Fog Computing May Help to Save Energy in Cloud Computing

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***Abstract*—Tiny computers located in end-user premises are becoming popular as local servers for Internet of Things (IoT) and Fog computing services. These highly distributed servers that can host and distribute content and applications in a peer-to-peer (P2P) fashion are known as nano data centers (nDCs). Despite the growing popularity of nano servers, their energy consumption is not well-investigated. To study energy consumption of nDCs, we propose and use flow-based and time-based energy consumption models for shared and unshared network equipment, respectively. To apply and validate these models, a set of measurements and experiments are performed to compare energy consumption of a service provided by nDCs and centralized data centers (DCs). A number of findings emerge from our study, including the factors in the system design that allow nDCs to consume less energy than its centralized counterpart. These include the type of access network attached to nano servers and nano server's time utilization (the ratio of the idle time to active time). Additionally, the type of applications running on nDCs and factors such as number of downloads, number of updates, and amount of preloaded copies of data influence the energy cost. Our results reveal that number of hops between a user and content has little impact on the total energy consumption compared to the above-mentioned factors. We show that nano servers in Fog computing can complement centralized DCs to serve certain applications, mostly IoT applications for which the source of data is in end-user premises, and lead to energy saving if the applications (or a part of them) are off-loadable from centralized DCs and run on nDCs.**

***Index Terms*—Energy consumption, nano servers, centralized DCs, Cloud computing.**

I. Introduction

FOG computing [1] is a new paradigm refers to a platform for local computing, distribution and storage in end-user devices rather than centralized data centers (DCs) [1]. This platform is becoming popular and even critical for wide range of applications, especially Internet of things (IoT), such as geo-distributed, mobile applications, real-time and latency-sensitive applications [1]. In this paper we study very small servers known as "nano data centers" (nDCs) located in end-user premises for hosting and distributing content and applications in a peer-to-peer (P2P) fashion [2].

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Fog computing is becoming an alternative to cloud computing for some applications [1]. But there has been little analysis, in the literature, of the energy consumption of Fog computing. There are different points of view on energy consumption of data storage and distribution from end-user premises in the literature. For example, in [3] and [2], it is claimed that this solution is more energy-efficient than sharing videos from centralized DCs. However, other works [4], [5] show that P2P content distribution from end-user premises consumes more energy than the centralized solution. This difference is largely due to different models for equipment energy consumption in different research work. In addition, some studies have either ignored the transport network or used an overly simple model of the transport network.

In this work, we aim to identify scenarios for which running applications from nano servers are more energy-efficient than running the same applications from centralized DCs using measurement-based models for network energy consumption that are more accurate than used in previous work. We first consider an end-to-end network architecture that includes all equipment required for distributing and accessing data from centralized DCs and nDCs. 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 network equipment located in the end-user premises which is not shared by many users.

To apply and validate our proposed models using experiments, we study the energy consumption of the application Wordpress [6] which can host content in servers within centralized DCs or servers in the end-user premises. Nano servers are implemented using Raspberry Pi's (very small and low power single board computers) [7] and are characterized by traffic and power consumption measurements. Using the energy models, the energy consumption of requesting data from a nano server is compared to that of the same request served from a server within a centralized DC.

Our results indicate that while nDCs can save a small amount of energy for some applications by pushing content closer to end-users and decreasing the energy consumption in the transport network, they also can consume more energy when the nano servers are attached to an energy-inefficient access network or when the active time of dedicated nano servers is much greater than its idle time.

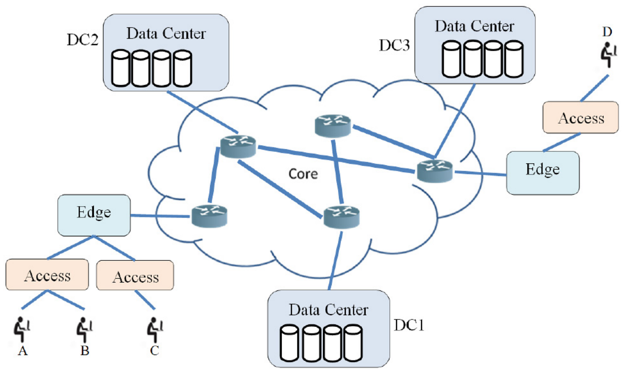

Fig. 1. Network model of centralized data centers.

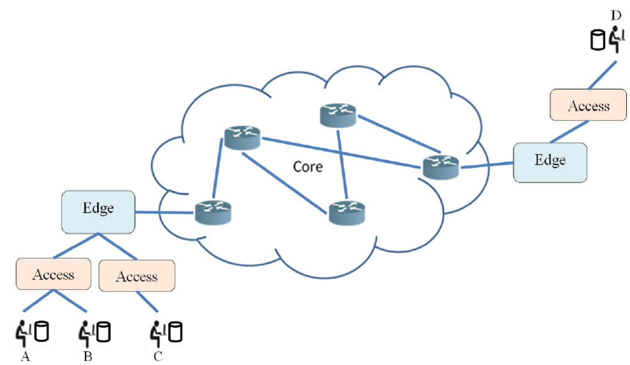

Fig. 2. Network model of distributed nano servers.

We investigate what type of applications can be run from nano servers to save energy. We find that parameters such as the number of downloads, the number of updates and the amount of data pre-loading play a significant role on the energy consumption of the applications. Our results show that the best energy savings using nano servers comes from applications that generate and distribute data continuously in end-user premises with low access data rate such as video surveillance applications.

Consequently, the most energy efficient strategy for content storage and distribution in cloud applications may be a combination of centralized DCs and nano servers. By identifying applications (or parts of there-of) best located in nano servers, rather than centralized DCs, the energy efficiency of those applications can be improved.

The rest of this paper is organized as follows. The network topology and energy consumption models are elaborated in § II and § III, respectively. § IV presents practical experiments and measurements. Energy consumption of centralized DCs and nDCs is compared in § V. Parameters for executing applications efficiently in terms of energy cost on nano servers are explained in § VI. Finally, the paper is concluded in § VII.

II. Network Topology

The end-to-end network topology for both centralized DCs and nDCs is described in this section.

A. End-to-end network model for centralized data centers

A cloud service provider has one or a few centralized DCs attached to the core of the network which host content as shown in Figure 1. The network within the DCs includes servers, storage, aggregation switches and one or more edge routers. Data center content is transported through large core routers and optical links to the edge network. The edge network generally consists of a metro Ethernet switch, broadband network gateways (BNGs) and edge routers. The content passes through an access network which might be an Ethernet, WiFi, PON, 3G or 4G connection, or a combination of these to reach the end-user terminal [8]–[11].

B. End-to-End Network Model for Nano data Centers

In nDCs architecture, there are no large, centralized DCs attached to the core network. Rather, each end-user is equipped with a device to host and distribute data. We may view the nDCs approach as data storage and processing distributed amongst users with a piece of data allocated to each user as shown in Figure 2. Different network paths will be required for transporting content from the distributed servers depending on the user's geographical location. The requests are either sent from (i) "home peers" who are users located in the premises of the nano server (such as user A and user B), (ii) "local peers" who are users located in the same ISP of the nano server (such as user A and user C), or (iii) "non-local peers" who are users located in a different geographical region away from the nano server (such as user A and user D).

