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doi:10.15199/48.2023.09.25

Energy-Efficient Network Architecture for Smart City Development

***Abstract**. The growing number of objects connected to the Internet due to the evolution of smart cities development and the tremendous data in the future 6G networks with extensive processing has produced massive amounts of data that need to be processed. This will burden the conventional clouds to process the data besides reducing the Quality of Services due to high latency. Also, the increase in data volumes increased the energy consumed by transport networks and the cloud. Therefore, fog computing has been introduced to overcome the limitation of the cloud. This study proposed a new fog computing architecture for Internet-of-Things (IoT) applications based on wireless access networks using WiFi technology. A new mathematical model has been developed to optimize the number and locations of the fog servers at the access network to minimize the energy consumption of the networking and processing equipment at the access layer. This is beneficial for smart city development which contributes to the 2030 Agenda for Sustainable Development Goals (SDG) under Goal 7. The Mixed Integer Linear Programming (MILP) model using AMPL software with CPLEX solver is used to model the energy-efficient fog computing architecture considering twelve tourist locations in Melaka as the case study. The results show that the proposed optimized approach (OA) has 52.6% energy saving as the low number of fog servers and networking devices are utilized in the network compared to the non-optimized approach (NOA). Besides, the energy saving increased up to 81.1% when high processing server capacity is considered in the network. In addition to that, the results also show that increasing the traffic demands by each user does not give a significant energy increment when considering a fog server with high processing capacity in the network.*

***Streszczenie.** Rosnąca liczba obiektów podłączonych do Internetu w wyniku ewolucji rozwoju inteligentnych miast i ogromne ilości danych w przyszłych sieciach 6G z ekstensywnym przetwarzaniem wytworzyły ogromne ilości danych, które trzeba przetworzyć. To obciąży konwencjonalne chmury do przetwarzania danych, oprócz obniżenia jakości usług z powodu dużych opóźnień. Również wzrost wolumenu danych spowodował wzrost zużycia energii przez sieci transportowe i chmurę. Dlatego w celu przezwyciężenia ograniczeń chmury wprowadzono obliczenia mgły. W badaniu tym zaproponowano nową architekturę mgły obliczeniowej dla aplikacji Internet-of-Things (IoT) w oparciu o sieć dostępu bezprzewodowego wykorzystującą technologię WiFi. Opracowano nowy model matematyczny w celu optymalizacji liczby i lokalizacji serwerów mgły w sieci dostępowej, aby zminimalizować zużycie energii przez sprzęt sieciowy i przetwarzający w warstwie dostępowej. Jest to korzystne dla rozwoju inteligentnych miast, które przyczyniają się do realizacji Agendy na rzecz celów zrównoważonego rozwoju 2030 (SDG) w ramach celu 7. Model programowania liniowego mieszanych liczb całkowitych (MILP) z wykorzystaniem oprogramowania AMPL z solverem CPLEX jest wykorzystywany do modelowania energooszczędnej architektury przetwarzania mgły z uwzględnieniem dwanaście miejsc turystycznych w Melace jako studium przypadku. Wyniki pokazują, że proponowane zoptymalizowane podejście (OA) zapewnia 52,6% oszczędności energii, ponieważ w sieci wykorzystywana jest niewielka liczba serwerów mgły i urządzeń sieciowych w porównaniu z podejściem niezoptymalizowanym (NOA). Poza tym oszczędność energii wzrosła do 81,1%, gdy w sieci uwzględniono wysoką wydajność serwerów przetwarzających. Oprócz tego wyniki pokazują również, że zwiększenie zapotrzebowania na ruch przez każdego użytkownika nie daje znaczącego przyrostu energii, biorąc pod uwagę serwer mgły o dużej mocy obliczeniowej w sieci. (**Energooszczędna architektura sieci dla rozwoju inteligentnych miast**)*

Keywords: Fog computing, energy efficiency, Internet of Things, wireless network, WiFi technology
Słowa kluczowe: Obliczenia mgły, efektywność energetyczna, Internet rzeczy, sieć bezprzewodowa, technologia WiFi

