Connection Steering Mechanism between Mobile Networks for reliable UAV's IoT Platform

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***Abstract*—This paper presents a mechanism for steering connections to different mobile networks for UAV-based reliable communications. This connection steering mechanism works by selecting the best Radio Signal Strength Indicator (RSSI) quality among the available networks in order to ensure the highest availability. In this work, we developed a test-bed to evaluate the performance of the steering mechanism. In addition, to mimic the mobility of UAVs, we analyze our work by applying Discrete Time Markov Chain (DTMC) to evaluate the performance of the test-bed results. The results obtained from our analysis and testbed-based evaluation show the efficiency of the proposed connection steering mechanism. These results demonstrate the efficiency of the proposed connection steering mechanism in terms of data packet transmission rate and energy consumption saving.**

I. INTRODUCTION

The applications of Unmanned Aerial Vehicles (UAV) are diverse. They are applied in many industries and public services [1], such as disaster management, traffic management, and surveillance [2]. UAVs are able to carry out Internet of Things (IoT) services by embedding cameras, sensors, communication devices, etc. [3]. They can be equipped with different radio access technologies such as those of cellular networks to overcome the problem of coverage limitations. In addition, till the deployment of next generation mobile networks, and in order to achieve a high throughput and high speed Internet connectivity, the 4G Long Term Evaluation (LTE) networks are the potential candidates to be used on-board UAVs. Particularly, having a reliable network becomes vital when UAVs are used in real-time applications, such as crowd surveillance.

Although UAVs need to be accessed through 4G networks, the use of only one network connection is not sufficient to provide a steady and reliable connectivity [4] [5]. As most operators do not support total coverage for urban and rural areas, the signal strength of their radios may vary in different places and there may be areas not covered at all by a specific operator. For the safe remote control of different UAVs, a reliable connection to the monitoring server is required. The use of only one network connection is sufficient for ensuring such a reliable connection of UAVs. Moreover, weak signal strengths may prevent UAVs from appropriately performing their tasks. Therefore, there is need to provide UAVs with the flexibility to connect to multiple mobile networks and choose the best out of them in terms of signal strength. This defines the core objective of this paper.

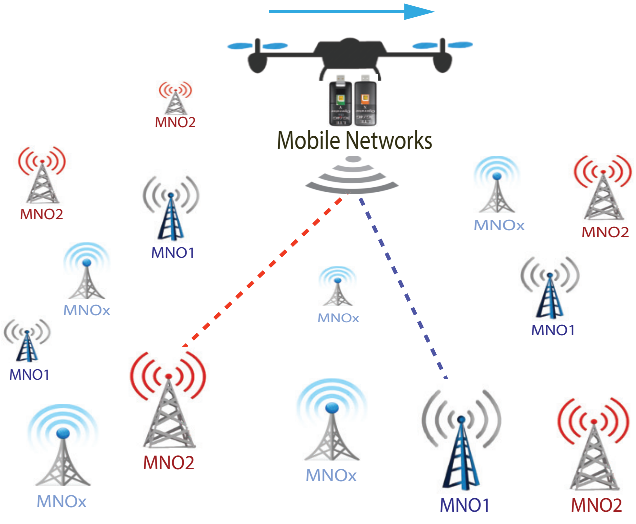


Fig. 1. Connection to two Mobile Network Operators (MNO)s.

Usually, a UAV is equipped with a gateway that facilitates the connection of the UAV to the monitoring server (i.e., command and control station). The gateway also controls the different IoT devices on board the UAV. In this paper, we propose a mechanism, to be implemented in the gateway, for the steering of connections to multiple mobile networks. As depicted in Fig. 1, two LTE 4G/3G USB Modems are connected to the IoT gateway for ensuring reliable connection. This mechanism is to overcome the problem of network's coverage limitations and signal strength fluctuations. The benefit beneath employing such mechanism is to select the mobile network that provides the best signal quality. This means that UAVs will be able to select the network operator with the highest RSSI.

