements power over all the flows through the element. We refer to this as a "flow-based" model.

Network elements consume power whether idle or active. The power consumption of one typical network element can be modeled by the linear form $P(C) = P_{\text{idle}} + C(P_{\max} - P_{\text{idle}})/C_{\max}$ [22, 23]. The idle power (P_{idle}) can be a significant proportion of $P_{\max}$ (up to 90%), therefore we cannot ignore P_{idle} when calculating the energy consumption of the service.

Because the vast majority of network elements have the same linear [24] power profile, we can do likewise for all the equipment in the network which is shared by multiple services. Recognizing that network traffic is a random process that may exhibit significant short term variations, network designers only operate the elements up to a pre-set utilization ($U_{\max} < 1$). The cumulative power consumption of a network can be represented by a staircase curve as shown in Figure 1. Each step corresponds to the deployment of additional network equipment because the capacity per network element reaches the pre-set maximum operating load threshold, $U_{\max}$. Under normal operating conditions we have $U < U_{\max}$.

To construct an energy model for the overall service, we compute the energy-per-bit of a network path by first averaging across the equipment in each node, and then averaging across the nodes in the network path used by the given service.

We consider a network in which the average number of network elements in each node is $n >> 1$. Let $< P_{\text{idle}} >$ be the mean idle power for the network elements in the node. Similarly we define the mean network element maximum power, $< P_{\max} >$, and mean network element maximum capacity, $< C_{\max} >$. The average energy-per-bit ($E'_{\text{b-flow}}$) for $n >> 1$ shared network elements is given by:

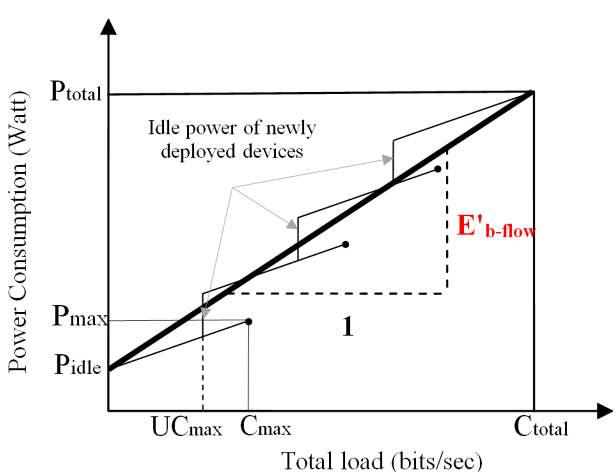

Figure 1: Power consumption trend under large-scale equipment deployment

$$E'_{\text{b-flow}} \approx \frac{P_{\text{total}} - < P_{\text{idle}} >}{C_{\text{total}}} = \frac{< P_{\text{idle}} >}{U < C_{\max} >} + \frac{< P_{\max} > - < P_{\text{idle}} >}{< C_{\max} >} \quad (1)$$

where, C_{total} is the capacity of all network elements in a node and U is the mean utilization of the network elements.
The energy consumption of a service that uses a network path shared with many other traffic flows, is then given by:

$$E_{\text{S-flow}} \approx m E'_{\text{b-flow}} N_{\text{bit}} \quad (2)$$

where, N_{bit} is the number of transferring or retrieving bits through the node and m in the average number of nodes in the service network path.

2.2 Single User Network Elements

For equipment that is not shared over multiple services, such as home equipment and nano servers, we construct a "time-based" energy consumption model for the cloud service based upon the amount of time that equipment spends dealing with that cloud service data. Consider a user accessing a service via their home equipment and an access device (ONU, modem,..). A typical user's use of a service could be represented by the plots in Figure 2.
The user is active in accessing the service during times $t_k, k = 1, .., n$ and not accessing the service for times T_k. The total time of the user's cloud service session is $\sum_{j=1}^{n} T_j + t_j = T_{\text{tot}}$, as shown in Figure 2. The total active time for the service is $t_{\text{act}} = \sum_{j=1}^{n} t_j$.

