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EXECUTIVE SUMMARY

The hi-STAR project addresses one of the most critical challenges for the next generation wireless networks, which is integration of non-terrestrial networks with terrestrial 5G network. The general objective of the WP4 is to develop a traffic control unit (TCU) that will benefit from multiple RANs (radio access networks), and increase the reliability of users communication. In order to develop the TCU and verify its performance, it is necessary to create simulation environment and propose the handover procedure that will improve the user experience.

This deliverable is a result of the work done in the context of WP4 Subtasks T4.1 (Simulation environment creation) and T4.2 (Design of traffic control module placed in HUT). We explain the simulation environment that includes LEO (Low Earth Orbit) satellite-to-ground communication links and terrestrial millimeter-wave links. Then, we propose a user-centric handover execution method that measures instantaneous signal-to-noise ratio and incorporates deep neural networks to predict channel state information and reduce the data loss probability of the transmission.

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ABBREVIATIONS

ACM	**Adaptive Coding and Modulation**
AWGN	**Additive White Gaussian Channel**
DNN	**Deep Neural Network**
GEO	**Geostationary Earth Orbit**
FEC	**Forward Error Correction**
FER	**Frame Error Rate**
LDPC	**Low-Density Parity-Check**
LEO	**Low-Earth-Orbit**
PLHEADER	**Physical Layer HEADER**
PLSCODE	**Physical Layer Signaling CODE**
RAN	**Radio Access Network**
TWDP	**Two-Wave with Diffuse Power**
SOF	**Start Of Frame**
SNORE	**Signal-to-Noise-Interference Ratio estimator**
SNR	**Signal-to-Noise Ratio**
WP	**Work Package**

SECTION 1 - INTRODUCTION

With constant increase of communication infrastructure and access points of multiple RANs (Radio Access Networks), ensuring seamless handover is recognized as one of the major challenges in the communication industry [1]. Finding efficient handover execution strategies can increase the reliability of the communication, potentially increase information rates through load balancing, and improve overall user experience. Recent attempts of integrating LEO (Low Earth Orbit) satellites into 5G ecosystem further highlight the significance of the handover operation.

Usually, the decision which RAN end terminals will be using is left to the network core (i.e., ***network-centric*** handover approach), which will create directives that are passed to each individual user [2]. In this way decision process is centralized and the communication infrastructure is efficiently utilized. However, the decision process is slower, since the network core needs to collect parameters measured in every end user terminal (like channel state information), combine them with network-based restrictions and perform real-time computationally hungry optimization. Additional downside of the network-centric handover execution is that all the RANs available to the user need to be integrated into single core network, which currently is considered to be unrealistic assumption – it is more likely that connectivity through terrestrial and satellite radio networks is establish by different service providers, which optimize usage of their communication infrastructure independently.

This document contains our findings related to alternative handover execution technique, in which user, based on the measurements and prediction of the channel state information and taking into account restrictions related to network resource allocation, makes the decision which RAN (or access point) to use in order to receive the information data sent to him. The above approach is called the ***user-centric*** handover [3-7], and its benefits include faster handover execution and possibility to be used in heterogeneous networks without common network core operations. In the considered approach, the sender of information, based on the end user decisions, simply routes the information based on some multi-path transport protocol (for example multi-path TCP) towards dedicated radio access points. Although the user-centric handover from the perspective of service providers could be seen as suboptimal, it can be allowed to some priority users, for which communication reliability needs to be as high as possible.

The Deliverable D4.1 summarizes the initial work carried within WP4 subtasks T.4.1 and T4.2. In the above subtasks we have investigated possibility to perform user-centric handover in heterogeneous radio environment, where the end user could establish connectivity through 5G base station, or multiple LEO satellites. The terrestrial channel is modeled based on the two-wave with diffuse power (TWDP) diffuse model, which is characteristic for the millimeter wave transmission, while satellite communication is considered to be affected by shadowed-Rician propagation. The aforementioned channel models were developed and tested in WP2, while the integration into simulation framework was conducted in WP4 subtask T.4.1. We propose the handover execution strategy in which the user performs periodical measurements of the instantaneous signal-to-noise ratio (SNR) for each available communication channel, and based on the current and previously measured SNR values decides not only which RAN is preferable, but also which information rate will be used for communication. The optimization strategy relies on the deep neural network (DNN) to provide the optimal decisions. In other words the DNN is used to predict reliability of each communication channel.

This deliverable is structured as follows: In Section 2 we briefly explain system simulation model and propagation conditions used in the simulator. In Section 3 we describe handover execution method and give some numerical results. Section 4 concludes the document.