As can be seen in Figure 2, for local and non-local peers, the content can be accessed by traversing two access networks (one is the access network for the users hosting the content and other is the access network for the users requesting the content). To reach the content from the local peers in the same geographic region, number of hops in the core and edge networks is less than the number required to access the content from a remote centralized DC. However, when accessing the content from a non-local peer, the number of core and edge router hops may be greater than the centralized DC scenario.

III. Energy Consumption Models

In this section, we describe energy consumption models for network equipment. The network equipment are categorized into two types: 1) Equipment 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 which deal with a large amount of traffic we present a "flow-based" energy model that proportionally allocates the equipment's power consumption over all the flows through the equipment. For the equipment in end-user premises which are not shared by many users and services, we construct a "time-based" energy consumption model based upon the amount of time that equipment spends dealing with a cloud service.

A. Flow-Based Energy Consumption Model

For equipment shared by many users and services such as routers and switches in the core of the network, the measure of the energy consumption of a cloud service is based upon

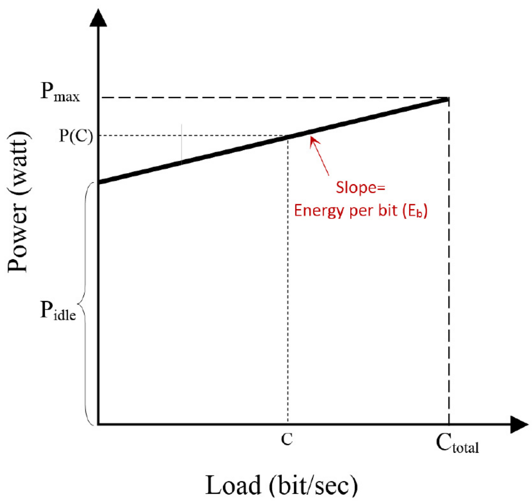

Fig. 3. Power consumption trend versus load for a network equipment (i.e. one router) [2], [10]–[12].

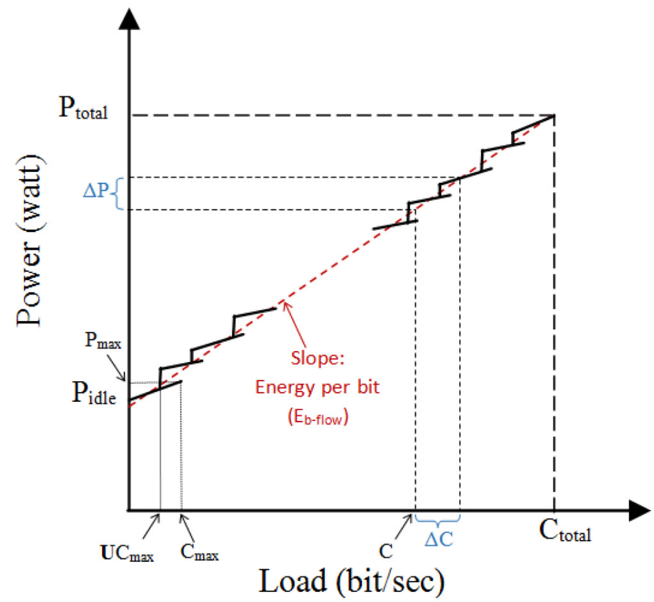

Fig. 4. Power consumption of a set of shared network equipment (i.e. routers) in one node located in a single location.

proportional allocation of the equipment's power consumption over all the flows through the equipment. We refer to this as a "flow-based" energy consumption model.

Network equipment consumes power whether idle or active. The power consumption of a typical network equipment as shown in Figure 3 can be modeled by the linear form as [2], [10]–[12]:

$$P(C) = P_{\text{idle}} + C\frac{P_{\max} - P_{\text{idle}}}{C_{\max}} = P_{\text{idle}} + CE_{\text{b}} \qquad (1)$$

The idle power (P_{idle}) can be a significant proportion of $P_{\max}$ (up to more than 90%), therefore we cannot ignore P_{idle} when calculating the energy consumption of a service.

Because the vast majority of network equipment has linear power profile [13], we use the same model for all the equipment in the network which are shared by multiple users and services. The cumulative power consumption of a set of network equipment in a node located in a single location can be represented by a staircase curve as shown in Figure 4. Each step corresponds to the deployment of additional network equipment once the capacity per network equipment reaches the pre-set maximum operating load utilization, U.

To calculate the joules per bit for the additional traffic generated by a service that is spread over many machines distributed across a network (such as Facebook photo-sharing), we can adopt the following approach.

We consider a network initially carrying total capacity C as shown in Figure 4. To this capacity the service under consideration adds incremental capacity ΔC. This incremental capacity is much greater than the average maximum capacity of the network elements used in the network. Therefore, if $< C_{\max} >$ is the average maximum capacity of the network elements, then $\Delta C \gg \; < C_{\max} >$. Typically, the network elements are not operated at their maximum capacity, they are operated at a fraction, U, of $C_{\max}$. Therefore, the operational capacity per machine is $UC_{\max}$.

We assume the service generates the additional capacity ΔC in the form of many small capacity increases roughly evenly distributed across the metro edge of the entire network. That is, $\Delta C = M\delta C$ where $M \ggg 1$ and δC is relatively small (such as the size of a photo file). The parameter M represents the many of millions of users who are each "simultaneously" uploading a file of average size δC.

Data flows through a network will typically go through several network nodes as they travel across the network from source and destination. To accommodate a uniformly distributed increase in traffic, ΔC, extra equipment will be required at each node. Let m be the average number of nodes in the path of a service. The total amount of additional network elements required across the network to accommodate ΔC will be $m\frac{\Delta C}{U<C_{\max}>}$ where U is the utilization of the elements, set by policy of the network operator, and $< C_{\max} >$ is the average maximum capacity of the network elements.

Therefore, the incremental energy per bit ($E_{\text{b-flow}}$) due to increase in traffic, ΔC, will be

$$E_{\text{b-flow}} = \frac{\Delta P}{\Delta C} \approx m\left(\frac{< P_{\text{idle}} >}{U < C_{\max} >} + < E_{\text{b}} >\right) \qquad (2)$$

The additional energy consumption of a service (such as service k), $E_{\text{k-flow}}$, that transfers $N_{\text{bit,k}}$ bits across the network will be:

$$E_{\text{k-flow}} \approx E_{\text{b-flow}} N_{\text{bit,k}} \qquad (3)$$

where, $N_{\text{bit,k}}$ is the number of exchanged bits of service k through the node by the service under consideration and m in the average number of network nodes in the service path. All defined parameters in this sub-section for the flow-based energy model are listed in Table I.

