Hybrid BLE/LTE/Wi-Fi/LoRa Switching Scheme for UAV-Assisted Wireless Networks

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Abstract: The unmanned aerial vehicles are deployed in multiple layers to monitor an area and report the information to the ground control station. When we use a single communication protocol such as Bluetooth Low Energy (BLE)/Wi-Fi with low range, the data has to pass through multiple hops for data transfer. This in turn, increases the delay for data transmission. Even though LoRa protocol supports longer distances, the delay is more due to the limited bandwidth. Thus, in this work, we propose a hybrid BLE/LTE/Wi-Fi/LoRa switching scheme that consumes lower energy in addition to reducing the average delay in the network. The proposed scheme switches between the communication technologies based on the lower energy consumption. The performance of the proposed hybrid switching scheme is compared with the individual communication protocols in terms of both energy consumption and average delay. Through extensive numerical results, we show that the proposed hybrid switching scheme performs better in comparison to the individual communication technologies.

F.1 Introduction

Recent technological developments have brought unmanned aerial vehicles (UAVs) in the forefront for several leading applications ranging from precision agriculture [1], construction [2], mining [3], aerial photography [4], and disaster management [5]. Due to these vast applications, market experts predict that the revenue from the UAV market can exceed 8.5 billion dollars by 2027 [6]. UAVs are capable of providing enhanced services due to their inherent ability to fly and take useful measurements from the environment. The sensed information along with telemetry and other data is transmitted to other UAVs or ground control station (GCS) so as to facilitate safe and secure decision making. The transmission of this information is performed using hardware communication modules. Depending on the application, the size of data, and other factors, UAVs can be equipped with different communication modules [7].

Some of the communication modules used in UAVs are Bluetooth Low Energy (BLE) [8], Wireless Fidelity (Wi-Fi) [9], Long Term Evolution for machine-type communication (LTE-M) [10], and Long Range (LoRa) [11]. BLE is capable of transmitting data with sufficiently low energy for short distances (around 300 m) [12, 13]. This makes them suitable for a variety of low power and short range UAV applications that includes smart agriculture [14]. In [8], the authors have proposed a scheme by which UAVs are utilized to collect the data from various sensor nodes deployed in a large farmland. In this scheme, the crop health information from the sensor nodes is sent to the nearby UAV by using BLE. In applications that demand high data rates, the Wi-Fi communication protocol is favoured. In [9], the authors have proposed a UAV system that can be used in disaster affected areas to send Voice over Internet Protocol (VoIP) information to the GCS for monitoring. Here, Wi-Fi is used as the communication protocol for sending the video information as it is reliable and offers high data rates. LTE-M on the other hand is an enhanced version of the popular LTE protocol which is designed for enabling seamless communication for Internet-of-Things (IoT) devices. An analysis of the usage of LTE-M and other Low Power Wide Area Network (LPWAN) protocols has been carried out in [10] for UAV-assisted wireless networks. Here, the performance has been evaluated in terms of latency and throughput by carrying out real world experiments. Finally, it has been concluded that LTE-M and other LPWAN protocols can be effectively used for reliable communication among high speed moving objects [10]. LoRa is one of the most commonly used communication protocol for long distance communication. LoRa stands for long range and it provides a coverage distance of around 10 km with low power consumption of 0.025 watts [15, 16]. In [11], the authors have discussed the reliability of various communication technologies such as LoRa, Wi-Fi, and LTE from a UAV swarm perspective. Further, they have developed an open source named EasySwarm in order to demonstrate the reliability of these protocols under different scenarios. It has been observed that LoRa protocol offers better reliability for long range communications with higher UAV swarm density when compared with Wi-Fi.

The usage of a single communication protocol may not be efficient to support the needs of an adaptive UAV-assisted wireless network. For example, the LoRa protocol can be used for long distance based communications. However, it fails to offer higher data rates when the UAV moves near to the GCS due to its mobility. In this case, switching to either BLE or Wi-Fi may offer higher data rates for the same distance.

Motivated by this, in [17], the authors have considered a multi-layer ad-hoc UAV network in which the BLE and Wi-Fi are used to improve the throughput and latency of the network. Initially, the UAV-assisted network is divided into multiple clusters. The authors have considered BLE for communication within a cluster and between each cluster head and gateway UAV. Further, Wi-Fi is considered for the communication between the gateway UAV and GCS. Simulations are performed in Optimized Network Engineering Tool (OPNET) and the performance of the proposed scheme and standalone communication protocols is evaluated and compared. It has been concluded that the proposed scheme outperforms the individual standalone communication protocol in terms of throughout and latency. However, this scheme has not provided sufficient emphasis on the energy consumption of the UAVs.