Introduction

In Malaysia, a smart city is believed to be the future approach to urban planning, development and management which can provide solutions to urban challenges to improve the quality of life of urban people besides stimulating economic and social development. Therefore, Malaysia's smart city framework (MSCF) has been developed to ensure that Malaysia is keeping abreast with the global urban development trend so that the objectives of the Sustainable Development Goals (SDGs) are achieved [1]. It has been reported that, by 2025, the world's population living in cities will rise from 54% to 64% which may increase the traffic in the network due to the increased uptake of Internet of Things-based services [2]. In the meantime, it has been reported that the proportion of Internet users has increased to more than 90% in many developed countries [3]. This is due to the growing popularity of traffic-intensive applications, such as Internet Protocol TV and high-definition TV. For example, in Malaysia, more than 80% of the population has Ethernet access [4]. In addition, it is reported that the data traffic in Malaysia Internet Exchange is approximately 35 Gbps per day and between 2020 and 2025, it is estimated to grow by about 5- 10% [4]. Therefore, with the increasing traffic, information and communications technology (ICT) organizations have focused on increasing the network energy efficiency, given the ecological and economic drivers that are currently high profile. This is because, the Internet of Things (IoT) devices have limited memory, storage and processing capability, hence offloading a massive amount of data generated by the IoT devices which cannot be processed locally to the cloud through the Internet for processing contributes to high energy consumption within the network as the data have to travel multi hops over the network to the cloud for processing. This has also been reported in [3], [5], [6] where the production and operation of ICT are expected to rise to 21% of global electricity consumption by 2030 in which electricity consumed by digital devices and infrastructure is estimated to be 7% per year. Therefore, fog computing has been introduced as a new platform by Cisco to overcome this shortcoming [7]. Fog computing extends the cloud-based Internet by initiating an intermediate processing layer using fog servers for example, between IoT devices and the cloud. The fog servers are a highly virtualized computing system equipped with data storage, as well as computing and communication facilities, which appear similar to the cloud servers. It is also possible to connect the fog servers to the cloud to leverage

the rich functionality and available application tools. Furthermore, as fog servers are disseminated at the network edge, fog computing may have dense geographical coverage and mobility support [8]. Therefore, fog computing can reduce the energy consumed in cloud networking infrastructures while delivering Quality of Service (QoS) metrics. Several recent studies have applied fog computing to develop efficient IoT-based systems in terms of bandwidth efficiency, scalability, reliability, latency and power consumption considering various access network topologies [9]–[11]. In [12], the authors investigate the joint communication and computation resource allocations for latency minimization in a cloud-edge collaboration system. Two sub-problems related to the communication resource allocation and the computation resource allocation have been identified to perform the optimization in allocating the demands either to be at the edge or cloud computing. The results show that compared to the conventional schemes, considering collaboration between the edge and cloud computing can improve the delay. In [13], the authors proposed three transmission schemes, the full caching bulk transmission scheme, the partial caching bulk transmission scheme (PCBT) and the partial caching pipelined transmission scheme (PCPT) to minimize the latency for cache-enabled multi-group multicasting networks. The performance of the three schemes is evaluated considering the delay due to fetching the un-cached files from the BBU, processing the signal at the BBU and transmitting the requested files to the users. The results show that the PCPT scheme has lower delivery latency compared to the other schemes. Meanwhile, the work in [14] has proposed a big-data-driven evolutionary smart manufacturing architecture that collaborates the edge and cloud processing. In this architecture, the assets and the material of the manufacturing resources are converted into smart cloud assets and objects where their interaction is captured by a smart gateway at the edge network. Also, the work proposed an AI-enabled manufacturing operation (AI-Mfg-Ops) mode with a supporting software-defined framework to control the evolvement of the cloud and edge processing to support the latency-sensitive applications for real-time response. Meanwhile, since the network is one of the significant contributors to the total energy demand in many developing countries [15] and energy efficiency is one of the main priorities for information and communication technology (ICT) organizations, reducing the transport network's energy consumption is very important. In [8], an energy-efficient fog-based architecture has been proposed for health monitoring applications where the fog has been optimized only at the access layer to process the health data. The results also show that, under increasing demand, the energy consumption of the network and processing increases due to the limited number of fog that can be served at each candidate node. However, the work considered the Long Term Evolution (LTE) for data communication and transmission which has longer coverage range besides can serve more users compared to Wi-Fi communication where the coverage range is limited by the capability of the routers.