B. Time-Based Energy Consumption Model

For equipment located in the end-user premises, such as end-user terminal and nano servers, we construct a "time-based"

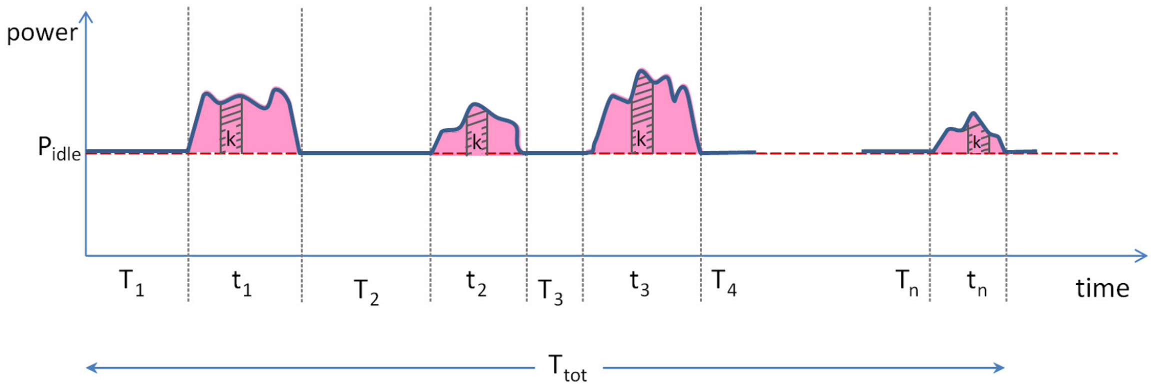

Fig. 5. Power consumption of a home equipment unit for serving/accessing services.

TABLE I
NOTATION FOR THE FLOW-BASED ENERGY MODEL

Parameters	Description
$P(C)$	Power consumption under load C
C	Load of a network equipment
P_{idle}	Idle power consumption of a network equipment
$P_{\max}$	Maximum power consumption of a network equipment
$C_{\max}$	Maximum capacity/load of a network equipment
E	Incremental energy per bit
P_{tot}	Total power consumption of all equipment in a node
N	Number of network equipment in a node
U	Load threshold
$E_{\text{b-flow}}$	Energy per bit in flow-based model
$E_{\text{k-flow}}$	Total energy consumption of service k
m	Average number of network nodes in a service path
$N_{\text{bit,k}}$	Number of exchanged bits

energy consumption model based upon the amount of time that equipment spends providing access to the services. Consider a nano server in a home, a typical nano server's power consumption providing accessing a service can be represented by the plots in Figure 5.

The device is actively accessing the services of interest during times $t_i, i = 1, .., n$ (the pink areas) and not serving that service for times T_i. The total time of the nano server session is $\sum_{j=1}^{n} T_j + t_j = T_{\text{tot}}$, as shown in Figure 5. The total active time is $t_{\text{act}} = \sum_{i=1}^{n} t_j$.

T_{tot} is the duration of using a service (service k) which is the service of interest, such as email, social network, VoD, etc. During this time, there will be spans of time when we exchange data with the service, these times are $t_{\text{act,k}}$. At other times during T_{tot}, we may still be using the service, but not active. For example, we may have downloaded a web page and are reading it. This will be inactive time with in T_{tot} and so will be part of the idle time. After we have finished the session, we are not interacting with the service k during the time outside of time interval T_{tot}.

The energy consumption of the customer premises equipment (E_{cpe}) including the nano servers for serving multiple services is given by:

$$E_{\text{cpe}} = P_{\text{idle}} T_{\text{tot}} + \int_{t_{act}} (P(t) - P_{\text{idle}}) \mathrm{d}t \tag{4}$$

where, P_{idle} is power consumption of the device in the idle mode.

In this work we assume that the device can serve one or multiple services. Therefore, the active times of the device (pink areas) can correspond to one service or multiple services. To determine energy consumption of one specific service running on the device such as service k (the hatched area in Figure 5, two parts are considered: 1) incremental energy consumption due to running this specific service ($E_{\text{inc,k}}$); 2) idle power allocated to running the service ($E_{\text{idle,k}}$). Our approach for allocating the idle power to the service k is to allocate the idle power in proportion to the ratio of active time of service k ($t_{\text{act,k}}$) to the total active time of the device (t_{act}). Using this approach, the total energy consumption of the service over the duration T_{tot} is:

$$\begin{aligned} E_{\text{k-time}} &= E_{\text{idle,k}} + E_{\text{inc,k}} \\ &= E_{\text{idle}} \frac{t_{\text{act,k}}}{t_{\text{act}}} + \int_{t_{\text{act,k}}} (P(t) - P_{\text{idle}}) \mathrm{d}t \\ &\approx P_{\text{idle}} T_{\text{tot}} \frac{t_{\text{act,k}}}{t_{\text{act}}} + \sum_{l} (\bar{P}_{\text{k,l}} - P_{\text{idle}}) t_{\text{act,k,l}} \end{aligned} \tag{5}$$

where, $\bar{P}_{\text{k,l}} = \frac{1}{t_{\text{act,k,l}}} \int_{t_{\text{act,k,l}}} P(t) \mathrm{d}t$. The data rate of the service during active times is the total exchanged bits ($N_{\text{bit,k}} = \sum_{l} N_{\text{bit,k,l}}$) divided by the total active time ($t_{\text{act,k}} = \sum_{l} t_{\text{act,k,l}}$) of the service which is $C = \frac{N_{\text{bit,k}}}{t_{\text{act,k}}} = \frac{N_{\text{bit,k,l}}}{t_{\text{act,k,l}}}$. Hence we can re-write the above equation as:

$$E_{\text{k-time}} \approx P_{\text{idle}} T_{\text{tot}} \frac{t_{\text{act,k}}}{t_{\text{act}}} + \sum_{l} (\bar{P}_{\text{k,l}} - P_{\text{idle}}) \frac{N_{\text{bit,k,l}}}{C} \tag{6}$$

In the next subsection, we study the effect of idle time and active time of a nano server on the energy consumption of service k.

1) Ratio of Idle Time Versus Active Time (α): Below (in Section V-C) we parametrize the energy per download to compare the energy consumption of centralize DCs and nDCs. In order to do this, we define a coefficient (α) which is the ratio of the idle time of the device to the active time. The coefficient (α) is given by:

$$\alpha = \frac{t_{\text{idle}}}{t_{\text{act}}} \tag{7}$$

The minimum value for α is 0 when the CPE is fully utilized and $t_{idle} = 0$. The maximum value for the CPE is $\frac{T_{tot} - t_{act,k}}{t_{act,k}}$

TABLE II
NOTATION FOR THE TIME-BASED ENERGY MODEL

Parameters	Description
t_{i}	Active time of a CPE or a nano server in interval i
T_{i}	Idle time of a CPE or a nano server in interval i
T_{tot}	Total time of a CPE or a nano server
E_{cpe}	Total energy consumption of a CPE
$E_{\text{k-time}}$	Energy of service k in unshared equipment
$E_{\text{idle,k}}$	Idle energy consumption allocates to service k
$E_{\text{inc,k}}$	Incremental energy consumption allocates to service k
t_{act}	Active time of a CPE or a nano server
$t_{\text{act,k}}$	Active time of service k
α	Active to idle time

when the only service run on the CPE is the service k and whole idle power dedicates to the service k and $t_{idle} = T_{tot} - t_{act,k}$ $(0 \leq \alpha \leq \frac{T_{tot}-t_{act,k}}{t_{act,k}})$. In this paper, we assume $t_{\text{act,k}} > 0$ because we require there to always be at least one service (service k) running from nano servers. The α parameter was defined by the form in (7) to provide a heuristic relationship with the energy per bit of the services it is providing. Low values of α correspond to high utilization of the CPE and so low energy per bit for the services. According to α, Equation 5 can be re-write as:

$$E_{\text{k-time}} = P_{\text{idle}}(\alpha+1)t_{\text{act,k}} + \int_{t_{\text{act,k}}} (P(t) - P_{\text{idle}})\mathrm{d}t \qquad (8)$$