SECTION 2 – SYSTEM MODEL

2.1. HYBRID NETWORK

In the considered scenario, the end-user could establish connection through several LEO satellites and terrestrial base station that supports 5G millimeter wave communication. We only consider downstream traffic direction from the network core to the end user. We consider that each radio link supports adaptive coding and modulation (ACM) technique meaning that the sender of information adopts the data rate to the channel state information. We assume that the information is transmitted through satellite links by using DVB-S2X protocol. This protocol was developed for the GEO satellite communication and is mostly used for video broadcasting and incorporates frames that contain 64800 bits. However, DVB-S2X protocol also supports data transmission, which is more sensitive to propagation delay, for which so called short frames of length 16200 bits are used. According to the protocol spec [8], DVB-S2X supports the range of spectral efficiencies 0.2b/Hz/s - 5.6b/s/Hz, and each spectral efficiency is represented by a couple (modulation format, code rate) referred as MODCOD. However, according to the statistics of the used MODCODs, provided in [8], DVB-S2X operates most frequently in 2b/s/Hz - 3b/s/Hz spectral efficiency range. In Fig. 1. we give the percentage of time that each MODCOD is used, according to statistics from the year 2010.

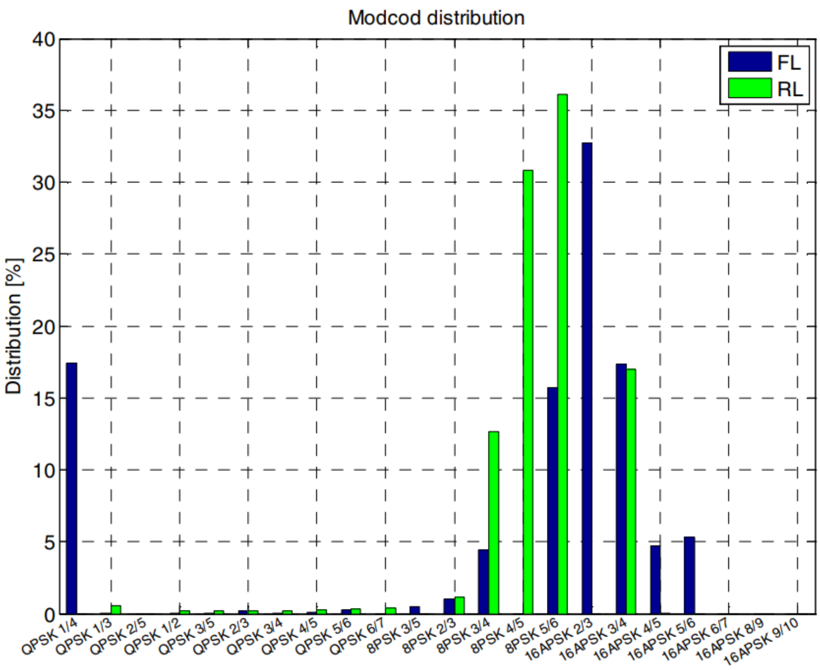

Figure 1. The frequency of MODCOD usage (FR – forward link, RL – reverse link).

Thus, we restrict our simulation to the most used MODCODs and simply consider that spectral efficiencies below predefined lower value are not sufficient for the successive application run, while spectral efficiencies higher than the predefined bound are also not needed as they overcome the user information rate requirements. The goal of our multiple RAN access is to enable steady usage of spectral efficiencies in 2b/s/Hz - 3b/s/Hz range, minimizing percentage of time when such efficiencies cannot be achieved. The chosen MODCODs, together with signal-to-noise radios, required to achieve the different frame error rates (FERs) are presented in Table 1. In order to obtain the results given in Table 1, we conducted Monte Carlo simulation, under the assumption of AWGN (*Additive White Gaussian Noise*) channel, and investigate performance of FEC (*Forward Error Correction*) module. In the rest of the deliverable, for the illustrational purposes, we will consider that level of tolerated transmission unreliability is 10^{-5}, however, our handover procedure does not depend on the required reliability level.

We assume that terrestrial communication is conducted in frequency band allocated for 5G millimeter waves, however, for the purpose of illustration of user-centric handover procedure it is not necessary to implement complex physical layer of 5G communication system. It is sufficient to implement module for channel state information measurements and selection of MODCOD that will be used in the subsequent communication. The performance of FEC module of 5G radio are similar as performance of DVB-S2X correction module, thus, for reason of simplicity we assume that the 5G system supports the same MODCODs, with the same performance as DBV-S2X system.

