DURATS: Distributed User-centric Radio Access Technology Selection framework

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***Abstract*—Many studies have identified the numerous advantages of heterogeneous network architectures in enhancing resource efficiency and user experience. However, there are still open questions related to the decision-making process. In this paper, we present DURATS: Distributed User-centric Radio Access Technology Selection framework formulated as a Multiple Criteria Decision Making (MCDM) problem in the decision-making step. Realistic evaluation scenarios were conducted with a full-stack network simulator to prove the efficiency of this proposal. Our findings show the benefits of DURATS, under low and high-density network configurations, in enhancing network performance perceived by end-users while considering Quality of Service (QoS) constraints.**

***Index Terms*—Heterogeneous network architectures, RAT selection, MCDM.**

I. Introduction

Access technologies are one of the fundamental assets of networking and are commonly designed to optimize network performance in a given context. Meanwhile, the paradigm of recent generation networks such as 5G is expected to revolutionize our communication techniques by supporting a wide range of novel applications that compel low latency and high data rates for both indoor and outdoor use cases. Thus, the cohabitation of networks with heterogeneous access technologies in a common area is a fundamental feature in current communication networks. In such heterogeneous networks, answering how should a user select an access technology at a given time while guaranteeing application needs, and leading to efficient utilization of network resources is an open research area.

In this paper, we propose a radio access technology selection framework for Always Best Connect (ABC) applications with QoS requirements. We call this framework DURATS, for Distributed User-centric Radio Access Technology Selection. We consider network nodes having a set of use case application profiles, and a set of access technologies. Each application profile generates data where a functional module called *Decider* chooses the most suited transmission interface based on local statistics. This is motivated by the need of providing a decision framework based on decision metrics that network nodes can collect locally without the need for a specific coordination mechanism with other nodes and by using their standard interfaces.

The contributions of this paper are threefold. (i) A mathematical model of DURATS is derived with a Data Life-Time (DLT) interval adaptation mechanism and Exponential Moving Average (EMA) in the decision data gathering stage, and the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) at the stage of ranking available RATs. (ii) In addition, we propose objective methods to derive subjective weights of network attributes as user preferences. (iii) Lastly, in contrast to most existing mechanisms, which are only implemented and evaluated in MATLAB, the effectiveness and efficiency of DURATS are evaluated using a full-stack network simulator. In this paper, we consider two typical very commonly used RATs: IEEE 802.11 and LTE-D2D [1]. Note that the proposed technique can be applied to systems with more RATs and different technologies.

The remainder of the paper is structured as follows. In Section II, we investigate research efforts on network selection schemes in heterogeneous architectures and discuss the design rationale of our proposal. The decision process mechanisms of the proposed framework are specified in Section III. The evaluation results are presented in Section IV. Finally, conclusion and future research directions are given in Section V.

II. Background and related work

In this section, we investigate research efforts on network selection schemes in heterogeneous architectures.

In heterogeneous networks, the problem of RAT selection relates to the astute decision on which technology should be associated with a handover or a newly arrived session. There are three main issues related to this. (i) Estimation of the performance of access technologies based on decision criteria (e.g. throughput, delay, loss rate, etc.). (ii) Quantification of the QoS constraints of the application profiles. This refers to the notion of prioritisation of decision criteria for each application profile. (iii) And the actual decision algorithm for the assignment of application traffic to access technologies taking into account the estimated criteria and their weights in the decision.

There are two approaches to access technologies performance estimation: analytical and empirical. Analytical methods are mainly based on access layer state variables of the technology (e.g. contention window). Whereas empirical methods are mainly based on communication history. A common issue of analytical approaches is that they are criterion-specific for a given version of the technology, and therefore, are not general-purpose solutions [2]. Thus, we choose an empirical approach where the main issue relates to the control of traffic history.

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The quantification of the QoS constraints of the application profiles refers to the notion of weights of the decision criteria. There are two main categories of weights: objective and subjective [3]. Objective weights are used when there is a lack of background knowledge for the decision-maker or when the user or the operator do not have any special requirements. When supported end-user applications have special requirements such as QoS, subjective weights are used.

