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RESEARCH ARTICLE

Energy-Efficient Real-Time E-Healthcare System Based on Fog Computing

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Abstract: The rapid development of Internet of Things (IoT)-enabled systems in public and private spaces offers consumers numerous conveniences. Among different Internet-connected systems, the use of e-health systems is growing rapidly. The utilization of IoT devices and cloud-fog network technologies has made e-healthcare provision more convenient. While providing valuable services to the healthcare sector, like any other IoT-enabled systems it is putting pressure on energy, an essential element of life. Therefore, it is imperative to know the energy consumption model of e-health systems. Considering the importance of energy consumption in IoT-based systems, this article develops a cloud-fog-based e-health system and makes it energy efficient by understanding energy consumption at different layers of communication. Moreover, how fog integration with the cloud reduces energy consumption and delays at different stages of communication is discussed.

Keywords: e-health, Internet of Things, fog computing, cloud computing, energy efficiency

1. Introduction

The Internet of Things (IoT) is the smart representation of “ubiquitous computing” in today’s world. This idea was first introduced in 1999 by Ashton (2009) and termed IoT in 2005. Kevin’s vision of IoT was the ability of networked devices to communicate and circulate physical phenomena of the surrounding world through the web (Alam et al., 2010). Although the term was introduced in the 20th century, the definition, characterization, and explanation of this term persist. According to Ali et al. (2015), IoT is the ecosystem of the Internet, wireless sensor networks, and smart items contained in a smart environment. Mohan and Manikandan (2020) defined IoT as an ecosystem of interconnected computing units, digital and mechanical components, or any physical objects, including humans that are uniquely identifiable and can transmit data over the Internet without any human-to-computer or human-to-human interactions. Due to huge data storage pressure on IoT alongside limited computation capability, a new virtual data storage and management system model is idealized in the 1960s termed cloud computing by Joseph Carl Robnett Licklider (Gautam, 2022). Although the idea dates back to the 20th century, Amazon Mechanical Turk first launched the Elastic Compute Cloud in 2006 (Raghavendran et al., 2016). With the escalation of mobile users, cloud network has been easily accessible. The term cloud computing refers to a system where clients can access, allocate, control, regulate, and manage information online (Dhar, 2012). In the modern world, cloud computing and networking are one of the widely quoted topics in the research world. Several cloud models have been proposed in the past few years (Azodolmolky et al., 2013; Dhar, 2012; Raghavendran et al., 2016) depending on the client’s needs.

In Raiciu et al. (2011), Bodik et al. (2012), and Detal et al. (2013), authors worked on the dynamic management of cloud assets. Researchers also focused on fault tolerance (Bodik et al., 2012), energy consumption (Aishwarya & Gagana, 2021; Katal et al., 2023; Li, 2017; Prabha et al., 2021; Vishwanath et al., 2015), and data security (Albugmi et al., 2016; Kacha & Zitouni, 2018; Wang, 2017). It has been found that energy consumption is one of the most critical factors for cloud computing networking as it requires to be in service all the time. Also, with the growing number of users, energy requirement is accelerating at an alarming rate. Although some solutions to data security such as access control (Wang, 2017) and encryption have been widely used, the trust of the client toward the service provider can also affect the cloud involvement (Kacha & Zitouni, 2018).

To reduce the burden of storage and energy consumption on cloud computing and increase the response time, data security and a partially separated fog computing networking are established. Fog computing is a distributed computing architecture that brings cloud computing services to the edge of the network. It is said to be a cloud closer to the ground. Fog is a geo-distributed intermediate layer situated between end devices and the cloud data server which

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provides logical intelligence to the end devices and filters data for the cloud servers. It is a highly virtualized paradigm that provides computing power, storage, and networking facilities to the end devices. It has been introduced at first in the telecommunication sector, but nowadays cloud models are being proposed with fog nodes. It has been concluded by the researchers that fog can work as an edge network and also it can be an amalgam of cloud that is placed intermediate of cloud and user sensor although researchers doubted its quality of service (QoS) (Bermbach et al., 2018). If a system uses only a fog network, then the energy consumption is not efficient, fog with a cloud can be a solution to this problem (Prakash et al, 2017).

A typical architecture of the fog computing concept consists of three layers. The lowermost layer consists of end devices such as sensor nodes, along with gateways and edge devices. The topmost layer is the cloud layer. Fog devices are placed between the cloud layer and end devices. Fog computing not only provides cloud computing services to the network edge but also addresses the challenges of cloud computing infrastructure. It offers low and predictable latency, real-time interaction, geo-distribution, context awareness, interoperability, data privacy, and security to the end devices. Due to these properties, fog computing is a suitable platform for a large number of applications, especially latency-sensitive applications like healthcare monitoring systems. Such characteristics of the fog paradigm make it a unique platform to support cloud computing to meet the QoS requirement of the IoT context. The response time of fog that is near to IoT device and aggregation node varies from millisecond to second while in the case of the cloud, it can be minutes or days. The data storage time limit is also much lower for fog computing; fog near IoT cannot store data while fog that aggregates can store for a short duration of perhaps a few hours or weeks but the cloud can store data for several years.

1.1. Literature review

IoT, cloud, and fog have found impactful advantages in the field of healthcare (Azodolmolky et al., 2013; Gope et al., 2020; Prakash et al., 2017; Vishwanath et al., 2015). With the aggression of modern telecommunication devices and smart technology, “e-health” has become acceptable by the user. The World Health Organization’s definition of e-health is “the use of information and communications technology in support of health and health-related fields” (World Health Organization, 2019). According to Lösch et al. (2022), the telematics infrastructure and a number of citizen-focused digital services have seen increased adoption according to the German e-Health Monitor 2022, but there has been a delay in the deployment of electronic patient records and there is uncertainty regarding the future of e-prescriptions.