Table 1. Required SNRs for chosen MODCODs.

Modulation	8PSK	16APSK	16APSK	16APSK	16APSK
Code rate	0.448	0.448	0.512	0.555	0.638
M_i [b/s/Hz]	1.22	1.63	1.86	2.02	2.48
$T(M_i)$ for FER=10^{-5}	3.95	6.1	7.1	7.75	9.8
$T(M_i)$ for FER=10^{-4}	3.8	6.0	7.0	7.6	9.75
$T(M_i)$ for FER=10^{-3}	3.75	5.9	6.85	7.55	9.65
$T(M_i)$ for FER=10^{-2}	3.7	5.85	6.75	7.45	9.6

We next explain the framing in DVB-S2X system, described in Fig. 3. From the handover procedure perspective, the most important part is the PL (Physical layer) frame, where a packet is formed from information payload coded with LDPC (*low-density parity-check*) code and fields SOF and PLSCODE, which together form a PL header (PLHEADER).

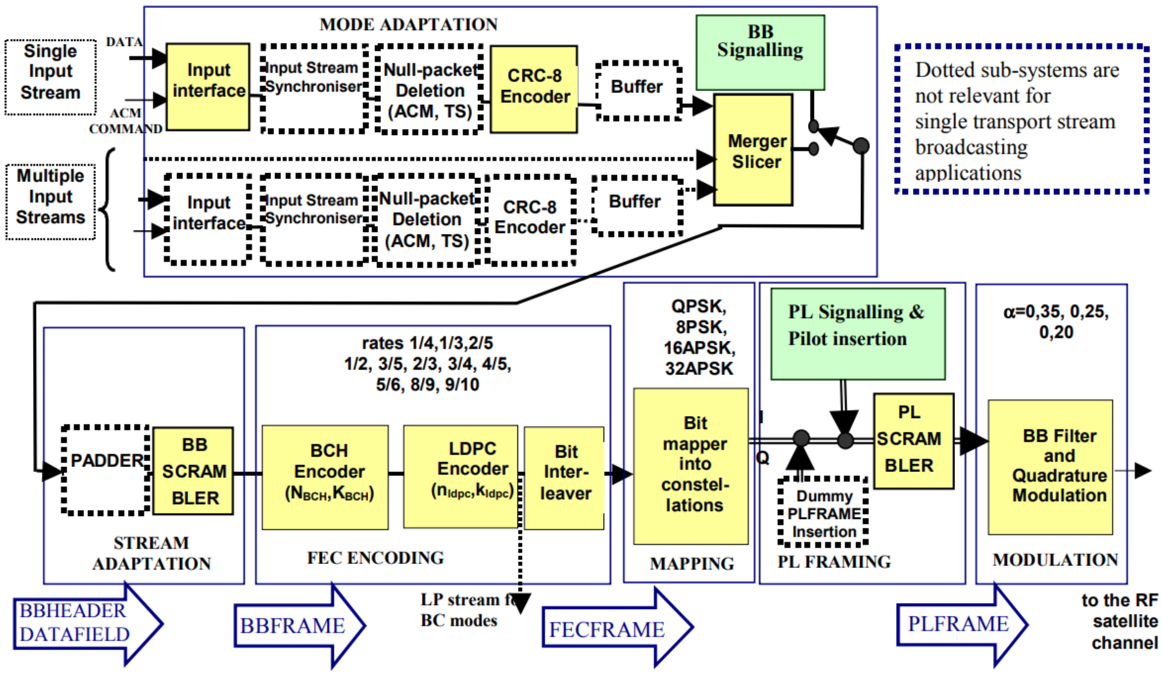

Figure 2. Physical layer operation in DVB-S2X transmitters [8].

SOF	PLSCODE	LDPC coded frame

Figure 3. Physical layer framing fields.

The SOF (Start of Frame) field represents a known 26-symbol pattern that is used for synchronization purposes, while PLSCODE (*Physical Layer Signaling CODE*) field contains 7-bit information related to modulation scheme, code rate, pilot configuration and length of the LDPC coded data, coded by a linear block code with rate 7/46. The SOF and PLSCODE fields are modulated independently of used MODCOD, by always using pi/2-BPSK modulation. According to the pilot insertion procedure, presented in Fig. 4, the LDPC coded frame is split in segments, and, after each segment, 36-symbol pilot sequence (denoted by UW) is added to the frame. The pilot sequences are used to estimate the channel state information.