Using this connection steering mechanism on-board UAVs has two main advantages. First, it will decrease the energy consumption by the UAVs as they do not have to perform data re-transmissions. Second, it will guarantee a higher data transmission rate as they select the network with stronger RSSI. To study the performance of the proposed mechanism, a real test-bed is developed. We established two 4G network connections on one IoT gateway and studied the behavior of energy consumption and packets transmission rate in the case of a video streaming application. In addition, to mimic the mobility of UAVs, we analyzed our work by adopting a DTMC model to evaluate the performance of the connection steering mechanism. The results of the performance evaluation prove the reliability of our mechanism.

This paper is organized in the following fashion. Section II reviews some related work, while Section III describes our developed test-bed for connection steering mechanism between the two 4G networks. Section IV shows the results of the performance evaluation using a DTMC model. Finally, the paper concludes in Section V.

II. RELATED WORK

Recently, several studies [6], [7] have investigated the benefits of using cellular networks for connecting UAVs. These studies have shown the following advantages: $i)$ the network coverage in cellular systems can be extended over large areas by using multiple Base stations (BSs); $ii)$ mobile networks can provide high throughput rate by using advanced cellular technologies. Another study in [8] presents an architecture for real-time video streaming over 4G-LTE networks. This study evaluates the streaming performances in terms of different Quality of Service (QoS) metrics such as throughput, loss rates, delay, multi-path propagation loss, shadowing, and fading models. Authors in [9]–[11] have been studied bandwidth an aggregation-aware QoS negotiation mechanism and multipath scheduling algorithms for real-time video applications. The proposed algorithms show an efficient strategy to deliver real-time video packets under a QoS system. The simulation results illustrate that employment of a time-slotted approach for bandwidth allocation largely mitigates the packet reordering issue. In addition, the employed mechanism maintains a scalable and fair use of the network resources. Moreover, many other researches [12]–[15] have been initiated to study the network performance parameters with the mobility of UAVs. They study the area coverage, throughput, and network connectivity as their performance metrics. Another research in [16] presents an algorithm for energy efficiency of UAV networks.

A different study [17] discusses the use of UAVs as wireless flying relays. The aim of this study is to provide 4G-LTE network services in remote areas that suffer from limited network coverage. Many other studies (e.g., [18]) explain the benefits of using 4G-LTE networks from the reliability and connectivity point of view. Therefore, we can conclude that 4G networks are promising candidates to support the high mobility of UAVs. Our work studies connection steering mechanism between two different mobile networks for UAVs. Using this mechanism, we will guarantee to have a stronger signal connectivity for UAVs to enhance the quality of their communications. In addition, to the best of our knowledge, a prior study does not exist for connection steering between different mobile networks for UAVs. Most of the related works have proposed using services provided by only one network in their communications model.

Fig. 2. Laboratory experiment (Test-bed)

III. TEST-BED FOR CONNECTION STEERING MECHANISM BETWEEN MOBILE NETWORKS

A. Test-bed setup

To study the feasibility and efficiency of connection steering mechanism between 4G networks, we developed a test-bed in our laboratory environment. Fig. 2 shows this test-bed that consists of the following equipments: one Raspberry Pi2 that works as the IoT gateway on-board UAV; a USB hub which increases the number of USB ports, a web camera for video streaming; and two LTE 4G/3G USB modems, each one loaded with the SIM card of a Finnish mobile network operator, namely Elisa and Sonera. For network connection, wvdial point-to-point dialer [19] is used to dial and establish modem-based Internet connections to the networks. The wvdial utility was configured to enable the Internet connection through both modems.

The signal strength quality (RSSI) can be measured from different USB modems using any programming language, such as Python. The quality of RSSI values can be grouped in four quality ranges: Poor, Good, Very Good, and Excellent [20]. In our experiment, these RSSI values are used to test the packet transmission rate ($\mathcal{N}$) from the IoT gateway and the amount of energy consumption ($\mathcal{E}$) by the IoT gateway. In the test-bed, we used a Radio Frequency (RF) chamber to attenuate the measured signal at the transmitter i.e., 4G modems. The code source of this experiment is developed by using the Python programming language and Transport Control Protocol (TCP) in order to perform a reliable transmission of the video frames.