Routine checkups of elderly people, treatment facilities for people living in remote areas, and people diagnosed with infectious diseases have become easily accessible online. In Yosser et al. (2020), a framework for an e-health system at war zone has been proposed. They also showed that the expense of healthcare is rising and becoming unaffordable in wealthy nations. In the USA, more than forty million people lack health insurance and cannot afford medical care. Fiscal pressure has pushed for improvements to improve healthcare efficiency even in nations with universal healthcare systems. By expanding stakeholder participation, an effective healthcare system would decrease patient exclusion based on social inequities. E-health would help achieve these goals since it would make it easier for stakeholders to participate, thanks to its self-service paradigm. Fascinating features such as low transmission cost and flexibility to check health anytime (Kaur et al., 2019; Wang & Yu, 2022) alongside user’s favorable attitude toward this system demanded improvement of this system. Thus, several frameworks have been developed, and framework factors and challenges have been discussed by the researchers throughout the time after COVID-19 (Kovačić et al., 2022; Kluge, 2020; Marcelo et al., 2022; Wang et al., 2022). A simplified framework has shown that the involvement of the government and the national owner provides a cost-efficient e-health system (Kovačić et al., 2022). The most simplified framework prototype implementation was reported by Mumrez et al. (2019), where patients can store and send data related to temperature, pressure, and BP to healthcare providers. The advantages and fraud identification of this system were discussed in Jayadeep and Farooq (2017). Twenty-six individuals belonging to the targeted demographic groups participated in a survey to find out what features would be best for the system. As an illustration, 60%, 52%, and 58% of participants, respectively, agreed that cloud-based video call appointment services, e-prescriptions, and cloud-based symptom diagnostic tools are viable and beneficial features for e-healthcare systems. Sixty-one percent also concurred that they find intelligent e-healthcare solutions to be generally user-friendly and would suggest such systems to other users (Ishak et al., 2021). A comparison between the traditional hospital system and a proposed e-health system is shown in this study where it is clear that e-health provides advantages over symptom checkers, online appointments, patient record management, text messaging, and video call services.

Although e-health has several advantages, implementation in regional areas is difficult due to a lack of user skill in sensory device use. Therefore, emphasizing digital literacy, particularly e-health knowledge and skill in device use, is a major factor in developing countries (Sayed & Mamun-ur-Rashid, 2021). Fog computing in healthcare was first reported in 2012 (Elhadad et al., 2022). The performance metrics of the fog computing architecture have been the author’s primary focus, and they have evaluated its applicability in the IoT context. The fog computing architecture has been theoretically described in terms of energy usage, response time, CO2 emission, and overall system cost. They have shown a case study in which traffic is produced from the 100 largest cities in terms of population and is handled by data centers that are spread out geographically (Sarkar et al., 2018). The management of energy is essential for regulating power generation and consumption in homes, businesses, and other commercial settings like microgrids, according to Al Faruque and Vatanparvar (2015). They have used the fog computing platform to implement energy management as a service in their works. The benefits of choosing fog networking in e-health (such as latency reduction) have been discussed in Elhadad et al. (2022). Here, authors also worked with the data security of patients and methods to expand storage. A cost-effective health monitoring system comprised of a fog layer and energy-efficient sensor nodes was proposed. With this approach, the expenditure on healthcare is reduced while the standard of care is raised. These energy-efficient sensor nodes are assembled using the nRF protocol. The system makes effective decisions and provides services that require prompt attention. An integrated healthcare model has been introduced by Al-Sharhan et al. (2019) for national implementation and a cloud-based security model. This work presented a novel e-health model for widespread national adoption. It also tried to avoid the drawbacks of cloud computing, particularly the lack of security and privacy, by introducing an innovative security framework based on chain ontology. Also, in Mengiste et al. (2023), researchers have pointed out the reasons for the inefficiency of e-health models published in several works. Their study identified the key elements influencing an efficient e-health policy framework and discovered a gap in the context of developing nations, and proposed a four-step e-health policy implementation guideline for effective e-health implementation in the context of developing countries. A review conducted by Jacob et al. (2023) added to the expanding body of research that explored the standards used to evaluate the effectiveness and implications of e-health tools. It proved that different frameworks are employed in different ways to evaluate the effectiveness and value of e-health solutions. It also emphasized the demand for a more thorough strategy that balances the social, organizational, and technical assessment criteria in an approach which demonstrates the interrelated nature and complexity of the healthcare ecosystem and is in line with the elements that influence user adoption to ensure long-term uptake and adherence. The findings of the study in Bottel et al. (2023) suggest that using telemedicine services to address persons affected (PA) and concerned significant others (CSO) and create a connection to the neighborhood healthcare system may be a promising strategy. Internet use disorder is a digital-age disorder that is becoming more and more of a global issue. It seems that institutional and interpersonal impediments prevent many PA and CSO from accessing the healthcare system up to this point, allowing the disease to progress and chronify. With the intention of reaching out to PA and CSO to offer low-threshold assistance and refer the participants to the local healthcare system, a telemedicine counseling service for PA and CSO of PA unwilling to join treatment with two webcam-based sessions of 60 min for each group was developed. Participants provided sociodemographic information and answers to questions concerning their usage of the Internet. Six months following the study, participants were emailed to inquire about whether they had used the community healthcare system. In addition to providing their own responses, CSO provided a third-party assessment of PA's resistance to seeking treatment. Randomizing this system needs controlled trials to produce similar outcomes.

Another burning question of the e-health system is energy consumption. For massive storage, power consumption for 24/7 real-time data analysis is huge. It is necessary to send application instances to the cloud to aggregate, conduct historical analysis, and store data for an extended period of time. The fog computing layer receives data that calls for low latency, real-time interaction. As per the author's knowledge, energy consumption for a cloud-fog-based e-health system model has not been investigated yet.