The α factor is expressly defined for unshared equipment, representing the ratio of idle and active times for the unshared nano data center. Nano data centers, by definition, are too small to highly share over many workloads and so we apply the time based model for the nano data center and the α parameter is applicable. In contrast, a centralized data center is highly shared over many (thousands) of workloads. Therefore, we adopt a shared equipment flow based model for the centralized data center because it is impractical to monitor the data center time allocated to each user. Being shared equipment, a flow model is applied and so the alpha factor is not applicable to the data center. All defined parameters in this sub-section for the time-based energy model are listed in Table II.

C. Centralized Data Centers and Nano Data Centers

The energy consumed when using a service located in a centralized DC can be modeled by splitting it into three components: (a) energy consumption of end-user equipment for accessing the service. This includes the end-user terminals and access technology; (b) energy consumption of the transport network (aggregation, edge and core networks); and (c) energy consumption of the DC including its internal network, storages and servers.

The total energy consumed by service k provided from a centralized DC ($E_{\text{k-dc}}$) can be expressed as:

$$E_{\text{k-dc}} = E_{\text{k-cpe}} + E_{\text{k-access}} + E_{\text{k-edge}}h_{\text{e}} + E_{\text{k-core}}h_{\text{c}} + E_{\text{k-cent}} \qquad (9)$$

where $E_{\text{k-cpe}}$, $E_{\text{k-access}}$, $E_{\text{k-edge}}$, $E_{\text{k-core}}$ and $E_{\text{k-cent}}$ are the energy consumed for service k in devices located in end-user premises, access network, energy per edge network element, energy per core network element and DCs, respectively.

TABLE III
NOTATION FOR ENERGY CONSUMPTION OF SERVICE k PROVIDED BY DCS AND NDCS

Parameters	Description
$E_{\text{k-dc}}$	Total energy consumption of service k provided by DCs
$E_{\text{k-ndc}}$	Total energy consumption of service k provided by nDCs
$E_{\text{k-cpe}}$	Energy consumption of service k in CPE
$E_{\text{k-access}}$	Energy consumption of service k in the access network
$E_{\text{k-edge}}$	Energy consumption of service k per edge network element
$E_{\text{k-core}}$	Energy consumption of service k per edge network element
$E_{\text{k-cent}}$	Energy consumption of service k in centralized DCs
$E_{\text{k-nano}}$	Energy consumption of service k in nDCs
$E_{\text{k-access2}}$	Energy consumption of access network attached to nDCs
h_{e}	Number of hops in the edge network
h_{c}	Number of hops in the core network

Parameters h_{e} and h_{c} are the number of edge and core routers traversed.

We have used the time-based energy consumption model for $E_{\text{k-cpe}}$ and applied the flow-based energy consumption models for $E_{\text{k-access}}$, $E_{\text{k-edge}}$, $E_{\text{k-core}}$ and $E_{\text{k-cent}}$. We also used flow-based energy consumption model for centralized data centers since the centralized data centers are shared by many users and services.

In the case of nano servers, the energy consumption of the service consists of three components: (a) the energy consumed by end-user devices requested the content; (b) the energy consumption of the transport network between the end-user requesting data and the end-user hosting the data (access network is counted twice for local and non-local peers, once for each user); and (c) the energy consumed by the nano servers located in the end-users premises.

The total energy consumed by service k provided from nDCs can be expressed as:

$$\begin{aligned} E_{\text{k-ndc}} &= E_{\text{k-cpe}} + E_{\text{k-access}} + E_{\text{k-edge}}h_{\text{e}} \\ &\quad + E_{\text{k-core}}h_{\text{c}} + E_{\text{k-access2}} + E_{\text{k-nano}} \end{aligned} \qquad (10)$$

where $E_{\text{k-access2}}$ is the energy consumed by access network attached to nano servers for service k and $E_{\text{k-nano}}$ is energy consumption of service k in nano server devices located in the end-user premises. We have used the time-based energy consumption model for $E_{\text{k-nano}}$ because the nano servers are not shared by many users and services. All defined parameters in this sub-section for modeling services' energy consumption are listed in Table III.

Using the expressions for device energy above and comparing (9) and (10), for a given end-user device and access technology, we note that the differences between energy consumption of a service provided from a centralized DC compared to nDCs is primarily determined by the following:

– The number of bits exchanged between the user and DC (N_{bit});
– The number of hops for the two cases (h_{e}, h_{c});
– The value of $E_{\text{k-cent}}$ compared to $E_{\text{k-access2}} + E_{\text{k-nano}}$.

To evaluate this difference we require models for each of these contributions.

IV. MEASUREMENTS FOR ENERGY MODELS

To quantify the models for $E_{\text{k-dc}}$ and $E_{\text{k-ndc}}$, we use power and traffic measurements undertaken using the Wordpress IV

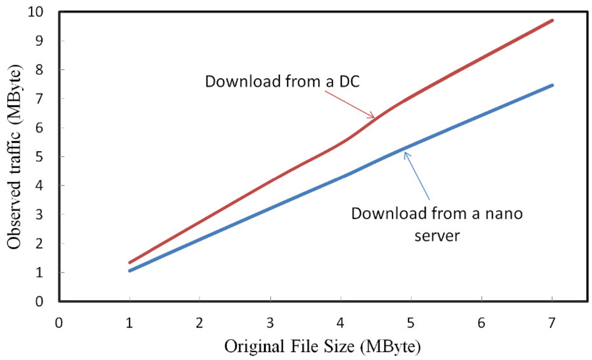

Fig. 6. Exchanged bytes during downloading files varying in size from Wordpress website versus the original sizes of files.

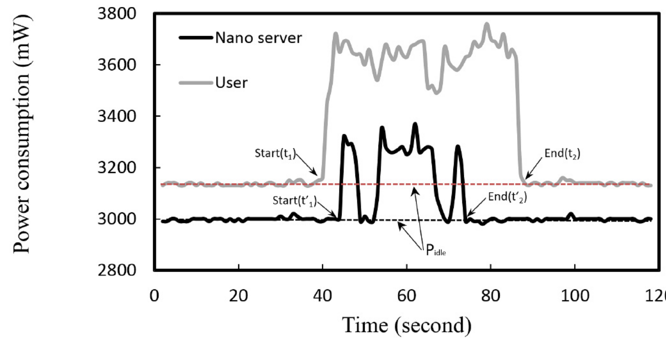

Fig. 7. Power consumption of an end-user device and a nano server while uploading a file to Wordpress.

application which is an open source website and blogging tool. There are two options for Wordpress users: 1) Sign up for an account from the Wordpress website and connect to the Wordpress centralized DCs; 2) Install Wordpress software locally and create a web-server and host the content locally on a nano server.