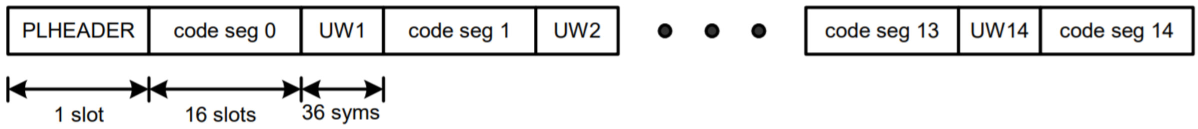

Figure 4. Insertion of pilot symbols [8].

Although in 5G systems, measurement of the channel state information is performed by differently placed pilot symbols within 5G recourse grid, the selection of MODCOD depends only on quality of channel state information assessment. Unlike in DVB-S2X simulated link, where we performed exact measurement of SNR, in our 5G simulation scenarios we considered that the 5G receiver is able to measure SNR with small inaccuracy, modeled as random Gaussian distributed variable.

2.2 CHANNEL MODELING

In this deliverable we are only interested to investigate what effects instantaneous SNR, denoted by $\gamma(t)$ has on handover procedure, defined as following

$$\gamma(t) = \frac{P_T}{\sigma^2}\frac{|h(t)|^2}{d^\beta},$$

where P_T is transmitted power, σ^2 is noise variance, d is distance between source and destination, β is path-loss factor and $|h(t)|^2$ is time-varying channel power gain. The probability density function of the channel gain *h(t)* depends on the propagation environment, which is different in satellite-to-ground and terrestrial communications. It is widely assumed that channel gain between LEO satellite and ground end user is composed of two time-vary components: i) scattering and ii) line-of-sight (LOS) component, i.e., [9-11]

$$h(t) = a(t)e^{j\alpha(t)} + z(t)e^{j\alpha_0},$$

where $a(t)$ represents instantaneous scattering amplitude which is Rayleigh distributed, $\alpha(t)$ is uniformly distributed random phase, $z(t)$ is amplitude of the LOS component which is Nakagami-*m* distributed, and α_0 is deterministic phase. The probability density function of channel gain amplitude $r(t)=|h(t)|$ can be represented as

$$f_R(r) = \left(\frac{2b_0 m}{2b_0 m + \Omega}\right)^m \frac{r}{b_0} e^{-\frac{r^2}{2b_0}} {}_1F_1\left(m, 1, \frac{\Omega r^2}{2b_0(2b_0 m + \Omega)}\right), \qquad r \geq 0,$$

where $2b_0$ denotes the average power of scattering component, Ω is average power of LOS component, m represents parameter of Nakagami-*m* distribution and ${}_1F_1()$ is confluent hypergeometrical function. By using three degrees of freedom (b_0, Ω and m) the introduced channel model can accurately describe different propagation environments, as well as different LEO satellite elevation angles. Usually, quality of the channel can be described by the level of shadowing included in the model and we distinguish low, average and heavy shadowing, with parameters given in Table 2.

The frequency band used for communication between 5G base station and end-user is assumed to belong to millimeter wave bandwidth, which is modeled in the literature by so called two-wave with diffuse-power (TWDF) model. In case of TWDF propagation, the channel gain can be represented as [12]

$$h(t) = V_1 e^{j\Psi_1(t)} + V_2 e^{j\Psi_2(t)} + a(t) e^{j\alpha(t)},$$

where the first two components are specular and have constant amplitudes (V_1 and V_2) and random uniform phases (Ψ_1 and Ψ_2), while the third component is diffuse with Rayleigh distributed amplitude $a(t)$, and uniformly distributed random phase $\alpha(t)$. Unfortunately, the exact closed-form expression for the probability density function of TWDF channel gain does not exist, and we do not present available expressions here.

In our handover simulator we have incorporated one TWDP model for the terrestrial channel and several uncorrelated satellite-to-ground channels, which mimic potential communication to different LEO satellites.

Table 2. Satellite channel parameters for different scenarios.

Propagation scenario	b_0	Ω	m
Infrequent low shadowing	0.158	1.29	19.4
Average shadowing	0.126	0.835	10.1
Frequent heavy shadowing	0.063	0.000897	0.739

SECTION 3 – HANDOVER PROCEDURE

Our handover procedure consists from the following steps

- The end user makes statistics of RANs usage in a predefined time window. All RANs, which utilization (in the time window) is below some threshold, compose a set of *available RANs*;
- The end user also collects pilot symbols from all the available RANs and periodically measures SNR values;
- Based on the current and previous SNR measurements end user makes predictions of future SNR values for each available RAN, by using DNN;
- Based on the SNR predictions, MODCOD for potential subsequent communication is obtained for each RAN;
- If there exists available RAN with the predicted MODCOD that offers higher spectral efficiency than correctly used RAN, handover execution is triggered by the end user.