Moreover, this scheme has not considered other communication protocols that can facilitate long range communication between UAVs and GCS. Furthermore, the authors have considered only the free space path loss model. This may not work well for most practical scenarios wherein, there is multipath propagation.

Hence, in this paper, we aim to overcome some of these shortcomings and provide a detailed analysis of a novel hybrid switching scheme for UAV-assisted wireless networks. The key contributions of this work are given below:

- We propose a hybrid BLE/LTE/Wi-Fi/LoRa switching scheme for a multi-layer UAV-assisted network.
- The proposed scheme aid in selecting the communication technology that consumes low energy for transmitting the available data from a UAV to the GCS.
- We formulate the optimization problem in terms of total energy consumption for each communication technology for transmitting the available data from a UAV to GCS.
- We then propose an algorithm to solve the optimization problem for both free space (FS) and free space and multipath (FSMP) energy consumption models.
- Through extensive simulations, we compare the performance of the proposed scheme with individual communication protocols in terms of network energy consumption and average delay incurred.

The remaining sections of this paper is organized as follows: Section F.2 discusses the system model and the problem formulation. The proposed hybrid communication scheme is discussed in Section F.3. Section F.4 provides the definitions of the key performance metrics which are employed in this paper. The extensive numerical results are presented in Section F.5. Finally, Section G.8 concludes the paper with potential future work.

F.2 System Model and Problem Formulation

We consider a multi-layer UAV scenario as shown in Fig. F.1 where, N UAVs deployed randomly over an area of l x b m^2. Further, the UAVs randomly select the hovering height from the set $\in \{h_1, h_2, \cdots, h_m\}$ where, m is the number of altitude levels. These UAVs collect the data and transmit it to the GCS for monitoring which is situated on ground at $(l/2, b/2)$. We assume the packet arrival rate follows Poisson distribution with parameter chosen randomly [18]. After successful transmission of data to the GCS, each UAV moves to another location, in a randomly chosen direction, with a velocity of V m/s for a time interval t.

We consider four communication technologies such as BLE, Wi-Fi, LTE-M, and LoRa for communication between each UAV and GCS that exhibit their own unique attributes. Some of these attributes that are considered includes transmit power (P_T), delay (T_d), data rate (R), and path loss reference distance (d_{g_0}). We consider

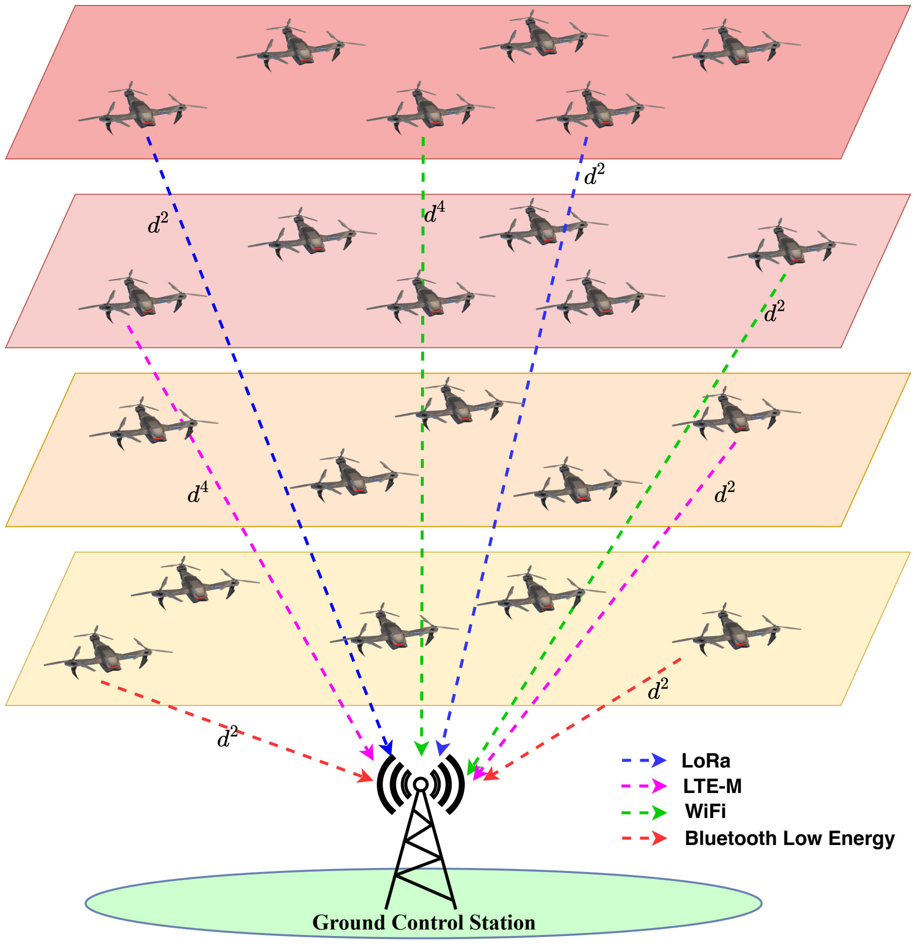


Figure F.1: System model.