In the test-bed, we studied the performance of the steering mechanism between two 4G networks. This performance is studied in terms of energy $\mathcal{E}$ and packet transmission rate $\mathcal{N}$ at the IoT gateway. For computing $\mathcal{E}$, a TOE8842 dual power supply is used as input DC power of RPi and a $6\frac{1}{2}$ digit resolution Multi-meter is employed to measure the Current $\mathcal{I}$. The current consumptions are stored in excel files through KI-Tool which was installed in a separate laptop. To calculate the $\mathcal{N}$ from the IoT gateway we installed Wireshark on a laptop i.e., client and we filtered the TCP packets sent from the source IP addresses.

To test our proposed steering mechanism, a connection via the first 4G USB modem on the IoT gateway is established and a request for the video streams from the client is sent. To compute $\mathcal{E}$ and $\mathcal{N}$, this experiment was made following

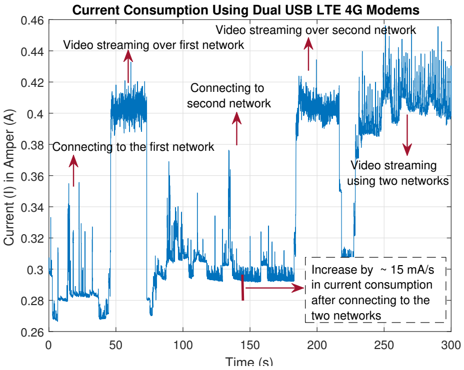


Fig. 3. Current consumption using dual LTE modems

three steps. First, using the RF chamber and the attenuator, we adjusted the RSSI values twelve times within different ranges at the first 4G USB modem. These ranges hold different RSSI values for the first network operator. The video streaming is established over the connected 4G link for a duration of 60 seconds. We then computed $\mathcal{E}$ and $\mathcal{N}$ for the first operator's network. For the second step, we applied the same approach for the second mobile operator's network. Then we computed $\mathcal{E}$ and $\mathcal{N}$ for the same duration. Based on our experiment the measured RSSI values are varied in the ranges of (RSSI-0.99 ; RSSI+0.99) each time in different RF chamber attenuation. In the last step, we connected both 4G networks i.e., Elisa and Sonera, to the IoT gateway. We then applied the same procedure as in steps one and two to perform connection steering mechanism. This is done to select the best network, i.e., the network with the strongest signal and highest quality. For this purpose, using Python programing language, we developed the code that selects the network with the highest RSSI value. Eventually, we established video streaming to record $\mathcal{E}$ and $\mathcal{N}$.

B. Test-bed Result Analysis

The obtained measurements in Fig. 3 show the impact of current consumption $\mathcal{I}$ by the IoT gateway when one and two 4G USB modems with their networks are connected to RPi in silent and active modes, i.e., video streaming. The obtained results show the current consumption $\mathcal{I}$ over the time in seconds. From this figure, we observe that the current consumption is approximately 15 mAp/s if two modems are connected to IoT gateway. This amount is very small compared to the times when the modems are in the streaming modes. This means that having two 4G USB modems on-board UAVs does not have high impact on the UAV's energy consumption.