1.2. Contributions

In this work, we proposed a system model for e-health using cloud and fog networks with sensory equipment. In the proposed system, we determined the energy consumption and delay for forwarding, processing, and storing the data which are captured by the sensor node of the wireless body sensor network (WBSN). The total power consumption to serve the requests made by the application instances is divided into three parts: power consumption for data transmission, processing, and storing. With data forwarding, energy is consumed due to receiving information, processing for routing, and forwarding the data. The edge gateway decides which data are needed to be transmitted to the cloud and which data are needed to be transmitted to fog. Depending on the requirement, streams of data are sent to the cloud and fog computing layers.

The remainder of this article is arranged as follows. In Section 2, a network framework has been proposed for a real-time and energy-efficient healthcare network system, which will implement the concept of fog cloud computing in health. In Section 3, a mathematical framework is provided for joint energy efficiency and a low-delay system considering energy consumption and time delay in both the fog layer and cloud layer due to transmitting, processing, and storing of data. In Section 4, a graphical representation of energy consumption reduction due to fog adaption has been provided. We also provided a comparative discussion of our proposed model with some established e-health systems. Finally, Section 5 concluded the article.

2. Proposed System Model and Network Scenario

Conventional health monitoring systems are composed of various types of devices that collect biosignals from a patient's body and transmit these signals via wires and cables for analysis and processing. But this system may be inconvenient in some situations like when a patient is in movement and needs continuous monitoring. The proposed system overcomes this drawback by using a sensor node that provides mobility and wireless transmission. Patients' health-related information is recorded by these body-worn or implantable sensors. Again, fog computing provides mobility support, geo-distribution, and location awareness that allows location discovery of patients in emergencies.

Figure 1 shows the architecture of the proposed e-health network. The architecture of the proposed system can be divided into three main subparts.

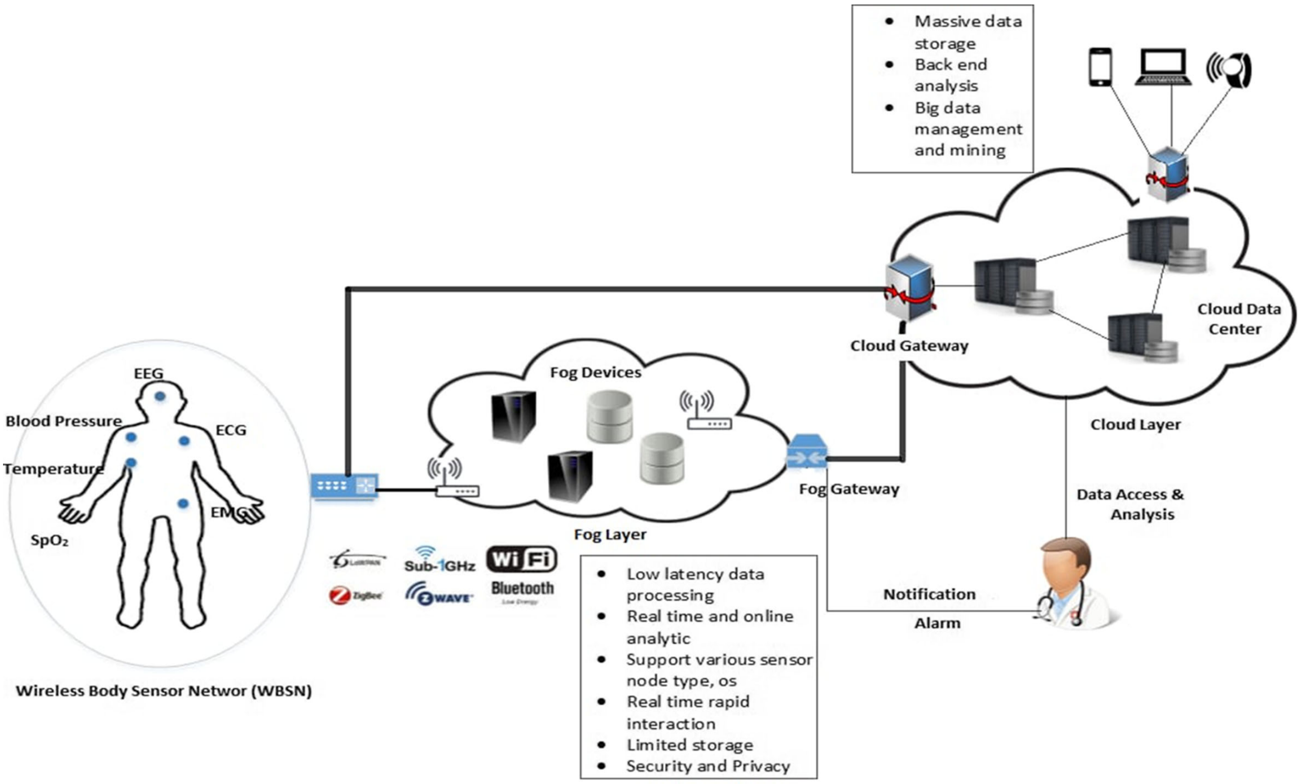
- WBSN for data acquisition
- Fog computing layer for onsite processing and semi-permanent storage
- Cloud computing layer for back-end analysis and permanent storage

2.1. Wireless body sensor network

WBSN consists of various types of sensor nodes which can collect biosignals such as ECG, EEG, EMG, heart bit rate, and blood pressure from a human body. A sensor node is a tiny complex device that can be used to acquire physical information and convert that acquired information to electrical signals that can be measured. The sensor node can be wearable or implantable in the human body. Therefore, it should be as small as possible so that it is convenient for a person to carry it without much effort for a long time. Since the sensor node is resource constraint and battery-powered, it cannot operate for a long period of time. But for this type of system, if sensor nodes stop working, the whole system will be shut down. Hence, energy efficiency is a major concern for such a system. One possible solution is to offload most of the tasks of sensor nodes to other devices that will perform the operation on behalf of the sensor nodes. In this work, an architecture has been proposed that will improve the energy efficiency of the system by implementing the concept of fog computing.