3.1 SNR MEASUREMENT METHOD

One of the basic operation pre-required for the handover execution is measurement of the channel state information, i.e., measurements of instantaneous SNR. In our simulation environment we use data-added with pilots variant of so called SNORE (*Signal-to-Noise-Interference Ratio estimator*) algorithm, developed in *NASA Jet Propulsion Laboratory*.

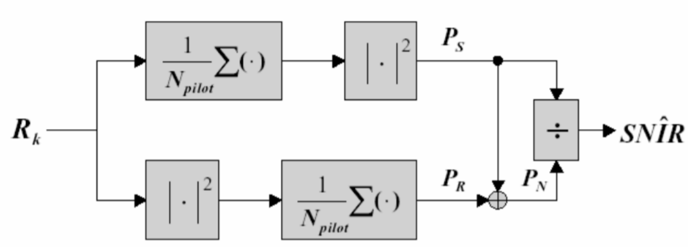

Figure 5. Block diagram of SNORE method [8].

The estimator collects N samples after match filtering and carrier phase recovery at position if frame dedicated to pilots and forms a complex array $\mathbf{r}=(r_1,\ldots r_N)$, where $r_i=r_{i,I}+jr_{i,Q}$. The receiver also has information of actual pilot values transmitted through the channel denoted by $\mathbf{p}=(p_1,\ldots,p_N)$, where $p_i=p_{i,I}+jp_{i,Q}$. Then, the useful signal power can be estimated by

$$P_s = \frac{1}{N}\sum_{i=1}^{N}(r_{i,I} \times p_{i,I} + r_{i,Q} \times p_{i,Q})$$

while noise power P_N is equal $P_N=P_R-P_s$, where

$$P_R = \frac{1}{N}\sum_{i=1}^{N}|r_i|^2.$$

The estimated SNR is calculated as P_s/P_N. The described procedure is performed periodically, for all available RANs.

3.2. HANDOVER EXECUTION METHOD

Let us denote a set of MODCODs spectral efficiencies $M=\{M_1,M_2,\ldots,M_K\}$, where according to Table 1, $K=5$. Let us also define monotonously increasing function $T: M \to \mathbb{R}$: where $T(M_i)$ represents minimal SNR value needed to operate in the MODCOD M_i. If we denote the instantaneous SNR in the channel by γ then the *optimal MODCOD* is the greatest element in a set $S_\gamma \subseteq M, S_\gamma = \{M_i | T(M_i) \leq \gamma\}$, i.e., supremum of S_γ denoted as $\sup(S_\gamma)$. In a special case when $S_\gamma = \emptyset$, the lowest spectral efficiency M_1 will be used for transmission.

Let us enumerate all of total N RANs that end-user can use to establish communication by a set $I=\{1,2,\ldots N\}$. At a time interval $(t_{j-1},t_j]$ the end-user measures instantaneous SNRs for all the currently available RANs, i.e., RANs from a set $I_j \in I$. The principle of forming the I_j set will be discussed later. The measured values form a set $\Gamma_j = \{\hat{\gamma}_{j,i} | i \in I_j\}$, where $\gamma_{j,i}$ represents measured SNR in [dB] of the i-th RAN, during time interval $(t_{j-1},t_j]$. Then, a prediction function $f: \mathbb{R}^3 \to M$ is executed, which for all the available RANs produces the MODCODs that will potentially be used until the next SNR measurements are completed, i.e., in the time interval $(t_j,t_{j+1}]$. The goal of the function $f()$ is to make predictions regarding the optimal MODCOD, based on the current and previous SNR measurements. We assumed that the current measurement mainly contributes to the predicted output, while the previous measurements have incremental influence. Let $S \subseteq M$ be a set of MODCOD efficiencies form in the following way

$$P = \left\{M_m \middle| \gamma_{j,k_j} - g(\hat{\gamma}_{j,i}, \hat{\gamma}_{j-1,i}, \hat{\gamma}_{j-2,i}) \geq T(M_m)\right\}$$

where $\gamma_{j,i} \in \Gamma_j$, while $g: \mathbb{R}^3 \to \mathbb{R}^+$ produces positive increment which is subtracted from the current SNR measurement in order to create a margin that will compensate for the potential drop of the SNR in the subsequent interval. If the margin is too big the RAN is not efficiently used, since even for high measured SNR, the end-user will choose a low spectral efficiency MODCOD, while too small margin could potentially cause loss of the transmitted data.
Thus we have

