Distributed Antenna System Based Frequency Switch Scheme Evaluation for High-Speed Railways

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***Abstract*—High-speed railway (HSR) has witnessed a huge growth globally, and now is reaching a maximum speed of 575 km/h. This record of speed makes mobile communications difficult for HSR since the handover (HO) frequency increases which results in a high loss of connectivity. Based on distributed antenna systems (DASs), this paper utilizes the two-hop network architecture for HSR broadband wireless communication systems. With the target of achieving high system capacity, superior transmission reliability, and consequently high-quality broadband wireless communication service for passengers in HSR. Moreover, a Frequency Switch (FSW) scheme is proposed for the two-hop network architecture to alleviate the frequent HO issue in traditional HSR wireless communication systems where HO generally happens between the successive remote antenna units (RAUs) connecting to the same central unit (CU) control. The FSW scheme provides mobility robustness signalling process that guarantees a successful frequency switching instead of HO, and reduces the probability of radio link failure (RLF) compared to HO process in traditional HSR systems, where the HO failure (HOF) rate is about 21%. The analytical results show that the proposed scheme outperforms traditional HO schemes.**

***Index Terms*—Mobile Relay, Distributed Antenna System, Handover, Frequency Switch, High-speed Railway, Moving Frequency Concept.**

I. INTRODUCTION

Nowadays, more and more efforts have been made to meet the ever-increasing demands for internet access as a result of the increased popularity of social media, the wide spread of smart phones, and tablets. Users' requirements vary from a simple internet access, high quality voice service to mobile video communication, such as on-line gaming and video conferencing. Recently, there has been an increasing interest in high-speed trains to provide internet access for passengers with high quality of services (QoS) to attract more travellers. High-speed railway (HSR) has been making a great success globally, and now its one of the most popular transportation means. However, the current broadband wireless communication systems are optimized for low to medium mobility situations [1–5]. For HSR, frequent handover (HO) is needed due to the high moving speed which may result in an increase in the drop off rates, and thus can degrade the overall system throughput seriously.

Distributed antenna system (DAS) has become very promising for future mobile system. DAS is considered as the most effective solution to deal with the HO issue in HSR mobile communications [6]. In such networks, multiple remote antenna units (RAUs) spread along the rail side and are connected to a central controller unit (CU) via optical fibres, where, a train does not need to HO between RAUs that fall under the same CU control, thanks to the moving frequency concept (MFC), in which a frequency pattern in each RAU moves/switches along with the train, so that the train is always served by the same frequency [7]. The frequent HO issue within the coverage of one CU can be then eliminated by DAS as each CU can control RAUs up to 20 km, as a result, less HO frequency will take place.

Recent published results from a LTE field tests taken place in a dense urban area exhibit a high HO failure (HOF) rate. The main reason of HOF is the transmission failure of the radio resource control (RRC) connection reconfiguration (RCR) command or what is known as the HO command [8]. In this paper, a new scheme, called Frequency Switch (FSW) scheme, is proposed to replace the traditional HO between RAUs controlled by the same CU by adopting the MFC into the RAUs under the control of the same CU, with the target of reducing the probability of failure, and thus, providing a fast and a robust mobility signalling process that guarantee a successful switching between the successive RAUs. The proposed FSW scheme consists of three phases, switch preparation, switch execution, and switch completion. In this scheme, a frequency switch is triggered based on a channel measurement report sent from the train to CU via RAUs. The FSW scheme is backward compatible with long-term evolution advanced (LTE-A). Also, we have proposed a new approach to prevent any early/late FSW/HO triggering event due to the train varying speed.

The remainder of this paper is organised as follows. Section II introduces the system architecture. An FSW scheme is proposed in section III. Section IV presents the switching performance via numerical analyses and simulations. Finally, section V concludes the paper.