We consider a coefficient R which defines the ratio of the time when the service is active to the whole duration:

$$R = \frac{t_{\text{act}}}{T_{\text{tot}}} < 1 \quad (3)$$

The data rate of the device during active times is the total bits delivered and received (N_{bit}) into the network divided by the total active time (t_{act}) which is $C_{\text{act}} = \frac{N_{\text{bit}}}{t_{\text{act}}}$. This is the port line rate of the device when active.

In addition, we define the effective data rate ,$C_{\text{eff}} = \frac{N_{\text{bit}}}{T_{\text{tot}}}$,which is the overall effective data rate for the service of interest when we take the ratio of total bits divided by the total cloud service session time. The energy consumption of the customer premises equipment (CPE) is given by:

$$E_{\text{cpe}} = P_{\text{idle}} T_{\text{tot}} + \int_{t_{act}} (P(t) - P_{\text{idle}}) dt = E'_{\text{b-time}} N_{\text{bit}} \quad (4)$$

where $E'_{\text{b-time}}$ is the energy-per-bit for a network device that is not shared by other traffic flows. It is given by:

$$E'_{\text{b-time}} = \frac{E_{\text{cpe}}}{N_{\text{bit}}} = P_{\text{idle}} \left(\frac{1}{C_{\text{eff}}} - \frac{1}{C_{\text{act}}}\right) + \frac{1}{t_{\text{act}} C_{\text{act}}} \int_{t_{act}} P(t) dt = \frac{1}{C_{\text{act}}} \left(P_{\text{idle}} \left(\frac{1}{R} - 1\right) + < P >\right) \quad (5)$$

In this $< P >$ is the mean power consumption of the device during active times.

2.3 Centralized and Nano Data Centers

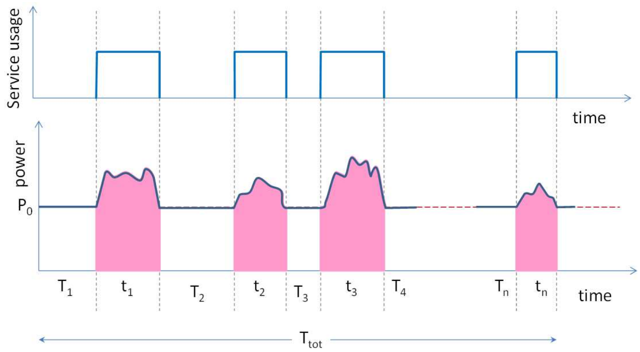

Figure 2: Usage and power consumption of a home equipment unit for a service

The energy consumed when accessing or storing content in a centralized data center is modeled by splitting the energy into three components: (1) energy consumption of accessing the service. This includes the end-user terminals and access technology; (2) energy consumption of the transport network (aggregation, edge and core networks); and (3) energy consumption of the data center including its internal network and servers. The energy consumed by a cloud service using a centralized data center for one request ($E_{\rm cent}$) can be expressed by:

$$E_{\rm cent} = E_{\rm cpe} + E_{\rm access} + E_{\rm edge} h_{\rm e} + E_{\rm core} h_{\rm c} + E_{\rm dc} \tag{6}$$

where $E_{\rm cpe}$, $E_{\rm access}$, $E_{\rm edge}$, $E_{\rm core}$ and $E_{\rm dc}$ are the energy consumed in the end-user device, access network, edge network, core network ,and data centers, respectively. $h_{\rm e}$ and $h_{\rm c}$ are the number of edge and core routers traversed.

In the case of nano data centers, the energy consumption for accessing the content consists of (1) the energy consumed by end-user devices requested the content; (2) the energy consumption of the transport network between the end-user requesting data and the end-user hosting the data (access network should be counted twice, once for each user); and (3) the energy consumed by storing and processing the content in the end-user premises. This energy is given by:

$$\begin{aligned} E_{\rm nano} =& E_{\rm cpe} + E_{\rm access} + E_{\rm edge} h_{\rm e} \\ &+ E_{\rm core} h_{\rm c} + E_{\rm access2} + E_{\rm nserver} \end{aligned} \tag{7}$$

where $E_{\rm access2}$ is the energy consumed by access network attached to nano servers and $E_{\rm nserver}$ is energy consumption of nano server devices located in the end-user premises.