FS path loss model that follows d^2 energy consumption model within a maximum range of r [19]. We also consider FSMP model wherein, the energy consumption follows d^2 model for $d_g \leq d_{g_0}$ and d^4 energy consumption model for $d_g > d_{g_0}$ [19], where d_g is the geographical distance from the UAV to the GCS.

F.2.1 Problem Formulation

In this section, we formulate the problem in terms of the total energy consumed for transmitting the data from a UAV which is located at a distance, d_g, to the GCS.

The overall energy consumption is obtained as the sum of the energy consumed for transmitting the total data and the energy consumed for transmitting this data over a distance. The energy consumed for transmitting k-bits of information is given by [20]

$$E_1 = \frac{P_T k}{R}\,, \tag{F.1}$$

where, P_T denotes the transmit power and R denotes the data rate. As described earlier, the distance based energy consumption model depends on the consideration of the path loss model [19]. We describe the energy consumption models for both FS model and FSMP model in the following sections.

F.2.1.1 Free space model

We consider the d^2 energy consumption model. However, this model is restricted by a maximum range for each communication technology. Thus, the amount of energy consumed for transmitting k-bits of information over a distance d_g ($d_g < r_i$) is given as [19]

$$E_2 = k\mathcal{E}_e + k\mathcal{E}_{fs} d_g^2 \tag{F.2}$$

where $\mathcal{E}_e$ represents the energy losses due to the electronic circuit per bit and $\mathcal{E}_{fs}$ is the power amplification energy in free space. Here, r_i for $i \in \{\text{Bluetooth, LTE-M, Wi-Fi, LoRa}\}$ represent the maximum range for transmitting with BLE, LTE, Wi-Fi, and LoRa communication technologies, respectively. Beyond this range, the communication protocol does not support the transmission. In this case, there will be multi-hop based communication. We consider conventional shortest path routing method for packet transmission from a UAV to the GCS.

F.2.1.2 Free space and multipath model

In this model, d^2 energy consumption model is followed for a distance $d_g \leq d_{g_0}$ (free space model). Beyond this threshold, the energy consumption follows d^4 model due to multipath. The energy consumed for transmitting k-bits of data over a distance d_g is obtained as [19]

$$E_2 = \begin{cases} k\mathcal{E}_e + k\mathcal{E}_{fs} d_g^2, & \text{when } d_g < d_{g_0}\,; \\ k\mathcal{E}_e + k\mathcal{E}_{mp} d_g^4, & \text{when } d_g \geq d_{g_0}\,. \end{cases} \tag{F.3}$$

For the simulation, we have used $\mathcal{E}_e = 25 \times 10^{-9}$ J/bit and $\mathcal{E}_{fs} = 10 \times 10^{-12}$ J/bit/m^2. The parameter $\mathcal{E}_{mp}$ refers to the power amplification energy in the multipath fading model and is given by,

$$\mathcal{E}_{mp} = \frac{\mathcal{E}_{fs}}{d_g^2} \tag{F.4}$$

Thus, the total energy consumption is given by,

$$E = E_1 + E_2 \tag{F.5}$$

Finally, the cost for transmitting the data from all UAVs to GCS is obtained as

$$C = \sum_{i=1}^{N} E_{i,GCS}\,. \tag{F.6}$$

where, $E_{i,GCS}$ is the total energy consumed for transmitting the data from i-th UAV to GCS.

F.3 Proposed Scheme

In this section, we describe the algorithm for the proposed hybrid switching scheme for minimizing the overall cost of the network described (F.4).

As the overall objective is to minimize the energy consumption of the network, each UAV should choose the communication protocol which uses minimum energy for transmitting the available data. Based on two energy models that are employed we have two different approaches:

F.3.0.1 For the case of free space model

Each UAV checks the possible communication technologies for transmission based on its distance from the GCS. Then, it calculates the energy consumed for transmitting the data. A UAV selects the communication technology that consumes less energy in comparison to other protocols. This in turn, reduces the energy consumption for transmitting the same data as described in Algorithm. 5.

F.3.0.2 For the case of free space and multipath model

As described earlier, a UAV can communicate with the GCS by using any of the available communication technologies. However, the energy consumption changes based on its distance with respect to the threshold. Thus, each UAV calculates the amount of energy consumed by each communication technology for transmitting the available data. Then, it switches to the communication technology that consumes less energy in comparison to other communication technologies as described in Algorithm. 5.