To the best of our knowledge, most studies have dismissed the essential aspect of considering the energy consumption in transport networks and processing when distributing the fog servers considering the wireless access network using Wi-Fi communication technology. Also, the impact of fog server capacity on the energy efficiency of networking and processing in the fog network architecture is not discussed in detail. In this study, a new framework for energy-efficient IoT-based applications is considered to leverage the concept of fog computing by optimizing the number and location of the fog servers in the wireless access network to support the development of a smart city. In this work, we expend the candidate location of the fog servers to be at the access network services to bring the services to the users' proximity besides varying the processing capacity of the fog servers to serve different IoT-based applications that have different processing demands and traffic.

Methodology

The architecture of the proposed fog computing architecture for the IoT-based smart city applications with the Wi-Fi access network that is characterized by two layers is as shown in Fig.1. The first layer is the IoT layer comprised of IoT devices including mobile phones, Ipad, laptops etc. The second layer is the access layer where the fog processing resources reside. At this layer, the data from the IoT layers will be aggregated via a Wi-Fi access point and will be sent to the fog server for processing. Note that, each Wi-Fi access point will be connected to a fog server via an Ethernet switch. Also, note that communication between the Wi-Fi access points that are within their coverage range is also allowed in this scenario.

Table 1. The latitude and longitude of the candidate locations

Ref	Tourist Location	Latitude	Longitude
1	Jonker Street	2.1948	102.2484
2	Church of St. Francis Xavier	2.1953	102.2506
3	Christ Chruch Melaka	2.1943	102.2495
4	Melaka Clock Tower	2.1944	102.2491
5	The Stadthuys	2.1942	102.2496
6	Istana Kesultanan Melaka	2.1928	102.2505
7	Independence Memorial	2.1919	102.2509
8	St. Paul's Church	2.1925	102.2496
9	A' Famosa	2.1918	102.2504
10	Menara Taming sari	2.191	102.2473
11	Royal Malaysia Navy Museum	2.1913	102.2467
12	Maritime Museum	2.1919	102.2466

Table 2. The distance between the candidate locations

Ref / Ref	1	2	3	4	5	6	7	8	9	10	11	12
1	0	90	134	149	251	322	288	379	433	440	401	426
2	90	0	46	60	194	236	218	393	436	428	323	342
3	134	46	0	16	165	200	200	418	456	441	295	309
4	149	60	016	0	165	185	189	420	456	438	281	294
5	251	194	165	165	0	278	331	583	621	603	390	380
6	322	236	200	185	278	0	105	445	454	408	112	110
7	288	218	200	189	331	105	0	340	349	305	118	159
8	379	393	418	420	583	445	340	0	68	127	422	478
9	433	436	456	456	621	454	349	68	0	75	415	471
10	440	428	441	438	603	408	305	127	75	0	356	412
11	401	323	295	281	390	112	118	422	415	356	0	57
12	426	342	309	294	380	110	159	478	471	412	57	0

To evaluate the performance of the proposed fog computing infrastructure using a Wi-Fi access network, we considered twelve tourist locations in Bandaraya Melaka as the candidate locations to place the fog servers. The twelve candidate locations include the A'Famosa, Church of St. Francis Xavier, Jonker Street, Independence Memorial, Istana Kesultanan Melaka, Maritime Museum, Melaka Clock Tower, Crist Church, Menara Taming Sari, Royal Malaysia Navy Museum, St. Paul Church and The Stadhuys. Fig.2 shows the Melaka Tourism Map that consists of the twelve candidate locations (i.e. highlighted in red circle). Table 1 shows the actual locations of the considered locations (i.e. latitude and longitude) which had been obtained from Google Maps while Table 2 shows the distances between the considered locations. In this work, the twelve candidate locations will be equipped with a Wi-Fi gateway to aggregate data from the users or IoT devices. Also, note that MATLAB software will be used to determine the location of the AS based on the nearest distance to the gateways (i.e. Wi-Fi access point).