II. SYSTEM ARCHITECTURE

The FSW scheme is proposed in a two-hop architecture, including RAU-mobile relay (MR) and MR-onboard, proposed in [7, 9, 10] as shown in Fig. 1. By deploying MRs which are on the top of the train, the user equipments (UEs) communicate with the access points (APs) deployed inside each carriage, and then the APs forward the UEs packets to RAUs via MRs. This two-hop architecture is used to avoid the penetration loss of the direct link (RAU to UE and vice-versa) as well as enable simultaneous group HO associated with hundreds of devices

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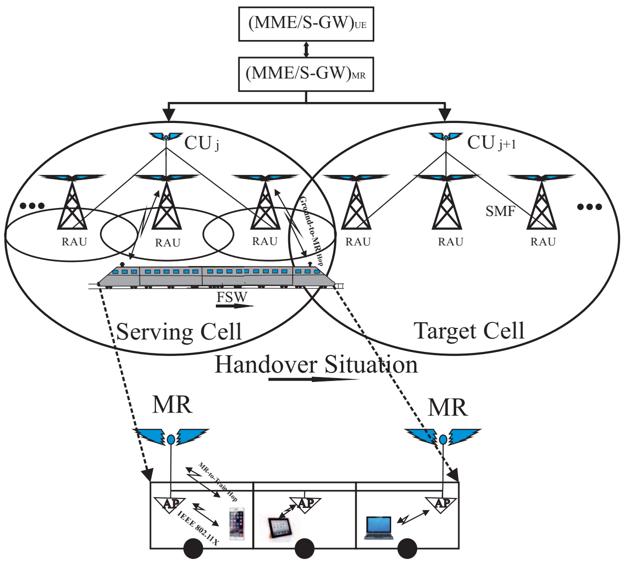

Figure 1: System architecture.

that need to be HO/FSW at the same time. Each MR represents all the UEs associated with it, therefore, the burden of the CU side will be considerably reduced during both HO and FSW processes. RAUs in the DAS will be deployed linearly along the track in a one dimensional fashion, since the new HSR tracks tend to have less inclination angles, and linear deployment can increase the possibility of a continuous line-of-sight (LoS) connection between RAUs and MRs. The need for HO between adjacent RAUs under the control of the same CU can be eliminated, by exploiting FSW scheme. In this scenario, each RAU propagates one or more non-interfering radio frequencies (RFs) and correspondingly associates with one or more RFs in the CU. In this paper, two MRs are considered on the train, and correspondingly the CU are associated with two different RFs. The core network contains a separate mobility management entity (MME) and serving/packet-gateway (S/P-GW) noted as ((MME)/(S/P-GW))$_{MR}$ and ((MME)/(S/P-GW))$_{UE}$ for MRs and UEs, respectively. Moreover, all the RAUs in the cell transmit data with equal power.

III. Frequency switch/Handover scheme

Based on the two-hop architecture, the MR is proposed to perform two schemes. The first is the FSW scheme to switch the serving frequency between two RAUs controlled by the same CU when the train moves from one RAU to the other RAU. When the train moves to a target RAU belonging to another CU, HO scheme will be triggered. The FSW/HO trigger selection process is shown in Fig. 2. Both schemes are designed based on the 3GPP specification [11], and the details of each scheme are as follows.

A. Proposed Scheme

In this section, an FSW scheme is proposed consisting of three phases: switch preparation, switch execution, and switch completion. In the following, without loss of generality, the FSW process of the first MR is described. The details are as follows:

Phase I: Frequency Switch Preparation

1) At the MR side, After receiving the measurement control command from the serving CU (CU$_j$), which includes list of current and target RAU IDs, and metrics to be measured. The metrics, such as the received signal strength (RSS), is used to evaluate the need to trigger the FSW/HO scheme. Also, the measurement control includes the time-to-trigger (TTT) value, during which the FSW/HO triggering condition should be satisfied, which assumed to be zero here, as the RAU has a small coverage area. Further, the measurement control command also instructs whether the type of triggering is periodical or event-based. This paper assumed the event-based type, as the periodical type delays the FSW/HO triggering process which may lead to increment in the failure rate. This delay is because CU$_j$ needs to wait for continuous z reports that satisfies the triggering condition in order to start the FSW/HO scheme. While, the event-based type triggers the FSW/HO process once the measured metric satisfies the triggering condition threshold [12].

2) MR will issue a measurement report to CU$_j$ as soon as the thresholds are satisfied for a TTT time. The measurement report includes the RAU ID that has the highest RSS.

3) Once CU$_j$ receives the measurement report issued by the MR, CU$_j$ will perform the FSW/HO decision algorithm to determine whether to switch/HO. Further, there will be no need to perform admission control during this phase as CU$_j$ does not change.