For the actual decision algorithm for the assignment of access technologies, there are two approaches in the literature: centralized and decentralized. In a centralized or decentralized approach, the issue of decision algorithm in RAT selection can be formulated as a Multiple Attribute Decision Making (MADM) [4]. Typical MADM algorithms are Hierarchical Analysis Process (AHP), Fuzzy Analytic Hierarchy Process (FAHP), Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), and Entropy. In addition to these schemes based on MADM, many Artificial Intelligence (AI) based algorithms have also been applied to solve this issue, such as Artificial Neural Networks (ANN) and Q-Learning[4]. Compared to AI-based algorithms, MADM algorithms are relatively straightforward without any random factors in the whole runtime. They can obtain the definite result almost directly, relying only on their corresponding formulas rather than multiple loops [5].

Depending on Decision-Maker (DM) location, a centralized approach can either be network-centric, where decisions are made on the network level, user-centric, where decisions are made be each user, or a collaborative architecture which incorporates both methods [6]. We propose in this paper a user-centric mechanism with an approach based on MCDM methods in the decision-making phase. This approach has the advantage of not relying on network infrastructure and extra signaling for coordination. Paper [7] proposed a user-centric and context-aware architecture to improve user-experience. Simple scenarios were conducted to show the adaptability of this architecture and its capability to deal with contextual information changes. Authors in [8] propose a utility function based RAT selection mechanism taking into account user preferences, channel state information as well as network load and service cost. Using fuzzy logic, authors of paper [9] proposed an MIH-based framework to reduce handover failure probability.

All these works, representative of the literature, focus on the decision algorithm without specifying how the user could prepare the decision data or how it would quantify the QoS constraints of its applications. In what follows, we present a complete framework for RAT selection in wireless networks.

III. Distributed User-centric Radio Access Technology Selection framework (DURATS)

In this section, we present the different components of DURATS, from the decision critera, to data collection, to decision making.

A. Definitions and assumptions

Before going in-depth in the decision process, we start be fixing the context of the study. We consider that a network node has a set of use case application profiles and a set of access interfaces. Each application profile generates data where a functional module called *decider module* decides on the transmission interface based on local statistics. The purpose of the *decider module* is to better meet Quality of Service (QoS) requirements of the application profiles.

An application profile is characterized by a set of requirements in terms of network performance, such as minimum required throughput, maximum tolerated delay and packet loss. For each of these requirements, we will associate a weight w_i, where i denotes the i^{th} criterion. Weights will be calculated based on a subjective method described in III-E.

Access interfaces are characterized by criteria obtained based on statistical observation of the network performance. These criteria are specified in Section III-B. They are used by the *decider module* in order to choose the best suited interface given the application requirements of the current packet.

In this study, we focus on use case application profiles that generate unicast traffic requiring acknowledgements for each generated frame. We chose three use case application profiles: conversational, streaming, and interactive.

B. Decision criteria

In our study, we base our decision making process on three criteria: Data delivery ratio, Throughput, and Delay.

1) Data delivery ratio: We consider the Data Delivery Ratio (DDR) to model link reliability between nodes per access technology i. DDR is defined as the ratio between the number of data packets successfully sent *SuccessTransData* (for which the acknowledgement has been received) and the total number of data packets attempted to be transmitted *TransData* using interface i over anterior time interval bounded by δ_1.

DDR is calculated using eq.1.

$$DDR_i^t = \frac{SuccessTransData_i^{[t-\delta_1,t[}}{TransData_i^{[t-\delta_1,t[}} \tag{1}$$

2) Throughput indicator: We consider the effective data rate as the throughput indicator on interface i at time t as expressed using eq. (2). It is defined as the ratio of the amount of data correctly sent by interface i observed over an anterior time interval δ_2.

$$Th_i^t = \frac{SuccessTransData_i^{[t-\delta_2,t[}}{\delta_2} \tag{2}$$

3) Delay indicator: The transmission delay of a packet p using access interface i at time t is calculated based on two parameters:

- $QstayDuration_i^t$: an estimate of how long p remained in MAC layer queue starting from t until it reaches the top of the queue.

- $AccessDelay_i^t$: an estimate of the time it takes for the access procedure of interface i to send p on the medium at time t.

The transmission delay is defined in eq. 3:

$$D_i^t = QstayDuration_i^t + AccessDelay_i^t \tag{3}$$

where $AccessDelay_i^t$ and $QstayDuration_i^t$ are empirically estimated using collected data in $[t - \delta_3, t[$.