F.4 Performance Metrics

In this section, we describe the performance metrics such as average delay and network energy consumption for the evaluation of the proposed model.

F.4.1 Average Delay

It is defined as the ratio of the sum of delays for transmitting the data from all UAVs to GCS and the total number of UAVs. Total delay from a UAV to GCS is obtained as the sum of the propagation delay and transmission delay.

F.4.1.1 Transmission delay

It is the delay for transmitting a packet from one UAV to GCS. It usually depends on the data rate of the communication technology. For transmitting n packets of k-bits each over a communication channel, the incurred transmission delay is given by

$$T_{trans} = \frac{nk}{R}, \tag{F.7}$$

Algorithm 5: Proposed hybrid switching algorithm.

Input: N, d_g

Output: Average network delay and energy consumption

if *Employed energy model is free space model* **then**
    Calculate the energy for each communication technology using (F.1), (F.2) and (F.4);
    if $d_g < r_{Bluetooth}$ **then**
        Select protocol with minimum energy from the set $\{E_{Bluetooth}, E_{LTE-M}, E_{WiFi}, E_{LoRa}\}$;
    else if $d_g < r_{LTE-M}$ **then**
        Select protocol with minimum energy from the set $\{E_{LTE-M}, E_{WiFi}, E_{LoRa}\}$;
    else if $d_g < r_{WiFi}$ **then**
        Select protocol with minimum energy from the set $\{E_{WiFi}, E_{LoRa}\}$;
    else
        Select the LoRa communication protocol;
    end
else
    Employed energy model is free space and multipath model
    Calculate the energy for each communication technology using (F.1), (F.3) and (F.4);
    Select protocol consuming minimum energy from the set $\{E_{Bluetooth}, E_{LTE-M}, E_{WiFi}, E_{LoRa}\}$;
end
Obtain the average network delay and energy consumption ;

where, R is the data rate of the respective communication protocol.

F.4.1.2 Propagation delay

It is the delay incurred for propagating data from a UAV to GCS over a distance of d_g. The expression for the propagation delay is obtained as

$$T_{prop} = \frac{d_g}{c}, \tag{F.8}$$

where, c is the speed of light which is 3×10^8 m/s and d_g is the distance of the UAV from the GCS. From (F.7) and (F.8), the total delay is obtained as

$$T_d = T_{trans} + T_{prop}\,, \tag{F.9}$$

Finally, the expression for average delay of the network is given as

$$T_{avg} = \frac{1}{N}\sum_{i=1}^{N} T_{d_i}\,. \tag{F.10}$$

Table F.1: Various communication protocol attributes

Protocol	Transmit Power (W)	Data rate (bits/second)	Path loss reference distance (Normalized) d_{g_0}
Bluetooth [21]	0.01	1360 x 10^3	200
LTE-M [22], [23]	0.1	1 x 10^6	400
WiFi [24], [15]	2	1 x 10^7	600
LoRa [15], [16]	0.025	50 x 10^3	1500

F.4.2 Network Energy Consumption

The network energy is defined as the sum of the energies consumed for transmitting the data from each of the N UAVs to GCS. The expression for network energy consumption is given by

$$E_{total} = \sum_{i=1}^{N} E_{i,GCS} \,. \tag{F.11}$$

F.4.3 Packet Arrival Rate

We assume the packet arrival rate follows Poisson distributed random variable which is defined as

$$Pr(X = n) = \frac{\lambda^n e^{-\lambda}}{n!} \tag{F.12}$$

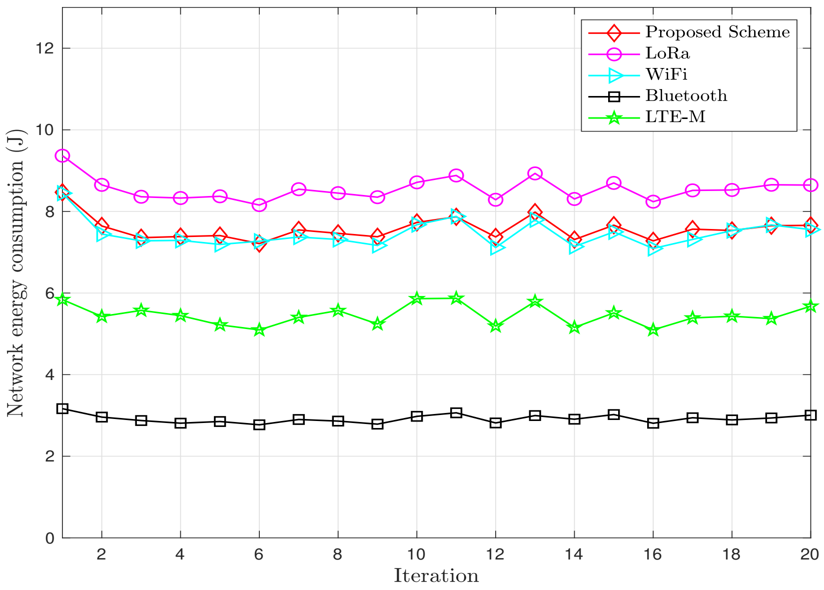
F.5 Numerical results

In this section, we provide the simulation comparison of the proposed scheme with the other protocols in terms of average delay and energy consumption.