The nano servers in the end-users premises were implemented using Raspberry Pi's [7]. Each Raspberry Pi has a SD card for storage and, if need be, an external hard drive can be attached to provide additional storage. The Raspberry Pis' low power draw, compact size and silent running make it a good choice for home servers [14].

A. Traffic Measurements (N_{bit})

In order to determine the number of exchanged bits (N_{bit}) between an end-user and a DC or a nano server when uploading files to Wordpress or downloading the same files, we measured the volume of traffic using a packet analyzer (Wireshark) running on the end-user device.

We uploaded files with their original sizes (without compression techniques) to both the DC and the nano server and downloaded the same files. Figure 6 shows the number of bytes exchanged during downloading various files, ranging from 1 MB to 7 MB, from the centralized DC and nano server versus their original size. Each session was repeated 10 times and the average traffic is displayed. The download curve for the nano server indicates the traffic exchanged is very similar to the original size of files. However, the traffic for downloading from the DC is higher than the original file size. Post-processing the Wireshark logs reveals that the download traffic from centralized DCs is higher than the original file size due to the existence of third party applications and advertisement traffic.

We also measured the upload traffic and found it was similar to download traffic although there are some cloud applications for which upload and download traffic are not the same; such as Google Drive and Facebook [10], [11].

B. Power Measurements (P_{cpe})

The power consumption of end-user terminals and nano servers when interacting with the Wordpress website was measured directly using a power meter. We used a PowerMate meter [15] with a resolution of 10 mW during uploading and downloading of data.

We measured the power consumption of end-user devices while uploading and downloading different files to Wordpress DCs and local nano servers. We also measured the power consumption of nano servers. As an example, Figure 7 shows the power consumption of two Raspberry Pi's when uploading a 5MB file to the nano server. One Raspberry Pi is set as an end-user device and another is as a 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 on the end-user device. Figure 7 displays the power (as a function of time) for uploading a file to the nano server. The sequence of events shown in Figure 7 for the upload was: first open the web browser in the end-user device and then upload a file (t_1 in the user curve). After that, the nano server starts to process and store the file (t'_1 on the nano server curve). After storing, the local server status switches to idle mode (t'_2 in the nano server curve). Then the end-user device completes the final processing after which it also switches to idle mode (t_2 on the user curve).

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

V. Energy Consumption Comparison

We can now compare the energy consumption of each component in (9) for a centralized DC and the corresponding components in (10) for a nDC to ascertain the difference in energy consumption. In both cases we consider a service which is one service (service k) of multiple number of services.

A. User and Access Network Equipment ($E_{k\text{-}cpe} + E_{k\text{-}access}$)

The access network includes (a) single user customer premises equipment (CPE) such as modems and (b) shared network equipment such as Ethernet switches and LTE base stations. Being customer equipment located in the homes, energy consumption of CPE is modeled using 6. Energy consumption of shared equipment, such as the OLT, Ethernet switch and base stations, is modeled using 3 with m set to unity representing a single access node in the data path.

TABLE IV
ENERGY PER BIT OF NETWORK EQUIPMENT IN ACCESS, EDGE AND CORE NETWORKS

	Power(Watt)		Traffic(Gbps)		Energy(nJ/bit)	
	Idle	Max	Downlink	Uplink	Downlink	Uplink
Fast Ethernet gateway (CPE)	2.8	4.6	0.1	0.1	N/A	N/A
ADSL2+ gateway (CPE)	4.1	6.7	0.024	0.003	N/A	N/A
4G gateway (CPE)	0.5	1.75	0.024	0.012	N/A	N/A
GPON gateway (CPE)	5.2	8.3	2.4	1.2	N/A	N/A
Ethernet switch	1589	1766	256	256	31.7	31.7
LTE Base-station	333	528	0.072	0.012	82820	12400
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

We have studied several technologies by which the CPE may be connected to the access network: Ethernet, WiFi, 4G or PON. As one would expect, the measurement results indicate, for a given connection technology, the energy consumption of end-user device for uploading and downloading data to the centralized Wordpress DC is approximately equal to uploading and downloading data to the nano server.

The first four rows of Table IV list the power consumption and throughput for CPE 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 were gathered from [16]. The corresponding values for shared access equipment are also provided in Table IV. The idle, maximum power and maximum capacity of Ethernet switch and OLT are gathered from [10] and [17], respectively. The energy per bit values for this equipment are calculated based on (2) assuming utilization $U = 50\%$.

The energy per bit for an LTE base station depends on 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 $P_{\max} = 528W$ and $P_{\text{idle}} = 333W$ by [18]. The aggregate achievable throughput ($C_{\max}$) of this base station is 72 Mbps with 20 MHz spectrum [19]. The energy per bit of this base station, considering a typical utilization (U) of 5% over a 24-hour cycle, would be 95.2 μJ/bit based on (2). However, it is reported that LTE 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 [18]. Therefore, the energy per bit of this base station would be 82.8 μJ/bit in the downlink and 12.4 μJ/bit in the uplink on average as listed in Table IV.

B. Edge and Core Network Equipment ($E_{k\text{-}edge}h_e + E_{k\text{-}core}h_c$)

The idle power, maximum power and capacity of equipment in the edge and core networks were gathered from [10] and the energy per bit values calculated using 2. To determine the values for the key network equipment we set $U = 50\%$. All values for equipment in the edge and core networks are summarized in the last three rows in Table IV.

According to (9) and (10), the energy consumed in the edge and core networks also depend on the number of hops in the edge and core networks (h_e, h_c). Using *traceroute* from end-user devices to the Wordpress servers, we estimate the average number of edge and core routers along the path between the end-users and servers within DCs to be 3 and 5, respectively. However, the number of hops in the case of nano servers depends on the location of end-users requesting the content relative to those hosting the content. The requests are either served from (a) a nano server at the premises of the user placing the request (home peers), (b) a nano server in the same ISP (local peers), or (c) a remote nano server in a different geographical location (non-local peers-longest path). The number of edge and core routers for non-local peers are measured to be 3 edge and 8 core hops and 2 edge hops and 1 core hop for the peers setting in the same ISP (using *traceroute*).

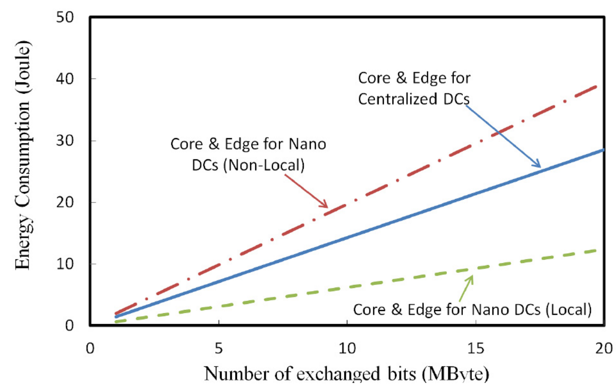

Fig. 8. Consumed energy in the core and edge equipment for accessing data from different locations.