The proposed system enables the patient to be under monitoring 24/7 and biosignals are collected by sensor nodes continuously. The collected medical data and contextual information (ECG, EMG, oxygen level, temperature, blood pressure, heart bit rate, location, humidity) are transmitted to the next layer through standard communication protocols such as Wi-Fi, ZigBee, Bluetooth, or 6loWPAN. Depending on the type of data, it will be transmitted either to the fog layer or to the cloud server. If data are latency sensitive and require onsite processing, it will be processed in the fog layer. If data require complex computation and long-term storage, it will be transmitted to the cloud server and this decision will be made at the edge gateway before transmitting. To filter data according to those requirements, several AI algorithms could be used at the edge gateway.

Figure 1
Proposed e-health network architecture



2.2. Fog computing layer

The fog computing layer is situated between the WBSN and the remote cloud server. The fog computing layer is composed of geographically distributed intelligent devices. Fog devices can be any devices that have the ability to process, store, and network such as access points, proxy servers, routers, gateways, and switches. In the edge gateway, data are analyzed to make the decision whether to transmit to the fog layer or the cloud layer. If the application requires historical data analysis, long-term storage, or powerful computation, then data will be transmitted to the cloud computing layer; otherwise, data will be transmitted to the fog computing layer. For latency-sensitive health-related data, the fog layer provides optimal latency as it is placed within the same network. Even if a network connection with the remote cloud server is unavailable, the fog layer enables visualization and real-time analysis that ensures reliability. The fog layer also provides local storage and onsite processing facilities. Since the e-health network deals with the sensitive medical data of a patient, the fog computing architecture provides privacy by keeping those data within the same network. As a patient is monitored 24/7, in case of emergency, fog components such as analyzer and notifier component can send notifications immediately to the doctor or pre-stored contacts by analyzing monitored data. In addition, the fog computing layer can improve the e-health network by providing location awareness, patient mobility, data filtering, compression, energy efficiency, etc. After being processed by the fog computing layer, some data need further processing; fog instances transmit those data to the cloud server.

2.3. Cloud computing layer

The cloud computing layer consists of powerful homogeneous data centers. Data centers are able to provide massive data storage, and powerful and sophisticated computation facilities to end devices. Health-related data that require historical data analysis and long-term storage can be processed in the cloud servers. E-health network usually communicates with the remote cloud server using wide area network. Sometimes it may cause unpredictable latency due to network connection. Therefore, latency-sensitive data are not processed in the cloud layer. The cloud layer finally provides the final visualization and feedback to the user as a graphical user interface. The collected medical data of patients represent a source of big data that can be further analyzed if required by users such as doctors. Doctors are connected to both fog and cloud layers and provide services to the user when needed. Unlike traditional cloud computing infrastructure, cloud data centers are not bombarded with every request of the e-health network system. By using fog computing, cloud tier can be used in a more efficient way. In an e-health network, energy efficiency and optimal latency are the two most important factors. In this work, energy consumption and service delay of the conventional cloud computing paradigm have been calculated. Then a model which uses the fog computing concept has been proposed and has shown that utilization of the fog concept significantly reduces energy consumption and service latency.

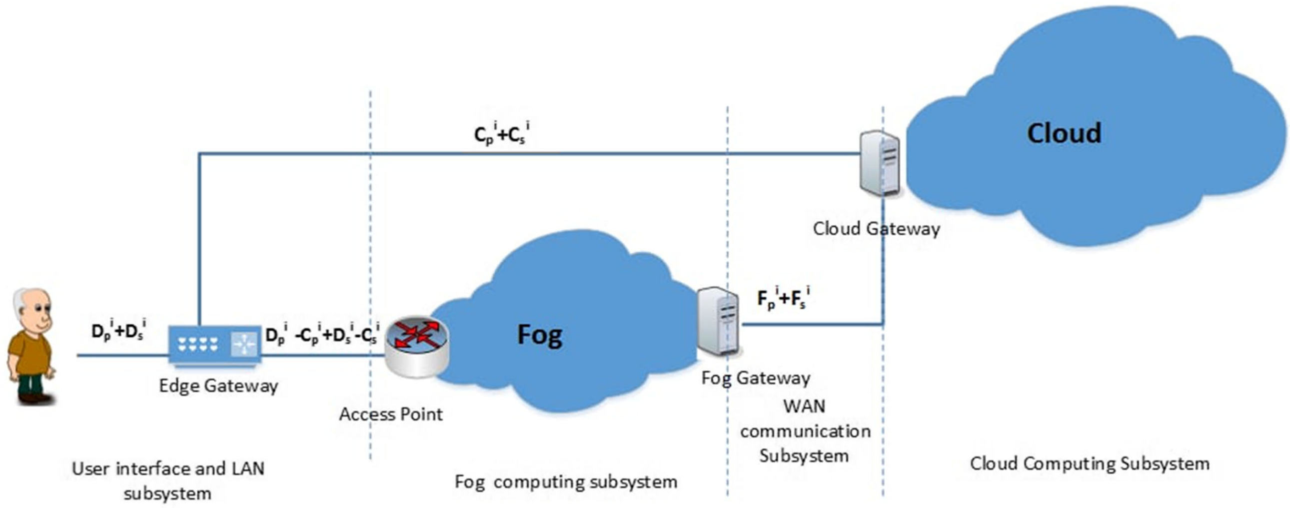
3. Mathematical Modeling for Energy Consumption and Delay Computation

3.1. Energy consumptions

3.1.1. Energy consumption for forwarding

Let there be a total N number of geo-distributed user equipment (UE) in this network. $D_p^i + D_s^i$ is the total amount of data produced by the i-th UE (such as a smartwatch) that are needed to be processed and stored. In the proposed system, there are three paths along which

Figure 2
Subsystem of e-health network and their interconnections



data can be passed. Figure 2 shows the subsystem of the proposed network and interconnections among different components.