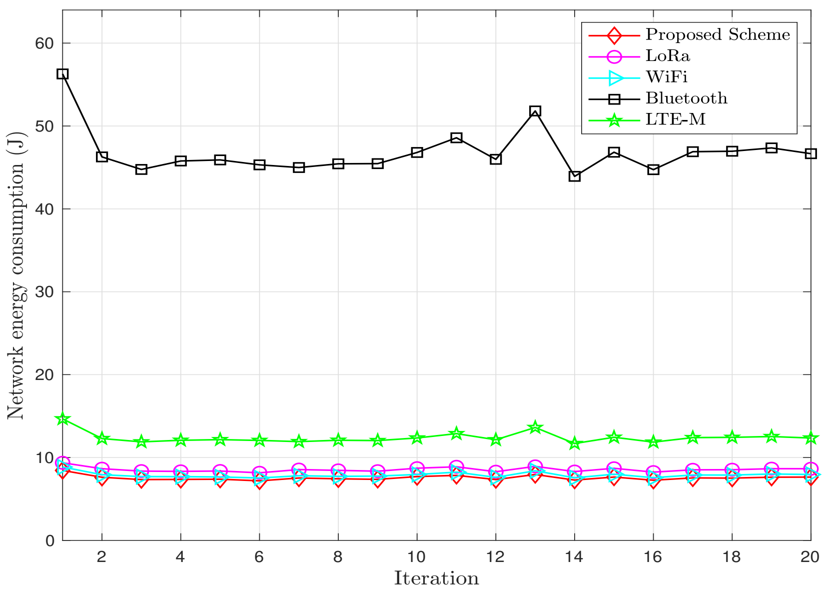
F.5.1 Experimental setup

We consider a scenario of $N = 500$ UAVs that are deployed randomly over a 1000 x 1000 m^2 area and a random hovering height h selected from the set $\{100, 200, 300, 400\}$. After each transmission, a UAV transits with a speed of 5 m/s for a duration of 60 seconds in a randomly chosen direction within the given area. Further, GCS is located at the center of the deployed area with coordinates $(50, 50, 0)$.

The UAVs are equipped with communication modules such as BLE, Wi-Fi, LTE-M, and LoRa. We have considered the typical values of different attributes for each communication technology as given in Table F.1. We consider that the packet arrival rate follows Poisson distribution with parameter chosen randomly from the set $\{1, 2, \cdots, 100\}$ and each packet is of 128 bits.



(a)



(b)

Figure F.2: (a) Total network energy consumption for free space energy model and (b) total network energy consumption for free space and multipath energy model.

F.5.2 Results

Fig. F.2a shows the variation of network energy consumption in each scenario with free space model. From Fig. F.2a, it is observed that the energy consumption of the proposed hybrid scheme is comparable to the energy consumption model when Wi-Fi is used alone for transmission. However, the proposed model provides better energy consumption than a standalone LoRa based scheme. The amount of energy consumed by stand alone BLE is less compared to the hybrid model due to the lower transmit power.

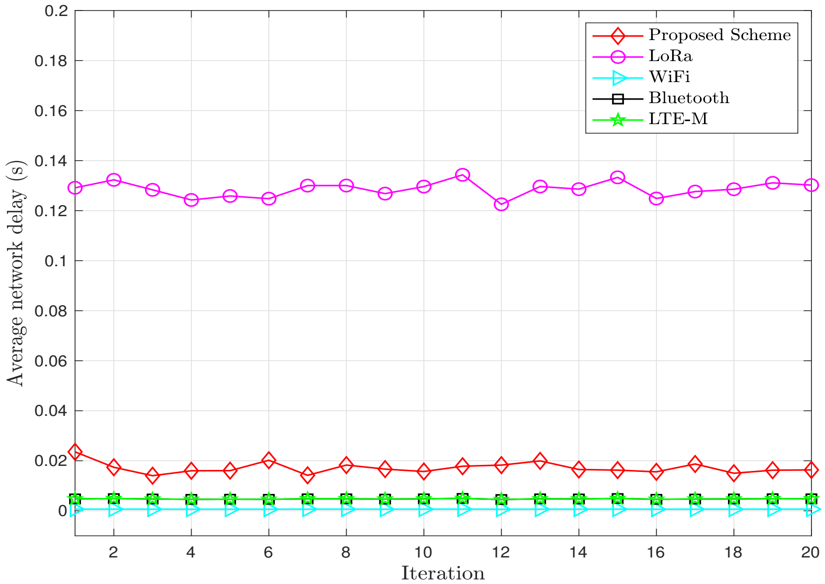
Fig. F.2b shows the simulation comparison of the proposed model with the individual communication technologies in terms of network energy consumption for FSMP model. From Fig. F.2b, it is observed that the hybrid scheme consumes less energy in comparison to the individual communication protocols due to the switching technique. In case of BLE, the energy consumption is more as most of the UAVs which are farther from threshold follows d^4 energy consumption model.