Placing the number of hops and the energy per bit values of BNG, edge and core routers listed in Table IV into (3), (9) and (10), we get Figure 8 which shows the energy consumed in the edge and core networks (as a function of N_{bit}) when accessing content from a DC (solid blue line) and a nano server hosted by a local peer (dashed green line) and a nano server hosted by a non-local peer (dot-dash red line). The figure indicates that the energy consumption resulting from requesting data from nano servers can be higher or lower than the energy consumed for accessing the content in centralized DCs depending on distance between the users and the stored content. The transport energy for home peers located in the same premises is zero because they do not pass edge and core routers.

C. Nano Servers ($E_{k\text{-access2}} + E_{k\text{-nano}}$) and Centralized Servers ($E_{k\text{-cent}}$)

In Section III-C it was noted that one of the primary factors when comparing the energy consumption of a service provided from a centralized DC with providing it from a nano server was the value of $E_{\text{k-cent}}$ compared to $E_{\text{k-access2}} + E_{\text{k-nano}}$. In this sub-section, we compare the energy consumption of a service provided by a nano server and its attached access network with that of a server within a centralized DC. In this paper, we assume there is always at least one service (service k) running from centralized DCs or nDCs.

Equipment in a centralized DC is highly shared and so is quantified using energy per bit. However, obtaining detailed information about servers within DCs and its associated internal networks to provide a value for energy per bit is very difficult because detailed information on power consumption of the systems within commercial DCs is not publicly available. Two comprehensive articles on DC architecture and dimensioning can be found in [20] and [21], in which a model design, with numbers and types of network equipment and servers, is described. Using the capacity of the data centers described in this model, together with DC traffic characteristics from [22], and several realistic assumptions on server utilization (around 20% [23] we developed estimates for DC 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 around 20 μJ/bit [23] for energy-efficient DCs (otherwise, it can be even higher). It should be noted that the utilization of the network can be somewhat different to that of the data center because the network will most likely be carrying traffic not destined for and independent of the data center. Therefore, the utilization factor used to calculated energy consumption of a service in the nano or centralized data center will be independent of the value used to calculate the energy consumption of the service traffic in the network that. (The reader may recall that the utilization of the network has been set to 50% in sub-section V-B above).

In order to estimate the energy consumption of running a service from a Raspberry Pi [7] (as a nano server) it must be recognized that the Raspberry Pi is located in a home and hence connects via the access network. To include this contribution to the energy model, we have used 6 adopting the values listed in Table IV for the access network and measurements for the Raspberry Pi.

Figure 9 shows energy consumption for serving data from centralized DCs and nano servers versus data traffic. A wide range of energy consumption values for centralized DCs are included in Figure 9 ranging from 4 μJ/bit to 20 μJ/bit which is indicated with an orange highlight. Nano servers with different access networks (GPON, Ethernet, WiFi and 4G) are also shown. It can be seen that the nano server attached to a 4G network consumes the greatest energy compared to others options, and a nano server attached to a GPON consumes the least energy. This figure indicates how the energy consumption of the access network can affect the energy consumption of a service provided by nano servers.

The values plotted in Figure 9 are based on the nano server being fully utilized serving multiple services. Hence the idle time is zero ($t_{\text{idle}} = 0$) and the ratio of the idle time of the device to the active time is zero ($\alpha = 0$). However, as we discussed in Section III, devices in end-user premises are not highly shared and so may be idle for a significant proportion of time.

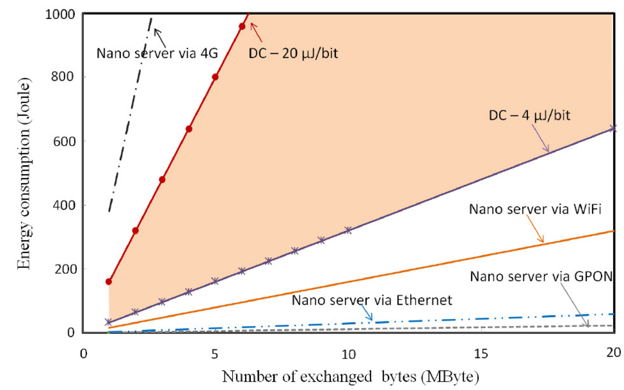

Fig. 9. Energy consumed by service k in various nano servers and DCs as a function of the volume of data exchanged.

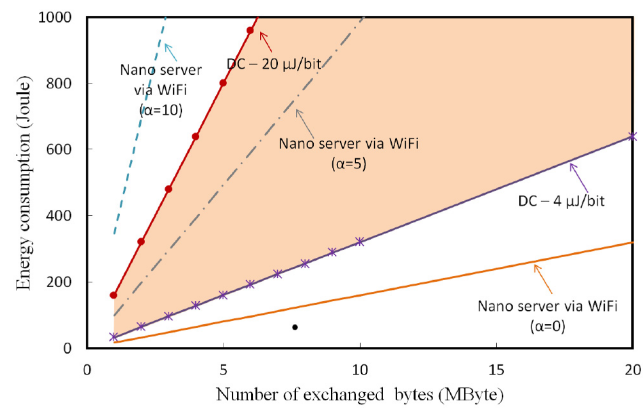

Fig. 10. Energy consumed by service k provided by WiFi nano servers with different ratios of idle time to active time (α) as a function of the volume of data exchanged.

Therefore, to study the effect of active and idle time of equipment in end-user premises, we consider a nano server with WiFi access technology (ADSL2+ in end-user homes) and various idle times ($t_{\text{idle}} = 0, 5t_{\text{act}}, t_{\text{act}} \Rightarrow \alpha = 0, 5, 10$). The energy consumption dependence on the data exchange for a service provided by a nano server with different proportions of idle time is compared with centralized DCs in Figure 10.

Although Figure 9 shows the energy consumption of the nano server connected via WiFi can be less than that of a relatively energy efficient centralize DC, Figure 10 shows without sharing the idle time of nano server with other services and with assigning more idle time to the service k (increasing α), the energy consumption of the service running on the nano server increases and dominates the energy consumption of running the same service from the DCs.

In Figure 10, the total time for the service, T_{tot}, is set to a constant. To calculate the lines for nano server energy consumption with constant α, we have assumed the total active time, t_{act}, is a constant and the amount of active time used by the service k, $t_{\text{act,k}}$, increases in proportion to the number of exchanged bytes for service k. From the results shown in Figure 9 and

Figure 10, we see that the energy efficiency of a service using a nano server compared using a centralized DC is not dependent on the number of byes exchanged. Rather, it is dependent upon factors such as the utilization of the nano server (α), the access technology used by the nano server and the energy per bit of the centralized DC.

Therefore, managing the idle time of nano servers (i.e. sharing the idle time with multiple services or using sleep mode during the idle time) is a determining factor for having low energy-consuming service k provided by nDCs.