$$f(\hat{\gamma}_{j,i}, \hat{\gamma}_{j-1,i}, \hat{\gamma}_{j-2,i}) = \sup(P).$$

The end-user simply chooses the RAN that will produce the MODCOD with the highest spectral efficiency, i.e.,

$$f\left(\hat{\gamma}_{j,n_j}, \hat{\gamma}_{j-1,n_j}, \hat{\gamma}_{j-2,n_j}\right) \geq f(\hat{\gamma}_{j,i}, \hat{\gamma}_{j-1,i}, \hat{\gamma}_{j-2,i}), \qquad \forall i \in I_j.$$

In case that there are multiple satellites that achieve maximal efficiency, and the previously used satellite is among then, the end-user does not perform a handover. Otherwise, the least used satellite in the current time window in selected, in order to reduce the possibility that selected satellite leaves a set of available satellites. If $n_j \neq n_{j-1}$ the handover procedure is triggered and the information of the preferred RAN is send to the network core via reverse link.

The margin could be optimized in order to achieve the desired level of communication reliability express in terms of the ***data loss rate***, i.e., the probability that during some time interval $(t_j,t_{j+1}]$ the sent information is lost. The data loss rate rate P_{loss}, can be expressed as

$$P_{loss} = \sum_{n_j=1}^{N} \sum_{i=1}^{K} \frac{M_i}{\lambda_{i,n_j}} \Pr\{M_x$$
$$= M_i, n_j \text{ is chosen}\} \left[\Pr\left\{\gamma_{j+1,N_j} < T(M_1)\right\} + \Pr\left\{\sup\left(\left\{M_i \middle| T(M_i) \le \gamma_{j+1,N_j}\right\}\right) < M_x\right\} \Pr\left\{\gamma_{j+1,N_j} \ge T(M_1)\right\}\right],$$

where $x = f\left(\hat{\gamma}_{j,n_j}, \hat{\gamma}_{j-1,n_j}, \hat{\gamma}_{j-2,n_j}\right)$ and

$$\lambda_{i,n_j} = \sum_{i=1}^{K} M_i \Pr\{M_x = M_i, n_j \text{ is chosen}\}.$$

represents the true SNR value in time interval $(t_j, t_{j+1}]$. The first term in the square brackets depicts the data loss caused by SNR drop below the lowest MODCOD threshold, while the second term represents the loss caused by inaccurate SNR prediction. By increasing the margin value $g(\hat{\gamma}_{j,i}, \hat{\gamma}_{j-1,i}, \hat{\gamma}_{j-2,i})$, the second terms can become negligible. Furthermore, in the case of slow-varying fading channel, the probability that instantaneous SNR is below the lowest SNR threshold in three successive time instants is close to 1, i.e.,

$$\Pr\left\{\gamma_{j+1,N_j} < T(M_1) | \gamma_{j,N_j} < T(M_1), \gamma_{j-1,N_j} < T(M_1)\right\} \approx 1$$

which means that, if $\Pr\left\{\gamma_{j+1,N_j} < T(M_1)\right\}$, we can argue that there is a high probability that RAN n_j was chosen in the previous time interval because all of the RANs had SNRs below the lowest operation thresholds, and under the assumption of mutually uncorrelated channels we have

$$P_{loss} > \frac{M_1}{\lambda_{1,n_j}} \sum_{i=1}^{K} \Pr\{n_j \text{ is chosen}\} \Pr\left\{\gamma_{j+1,N_j} < T(M_1)\right\}$$

It follows that the previous term can be made arbitrary small by increasing the number of RANs. The second term in the blockage rate expression describes the SNR prediction error. The effect of this error can be diminish by increasing the margin $g(\hat{\gamma}_{j,i}, \hat{\gamma}_{j-1,i}, \hat{\gamma}_{j-2,i})$. Then we can provide a low bound for the blockage probability as

$$P_{loss} > \frac{M_1}{\lambda_{1,n_j}} \prod_{N_j=1}^{N} \Pr\left\{\gamma_{j+1,n_j} < T(M_1)\right\}.$$

It should be noted that increasing the margin and operating close to the lower bound is not always beneficial, since high margins cancel the gain of adaptive coding and modulation and reduce the information data rate. Instead, the handover procedure should be designed to provide some tolerable level of blockage rate, while maximizing the overall ***achievable spectral efficiency*** which we define as

$$R = \sum_{n_j=1}^{N} \sum_{i=1}^{K} M_i \Pr\{M_x = M_i, n_j \text{ is chosen}\} \Pr\left\{\sup\left(S_{\gamma_{j+1,n_j}}\right) < T(M_1)\right\}$$

In other words we can optimize the margins for all the RANs and MODCODs in order to achieve desired goals. It is hard to perform such multidimensional optimization by conventional optimization methods, thus we used reinforcement learning technique that incorporates deep neural network to solve the optimization problem.