Phase II: Frequency Switch Execution

4) If CU$_j$ determines the need for switching/HO the MR to the next RAU, it checks if the target RAU (T) belongs to it. If so, CU$_j$ directly switches the downlink stream of the serving RAU (S) to T by modulating the intended stream on the same frequency (f) (of S) for T. Once the switching process is initiated, CU$_j$ starts buffering the intended packets of the correspondent MR. After a successful switching, all the buffered and upcoming packets will be sent in sequence starting from the new arrival packets. In this phase, there will be no need for bi-casting [13] or data forwarding from S to T [11]. As a result, there will be no extra delay introduced by data forwarding or its associated signalling overhead. Since the switching time is very short, and both RAUs are controlled by the same CU$_j$, therefore, CU$_j$ will be able to buffer the packets until a successful switching takes place. Thus, this scheme can deliver a lossless transmission during the switching process. Moreover, there will be no need for the MR to de-attach from S and perform a synchronization to T, as they will be using the same frequency to communicate and controlled by the same CU$_j$ as well. Furthermore, there will be no random access channel (RACH) preamble or access parameters negotiation. The chance for FSW failure can be then reduced compared to traditional HO.

Phase III: Frequency Switch Completion

5) Once CU$_j$ completes the switching process successfully for the first MR, the previous S will release the antecedent f

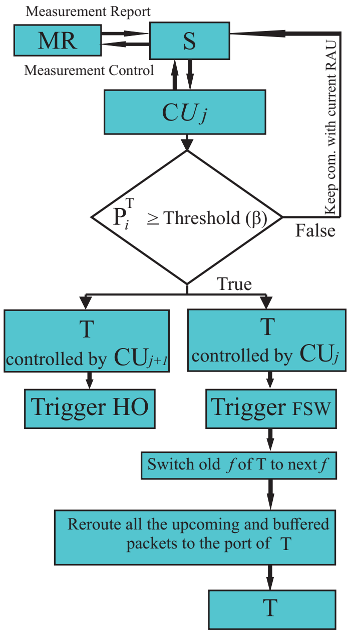

Figure 2: FSW/HO trigger decision selection.

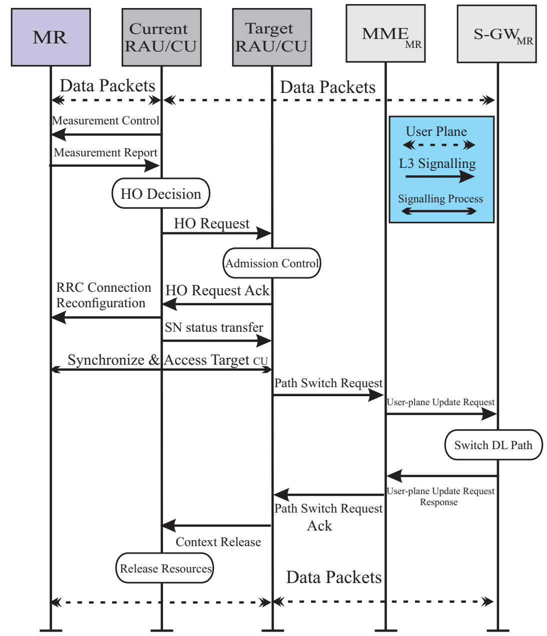

Figure 3: Central unit-central unit Handover.

and associate with the other frequency to communicate with the upcoming MR. Then a multiplexing process and transmission of the streams to the intended RAUs will take place.

For the FSW scheme, traditional HO phases including path switch, modify bearer, and UE context release will not be performed as CU_j is not changed. Also, there is no need for tracking area update as the S-GW is not changed too.

B. Central Unit-Central Unit Handover

If CU_j determines that T belongs to the target CU (CU_{j+1}), then, CU_j performs the HO scheme. Fig. 3 shows the signalling flow of the HO process, and the details are as follows:

1) CU_j sends an HO request to CU_{j+1}, where the admission control algorithm is performed to decide whether to accept the MR. The HO request includes the necessary information about the UEs QoS needs, which is used by the algorithm to evaluates CU_{j+1} ability to provide the required resources.

2) If CU_{j+1} is able to reserve the corresponding resources, it replies a HO request acknowledgment (ACK) to CU_j. Then, CU_j will command the MR to HO by sending RCR command to MR. RCR command includes the channel access parameters required to synchronize MR with CU_{j+1} as well as the crucial integrity protection and ciphering.

3) After successfully receiving the command, the MR uses the configuration included in the command to synchronize and access CU_{j+1} by sending the preamble message to CU_{j+1}. Meanwhile, CU_j sends a status transfer command to CU_{j+1} which initiates the data forwarding process. CU_{j+1} transmits the data to the MR once it becomes the serving CU.