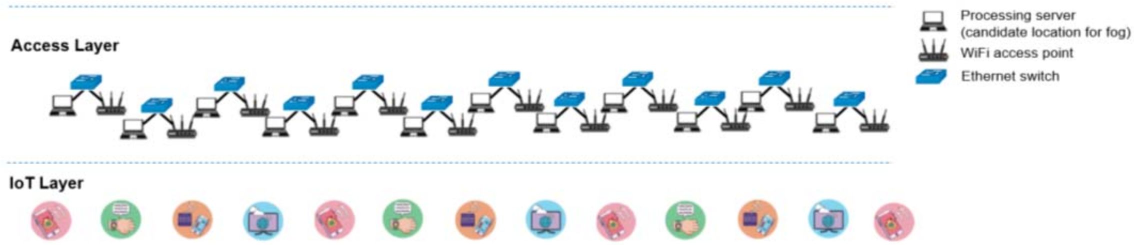

Fig.1. The fog computing infrastructure with Wi-Fi access network for Smart City Application

Fig.2. The Melaka Tourism Map that consists of the twelve candidate locations

Table 3. The sets, parameters and variables used in the MILP model

Set	
FS	Set of the fog server
IoT	Set of IoT group
AP	Set of access point
ETH	Set of Ethernet switch
N	Set of nodes ($N \cup IoT \cup AP \cup ETH$
Parameter	
IAP	Idle power consumed by access point
EAP	Energy per bit of access point
$IETH$	Idle power consumed by Ethernet switch
$EETH$	Energy per bit of Ethernet switch
IFS	Idle power consumed by the fog server
PFS	Power per MIPS of the fog server
CFS	Total MIPS can be served by each fog server
D	Size of data for each user
U_s	Number of users in each IoT group
CFS_s	Processing capacity for each device
$MIPS$	Amount of processing required by each user
M	A large enough number
Variables	
W_{sd}	Number of user from IoT group s serve by fog server d
L_{sd}	Total traffic transmit from node s to node d
L_{ij}^{sd}	Total traffic transmit from node s to node d that traversing at node i and j
X_i	$X_i = 1$ if the traffic traverses node i otherwise 0
T_{ij}	Total traffic traverses between node i and j
C_i	Total traffic traverses at node i
FS_i	$FS_i = 1$ if the fog server is used to serve the users, otherwise 0

In this work, a new mathematical model (i.e. optimized approach, OA) will be derived using Mixed Integer Linear Programming (MILP) model to optimize the number and locations of the fog server at the access network to minimized the energy efficiency of the networking and processing equipment. The proposed OA model will be compared with the non-optimized (NOA) model for benchmarking purposes. The MILP model is chosen because of its flexibility and powerful method to solve large and complex problems. Note that, we perform the MILP optimization of our fog computing architecture using the AMPL software with CPLEX 20.1 solver.

In the following, we show the energy consumption of the networking equipment at the access network layer and processing equipment which is the fog server. Note that, in this work, we did not consider the energy consumption of the IoT devices. Also note that the power consumption profile for the networking and processing devices is composed of a fixed idle power and load-dependent power. Table 3 shows the sets, parameters and variables used in the MILP model.

A. Energy consumption of networking equipment

The energy consumption of the networking equipment (E_N) consists of energy consumed by the Wi-Fi access point (E_{WF}), and Ethernet switch (E_{ETH}) to send the traffic to the fog server for processing as shown in Equation (1) – (3).

$$E_N = E_{WF} + E_{ETH} \tag{1}$$

$$E_{WF} = \sum_{i \in AP} X_i . IAP + T_i . EAP \tag{2}$$

$$E_{ETH} = \sum_{i \in ETH} X_i . IETH + T_i . EETH \tag{3}$$

B. Energy consumption of processing equipment

The energy consumption of processing equipment, (E_P), consists of the energy consumed by the fog server which is calculated based on its usage and the amount of traffic that the server needs to process as shown in Equation (4).

$$E_P = \sum_{i \in FS} FS_i . IFS + T_i . PFS \tag{4}$$

The objective function and constraints

The MILP model is defined as below: Objective: Minimize the energy consumption of networking equipment and processing equipment as shown below:

$$E_N + E_P \tag{5}$$

Subject to:

$$W_{sd} \le U_s . FS_d ; s \in IoT, d \in FS \tag{6}$$

$$\sum_{d \in FS} W_{sd} = U_s ; s \in IoT, d \in FS \tag{7}$$

Constraint (6) is to assign each user to a fog server while constraint (7) is to ensure that each user will be served by only one server.

$$\sum_{j \in Nm[i]: i \neq j} L_{ij}^{sd} - \sum_{j \in Nm[i]: i \neq j} L_{ji}^{sd} = \begin{cases} L_{sd} & if\ i = s \\ -L_{sd} & if\ i = d \\ 0 & otherwise \end{cases}$$
$$s \in IoT, d \in FN, i \in N \tag{8}$$

Constraint (8) is to ensure the flow conservation of the total incoming traffic of a node and total outgoing traffic from that node are equal.