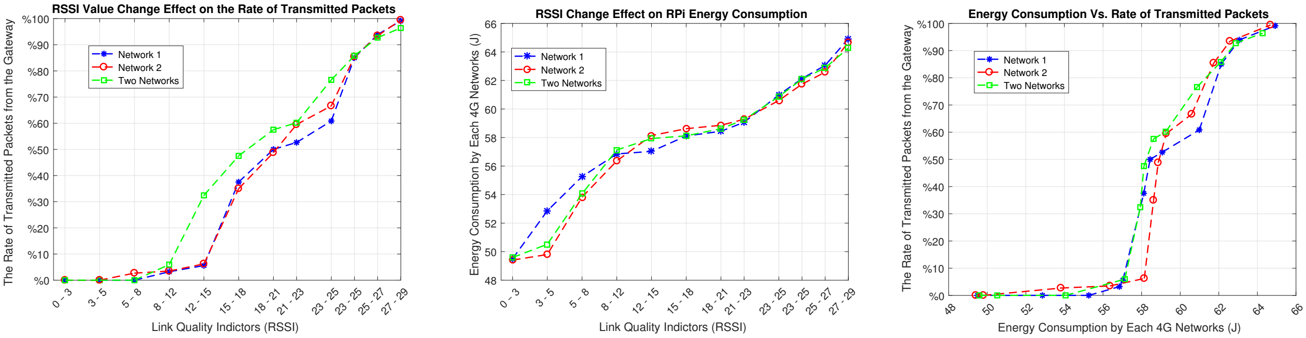
Fig. 4 shows the experimental results of connection steering mechanism between two mobile networks for UAVs. The obtained results are organized in three sub-figures i.e., 4.a, 4.b., and 4.c. These simulations show that using each of the networks, i.e., Elisa and Sonera, result in almost similar performance in terms of $\mathcal{E}$ and $\mathcal{N}$ with the changing RSSI qualities. Figures (4).a and (4).b show that the packet transmission rates $\mathcal{N}$ and energy consumptions $\mathcal{E}$ are increasing proportionally with different RSSI value intervals (ranges). In our setup, we made video streaming for 60 seconds per RSSI range. We aimed to send possible rate of $\mathcal{N}$ within this time per range (transmitting all the data packets was not our target). Thus, the rate of transmitted packets within this time varies in different RSSI intervals.

Fig. 4.a shows the performance of $\mathcal{N}$ through RSSI value changes. The figure depicts that $\mathcal{N}$ is increasing proportionally with RSSI strengthening. This can be explained as follows: When there is a weak RSSI quality, the transmission bandwidth is low, therefore more packets are dropped behind the transmitter until the simulation time expires. Accordingly, when the value of RSSI strengthens the bandwidth of the link increases that results in enhancement of $\mathcal{N}$. Fig. 4.b shows when RSSI quality at the IoT gateway is weak, the amount of $\mathcal{E}$ is low; and it correspondingly increases when the RSSI quality strengthens. This is due to the TCP speed limits when the RSSI quality is weak, the transmitter does not transmit and $\mathcal{E}$ remains low. Recalling that, in TCP, if a transmitter does not receive acknowledgement for it's sent packet, it will stop and wait a certain time until the next retransmission. Therefor in our experiment, when the RSSI value is low, the receiver will not receive the acknowledgements from the server and it will stop sending the packets until the waiting time is exceeded. Thus, in lower RSSI ranges less energy will be consumed. This continues until the simulation time, i.e., 60 seconds, expires. Fig. 4.c demonstrates the relation between the values of $\mathcal{E}$ and $\mathcal{N}$. The figure approves the obtained results from Fig. 4.a and Fig. 4.b.

The important advantage of the connection steering mechanism is to increase the network reliability and QoS when connecting UAVs. The network reliability guarantees a steady network connectivity for different UAVs with a stronger signal. Thus, employing our proposed mechanism for the UAVs, especially in real-time applications such as video streaming, will enhance the QoS, reliability and efficiency of their services.

IV. PERFORMANCE EVALUATION

The performance evaluation of connection steering mechanism between multiple mobile networks requires real field experiments. In our test-bed, we have made laboratory tests that does not allow us to perform real experiments. Due to the limitation of our experimental test, we employed DTMC for mimicking the UAVs mobility. Using the results from the test-bed, we obtained the information about the impact of different RSSI values on $\mathcal{E}$ and $\mathcal{N}$ for the two different 4G networks. Using DTMC and having the signal qualities, we can define a Markov model with different states and transition probabilities for our mechanism. We make our simulations in long-term with different transition probabilities that are estimated from our experiment. We use these probabilities in a transition matrix and we calculate the steady state of the DTMC model. In this section, we shortly overview the concept of DTMC in sub-section A; define a Markov model along with its transition matrix and diagram in sub-section B; and analyze the results of the DTMC model in sub-section C.