Comparing (6) and (7), for a given end-user device and access technology, we note that the differences between energy consumption of centralized and nano data center is primarily determined by the following:

– The number of bits exchanged between the user and data center ($N_{\rm bit}$);

– The number of hops for the two cases ($h_{\rm e}$, $h_{\rm c}$);

– The values of $E_{\rm dc}$ compared to $E_{\rm access2} + E_{\rm nserver}$.

3. PRACTICAL EXPERIMENTS AND MEASUREMENTS

To substantiate our models by experiment, we applied the models to the Wordpress[14] application which is an open source website and blogging tool. There are two options for Wordpress users to have their own online blogs and websites:1) Sign up for an account from the Wordpress website and connect to the Wordpress data centers (centralized option); 2) Install Wordpress software locally and create a web-server and host the content locally instead of keeping the content on the Wordpress data centers (nano servers).
To equip end-users for hosting and controlling their data, the nano servers in the end-user premises were implemented using Raspberry Pi's [6]. The Raspberry Pi's has SD cards for storage however external hard drives can be attached to provide more storage. The Raspberry Pis' low power draw and silent running make it a good choice for home servers [24].

3.1 Traffic measurements

The number of exchanged bits ($N_{\rm bit}$) is one of the parameters for calculating the consumed energy in the most of network elements based on (2) and (4). In order to determine the number of exchanged bits between an end-user and a data center or a nano server when writing (upload) to Wordpress or reading (download) the same post, we measured the volume of traffic using a packet analyzer (Wireshark) running from the end-user devices.

The posts contain different sizes of photos which are stored on both Wordpress data centers and nano servers. We uploaded the photos with their original sizes to both the data center and the nano server. Figure 3 shows the number of exchanged bytes during uploading photos ranging from 1 MB to 7 MB to the data center and nano servers versus their original size. Each session was repeated 10 times and the average traffic is displayed. The upload curve related to the nano server indicates the traffic exchanged is very similar to the original photo size. However, the traffic observed for uploading to the data center is higher than the original size of photos. Postprocessing the Wireshark logs reveals that uploading traffic to centralized data centers is higher than the original size of photos which is due to the existence of third party applications and advertisement traffic.

After uploading all photos to the data center and nano servers, we downloaded the same photos to examine the exchanged traffic between the end-user and the servers for downloading photos. The traffic observed for downloading from the data center and nano server is similar to the original size of photos since there is no compression. In this case the amount of download traffic is similar to the upload traffic.

3.2 Power measurements

The power consumption of devices such as end-user terminals and nano servers when interacting with the Wordpress website is

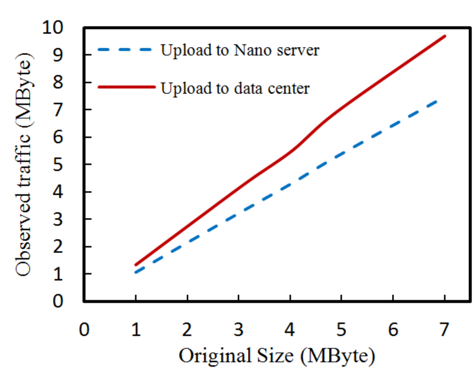

Figure 3: Exchanged bytes during uploading various sized photos to Wordpress website versus the original sizes of photos