The mechanisms for initializing and adjusting δ_1, δ_2, δ_3, which we call Data Life Time (DLT), are discussed in III-D.

C. Decision process

The goal of the decision process is to choose the current best access interface for an application profile based on a ranking of the access interfaces with defined criteria. For each data packet of an application profile, a functional decision module, called *decider module*, with two sub-modules *Queue* and *packer dispatcher*, chooses the transmission interface to use based on local statistics using Algorithm 1.

Algorithm 1: Access technology selection algorithm.

Input: Application packets $Queue$.
Result: Target access interface for each application packet.

1 Initialize Data Life-Times δ_1,δ_2,δ_3 ;
2 **while** *Queue not empty* **do**
3   Pop packet *P* from $Queue$;
4     $Nets \leftarrow$ available network indexes ;
5     $C \leftarrow$ networks attributes ;
6     $DM \leftarrow PrepareNetAttributes(Nets, C, \delta_1, \delta_2, \delta_3)$;
7     $targetNet \leftarrow rankIndex(DM, P_{profile})$;
8   Assign P to $targetNet$;
9 **end**

In Algorithm 1, the following steps are performed to assign access network to an application packet. **(Steps 4,5)** Alternative access networks are determined as well as the network selection criteria. **(Step 6)** *PrepareNetAttributes* is a procedure that prepares decision data in the form of a matrix called *decision matrix* considering Data Life-Time duration. The steps of this procedure are specified in III-D. The decision matrix is constituted of values x_{ij} of the criteria of the different network alternatives, where i is the index of the alternative interface and j is that of the criterion. The DLT parameter per interface criterion is initialized by f(0) at **(Step 1)** and is updated by the by taking into account the fluctuation of the interface statistics as well as its utilization rate. **(Step 7)** The *rankIndex* method uses decision process which includes normalization of the decision data, the determination of criterion weight of current application (namely $P_{profile}$), as well as the ranking Algorithm. These steps are detailed in section III-E.

D. Decision data processing

In the data-processing stage, criterion data is collected and processed based on steps of the following paragraphs. This allows us to update DLT δ_1, δ_2, δ_3 and to obtain the decision matrix.

At time t of decision, criterion data-set of current network index is retrieved using its DLT to control the freshness of the data. These data are statistic samples recorded and time-stamped in background, either through data traffic or through a periodic control traffic. A coefficient of variation (cv) of the network criterion is calculated from its statistic samples to update its DLT.

A function f determines DLT based on the cv of the network criterion. The goal of this function is to reduce the DLT when cv increases and to increase it when cv decreases. The rational is to increase the update frequency of the decision matrix (by reducing DLT) proportionally to the instability of cv due to data fluctuation. And conversely, to reduce this frequency proportionally to the trend of data stability. The determination of DLT interval length by f must be controlled in the function in order to guarantee a minimal and maximal sizes of the decision matrix. Based on the above reasoning, f is a decreasing function of cv with asymptote δ_{min}, which can be obtained using exponential modeling.

$f(x)$ can be modeled as a parametric function depending on δ_{max} and δ_{min} as given in equation (4).

$$f(x) = e^{-x+\ln(\delta_{max})} + \delta_{min} \tag{4}$$

For each interface, decision statistics are collected according to the transmission it makes. Thus, equation (5) gives the relationship between δ_{max}, the interface usage period τ, and statistic samples size γ.

$$\frac{\delta_{max}}{\tau} = \gamma \tag{5}$$

From (5) and (4) we derive eq. (6) as the Data Life Time function.

$$f(x) = e^{-x+\ln(\gamma*\tau)} + \delta_{min} \tag{6}$$

Exponential Moving Average (EMA) is then applied to each selected criterion data-set to form the decision matrix. EMA is a moving average that places a greater weight and significance on the most recent data points [10].