VI. Nano Servers for Improving Energy Efficiency of Applications

We study three different types of applications: (i) applications for which the data source is primarily in end-user premises with static content such as hosting a static website; (ii) applications for which the source of data is primarily in end-user premises with dynamic content such as video surveillance; (iii) applications for which the source of data is not created in end-user premises but must pre-download (pre-load) to nano servers from other source(s) such as Video-on-Demand (VoD) applications.

A. *Applications With Static Content for Which the Source of Data is Primarily in End-User Premises*

Applications with static content for which the source of data is primarily in end-user premises can be hosted and distributed from either nano servers or a centralized DC. In this case, we consider applications with static content (or with infrequent updates) and users download the content multiple times from a nano or centralize DC. The static content is a data file (such as a video file), which is downloaded N_{dl} times over a set duration. To run the applications with multiple downloads from nano servers and consume less energy than the centralized scenario, the following inequality must be met:

$$\begin{aligned} N_{\text{dl}}(E_{\text{dl-edge}}h_{\text{e}} + E_{\text{dl-core}}h_{\text{c}} + E_{\text{dl-access2}} + E_{\text{dl-nano}}) \\ < N_{\text{dl}}(E'_{\text{dl-edge}}h'_{\text{e}} + E'_{\text{dl-core}}h'_{\text{c}} + E_{\text{dl-cent}}) \\ + N_{\text{up}}(E'_{\text{up-edge}}h'_{\text{e}} + E'_{\text{up-core}}h'_{\text{c}} + E_{\text{up-cent}}) \qquad (11) \end{aligned}$$

where, N_{dl} is number of downloads for the application from end-users and N_{up} is number of updates for the application from its source. $E_{\text{dl-edge}}$, $E_{\text{dl-core}}$, $E_{\text{dl-access2}}$ and $E_{\text{dl-nano}}$ are the energy consumed per download in the edge network per network element, core network per network element, the access network attached to nano servers and nano servers, respectively. h_{e} and h_{c} are the number of hops in the edge and core networks in the nano scenario. $E'_{\text{dl(/up)-edge}}$, $E'_{\text{dl(/up)-core}}$ and $E_{\text{dl(/up)-cent}}$ are the energy consumed per download(/update) for the centralized DC scenario in the edge network, core network and a centralized DC. h'_{e} and h'_{c} are the number of hops in the edge and core networks in the centralized DC scenario.

Since we are considering applications with static content (or infrequent updates) in this section, we set $N_{\text{up}} = 1$ (or very low) in 11 and $N_{\text{up}}(E'_{\text{up-edge}}h'_{\text{e}} + E'_{\text{up-core}}h'_{\text{c}} + E_{\text{up-cent}})$ has a fixed value.

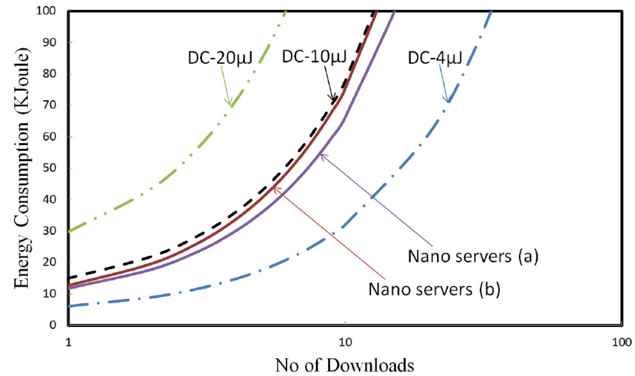

Fig. 11. Energy consumption of an application running form nano and centralized DCs vs number of downloads to users.

Figure 11 shows plots of the left and right hand sides of 11 showing the energy consumption as a function of the number of downloads, for an application running from centralized DCs with 4, 10 and 20 μJ/bit and a nano server attached to home WiFi access network with $\alpha = 5$. The energy consumption in Figure 11 includes the energy consumption of transport network and nano and centralized DCs. The size of file to be downloaded and uploaded is 100 MByte. For the nano server scenario, two user distributions are included:

(a) 20% of access events from non-local peers;
(b) 80% of access events from non-local peers.

Figure 11 indicates that the ratio of local to non-local requests has little impact in the total energy consumption. This is because the energy consumption of the application is dominated by the access network and data centers (nano or centralized). However, if the initial values of energy consumption of a DC and a nano server for hosting an application are close (such as the DC with 10 μJ/bit and the nano server attached to wireless network with $\alpha = 5$), the energy consumption due to the use of local or non-local peers can be a determining factor for which of centralize and nano DCs are more energy consuming. As shown in the figure for a limited number of downloads, energy consumption of the nano server is less than the DC-10 μJ/bit and it is more energy-efficient to execute the application from the nano server. However, as the number of downloads from non-local peers rises (the red line in Figure 11 with 80% of access from non-local peers), the energy consumption of the transport network in the nano scenario increases quickly and the nano server cannot efficiently serve the application.

Referring to (11), if noting that in most cases that the energy consumption in the core and edge networks for each download(/update) is very small compared to energy consumption of a nano server or a DC ($E_{dl-edge}h_e + E_{dl-core}h_c \ll E_{dl-access2} + E_{dl-nano}$ and $E'_{dl(/up)-edge}h'_e + E'_{dl(/up)-core}h'_c \ll E_{dl(/up)-cent}$), then we can approximate (11) with $(E_{dl-access2} + E_{dl-nano}) < E_{dl-cent} + (N_{up}/N_{dl})E_{up-cent}$.

Therefore, for applications with low number of updates relative to downloads, $N_{dl} \gg N_{up}$, we get $E_{dl-access2} < E_{dl-cent} - E_{dl-nano}$. It shows that the key factor is the access network energy for the nano server being smaller than the difference between the DC and nano server. Under these

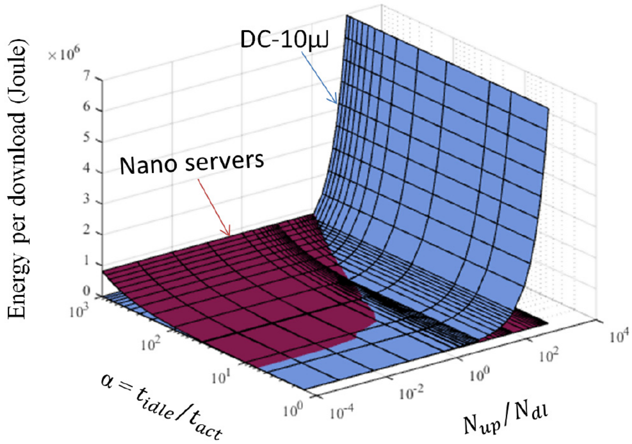

Fig. 12. Energy consumption an application running form a nDC and DC considering number of downloads and updates.

circumstances, to first order, the location of the nano servers is not that important. What is important is the utilization of the nano servers (i.e. α) and the technology used to connect them to the network.