	Power(Watt)		Traffic(Gbps)		Energy(nJ/bit)	
	Idle	Max	Downlink	Uplink	Downlin	Uplink
Fast Ethernet gateway (CPE)	2.8	4.6	0.1	0.1	352	352
ADSL2+ gateway (CPE)	4.1	6.7	0.024	0.003	2160	14809
4G gateway (CPE)	0.5	1.75	0.024	0.012	1615	3230
GPON gateway (CPE)	5.2	8.3	2.4	1.2	194	388
Ethernet Switch	1589	1766	256	256	31.7	31.7
LTE basestation	333	528	0.072	0.012	76200	19000
OLT	43	48	2.4	2.4	88	179
BNG	1701	1890	320	320	27	27
Edge router	4095	4550	560	560	37	37
Core router	11070	12300	4480	4480	12.6	12.6

Table 1: Energy-per-bit of network equipment in access, edge and core networks

measured directly using a power meter. We used a PowerMate meter [5] with a resolution of 10 mW during uploading and downloading a post.

We measured the power consumption of end-user devices while uploading and downloading different sized photos to Wordpress data centers and local nano servers. We also measured the power consumption of nano servers. As an example, Figure 4 shows the power consumption of two Raspberry Pi's. One of them is set as an end-user device and another is as a nano server when uploading a 5-MB photo to the nano server. The baseline power consumption of the Raspberry Pi acting as the end-user device is higher than the baseline power consumption of the nano server because of a web browser running at the end-user device. Figure 4 represents the power (as a function of time) for uploading a photo to the nano server. The sequence of events for the upload was: first open the web browser in the end-user device and then upload the photo (point t_1 in the user curve). After that, the nano server starts to work and store the photo (point t_1 in the nano server curve). After storing the photo, the local server status switches to idle mode (point t_2 in the nano server curve). Then the end-user device completes the final processing after which it also switches to idle mode (point t_2 in the user curve).

Similar power measurements have been done for estimating the energy consumption for downloading from the nano server to the user device.

4. ENERGY CONSUMPTION COMPARISON

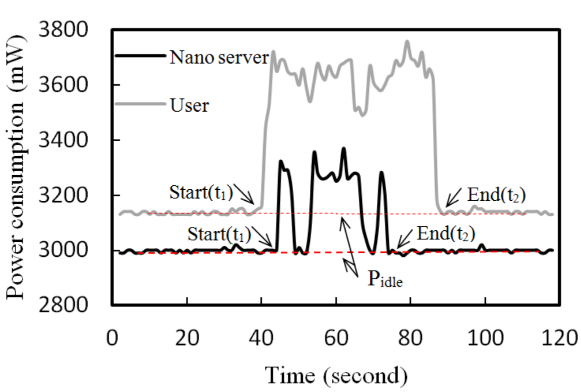

Figure 4: Power consumption of an end-user device and a nano server while uploading a photo to Wordpress

We compare the energy consumption of each part in a centralized data center with the related part in nano data centers to specify the difference in the consumed energy.

4.1 User Terminals and Access Network Equipment ($E_{\text{cpe}} + E_{\text{access}}$)

The power consumed by end-user terminals when interacting with the Wordpress website is measured by the PowerMate meter and the traffic is measured by Wireshark as explained before. The measurement results indicate the energy consumption of end-user terminals for uploading and downloading data to the Wordpress data center is similar to uploading and downloading data to the dedicated nano servers. The reason is that we consider similar end-user terminals in both centralized and nano data centers with same number of exchanged bits and same active time ratio (R), the consumed energy for both scenarios is similar according to (4) and (5).

To study the energy consumption of different access network technologies, Ethernet, WiFi, 4G and PON (passive optical network) technologies are considered. The access network includes (a) customer premises equipment (CPE) such as modems and (b) shared network equipment such as Ethernet switches and LTE base stations. The first seven rows of Table 1 list the power consumption, traffic and energy-per-bit for access network equipment when receiving data from the end-users (uplink) and transmitting data to the end-users (downlink). The idle power, maximum power, downlink traffic and uplink traffic of CPE are gathered from [3]. The energy-per-bit for CPE is calculated based on (5) considering the active time (R) is equal to 0.2. The idle, maximum power and maximum capacity of Ethernet switch and OLT are gathered from [23] and [1], respectively. The energy-per-bit values for them are calculated based on (1) assuming $U = 20\%$.