The route UE → edge gateway → fog layer denotes the data propagation path from the sensor network layer to the fog layer via the edge gateway. Likewise, the UE → edge gateway → cloud layer represents the route from the sensor network to the cloud server through the edge gateway. Finally, fog computing layer → fog gateway → cloud computing layer indicates data redirected from the fog computing layer to the cloud computing layer via the fog gateway and cloud gateway for further processing and aggregation. All of the data produced by the UE will be forwarded through the edge gateway first. During forwarding, energy consumption occurs because of receiving data stream from UE, pre-processing of data for routing and transmitting.

Therefore, the energy consumed for data forwarding by the edge gateway is

$$E_{df}^{edg} = X_{edg} \sum_{i=1}^{N} (D_p^i + D_s^i) \tag{1}$$

where X_{edg} is the energy consumed by the edge gateway to forward a unit byte of data. Data that are latency-critical and require real-time interaction are transmitted to the fog computing layer. Let $C_p^i + C_s^i$ be the remaining data that will be processed and stored in the cloud. Energy consumption during forwarding data by fog instances is expressed by

$$E_{df}^{fog} = X_{fog} \sum_{i=1}^{N} \left(D_p^i + D_s^i - C_p^i - C_s^i\right) \tag{2}$$

where X_{fog} is the energy consumed by the fog instances to forward a unit byte of data.

$F_p^i + F_s^i$ is the data that is forwarded from the fog instance to the cloud for further processing, storing, and aggregation. Thus, the total energy consumption due to data forwarding at the cloud gateway is

$$E_{df}^{cld} = X_{cld} \sum_{i=1}^{N} \left\{ \left(C_p^i + C_s^i\right) + \left(F_p^i + F_s^i\right) \right\} \tag{3}$$

where X_{cld} is the energy consumed by the cloud gateway to forward a unit byte of data.

The total amount of energy consumption for forwarding in the fog-cloud computing environment is

$$E_{df} = E_{df}^{cld} + E_{df}^{fog} + E_{df}^{edg} \tag{4}$$

Mean energy consumption for data forwarding in the fog-cloud computing environment is

$$E_{dff}^{M} = \frac{E_{df}}{\sum_{i=1}^{N} (D_p^i + D_s^i)} \tag{5}$$

Mean energy consumption for data forwarding in a traditional cloud computing environment is

$$E_{dfc}^{M} = \frac{X_{cld} \sum_{i=1}^{N} (D_p^i + D_s^i) + E_{df}^{edg}}{\sum_{i=1}^{N} (D_p^i + D_s^i)} \tag{6}$$

3.1.2. Energy consumption for processing

The total energy consumption due to processing is the summation of energy consumption in cloud and fog. The data which require onsite processing and temporary storage will be processed in the fog tier.

Let τ be time to live for those data that are needed to be analyzed and processed in the fog after data are removed from the fog storage. Energy consumption due to processing at fog is

$$E_{CP}^{fog} = Y_{fog} \sum_{k=0}^{\tau} \beta_k^{fog} \sum_{i=1}^{N} \left(D_p^i(k) - C_p^i(k)\right) \tag{7}$$

where Y_{fog} is the energy needed to process a unit byte of data at the fog computing layer. β_k^{fog} is the weight factor depending on the age of the data.

Data that require historical analysis, long-term storage, further processing, and high computational power are processed in the cloud. $C_p^i + F_p^i$ is the total amount of data that will be processed in the cloud, where F_p^i is transferred by fog instances to the cloud for further processing and aggregation. Energy consumption due to processing and analysis in the cloud can be represented as:

$$E_{cp}^{cld} = Y_{cld} \sum_{i=1}^{N} \left(C_p^i + F_p^i\right) \tag{8}$$

where Y_{cld} is the amount of energy required to process a unit byte of data by the cloud.

Total energy consumption due to processing in a fog-cloud computing environment is

$$E_{cpf} = E_{CP}^{fog} + E_{cp}^{cld} \tag{9}$$

Mean energy consumption due to computation in a fog-cloud computing environment is

$$E_{cpf}^{M} = \frac{E_{cpf}}{\sum_{i=1}^{N} (D_p^i + D_s^i)} \tag{10}$$

Mean energy consumption due to computation in a traditional cloud computing environment is

$$E_{cpc}^{M} = \frac{Y_{cld} \sum_{i=1}^{N} D_p^i}{\sum_{i=1}^{N} (D_p^i + D_s^i)} \tag{11}$$

3.1.3. Energy consumption for storage

Energy dissipation due to storage is analogous to the energy consumption due to processing. Fog computing provides semi-permanent storage, whereas cloud computing provides permanent storage. Fog storage is used to store intermediate data and cloud storage is used for long-term storage. However, storage power consumption does not depend on the age of the data. Hence, no time to live is assigned with the data packet.

Energy consumption due to storage at fog can be expressed by

$$E_s^{fog} = Z_{fog} \sum_{i=1}^{N} (D_s^i - C_s^i) \tag{12}$$

where Z_{fog} is the amount of energy required to store a unit byte of data at fog computing layer.

Energy consumption due to storage in cloud is

$$E_s^{cld} = Z_{cld} \sum_{i=1}^{N} (F_s^i + C_s^i) \tag{13}$$

where Z_{cld} is the energy required to store a unit byte of data at cloud tier.

Total energy consumption due to storage in fog-cloud computing environment is

$$E_{sf} = E_s^{cld} + E_s^{fog} \tag{14}$$

Mean energy consumption due to storage in fog-cloud computing environment is

$$E_{sf}^{M} = \frac{E_{sf}}{\sum_{i=1}^{N} (D_p^i + D_s^i)} \tag{15}$$

Mean energy consumption due to storage in traditional cloud computing environment is

$$E_{SC}^{M} = \frac{Z_{cld} \sum_{i=1}^{N} D_s^i}{\sum_{i=1}^{N} (D_p^i + D_s^i)} \tag{16}$$

Total energy consumption in the fog computing environment can be calculated by the summation of energy consumption due to forwarding, energy consumption due to processing, and energy consumption for storage at the fog computing layer.