E. Multi-Criteria Decision-Making

In this section, we discuss Multi-Criteria Decision-Making (MCDM) steps used as ranking algorithm. These steps include normalization and weighting methods. We will also discuss the rationales of the considered methods for this proposal.

a) Normalization: This step aims to eliminate dimensional units of the data in the decision matrix to obtain numerical and comparable input data using a common scale. We chose to use a variant of enhanced min-max, a linear normalization technique which aims to eliminate the usage of absolute min-max values [11]. This technique allows for a greater distance between an alternative's normalized values so that the ranking order will be clearer.

b) Weighting: The goal of this step is to determine the weight of each decision criterion according to an identified application App. The general form of the weight vector namely w_{App} is given by equation (7).

$$w_{App} = [w_D \quad w_{Th} \quad w_{DDR}] \tag{7}$$

We use the pair-wise comparison matrix method to obtain subjective weights w_{app}. This method allows us to assess the relative importance of different criteria based on binary comparisons matrix A_{App} of $M \times M$ having the following form [12]:

$$A_{App} = \begin{bmatrix} a_{11} & \cdots & a_{1J} \\ \vdots & \ddots & \vdots \\ a_{J1} & \cdots & a_{MM} \end{bmatrix}, \text{where} \quad \begin{cases} a_{ii} = 1 \\ a_{ji} = \dfrac{1}{a_{ij}} \end{cases} \tag{8}$$

In (8), M represents the number of criteria. The a_{ij} values, such that $1 < i < J, 1 < j < J$ and $j > i$, are the relative importance degree of criterion i compared to criterion j for application App. We specify in section IV-A how these a_{ij} values are calculated from specific use case applications. Then, we can obtain the effective weight w_{App} of application App either using, for example, the Eigenvector or the Weighted Least Square method [3] from the pair-wise comparison matrix A_{App}.

c) Ranking: This step consists of establishing a rank of order for each criterion by taking into account the normalized matrix and the weight of each criterion. Many techniques are available for the rank calculation [13]. We chose to apply Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). TOPSIS determines the best alternative based on the concepts of compromise solution. It is relatively simple and offers more accuracy in identifying the alternative rank compared to other MCDM algorithms [13].

IV. Evaluation scenarios and results

To evaluate the proposed model, we developed a framework for heterogeneous network simulation based on INET and SimuLTE. INET is a package of network simulation modules for OMNeT++ containing standard internet protocols. SimuLTE is an LTE protocol model written for OMNeT++ [14].

We consider three multimedia applications: Conversational (Conv), Streaming (Strea), and Interactive (Inter). Table I summarizes performance expectation of these use case applications from end-user perspective in terms of delay, data rate as well as the information loss [15].

A. Use case applications subjective Weights

Here, we drive the effective weights of use case applications from their performance requirements of table I. We start by normalizing the table. This step is essential to remove dimensional units and thus be able to compare each criterion's importance for a defined application. The normalized value $x'_{i'j'}$ of application i' regarding its performance criterion j' such that $1 < i' < N, 1 < j' < M$ is obtained in eq. 9.

TABLE I
End-user performance expectations of some multimedia applications [15].

Application	Delay	Data rate	Information loss
Conversational (e.g. audio call)	$< 400ms$ (end-to-end delay)	4-25 kbit/s	< 3 % (frame erasure rate)
Streaming (e.g. Movie clips)	$< 10s$ (start-up delay)	20-384 kbit/s	< 2 % (packet loss ratio)
Interactive (e.g. WWW browsing)	$< 4s$ (one-way delay)	4-13 kbit/s	0 (frame erasure rate)

$$x'_{i'j'} = \frac{x''_{i'j'}}{\sum_{j=1}^{J} x''_{i'j'}} \tag{9}$$

Where $x''_{i'j'} = x_{i'j'}$, if j'^{th} criterion is "larger-the-better", and $x''_{i'j'} = \frac{1}{x_{i'j'}}$, if j'^{th} criterion is the "smaller-the-better".

N represents the number of use case application profiles and $x_{i'j'}$ are the non-normalized values. The normalized Table II is obtained by applying eq. 9 on Table I.

TABLE II
Normalized end-user performance expectations of some multimedia applications.

Application	Delay	Data rate	Information loss
Conversational (e.g. audio call)	0,88	0,06	0,00033
Streaming (e.g. Movie clips)	0,035	0,91	0,0005
Interactive (e.g. WWW browsing)	0,088	0,033	0,99

Then, the a_{ij} values, such that $1 < i < M, 1 < j < M$ and $j > i$, representing the relative importance degree of criterion i compared to criterion j for application profile i' are assessed using eq. 10 for the construction of the pairwise comparison matrix.

$$a_{ij} = \frac{x'_{i'i}}{x'_{i'j}} \tag{10}$$

Finally, the effective weights are obtained by applying Weighted Least Square method on the pairwise comparison matrices. Table III gives the pairwise comparison matrices and the corresponding weights obtained.