4) If the MR successfully accesses CU_{j+1} by receiving the synchronization response command from CU_{j+1}, the MR responds back with RCR complete command to confirm the success of random access procedure. Then, CU_{j+1} sends a path switch request command to the $(MME)_{MR}$ to switch the routing path of the MR. Afterwards, the $(MME)_{MR}$ sends a user-plane update request command to $(S\text{-}GW)_{MR}$. Then, user-plane update request response is sent by $(S\text{-}GW)_{MR}$ back to $(MME)_{MR}$, and finally $(MME)_{MR}$ sends a path switch request ACK command to CU_{j+1}.

5) Next, operation and maintenance configuration update take place.

6) Finally, CU_{j+1} sends context release command to CU_j in order to release the reserved resources associated with the MR.

Table I: HO/FSW Success Latency Analysis.

HO/FSW Phases	Tp	Tp
HO/FSW decision	16 ms	5 ms
Synchronization	20 ms	-
Path Switch	13 ms	-
OAM	28 ms	-
Optical Switching	-	5 ns to 10 ms
Total	T_{HO}= 77 ms	T_{FSW} <=15 ms

C. Frequency Switch/Handover Triggering Condition

The FSW/HO scheme performs switching/HO to neighbor RAU if the RSS from the neighbor is above a predefined threshold value for the TTT time. As long as the above condition is satisfied, MR will trigger the measurement report to CU_j for evaluation, and CU_j will decide whether to switch/HO. The hysteresis parameter is not included in the above condition as the ping-pong effect [14] in the FSW/HO process will be eliminated since CU_j has a list of the current and target RAUs and the train is moving in a high-speed. In this way, a fast triggering condition that fits HSR speed as well as the RAU's small coverage area can be achieved.

Since railway is usually constructed in wide rural or viaduct areas, where multipath effect could be neglected most of the time, thus the main path signal is only considered [15]. With equal power allocation among RAUs, the RSS measured by the

Table II: Default Simulation Parameters.

Parameter	Value
Carrier Frequency	2 GHz
Symbol Duration	1/14 ms
Total Transmit Power with normally noise power	86 dBm
Path Loss Model	$30.6 + 26\log_{10}(\overline{d_i^k})$ dB
Shadow Fading Deviation	4 dB
Triggering Threshold β	-63 dBm
Total RAUs in each cell N	4
Cell radius	105 m
Overlap	10 m
Length of Train	400 m
Distance between RAU and Track	10 m

MR at the ith time interval from RAU k ($k \in S, T$) is denoted by P_i^k, and can be obtained as

$$P_i^k[dBm] = P_t - 10\log_{10} N - P_L + 10\log_{10} S_i^k, \quad (1)$$

where S and T are the serving and target RAUs, respectively. $P_t[dBm] = 10\log_{10}(P_T/(P_T\Delta + 1))$ represents the final transmitted power which takes into account the Doppler frequency shift effect on OFDM system that will cause intercarrier interference (ICI) [6]. A tight upper bound has been achieved for the ICI power in [16] as

$$\Delta = \int_{-1}^{1}(1-|x|)(1-J_0(2\pi f_D T_s x))dx, \quad (2)$$

where $J_0(.)$ is the zeroth-order Bessel function of the first kind. f_D is the maximum Doppler frequency shift, and T_s is the symbol duration. P_T is the total transmitted power. N is the total number of RAUs in each cell. $P_L[dB] = 30.6 + 26\log_{10}(\overline{d_i^k})$ [17] is the path loss where $\overline{d_i^k}$ is the distance between the MR and the kth RAU, $\overline{d_i^T}$ is given by $(\sqrt{(D-x_i)^2 + (d_v)^2})$, $\overline{d_i^S}$ is given by $(\sqrt{(x_i)^2 + (d_v)^2})$ [5], D is the inter-RAU distance between successive RAUs, x_i is the MR's current location, and d_v is the vertical distance between the RAU and the track (see Fig. 6). Shadowing at the ith time interval is represented by $\log_{10} S_i^k \sim \mathcal{N}$ $(0, \sigma_i^k)$ that follows a Gaussian distribution with a zero mean and standard deviation σ_i^k. Now let $A[dBm] = P_t - 10\log_{10} N - 30.6$. Then, the RSS can be represented as

$$P_i^k[dBm] = A - 10\gamma\log_{10}(\overline{d_i^k}) + 10\log_{10} S_i^k. \quad (3)$$

IV. Performance Evaluation

To investigate the performance of the FSW scheme, the FSW probability, and success FSW probability will be analysed and compared with traditional HO procedure scheme. It will be used to verify the FSW's ability to enhance the overall system performance by delivering the required QoS. Also the system performance will be investigated in terms of the required inter-RAUs' distance and the average latency. The default simulation parameters are presented in Table II.