Accordingly, overall energy consumption in the fog-cloud computing environment is

$$E_f = E_{dff}^{M} + E_{cpf}^{M} + E_{sf}^{M} \tag{17}$$

Overall energy consumption in the traditional cloud computing environment is

$$E_c = E_{dfc}^{M} + E_{cpc}^{M} + E_{sc}^{M} \tag{18}$$

3.2. Service delay

For e-health networks, service delay is a very critical issue as it deals with health-related data of a patient. The time required to serve a request made by the application node is known as service delay or response time. Service delay can be calculated by summing up the transmission delay and processing delay. Since devices are placed within the same network of WBSN, delays due to transmitting data from WBSN to the fog computing layer can be omitted. However, communication links between edge gateway and cloud gateway as well as fog gateway and cloud gateway are bandwidth constraints.

3.2.1. Delay for forwarding

The delay for transmitting delay-sensitive data from the WBSN to fog instances through the edge gateway can be expressed by

$$D_{tr}^{ef} = \alpha_{ef}(d) \sum_{i=1}^{N} \left(D_p^i - C_p^i + D_s^i - C_s^i\right) \tag{19}$$

where $\alpha_{ef}(d)$ is the delay for unit byte data transmission from the edge gateway to the fog gateway and d is the distance.

The transmission delay of the data which are transmitted from the edge to the cloud gateway is

$$D_{tr}^{eg} = \alpha_{eg}(d) \sum_{i=1}^{N} \left(C_p^i + C_s^i\right) \tag{20}$$

where $\alpha_{eg}(d)$ is the delay for unit byte data transmission from the edge gateway to the cloud gateway.

A certain amount of data generated from fog instances needs to be transmitted to the cloud for further processing and storage.

Transmission delay for transmitting those data from fog to cloud is

$$D_{tr}^{fg} = \alpha_{fg}(d) \sum_{i=1}^{N} \left(F_p^i + F_s^i\right) \tag{21}$$

where $\alpha_{fg}(d)$ is the delay for unit byte data transmission from the fog gateway to the cloud gateway.

Total transmission delay in the fog-cloud computing environment is

$$D_{trf} = D_{tr}^{ef} + D_{tr}^{eg} + D_{tr}^{fg} \tag{22}$$

The mean transmission delay in the fog-cloud computing environment is

$$D_{trf}^{M} = \frac{D_{trf}}{\sum_{i=1}^{N} (D_p^i + D_s^i)} \tag{23}$$

Mean transmission delay in the traditional cloud computing environment is

$$D^{M}_{trc} = \frac{\alpha_{eg}(d)\sum_{i=1}^{N}\left(D_p^i + D_s^i\right)}{\sum_{i=1}^{N}\left(D_p^i + D_s^i\right)} \tag{24}$$

3.2.2. Delay for processing

The time required to process the request made by the application instances (BSN) is the computational latency. Time to live is assigned with each data packet which will be processed at the fog computing layer.

Processing delay at fog can be expressed by

$$D_{cp}^{fog} = W_{fog}\sum_{k=0}^{\tau}\beta_k^{fog}\sum_{i=1}^{N}\left(D_p^i(k) - C_p^i(k)\right) \tag{26}$$

where W_{fog} is the delay for processing a unit byte of data at the fog layer. As the fog layer provides onsite and real-time processing, the waiting time for the fog server can be ignored. Similarly, for the application requests which will be served by the cloud layer, processing delay can be expressed as

$$D_{cp}^{cld} = W_{cld}\sum_{i=1}^{N}\left(F_p^i + C_p^i\right) \tag{26}$$

where W_{cld} is the delay in processing a unit byte of data in the cloud.

The total processing delay in the fog computing environment is the summation of the processing delay at the fog computing layer and the processing delay at the cloud computing layer.

$$D_{cpf} = D_{cp}^{cld} + D_{cp}^{fog} \tag{27}$$

The mean processing delay in the fog-cloud computing environment is

$$D^{M}_{cpf} = \frac{D_{cpf}}{\sum_{i=1}^{N}\left(D_p^i + D_s^i\right)} \tag{28}$$