Figs. F.3a and F.3b show the variation of the delay for FS and FSMP models, respectively. The delay depends upon number of bits to be transmitted and the distance over which the transmission occurs. Hence, it can be observed that the delay doesn't show significant variation for the proposed hybrid switching technique even with both energy models. In case of standalone communication protocols, the delay depends primarily on the total number of bits to be transmitted. Here, the overall delay depends mostly on the transmission delay as the propagation delay does not contribute much. Hence, it is concluded that the FSMP energy model for the hybrid switching communication scheme outperforms existing standalone communication technologies by providing minimum energy consumption and reduced average network delay as can be observed from Figs. F.2b and F.3b, respectively.

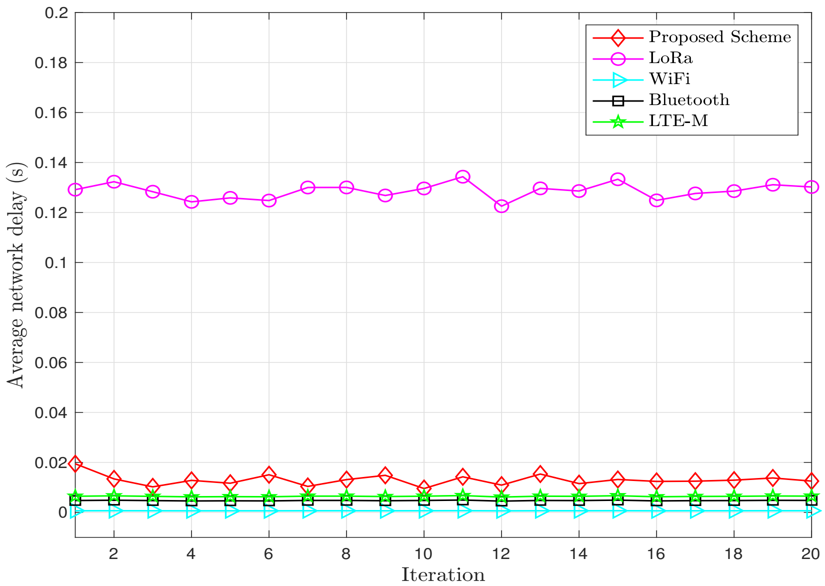
Figs. G.8a and G.8b show the simulation comparison in terms of energy consumption and average delay, respectively, for the hybrid scheme with FS and FSMP models. From Fig. G.8a, it is observed that the network energy consumption for both the models are similar with the FSMP model showing lower energy consumption. However, the average delay is varies greatly as can be observed from Fig. G.8b. This is due to the fact that the number of UAVs that are connected to BLE, Wi-Fi, LTE-M, and LoRa are 14, 279, 153, and 54, respectively, in the case of FS model. However, in case of FSMP model, the number of UAVs connected to BLE has increased to 21 and the number UAVs connected to LTE-M has increased to 162. Further, the number of UAVs connected to LoRa has reduced to 38. Since both BLE and LTE-M offers higher data rates in comparison to LoRa, the overall delay is less for FSMP model relative to FS model.

F.6 Conclusion

In this paper, we have proposed a hybrid BLE/Wi-Fi/LTE/LoRa switching scheme for UAV-assisted wireless networks. In the proposed scheme, each UAV switches the communication protocol based on the lower energy consumption for transmitting



(a)



(b)

Figure F.3: (a) Average network delay for free space energy model and (b) average network delay for free space and multipath energy model.