(9) $$L_{sd} = W_{sd} \,.\, D; s \in IoT, d \in FS$$

Constraint (9) is to calculate the traffic from each access point to the fog server.

(10) $$T_{ij} = \sum_{s \in IoT: s \neq d} \sum_{d \in FS: s \neq d} L_{ij}^{sd} \,; i \in N, j \in Nm[i]$$

(11) $$\sum_{j \in Nm[i]: i \neq j} T_{ij} = C_i \,; i \in N$$

Constraint (10) is to determine the total traffic traversing the link i and j while constraint (11) is to determine the total traffic traversing at each node, i.

(12) $$\sum_{i \in N: i \neq j} T_{ij} \leq C_j \,; j \in Nm[i]$$

(13) $$\sum_{i \in N} X_i \geq C_i$$

(14) $$\sum_{i \in N} X_i \leq M.C_i$$

Constraint (12) is to ensure that the total traffic traversing at node i does not exceed its maximum capacity. Constraints (13) and (14) are to determine the node, i that is used to relay the traffic to the fog server whereas $X_i = 1$ if node i is used to relay the traffic otherwise 0.

(15) $$\sum_{s \in IoT} W_{sd} \,.\, MIPS \leq CFS_d \,; d \in FS$$

Constraints (15) is to ensure the total MIPS that needs to be processed at each fog server does not exceed its maximum processing capacity.

Results and Discussion

This section presents the results and analysis of the proposed fog-optimized approach (OA) compared to the non-optimized approach (NOA) in terms of power consumption of the networking and processing equipment considering the different capacities of the processing server capacity, the size of traffic in the network and also the size of data for each user. The parameter related to the power consumption and the processing capacity of the networking and processing equipment and the traffic considered is shown in Table 4. Note that, AMPL software with CPLEX 12.8 solver running on a 3.2 GHz computer is used as a platform to solve the MILP model.

In this work, we consider twelve IoT groups with 10 users each and these groups are located at a different access points. It is worth noting that, the IoT group can also be served by several access points based on the distance between the access points. However, each user can only be served by one fog server. Fig.3 shows the total energy consumption of the proposed OA compared to the NOA. The results show that the energy consumption with the OA is lower compared to the NOA by 56.2%, 68.9% and 81.1%, for fog server A, fog server B and fog server C, respectively. The reduction is due to the lower number of utilized networking and processing equipment. This is shown in Fig.4 and Fig.5 where the energy consumption of the networking equipment and the energy consumption of the processing equipment with the OA is lower compared to the NOA for all types of fog servers. This is because, in OA the users are consolidated into the optimal number of fog servers for services, hence the lower number of Ethernet switches are utilized. Compared to the NOA, all fog servers are utilized to serve the users. This is shown in Fig.6, where the number of utilized fog servers with OA is lower compared to the NOA.

Table 4. Input parameters for networking and computing devices

Parameter	Value
Idle power consumption of access point, IAP	7.872 W [16]
Energy per bit of access point, EAP	7.173 J/Gbits [16]
Maximum capacity of access point, CAP	0.45Gbps [16]
Idle power consumption of Ethernet switch, $IETH$	0.57 W [17]
Energy per bit of Ethernet switch, $EETH$	0.184 J/Gbits [17]
Maximum capacity of Ethernet switch, $CETH$	16 Gbps [17]
Idle power consumption of Intel Xeon E5-2420 (fog server A), IFS	57 W [18]
Power per bit of Xeon E5-2420 (fog server A), PFS	1111μW/MIPS [18]
Maximum capacity of Xeon E5-2420 (fog server A), CFS	34.2 kMIPS [18]
Idle power consumption of Intel X5675 (fog server B) , IFS	57 W [19]
Power per bit of Intel X5675 (fog server B) , PFS	517μW/MIPS [19]
Maximum capacity of Intel X5675 (fog server B) , CFS	73.44kMIPS [19]
Idle power consumption of NVidia T4 GPU (fog server C) , IFS	45 W [20]
Power per bit of NVidia T4 GPU (fog server C) , PFS	27.7μW/MIPS [20]
Maximum capacity of NVidia T4 GPU (fog server C) , CFS	1080kMIPS [20]