(a) RSSI value change effect on the rate of transmitted packets

(b) RSSI change effect on RPi energy consumption

(c) Energy consumption versus the rate of transmitted Packets

Fig. 4. Performances of test-bed experiment.

A. *Discrete Time Markov Chain*

A Markov chain is a discrete-time stochastic process. It is a sequence of stochastic events on different times, where the current state of a system is independent of all past states. Let assume that X_n takes values in a finite set i.e., the state space $S = \{1, 2, ..., m\}$ [21].

Definition 1. *A Markov chain is a sequence of random variables such that the next state X_{n+1} depends only on the current state X_n. This means a sequence of random variables X_0, X_1, X_2,... take different values from the state space $\{1, 2, ..., m\}$. It is called a Markov Chain if there is an m-by-m matrix $P = [p_{ij}]$, where for any $n \geqslant 0$,*

$$\begin{aligned} P(X_{n+1} = j | X_n = i, X_{n-1} = i_{n-1}, ..., X_0 = i_0) \\ = P(X_{n+1} = j | X_n = i) = p_{ij} \end{aligned} \tag{1}$$

The matrix P is called the transition matrix of the chain and the p_{ij} is the transition probability from i to j. Generally P_{ij} with state space of i and $j = 0, 1, \cdots, m$, is the one-step transition probability matrix and is constructed as in the following:

$$P = \begin{bmatrix} P_{11} & P_{12} & \dots & P_{1m} \\ P_{21} & P_{22} & \dots & P_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ P_{m1} & P_{m2} & \dots & P_{mm} \end{bmatrix} \tag{2}$$

where p_{ij} has the following properties, considering that p^n_{ij} is n-step transition probability,

$$\begin{cases} \sum_j p_{ij} = 1 \\ 0 \leqslant p_{ij} \leqslant 1 \\ p^n_{ij} = P(X_n = j | X_0 = i) \end{cases} \tag{3}$$

Definition 2. *A row vector $\pi = [\pi_1, \pi_2, ..., \pi_m]$, such that $\pi_i \geqslant 0$ and $\sum_i \pi_i = 1$, is a steady state distribution for a Markov chain with transition matrix P if*

$$\sum_i \pi_i p_{ij} = \pi_j \quad equivalently \quad \pi_i P = \pi_j \tag{4}$$

Note that an initial probability vector (a column vector) is constructed from the steady state distribution matrix.

B. *DTMC Modeling of the mechanism*

For DTMC modeling, we leverage the results of our testbed described in Section III. The RSSI values achieved in our testbed are within the interval $[0.99, 29.99]$, whereby these values represent the signal quality of a network. These values can be divided in four quality ranges [20] that are presented in Table 1. For DTMC modeling and using Table 1, we define our state space as $S = \{P, G, V, E\}$, that includes four states. Based on the results of Fig. 4, our proposed connection steering mechanism always selects the best signal quality or remains with the same network if it does not detect a stronger signal elsewhere. This explains that, in our DTMC model, the states of the space intend to move or remain in the best state with a higher probability.

TABLE I
RSSI Quality Ranges

Quality	Ranges (α)
Poor (P)	$0.99 \leqslant \alpha \leqslant 8.99$
Good (G)	$9.99 \leqslant \alpha \leqslant 13.99$
Very Good (V)	$14.99 \leqslant \alpha \leqslant 18.99$
Excellent (E)	$19.99 \leqslant \alpha \leqslant 29.99$

Therefore, using our experiments, we define the transition probability matrix P as in (5). This matrix shows that the state remains with the probability 0.4 in the same state and moves to a better state with the probability 0.4. The movement to another state happens when the model detects a better signal quality. In matrix P, the probabilities for moving to a better state or remaining in the same state are set to higher values compared to other transitions. The reason is that the probability for a state to move to a better signal is higher than moving to a poor signal; meaning that the model always selects the highest signal strength if there is any. In addition, these values equal 0.4 accounting that the states persist to stay in the same state and not changing to a poor one. Based on the obtained results from the test experiments, the probabilities of other states are fixed to 0.1. The connection steering mechanism uses this approach to avoid dropping to a poor signal, as it is planned to select the higher quality signals.