A. Frequency Switch/Handover Success Probability

Since the FSW probability which is equal to the report triggering probability is the only procedure required for the FSW scheme to be activated and finished successfully, consequently, the success FSW probability is equal to the FSW triggering probability and that can be derived for one RAU as follows

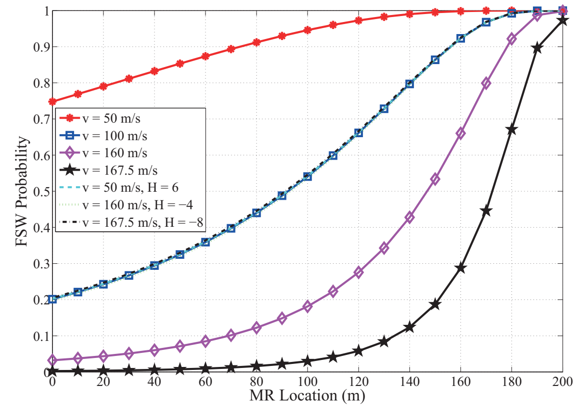

Figure 4: FSW probability versus MR location when β = -63 dBm, for train various speeds and correspondingly different H values (50 m/s, 100 m/s, 160 m/s, 167.5 m/s)

$$\begin{aligned}\mathbf{P}_{SW_s} &= \mathbf{P}\left\{P_i^T \geqslant \beta\right\} \\ &= \mathbf{P}\left\{A - 10\gamma\log_{10}(\overline{d_i^T}) + 10\log_{10} S_i^T \geqslant \beta\right\} \\ &= \mathbf{P}\left\{10\log_{10} S_i^T \geqslant \beta - A + 10\gamma\log_{10}(\overline{d_i^T})\right\} \\ &= Q\left(\frac{\beta - A + 10\gamma\log_{10}(\overline{d_i^T})}{\sigma_i^T}\right), \end{aligned} \quad (4)$$

where $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{\frac{-t^2}{2}}dt$ represents the Q-function, β is the triggering threshold. (4) also applies for the HO triggering probability. According to (4), when the MR is located at a location x_i, the FSW process can be triggered if the detected signal strength of T is equal to or better than β. Once the MR triggers the report to CU$_j$ a successful FSW process will be achieved. As the other FSW procedure is related to CU$_j$ side, there will be no more messages to be negotiated between CU$_j$ and the MR, which might be susceptible to losses and retransmission process. Further, varying speed results in a varying $\mathbf{P}_{SW_s}$ as shown in Fig. 4, therefore, to compensate for this effect we propose a new parameter H that will keep $\mathbf{P}_{SW_s}$ approximately the same regardless of the train speed. This assumption is true since the HSR does not vary its speed in a random patterns and perform acceleration and deceleration slowly and smoothly. For example, it takes 15 minutes for HSR in Taiwan to speed-up from 0 to 83.3 m/s [12]. Furthermore, since the system architecture is specially designed for HSR communication systems and all the parameters in the system are optimized for a specific speed (the speed that the train will be moving most of the times) which for our case is 100 m/s, then H can be expressed as

$$H = 10\log_{10}\frac{\Delta_s}{\Delta_c}, \quad (5)$$

where Δ_s and Δ_c are the ICI that result from the system specific and the current HSR speeds, respectively. Once the MR sense a varying speed it will weigh the speed variation and calculate a suitable H value based on (5) and apply it to (4), when the speed is fixed H is zero. Then, the switching triggering probability

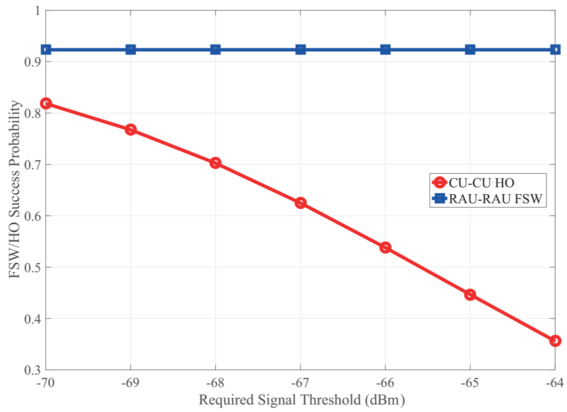

Figure 5: FSW/HO success probability versus U threshold at speed = 100 m/s evaluated at the MR's location of 160 m.