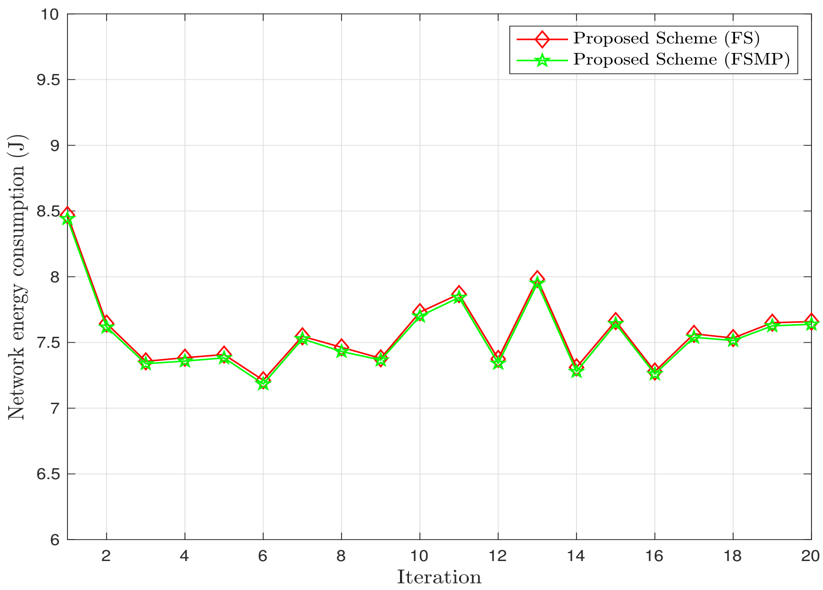


Figure F.4: Total network energy comparison with proposed method for free space and free space and multipath energy models.

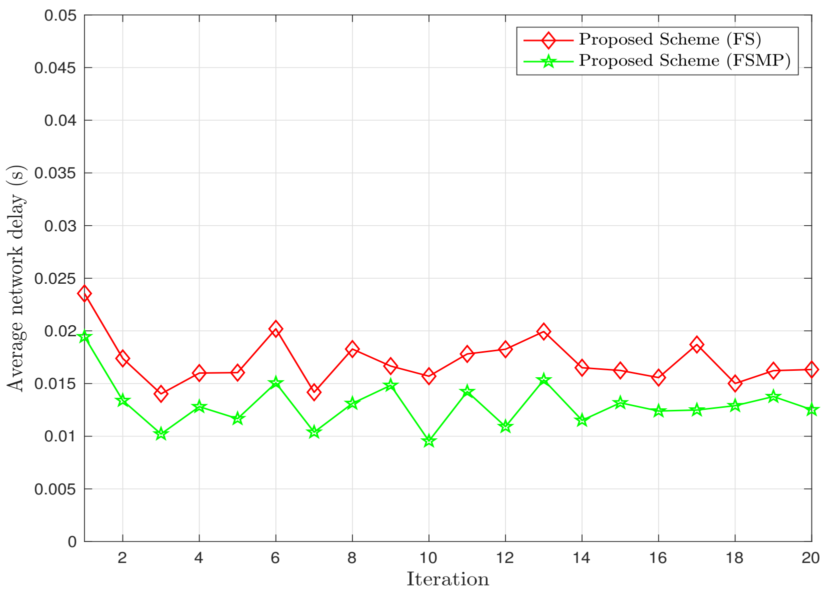


Figure F.5: Average network delay comparison with proposed method for free space and free space and multipath energy models.

the available data. Further, the performance of the proposed scheme has been evaluated for both free space (FS) and free space and multipath (FSMP) models. We have evaluated the performance of the proposed approach against the standalone communication protocols in terms of network energy consumption and average delay. It has been concluded that the proposed hybrid scheme outperformed other protocols for the FSMP model. Further, the proposed scheme performs well with FSMP model as compared to FS model. In future, we will analyze the performance of the proposed scheme in terms of additional parameters such as network lifetime and throughput. Additionally, the analytical expressions corresponding to all the performance metrics will be derived.

References

[1] Panagiotis Katsigiannis, Lazaros Misopolinos, Vasilis Liakopoulos, Thomas K. Alexandridis, and George Zalidis. An autonomous multi-sensor uav system for reduced-input precision agriculture applications. In *Proc. Mediterranean Conference on Control and Automation (MED)*, pages 60–64, Athens, Greece, Jun. 2016.

[2] Youngjib Ham, Kevin K. Han, Jacob J. Lin, and Mani Golparvar-Fard. Visual monitoring of civil infrastructure systems via camera-equipped Unmanned Aerial Vehicles (UAVs): a review of related works. *Visualization in Engineering*, 4(1):1, January 2016.

[3] He Ren, Yanling Zhao, Wu Xiao, and Zhenqi Hu. A review of UAV monitoring in mining areas: current status and future perspectives. *International Journal of Coal Science & Technology*, 6(3):320–333, September 2019.