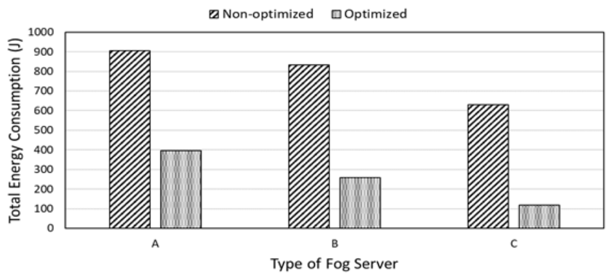

Fig.3. Total energy consumption of proposed OA and NOA

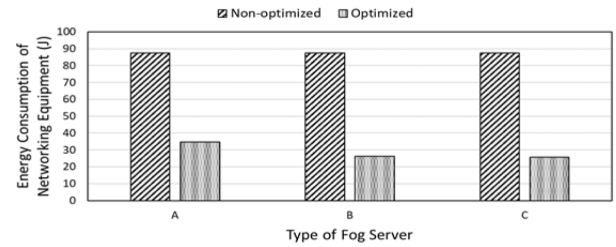

Fig.4. Energy consumption of networking equipment for the proposed OA and NOA

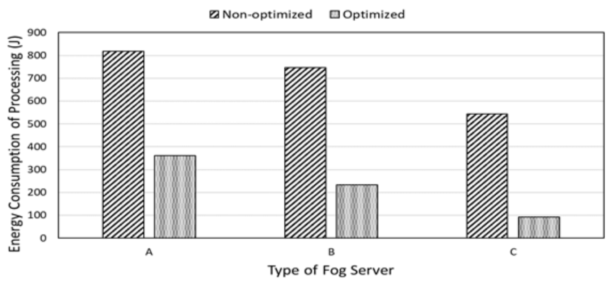

Fig.5. Energy consumption of processing equipment for the proposed OA and NOA

The results in Fig.3 also show that the total energy consumption was reduced when the processing capacity of the fog server increased for both OA and NOA. The reduction of total energy consumption for OA is due to reducing the energy consumption of both networking and processing equipment as shown in Fig.4 and Fig.5, respectively. This is because increasing the processing capacity of the fog servers has increased the number of users that can be served by a fog server, hence reducing the number of utilized fog servers as shown in Fig.6. It is worth noting that, the reduction of energy consumption of the processing equipment is also due to the lower idle power and the processing power of the fog server itself with the increasing capacity of the server as shown in Table 4. Besides, as more users can be served in a single fog server, the number of utilized Ethernet switches connected to the fog server is also reduced. Table 5 shows the optimal candidate locations that have been selected to deploy the fog server for the three types of fog server. Meanwhile, for NOA, the same number of fog servers is utilized in the network as shown in Fig.6. Therefore, the total energy reduction is mainly due to the low energy consumption of the processing equipment where the high capacity of the processing equipment has lower idle and processing power.

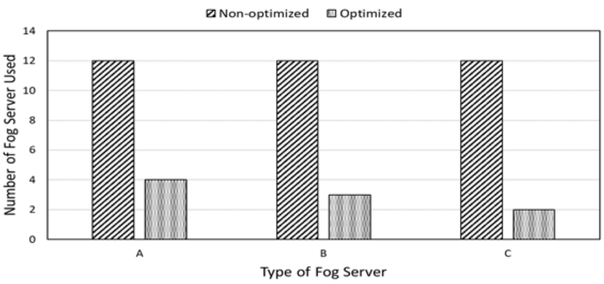

Fig.6. Number of utilized fog servers for the proposed OA and NOA

Table 5 Optimal location to deploy fog server with OA for a different types of fog servers

Type of Fog Server / Tourist Location	A	B	C
Jonker Street			
Church of St. Francis Xavier			
Christ Chruch Melaka	/	/	
Melaka Clock Tower			
The Stadthuys	/		
Istana Kesultanan Melaka		/	
Independence Memorial			
St. Paul's Church	/		/
A' Famosa			
Menara Taming sari			
Royal Malaysia Navy Museum			/
Maritime Museum	/	/	

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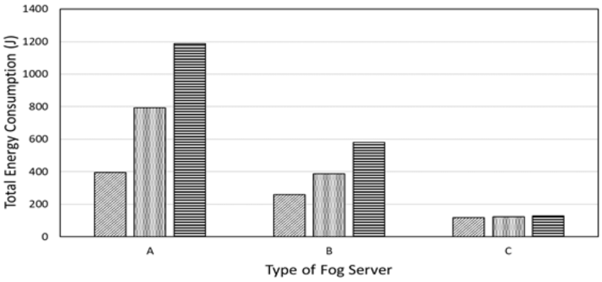