Several optimization procedures are possible:

- The margin is fixed for all RANs and all MODCODs;
- The margin is adaptable and depends on the MODCOD and RAN that is considered;
- The margin is precompiled in advance assuming typical propagation scenarios;
- The deep neural network is used "on the fly" to collect SNR measurements and DNN training is conducted in parallel with data transmission.

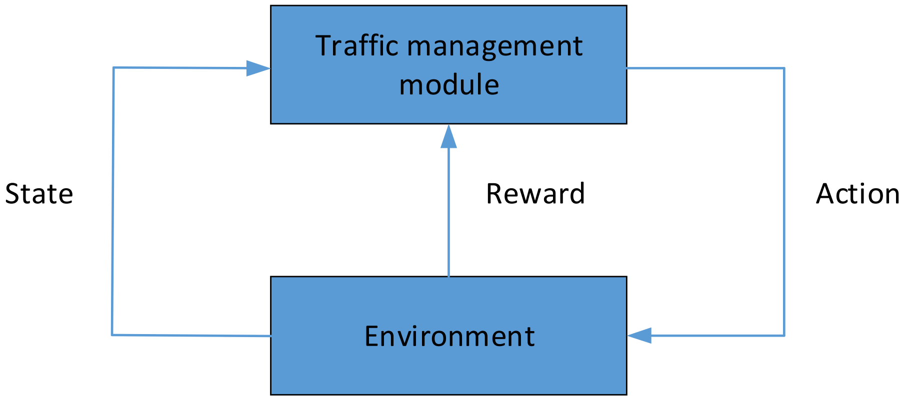

Figure 6. The reinforcement learning of traffic management module.

According to the reinforcement learning approach we define a set of states, actions and rewards that steers the learning process toward desired goal. The traffic management module performs actions, which we define as increment values (outputs of the function $g(\hat{\gamma}_{j,i}, \hat{\gamma}_{j-1,i}, \hat{\gamma}_{j-2,i})$), that are used to make MODCOD predictions. After each action, the environment calculates current system state – we define the state as the current data loss rate. Transitions between states are rewarded in order to constantly be in a proximity of target data loss rate. If the action pushes the environment toward target state, the reward is positive, while any deviation from the target state triggers the negative reward. Given the fact that action space could be large, we use DNN reinforcement models to learn the appropriate actions.

SECTION 4 NUMERICAL RESULTS

In this section we present numerical results related to the proposed handover procedure expressed in terms of achievable spectral efficiencies, data loss rates and number of executed handovers for a dual-connectivity approach, in which the end-user can use either terrestrial or satellite network. We assumed that available bandwidth is in each network equal to 40MHz and that both network have the same average SNR, while the propagation conditions are modeled as described in Section 2, while pulse shaping is performed by a square-root raised cosine filter, with roll-off factor equal to 0.1. In our simulation setup, the end-user measures the channel SNR every 5ms, for each available RAN simultaneously, based on the received pilot sequence. For the purpose of simplicity, we consider that all links have the same average SNR.

Firstly we examine the possibility to reduce the data loss rate by employing multiple satellites. We optimize the threshold in order to achieve either minimal data loss rate (min loss), or some desired, application driven target data loss rate (target loss). We verify that the performance obtained by DNN-based optimization matches the performance of the brute search. The results are presented in Fig. 7. We can observe that, for properly chosen margins and sufficiently large average SNRs, the use of two satellites can reduce the data loss rate by an order of magnitude, while employment of additional (third) satellite can produce nearly one more order of magnitude improvement.