[4] Petra Urbanová, Mikoláš Jurda, Tomáš Vojtíšek, and Jan Krajsa. Using drone-mounted cameras for on-site body documentation: 3D mapping and active survey. *Forensic Science International*, 281:52–62, Oct. 2017.

[5] Waleed Ejaz, Arslan Ahmed, Aliza Mushtaq, and Mohamed Ibnkahla. Energy-efficient task scheduling and physiological assessment in disaster management using UAV-assisted networks. *Computer Communications*, 155:150–157, Apr. 2020.

[6] Drone market outlook. [Online]. Available: https://www.businessinsider.com/drone-industry-analysis-market-trends-growth-forecasts.

[7] G. Pantelimon, K. Tepe, R. Carriveau, and S. Ahmed. Survey of Multi-agent Communication Strategies for Information Exchange and Mission Control of Drone Deployments. *Journal of Intelligent & Robotic Systems*, 95(3):779–788, September 2019.

[8] Shota Nishiura and Hiroshi Yamamoto. Large-term sensing system for agriculture utilizing uav and wireless power transfer. In *Proc. International Conference on Information Networking (ICOIN)*, pages 609–614, Jeju Island, South Korea, Jan. 2021.

[9] Vicente Mayor, Rafael Estepa, Antonio Estepa, and German Madinabeitia. Deploying a Reliable UAV-Aided Communication Service in Disaster Areas. *Wireless Communications and Mobile Computing*, 2019:e7521513, April 2019.

[10] Shie-Yuan Wang, Jui-En Chang, Hsin Fan, and Yi-Hsiu Sun. Performance comparisons of nb-iot, lte cat-m1, sigfox, and lora moving at high speeds in the air. In *Proc. IEEE Symposium on Computers and Communications (ISCC)*, pages 1–6, Rennes, France, Jul. 2020.

[11] Zhenhui Yuan, Jie Jin, Lingling Sun, Kwan-Wu Chin, and Gabriel-Miro Muntean. Ultra-reliable iot communications with uavs: A swarm use case. *IEEE Communications Magazine*, 56(12):90–96, Dec. 2018.

[12] Bluetooth 5: Go Faster. Go Further. [Online]. Available: https://www.bluetooth.com/wp-content/uploads/2019/03/Bluetooth_5-FINAL.pdf.

[13] Nian Xia, Hsiao-Hwa Chen, and Chu-Sing Yang. Emerging technologies for machine-type communication networks. *IEEE Network*, 34(1):214–222, Feb. 2020.

[14] Praveen Kumar Reddy Maddikunta, Saqib Hakak, Mamoun Alazab, Sweta Bhattacharya, Thippa Reddy Gadekallu, Wazir Zada Khan, and Quoc-Viet Pham. Unmanned aerial vehicles in smart agriculture: Applications, requirements, and challenges. *IEEE Sensors Journal*, pages 1–1, early access, 06 Jan. 2021.

[15] Pycom OEM module. [Online]. Available: https://pycom.io/product/l04-oem-module/.

[16] Semtech SX1276 - Datasheet. [Online]. Available: https://www.semtech.com/products/wireless-rf/lora-transceivers/sx1276.

[17] Muhammad Asghar Khan, Ijaz Mansoor Qureshi, and Fahimullah Khanzada. A hybrid communication scheme for efficient and low-cost deployment of future flying ad-hoc network (fanet). *Drones*, 3(1), Feb. 2019.

[18] Om Jee Pandey and Rajesh M. Hegde. Low-latency and energy-balanced data transmission over cognitive small world wsn. *IEEE Transactions on Vehicular Technology*, 67(8):7719–7733, Mays 2018.

[19] S. M. Mahdi H. Daneshvar, Pardis Alikhah Ahari Mohajer, and Sayyed Majid Mazinani. Energy-efficient routing in wsn: A centralized cluster-based approach via grey wolf optimizer. *IEEE Access*, 7:170019–170031, Nov. 2019.

[20] David Tse and Pramod Viswanath. *Fundamentals of wireless communication*. Cambridge university press, 2005.

[21] Bluetooth, Bluetooth Technology. [Online]. Available: https://www.bluetooth.com/learn-about-bluetooth/bluetooth-technology/.

[22] 3gpp Standards for the IoT. [Online]. Available: https://www.3gpp.org/news-events/3gpp-news/1805-iot_r14.

[23] 3gpp Release 13 Overview. [Online]. Available: https://www.3gpp.org/news-events/3gpp-news/1628-rel13.

[24] Evgeny Khorov, Anton Kiryanov, Andrey Lyakhov, and Giuseppe Bianchi. A tutorial on ieee 802.11ax high efficiency wlans. *IEEE Communications Surveys Tutorials*, 21(1):197–216, Apr. 2019.