Estimating the energy-per-bit for an LTE base station depends on different factors such as the number of concurrent users, deployment area, spectrum width, interference, etc. The maximum and idle power consumption of a 3-sector 2×2 MIMO 4G/LTE base station deployed in an urban area are reported as 528 W and 333 W by [14]. It is also reported that base stations consume different amounts of power in each direction roughly 87% of the energy is consumed in the downlink direction and the remaining 13% in the uplink direction [14]. The aggregate achievable throughput of this base station is 72 Mbps with 20 MHz spectrum [12]. The energy-per-bit of this base station, considering a typical utilization of 5% over a 24-hour cycle, would be 76.2 μJ/bit in the downlink and 19.0 μJ/bit in the uplink on average. All the energy-per-bit figures are summarized in Table 1.

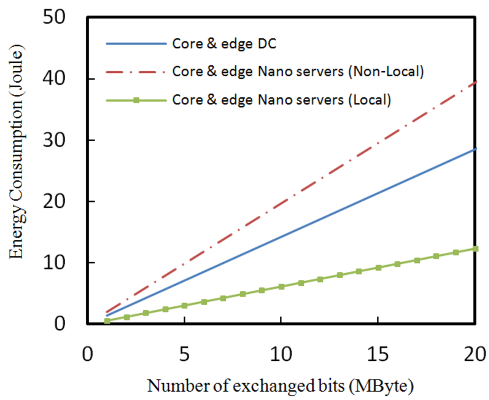

Figure 5: Energy consumption of core and edge equipment for accessing data from different locations

4.2 Edge and Core Network Equipment ($E_{\text{edge}}h_{\text{e}} + E_{\text{core}}h_{\text{c}}$)

The idle power, maximum power and capacity of equipment in the edge and core networks are gathered from [23] and the energy-per-bit values are calculated based on (1). To determine the values for the key network elements we set $U = 20\%$. All values for equipment in the edge and core networks are summarized in the last three rows in Table 1.

According to (6) and (7), the energy consumed in the edge and core networks also depends on the number of hops in the edge and core networks (h_{e}, h_{c}). Using *traceroute* from end-user devices to the Wordpess servers, we estimate the average number of edge and core routers along the path between the end-users and servers within data centers to be 3 and 5, respectively. However, the number of hops in the case of nano data centers depends on the location of end-users requesting the content relative to those hosting the content. The number of edge and core routers for two end-users located in different geographical spots are measured to be 3 edge and 8 core hops for non-local friends and 2 edge hops and 1 core hop for the closest friends setting in the same ISP (using *traceroute*).

Using the number of hops and the energy-per-bit values of BNG, edge and core routers listed in Table 1 in (2), (6) and (7), we get Figure 5 which shows the energy consumed in the edge and core networks (as a function of N_{bit}) when accessing content from a data center and a nano server hosted by a local friend (shortest path: located in the same ISP) and a nano server hosted by another end-user located another geographic location (longest path). The figure indicates that the energy consumption for requesting data from nano data centers can be higher or lower than the energy consumed for accessing the content in centralized data centers depending on location between the users and the stored content.

4.3 Nano Servers ($E_{\text{access2}} + E_{\text{nserver}}$) and Centralized Servers (E_{dc})

In this sub-section, we compare the service energy consumption of a nano server and its attached access network with that of a server within a centralized data center. Obtaining detailed information about servers within data centers and its associated internal networks is difficult because this information is not publically available. One of the most comprehensive articles on data center architecture and dimensioning can be found in [15, 16], in which a model design, with numbers and types of network equipment and servers, is described. Using the capacity of this model, together with data center traffic characteristics from [2], we develop estimates for data center energy consumption in the range 4-7 μJ/bit, excluding factors such as PUE and the need for replication. Including these factors increases the consumption to 20 μJ/bit [4].