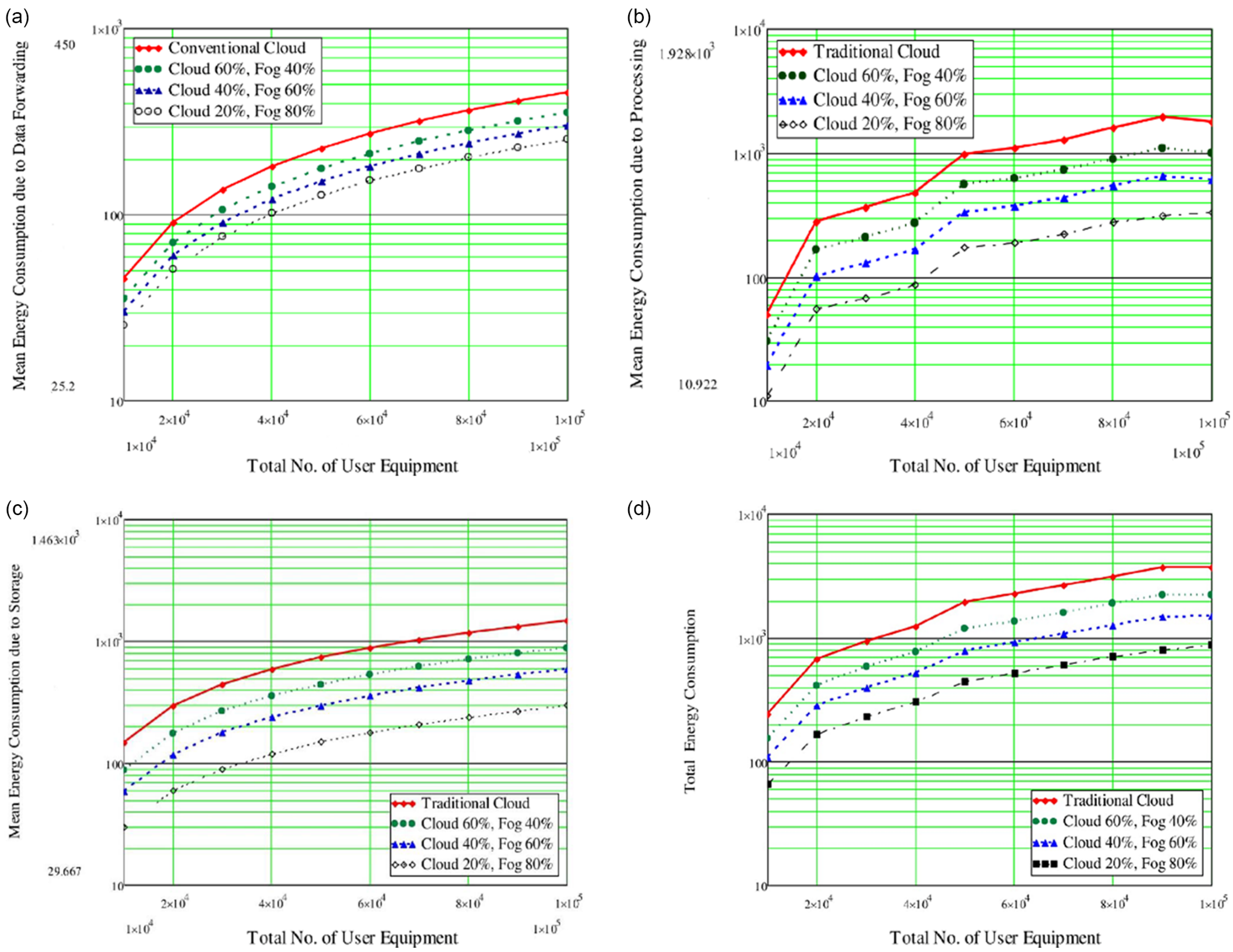
The mean processing delay in a traditional cloud computing environment is computed as

$$D^{M}_{cpc} = \frac{W_{cld}\sum_{i=1}^{N}\left(D_p^i + D_s^i\right)}{\sum_{i=1}^{N}\left(D_p^i + D_s^i\right)} \tag{29}$$

3.2.3. Delay for waiting at cloud

Waiting time is associated with the cloud. Since fog deals with data that require low latency and real-time interaction, waiting time is ignored in the fog. The amount of data produced by the end devices is

Figure 3
Comparison of different components of energy consumption and total energy consumption for different fog and cloud combinations



huge and increasing day by day and it will create a heavy bottleneck in the cloud server. Consequently, requests which are needed to be processed in the cloud may have to wait. We can divide the data that will be processed in cloud into M bytes. We assume that A_j= arrival time of j-th data byte and S_j= service time of j-th data byte.

Thus, average waiting time per unit byte can be expressed as

$$H_w = \frac{\sum_{j=1}^{M} (S_j + A_j)}{M} \tag{30}$$

Waiting time at the cloud server is

$$D_w^{cld} = H_w \sum_{i=1}^{N} (C_p^i + F_p^i) \tag{31}$$

where H_w is the waiting time for a unit byte data in the cloud. The mean waiting time in the fog-cloud computing environment is

$$D_{wf}^M = \frac{D_w^{cld}}{\sum_{i=1}^{N} (D_p^i + D_s^i)} \tag{32}$$

The mean waiting time in a traditional cloud computing environment is

$$D_{wc}^M = \frac{H_w \sum_{i=1}^{N} D_p^i}{\sum_{i=1}^{N} (D_p^i + D_s^i)} \tag{33}$$

So eventually, the mean service delay in a fog-cloud computing environment is the summation of mean transmission delay, mean processing delay, and mean waiting delay.