B. Applications With Dynamic Content for Which the Source of Data is Primarily in End-User Premises

There are applications whose the source of data is in end-user premises and content changes rapidly, such as applications for video monitoring in end-user homes. In this case we have $N_{up}/N_{dl} \geq 1$. We consider the energy consumption as a function of N_{up}/N_{dl} for these applications. To give a perspective on the dependence of energy consumption of a service on the ratio of idle to active time we include the α dependence (replace $E_{dl-nano}$ in (11) with (8). We re-write (11) in the form:

$$\begin{aligned} &E_{\text{dl-edge}}h_{\text{e}} + E_{\text{dl-core}}h_{\text{c}} + E_{\text{dl-access2}} \\ &\quad + P_{\text{idle}}(\alpha+1)t_{\text{act,k}} + \int_{t_{act,k}} (P(t) - P_{\text{idle}})\text{d}t \\ &\quad < (E'_{\text{dl-edge}}h'_{\text{e}} + E'_{\text{dl-core}}h'_{\text{c}} + E_{\text{dl-cent}}) \\ &\quad + \left(\frac{N_{\text{up}}}{N_{\text{dl}}}\right)(E'_{\text{up-edge}}h'_{\text{e}} + E'_{\text{up-core}}h'_{\text{c}} + E_{\text{up-cent}}) \end{aligned} \quad (12)$$

Figure 12 shows per download energy consumption of an application running from the DC with 10 μJ/bit and the nano server (attached to home WiFi access network with 80% of downloads from non-local peers) plotted against N_{up}/N_{dl} and α. It can be seen that as the number of updates increases, the nano server is more energy-efficient than the centralized DC for running the application even when the idle time of nano server is relatively high (i.e. $\alpha \gg 1$). Therefore, the ratio of updates to downloads of an application plays an important role in the relative energy consumption of providing an service from a centralized DC compared to a nDC.

For example applications such as video surveillance for which the image/video is continuously updated, it is not energy-wise to upload every update to the centralized DC. If the data generated by video monitoring is hosted in nano servers even when users access that data remotely (via the network) the energy consumption using a nDC is still less than uploading the data to a centralized cloud and accessing it from there. Consequently, applications with a higher upload rate and low download rate are more energy-efficient when provided via on the nano servers architecture.

C. Applications Requiring Data Pre-loading

In this section we assume all accesses to the application run on nano servers are 50% from local peers (not home peers) and 50% from non-local peers. Nano servers can also host and distribute data that is sourced outside of end-user premises such as Video on Demand (VoD) data. The general concept of reducing energy consumption by these applications is to push data closer to end-users to reduce the transport network energy consumption.

If we assume we have a nano server attached to an energy-efficient access network and the nano server has enough available time to host VoD efficiently, it is necessary to consider energy consumption of data pre-loading. The source of data to be pre-loaded will be either a server in a centralized DC or a content delivery network (CDN). The pre-loading process consumes energy which needs to be included in the model.

The energy consumption of an application (application k) provided by nDCs which requires data pre-loading is given by:

$$\begin{aligned} E_{\text{k-pl}} &= N_{\text{pl}}(E_{\text{pl-edge}}h_{\text{e}} + E_{\text{pl-core}}h_{\text{c}} + E_{\text{pl-access2}} + E_{\text{pl-nano}}) \\ &\quad + N_{\text{dl}}(E_{\text{dl-edge}}h_{\text{e}} + E_{\text{dl-core}}h_{\text{c}} + E_{\text{dl-access2}} + E_{\text{dl-nano}}) \end{aligned} \quad (13)$$

where, N_{pl} is the number of data pre-loadings and N_{dl} is the number of downloads for the application from other end-users. $E_{\text{pl(/dl)-edge}}$, $E_{\text{pl(/dl)-core}}$, $E_{\text{pl(/dl)-access2}}$ and $E_{\text{pl(/dl)-nano}}$ are the energy consumed for each data pre-loading (/per download) in the edge network, core network, access network attached to the nano server and the nano server.

The energy per download for the application with data pre-loading is given by:

$$\begin{aligned} \frac{E_{\text{k-pl}}}{N_{\text{dl}}} &= \frac{N_{\text{pl}}}{N_{\text{dl}}}(E_{\text{pl-edge}}h_{\text{e}} + E_{\text{pl-core}}h_{\text{c}} + E_{\text{pl-access2}} + E_{\text{pl-nano}}) \\ &\quad + E_{\text{dl-edge}}h_{\text{e}} + E_{\text{dl-core}}h_{\text{c}} + E_{\text{dl-access2}} + E_{\text{dl-nano}} \end{aligned} \quad (14)$$

Figure 13 shows the energy consumed per download of two nano servers(one requiring data pre-loading and the other not) as a function of the ratio the number of data pre-loading to downloads. As shown in the figure, the energy consumption increases as the number of data pre-loadings to number of downloads increases. As Figure 13 indicates, the number of pre-loaded data should be consistent to the number of downloads ($\frac{N_{pl}}{N_{dl}} \leq 1$) to execute an energy-efficient application on nano servers. It means that popular contents with more number of downloads for each data pre-loading are more energy-efficient to be run by nDCs compared to unpopular contents. Therefore,

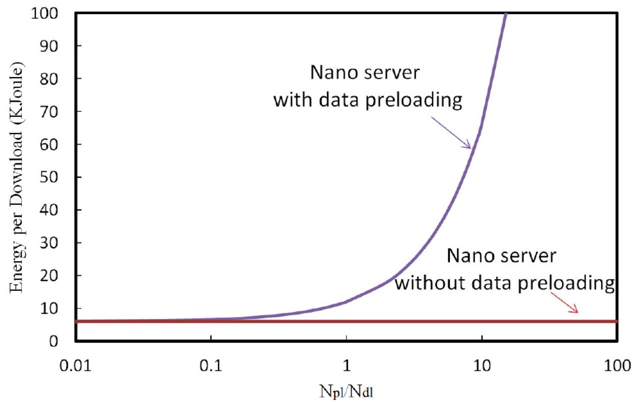

Fig. 13. Energy consumption versus number of data pre-loading to number of downloads ($\frac{N_{pl}}{N_{dl}}$).

the number of instances of pre-loaded content to the nano servers without downloads causes energy-efficient nDCs consume high amount of energy, even when using energy-efficient access networks such as Ethernet or PON.

VII. Conclusion

This paper has compared the energy consumption of applications using centralized DCs in cloud computing with applications using nano data centers (nDCs) used in Fog computing. To do this, new energy models for shared and unshared network equipment were introduced and a set of measurements and experiments were used to provide data for the models.

Our results indicate that nDCs might lead to energy savings depending on system design factors such as (a) type of access network attached to nano servers, (b) the ratio of active time to idle time of nano servers and, (c) type of applications which includes factors like number of downloads from other users, number of updates from the origin(s) and number of data pre-loading. It was also shown that number of hops between users and content has a little impact compared to the above-mentioned factors.

The results of this work show that the best energy savings using nDCs is for applications that generate and distribute a large amount of data in end-user premises which is not frequently accessed such as video surveillance in end-users homes.

The deployment of nDCs is occurring with the introduction of Fog computing and implementation of smart devices to end-user homes for Internet of Things (IoT) services. To take advantage of the new architecture and to complement centralized DCs, we should identify applications that are more energy-efficient when provided from nano servers and run them on this platform. In addition to saving energy by running some applications on the nano platform, a portion of energy currently consumed within DCs for serving such applications can be saved.

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