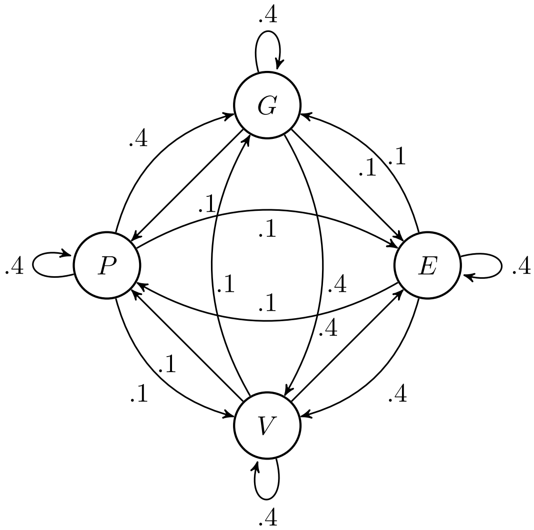


Fig. 5. Discrete time markov chain transition diagram

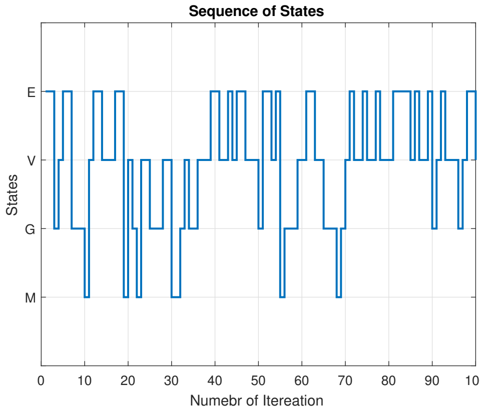
It shall be noted that in matrix P, each row of probability matrix corresponds to the current signal quality, and each column corresponds to the next appearing signal qualities.

$$P = \begin{bmatrix} .4 & .4 & .1 & .1 \\ .1 & .4 & .4 & .1 \\ .1 & .1 & .4 & .4 \\ .1 & .1 & .4 & .4 \end{bmatrix} \tag{5}$$

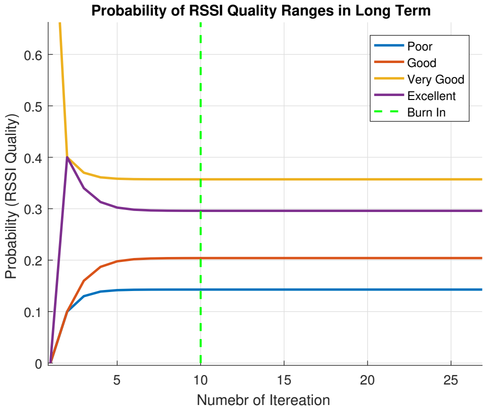
Thus, this mechanism can be modeled as a four state DTMC and can be presented as the transition diagram shown in Fig. 5. This diagram graphically describes the same information provided by the transition matrix. The four circles represent the four states for the RSSI quality ranges defined in Table. 1. The arrows show the transition probability from one state to another. DTMC moves to a better state if one of the modems (e.g., dongles) detects a stronger signal. For example, the DTMC stays in state ”P” if both modems detect poor signals and it moves to state ”E” if at least one of the networks gives a strong signal. The DTMC is an ergodic Markov chain as it is irreducible, aperiodic, and positive recurrent. Then, DTMC has a unique steady state that would be used for getting the simulation results, as discussed in the next Section.