$$D_{sf} = D_{trf}^M + D_{cpf}^M + D_{wf}^M \tag{34}$$

The mean service delay in cloud computing environment is

$$D_{sc} = D_{trc}^M + D_{cpc}^M + D_{wc}^M \tag{35}$$

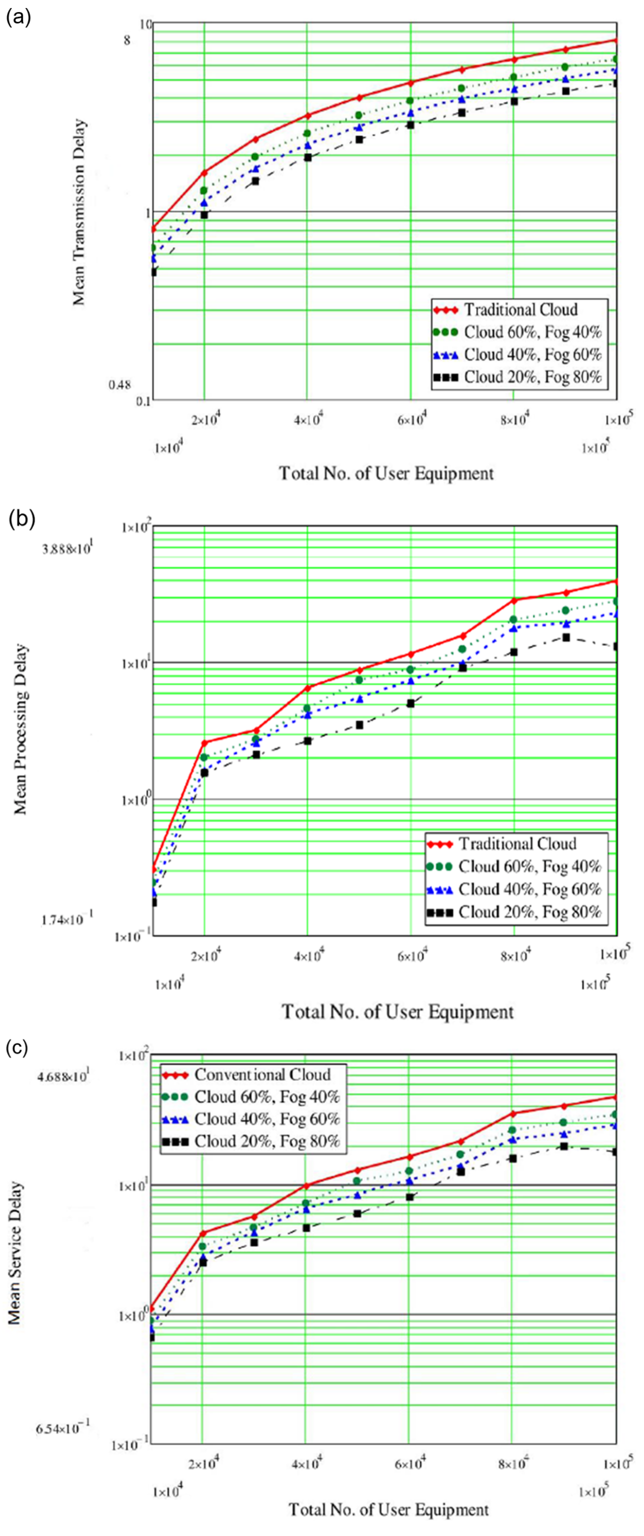
4. Simulation Results

This section includes a simulation of the proposed energy-efficient e-health network. The simulation results have been compared with the conventional cloud computing paradigm. The performance of the proposed system is evaluated in terms of energy consumption and service delay. It has been noticed that the performance of the proposed e-health system has been improved significantly because of the exploitation of the concept of fog computing.

First, the energy consumption of each subsystem of the network has been shown. The individual effect of energy consumption for forwarding, processing, storing, and the total energy consumption of the system has been calculated. In this work, three different combinations of fog and cloud (60% cloud + 40% fog, 40% cloud + 60% fog, and 20% cloud + 80% fog) have been used. The 100% cloud + 0% fog means traditional cloud computing paradigm.

In Figure 3(a) shows the energy consumption due to forwarding. As can be seen, the energy consumption because of forwarding increases with the number of UE linearly. The figure also shows that the energy consumption is much higher when we use the traditional cloud. Moreover, with the increase in the percentage of usage of fog, the consumption of energy is reduced significantly. Figure 3(b) and (c) shows the trend in power consumption due to processing and storage. Mean power consumption is shown against the number of UE. We can draw similar conclusions from these two figures. In both cases, energy consumption was reduced drastically when we

Figure 4
Comparison of different delays for different fog and cloud combinations



increased the usage of the fog layer. Figure 3(d) shows the total energy consumption of the system. Total energy consumption can be calculated by summing up the energy consumption due to forwarding, processing, and storage. By analyzing the result, we can conclude that mean energy consumption is always less in the

Table 1
Comparison of the proposed system with established e-health systems

Features	Daktarbhai (Healthcare Information System Ltd, 2023)	Health Plus (Robi/Airtel Health Plus, 2019)	Parent care (Moore, 2023)	WebMD (WebMD LLC, 2023)	Proposed system
Long-term data storage	×	×	×	√	√
User-end healthcare sensory system	×	×	×	×	√
24/7 patient monitor	×	×	×	×	√
Patient data security and privacy	×	×	×	√	√
E-prescription	√	×	×	×	√
Rapid response via fog gateway	×	×	×	×	√
Real-time online analytic	√	×	×	×	√
Online appointment	√	√	√	×	√

presence of fog than traditional. Savings of energy is almost up to 50% when we use the fog paradigm instead of the traditional cloud.

Now, Figure 4 shows different delays for different percentages of cloud and fog combinations. Figure 4(a) and (b) describes the delay for transmission and processing against the total number of UE, respectively. In Figure 4(a), the change in transmission delay has been observed while we use different percentages of fog and cloud. In Figure 4(b), mean processing delays are plotted against the total no. of UE. As can be seen, with the increase in the number of UE, the delay has also increased. But the more we use fog, the less delay is encountered.

Figure 4(c) shows the overall service delay of the system. Total service delay can be calculated by summing up the transmission delay, processing delay, and waiting time in the cloud. Total service delays for both computing paradigms follow the same pattern. In the case of the traditional cloud, the service delay is the highest. Service delays were reduced with the increase in usage of fog percentage, and it leads to saving of time by almost 55%.

Currently, several e-health monitoring systems have been developed after the COVID-19 pandemic. These e-health systems have earned a satisfactory reputation from their users (Quadery et al., 2021). A comparative study shows that patients can book online appointments and get an e-prescription using some of these systems (Ishak et al., 2021). From the point of view of the service providers' side, designed system efficiency is yet to be investigated. The features of the proposed system have been compared with the features of several existing e-health systems and the results are reported in Table 1.

5. Conclusion

In this work, an energy-efficient e-health network has been proposed based on simulated data. In e-health networks, energy consumption and service delays are two major issues. To reduce energy consumption and service delay while ensuring the QoS of the e-health network, the concept of fog computing has been implemented in this work. Mathematical characterization has been provided for the proposed system and the performance of the system was evaluated in terms of energy efficiency and optimal delay. The simulation results have been compared with the state-of-the-art cloud computing platform. The experimental results show that the consumption of energy is reduced with the increase of the usage of the fog paradigm and the savings of energy is almost 50%. Moreover, it was observed that service delay decreases with the presence of a fog paradigm and savings of time is almost 55%. So according to the simulation result, the proposed system can fulfill the QoS requirements of the e-health network. Since the current implementation is based on simulated data, in the future, it will be worthwhile to implement the system with real hospital data and assess performance by deploying the system in a real hospital environment. Furthermore, adequate privacy and security will improve the performance of the proposed system which is left for future work.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

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