Fig.7. Total energy consumption of the proposed OA with a different types of fog servers and traffic/processing demand

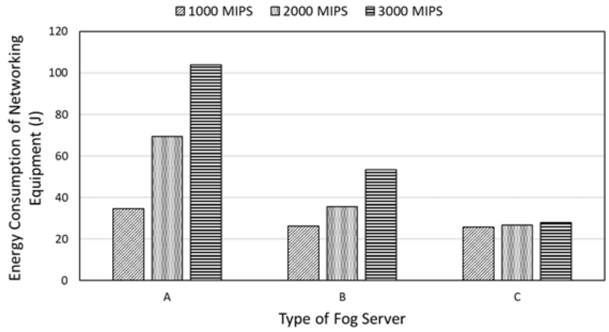

Fig.8. Energy consumption of the networking equipment for the proposed OA with a different types of fog servers and traffic/processing demand

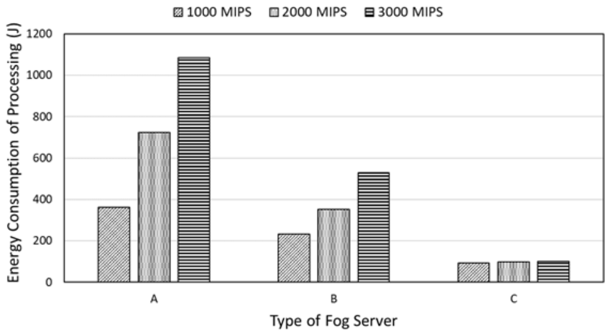

Fig.9. Energy consumption of the processing equipment for the proposed OA with a different types of fog servers and traffic/processing demand

In this work, we also investigated the impact of increasing the traffic in the network on the total energy consumption with the proposed OA. This is done by increasing the amount of traffic and the requested processing demand by each user from 1000 MIPS (i.e. 1 Mbps) to 2000 MIPS (i.e. 2 Mbps) and 3000 MIPS (i.e. 3 Mbps). Fig.7 shows that increasing the size of traffic has significantly increased the total amount of energy consumption when considering fog servers, A and B. This is mainly due to the increasing amount of utilized networking equipment and the fog server to serve the increasing traffic and processing demand by the users, hence increasing the energy consumption of the networking and processing equipment as shown in Fig.8 and Fig.9, respectively.

Meanwhile, Fig.7 also shows that the total energy consumption when considering fog server C has slightly increased with the increasing traffic and processing demand. This is because the same amount of networking equipment and fog servers are utilized regardless of the increasing traffic and processing demand. It is worth noting that the slight increase in energy consumption is only due to the increasing energy of the networking equipment and processing equipment to serve the increasing traffic which requires high processing demand as shown in Fig.8 and Fig.9, respectively where the energy consumption of both the networking and processing equipment is directly proportional with the size of the traffic and processing demand

Conclusion

This work has investigated the energy efficiency of an integrated smart city approach that uses fog computing at the access layer to serve the demands from the users. A MILP model has been developed to optimize the location of the fog server considering twelve tourist locations in

Melaka, so that energy consumption can be minimized. The result shows that distributing the fog server by optimizing the amount and the location of the fog servers at the access layer can reduce the total energy consumption by 52.1%. This is due to maximizing the utilization of the fog servers where the users will be consolidated into a minimum number of fog servers for services, hence reducing the energy consumption for the processing. Besides, this is also due to the lower number of utilized networking equipment that is used to serve the users. The results also show that, with OA, increasing the capacity of the fog servers can also increase the percentage of energy efficiency up to 81.1%. We also study the impact of increasing traffic and the processing demands from the user on energy efficiency. The results show that increasing the traffic and the processing demand from the users does not give a significant impact on the total energy consumption when considering the high processing capability of the fog server.

Acknowledgement
This research is fully supported by the PJP grant, PJP/2022/FTKEE/S01883. The authors fully acknowledged the Ministry of Higher Education (MOHE) and Universiti Teknikal Malaysia Melaka (UTeM) for the approved fund which makes this important research viable and effective.

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