C. Analysis of the performance results

The simulations in Fig. 6 present the probabilities of being in different quality-based states in long-term run. Fig. 6.a shows the sequence of states in different qualities. It describes the number of times that the model moves to different states, i.e., poor to excellent. It shows that the model is able to obtain the highest quality states most of the times; this means that the overall performance of the model is high. Accordingly, Fig. 6.b demonstrates the probabilities of the four states in the long-term run. We observe that in the second run, the probabilities of V and E start at 0.4. They continue so that the probability of V follows 0.38 and the probability of E continues at 0.3, both after reaching to a stable point (almost 10 iterations).



(a) Sequence of states in long-term run.



(b) Probability of RSSI value change in long-term.

Fig. 6. Simulation results using Markov chain.

These results explain that the connection steering mechanism obtains higher signal qualities with higher probabilities than the lower signal qualities, i.e., G and P. Moreover, these simulation results confirm our test-bed results, since the increase in RSSI increases $\mathcal{E}$. Therefore, the proposed mechanism consumes higher energy and accordingly the rate of $\mathcal{N}$ will be higher. Furthermore, the steady-state of an ergodic markov chain is a unique non-negative solution. In our model, the steady-state is:

$$[0.1250 \qquad 0.1964 \qquad 0.3750 \qquad 0.3036]$$

The interpretation of this steady-state vector is that the probability that the DTMC model will be on state Poor is 0.1250. The probabilities that the model will be on the states Good, Very Good and Excellent are 0.1964, 0.3750, and 0.3036, respectively. This output also confirms the results of Fig. 4.a. This means that the mechanism aims to select the highest qualities by moving to better states as Very Good (V) and Excellent (E). Thereby, the model will consume more energy and relatively the packet transmission rate will increase; meaning that the performance of the proposed mechanism will enhance and will provide better services. Moreover, by having the state space i.e., $S = \{P, G, V, E\}$, and using the test-bed results of the proposed connection steering mechanism, the

$\mathcal{E}_{Average}$ and $\mathcal{N}_{Average}$ can be calculated as follows:

$$\mathcal{E}_{Average} = \sum_{s \in S} p_s \cdot \mathcal{E}_s \tag{6}$$

$$\mathcal{N}_{Average} = \sum_{s \in S} p_s \cdot \mathcal{N}_s \tag{7}$$

Where $\mathcal{E}_{Average}$ is the average energy consumption and $\mathcal{N}_{Average}$ is the average rate of transmitted packets. Let p_s denote the probability of state s in the steady-state vector. Using these equations, we have $\mathcal{E}_{Average} = 59.2559$ Joule, and $\mathcal{N}_{Average} = 57.7384 \times 10^3$. These results explain the overall average performance of the DTMC model in all the states i.e., poor to excellent. This performance describes that the overall average performance of the mechanism is high. It also confirms a very good packet transmission rate $\mathcal{N}$ and guarantees a high QoS that is mandatory in real-time applications, e.g., video streaming. Finally, it affirms an acceptable amount of energy consumption $\mathcal{E}$ which is a vital factor in UAV's energy budget.

V. CONCLUSION

In this paper, we proposed a mechanism for connection steering among multiple 4G networks to be used on-board UAVs. This mechanism can be employed to ensure reliable connectivity to flying UAVs. This reliability is obtained by having steady links, coverage, and high RSSI values received at the IoT gateway. To evaluate the feasibility and performance of the mechanism, we developed a test-bed to study the amount of energy consumption and the packet transmission rate of the UAVs in case of video streaming application. The results of this test-bed show that the proposed connection steering mechanism supports high QoS ensuring high packet transmission rate from the IoT gateway. It also proves an acceptable amount of energy consumption for streaming different videos. In addition, we modeled and analyzed our work by DTMC to evaluate the performance of the test-bed results. The obtained results from the Markov model show that the mechanism increases the probability of having a high packet transmission rate in long-term. This means that, first, the mechanism provides high QoS and is well performing; secondly, it consumes an acceptable amount of energy which is an important factor in case of UAVs.

ACKNOWLEDGEMENT

Prof. JaeSeung Song was supported by the Institute for Information and communications Technology Promotion (IITP) grant funded by the Korea government (MSIP) [No.B0184-15-1001].

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