TABLE III
Weight vector obtained from pairwise comparison matrices.

Pairwise comparison matrix	Weight vector
$A_{Conv} = \begin{bmatrix} 1 & 14,84 & 2633,77 \\ 0,07 & 1 & 177,45 \\ 0,0004 & 0,006 & 1 \end{bmatrix}$	$w^T_{Conv} = \begin{bmatrix} 0.94 \\ 0.06 \\ 0.0004 \end{bmatrix}$
$A_{Strea} = \begin{bmatrix} 1 & 0,039 & 70,23 \\ 25,87 & 1 & 1817,12 \\ 0,014 & 0,0006 & 1 \end{bmatrix}$	$w^T_{Strea} = \begin{bmatrix} 0.037 \\ 0.96 \\ 0.0005 \end{bmatrix}$
$A_{Inter} = \begin{bmatrix} 1 & 2,65 & 0,088 \\ 0,38 & 1 & 0,033 \\ 11,4 & 30,19 & 1 \end{bmatrix}$	$w_{TI} = \begin{bmatrix} 0.078 \\ 0.029 \\ 0.892 \end{bmatrix}$

B. Simulation scenario

Our goal is to assess DURATS impact on network performances considering the before-mentioned use cases applications. To proceed, we have considered two group of nodes. The first group of nodes is called "Decision-makers". It is composed of 10 peer of nodes where in each peer there is a source node and a destination node. The traffic source nodes use DURATS to choose the RAT to transmit, namely "interface 0" and "interface 1", to send unicast traffic to the traffic destination nodes. The second group of nodes called "Dummy traffic generators" is composed of standard nodes that run a dummy service. The dummy service traffic acts as a disturbance traffic for "Decision-makers" on their "interface 0". We varied the disturbance traffic from 10% to 100% of the channel capacity for each scenario.

DURATS is assessed in a scenario where "interface 0" uses IEEE 802.11, and "interface 1" uses LTE-D2D unicast. Performance of DURATS is compared to a baseline method for each use case application. The baseline method consists of selecting the interface with the last known best value of criterion which has the highest weight for the application. For example for Conversational application, the baseline method consists of selecting the interface with the lowest delay.

Two traffic load densities are considered: Low and High. In low density, source nodes generate application data traffic which corresponds to 20% of the maximum reception capacity offered by the interface. The reception capacity of nodes is bounded by their technology's data rates (6 Mbps for IEEE 802.11 and 6.7 Mbps for LTE-D2D unicast). Whereas, with high traffic load density, source nodes generate application data traffic which corresponds to 70% of the maximum reception capacity. In addition to the data traffic, a periodic control traffic is deployed on each interface of source nodes. The control traffic running in background is to provide more accurate channel estimations and is 5% of the maximum capacity of the interface.

C. Simulation results

Figure 1, shows that DURATS outperforms the baseline algorithm for delay based decision in high load density scenarios. In low density scenarios, throughput and packet delivery rate performances are almost the same. Indeed, as traffic increases, there would be more fluctuation of the network metrics, hence the importance of the decision based on the moving average compared to the decision based on the last known values of the metrics. This explains the fact that the performance gap between DURATS and the Baseline mechanism becomes larger when disturbance traffic increases.

Figure 2 shows that DURATS outperforms the baseline algorithm for data delivery rate based decision in high load density scenarios. In low density scenarios, throughput and packet delivery rate performances are almost the same. We also note that, similarly to figure 1 results, the difference in performance between DURATS and the baseline method is more significant when disturbance traffic increases.