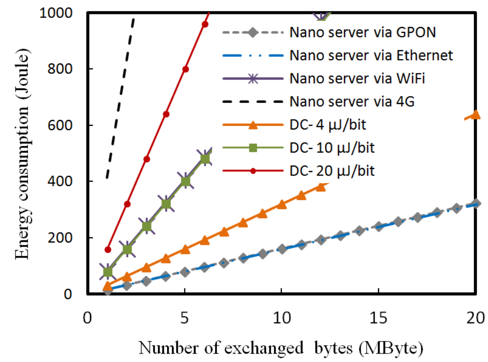

Figure 6: Energy consumption for requesting data from different data centers and various nano servers

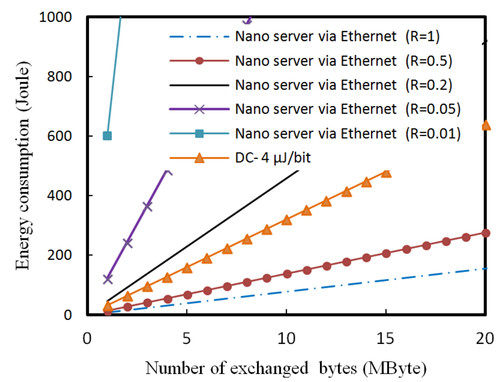

Figure 7: Energy consumption for requesting data from a data center and nano servers with different active time

In order to estimate the energy-per-bit of a nano server, we have measured the total energy consumed by a Raspberry Pi [6] when transferring and receiving data which was about 4 Watt over 10 Mbps bit-rate. Therefore, the energy-per-bit of the Raspberry Pi is about 1600 nJ/bit based on (5) assuming $R = 0.2$.

Figure 6 compares the energy consumed for serving data from a centralized data center with the consumption when data is served from nano servers located in end-user premises.
We consider premises with different access networks (GPON, Ethernet, WiFi and 4G) and data centers with wide range of energy consumption values (4,10 and 20 μJ/bit). It can be seen that the nano server attached to a 4G network consumes the greatest energy compared to others options, and the nano server attached to a GPON consumes the least energy. The energy consumption of the nano server via GPON is very close to the energy consumed by the nano server via Ethernet because the dominant consumption is that of the nano server (the curves for GPON and Ethernet are almost overlapped). This figure indicates how the energy consumption of the access network can affect the energy consumption of nano data centers. It should be noted that the curve for the nano server attached to WiFi is overlapped with the curve for the data center with 20 μJ/bit energy consumption.

To study the effect of active and idle time of network equipment in end-user premises, we compare the energy consumption of accessing data from a data center with 4 micro-joule/bit access rate value to a nano server via Ethernet access technology with different active time (R= 1, 0.5, 0.1, 0.05, 0.01). Although Figure 6 shows the energy consumption of the nano server via Ethernet is less than the energy consumed by data center with 4 μJ/bit access rate, Figure 7 shows with reducing the active time of the nano server and its attached network, the energy consumption of the nano server increases and dominates the energy consumption of the data center. Therefore, the ratio of active time over the whole duration is one of determining factors in studying energy consumption of network devices located in the end-user premises.

5. CONCLUSION

We introduced new energy models for shared and dedicated network elements to study the energy consumption of nano and centralized data centers. A number of valuable findings emerge from our study, including the factors that allow nano data centers consume less energy compared to its centerlized counterpart such as location of nano servers, type of access network attached to nano servers and the active time ratio of nano serves versus idle time. Other factors such as number of pre-loaded copies of data in nano serves and upload traffic rate of an application versus download merit further study to have an energy-efficient nano data centers.

Realization of nano data centers is occurring by implementation of smart devices to end-user premises for the Internet of Things (IoT) along with the new generation of small single-board computers and cloud-ready devices. To take advantage of the new architecture and to complement centralized data centers, we should categorize applications that are more energy-efficient with nano data centers and run them on this platform. In addition to saving energy by running some applications on the nano architecture, a portion of energy currently consumed within data centers for serving such applications can be saved.

6. ACKNOWLEDGMENTS

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