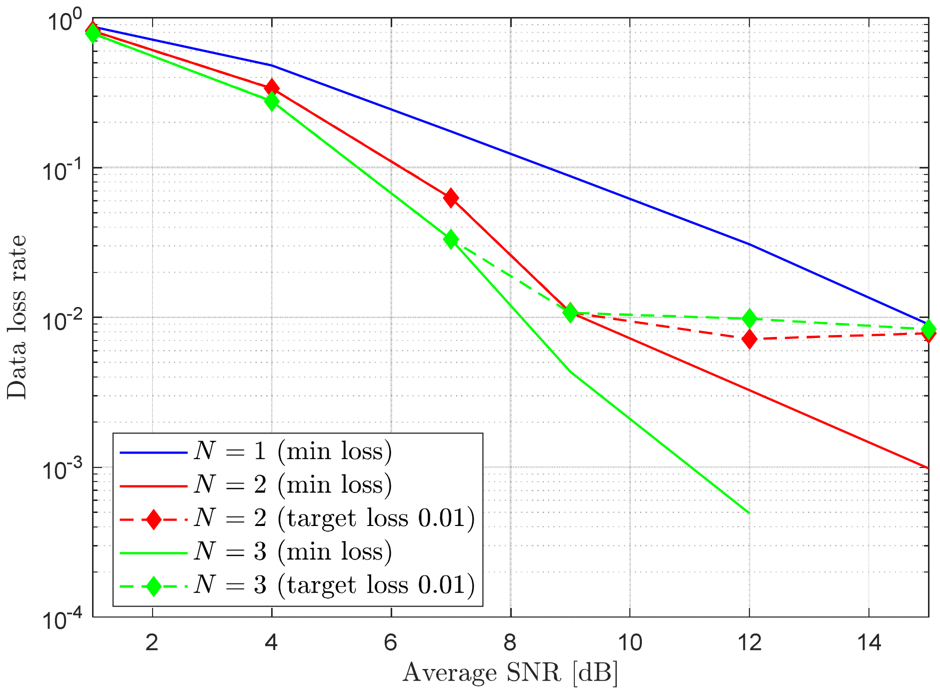

Figure 7. Data loss rate for multiple satellite connections.

We further examine the potential for increasing the spectral efficiency of the terrestrial communication by adding auxiliary satellite link. We can notice from Fig. 8 that approximately 1 dB of horizontal gain is achieved.

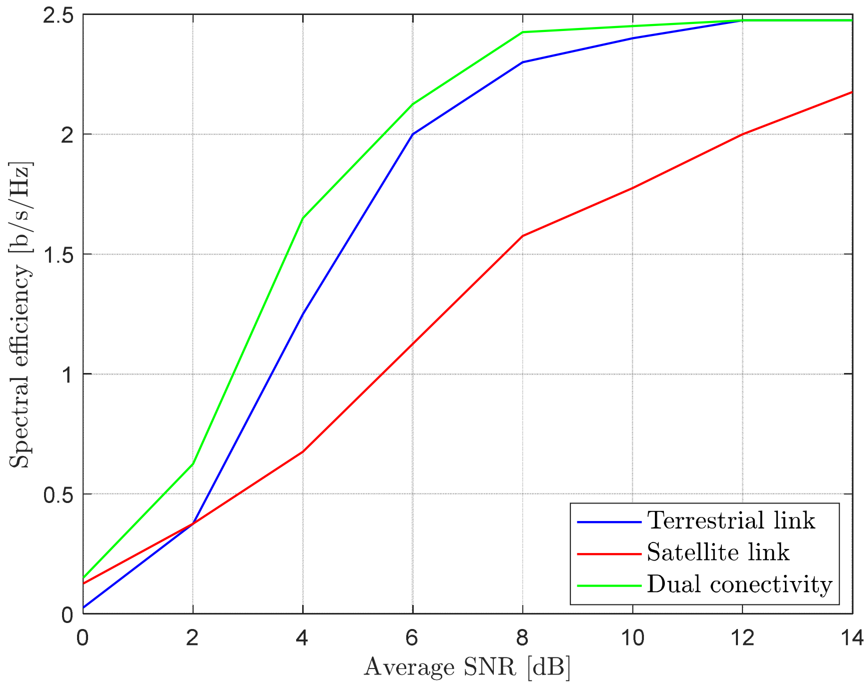

Figure 8. Achievable spectral efficiencies for terrestrial, satellite and dual connectivity end-users.

SECTION 5 CONCLUSIONS

In this deliverable we presented a handover procedure that based on the SNR measurements chooses appropriate RAN. We advocated usage of reinforcement learning to improve the achievable spectral efficiencies. We use adaptive margins to predict changes of the instantaneous SNR and explore benefits of multi-RAN connection. We have shown that if the end user could establish connection through multiple satellites the data loss rate can be reduced even by two orders of magnitude, while ensuring dual connectivity via terrestrial and satellite link can increase spectral efficiency.

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