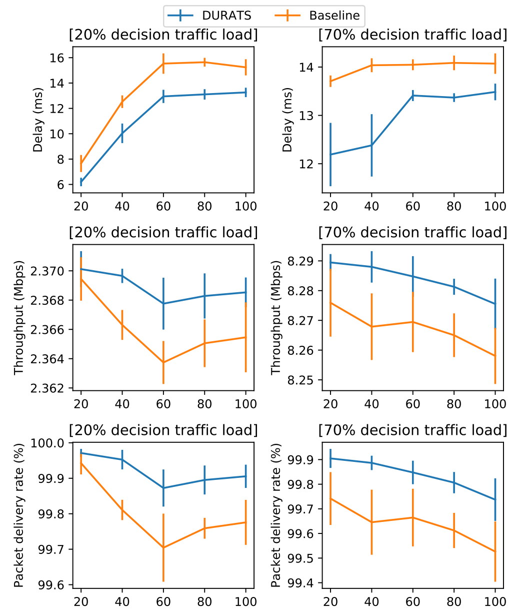

Fig. 1. Delay based decision results for Conversational application.

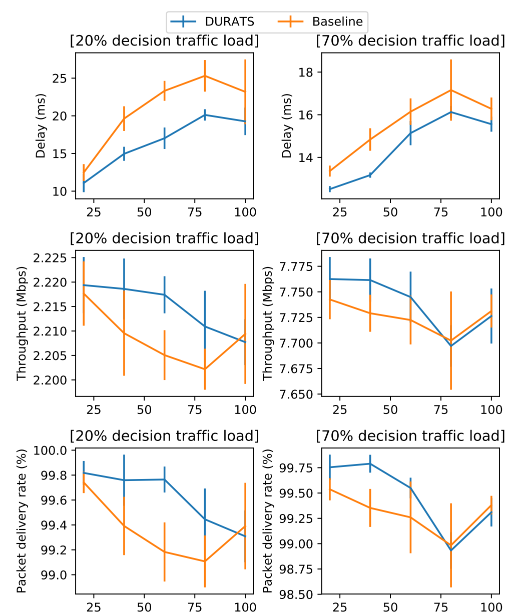

Fig. 2. *DDR* based decision results for Interactive application.

Figure 3 shows that DURATS outperforms the baseline algorithm for throughput-based decisions both in low and high load density scenarios as the disturbance traffic rate increases. We note that under a low disturbance traffic rate, the performances are slightly lower. We also note that the performance increases progressively as the interference increases. This is because the nodes choose Wi-Fi more often, which offers a slightly similar throughput to that of LTE at low interference. Then as the interference increases, they gradually select LTE more often.

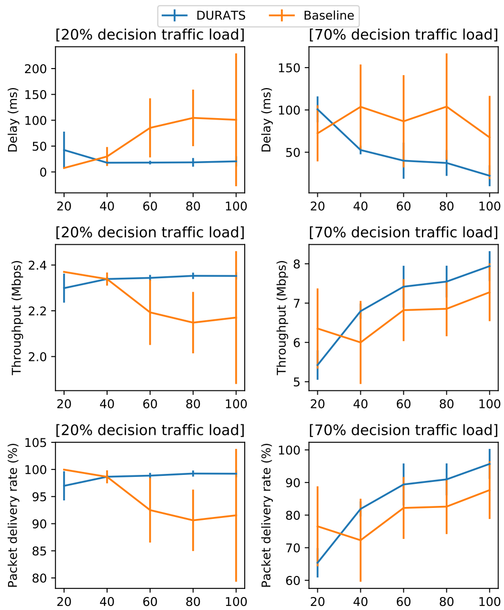

Fig. 3. Throughput based decision results for Streaming application.

V. Conclusion

The cohabitation of networks with heterogeneous access technologies in a common area is a fundamental feature in current communication networks. RAT selection for applications demanding QoS presents a challenging task for these networks as it relies on accurate decision data and decision-making algorithms. In this study, we proposed DURATS, a selection framework dealing with different stages of data-processing and decision-making dedicated for application with unicast traffic. Our simulated results show DURATS's benefits in achieving better performance compared to a baseline algorithm considering three use case applications with different requirements in terms of throughput, packet loss, and access delay.

The evaluation scenarios are somehow pessimistic since we considered a case where one interface becomes overloaded for all the nodes at the same time. We are aware that in real life, this will rarely happen. Nevertheless, the scenarios are studied for the sake of validating the soundness of our decision mechanism.

DURATS overloads the network with background traffic to obtain more accurate channel estimations. In our future studies we will evaluate its impact and we will try to reduce it. Moreover, in our future work, we will also consider scenarios where multiple applications running simultaneously in the same scenario. This would be more realistic and closer to real life usage.

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