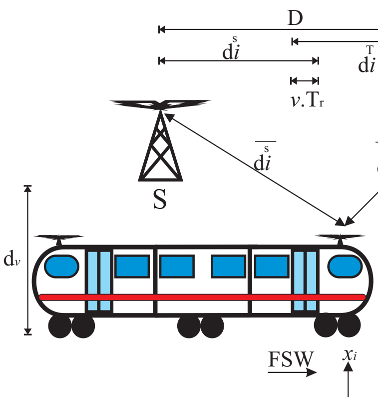

Figure 6: System model.

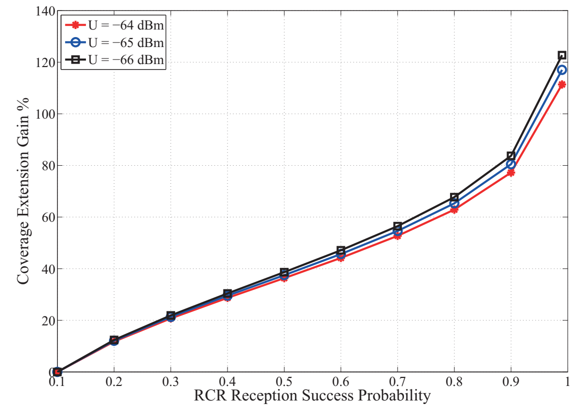

Figure 7: Coverage Extension gain versus successful RCR command reception at speed = 100 m/s, when β = -63 dBm.

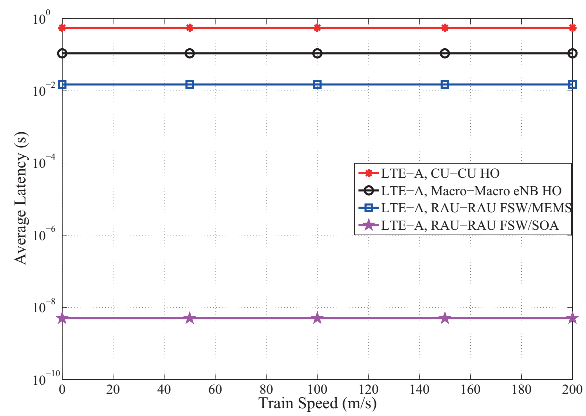

Figure 8: The average FSW/HO latency.

and correspondingly the successful switching probability when the train is accelerating or decelerating can be given by

$$\begin{aligned}\mathbf{P}_{SW_s} &= \mathbf{P}\left\{P_i^T \geqslant \beta + H\right\} \\ &= Q\left(\frac{\beta - A + 10\gamma\log_{10}(\overline{d_i^T}) + H}{\sigma_i^T}\right). \end{aligned} \quad (6)$$

Since FSW process can be triggered at any location between S, and T, the probability that the MR can perform successful FSW procedure can be depicted as in Fig. 4 for different speeds.

As traditional HO needs CU_j to send RCR command to MR to finish the HO successfully, losses and retransmission of this command will result in either increase in the HO latency or a radio link failure (RLF). This means that the FSW process is faster and more reliable compared to HO leading to a higher successful probability than traditional HO. The successful HO probability can be obtained as follows

$$\begin{aligned}\mathbf{P}_{HO_s} &= \mathbf{P}\left\{P_i^T \geqslant \beta\right\} \cdot \mathbf{P}\left\{P_i^S > U\right\} \\ &= Q\left(\frac{\beta - A + 10\gamma\log_{10}(\overline{d_i^T})}{\sigma_i^T}\right) \\ &\cdot Q\left(\frac{U - A + 10\gamma\log_{10}(\overline{d_i^S})}{\sigma_i^S}\right), \end{aligned} \quad (7)$$

where U is the required signal threshold for the MR to successfully recover the RCR command from S. (7) implies that in order to have a successful HO procedure, P_i^T should satisfy the threshold and P_i^S should be greater than U in order to be successfully received by the MR. Fig. 5 shows the numerical result of successful FSW/HO procedure probability evaluated at the MR's location of 160 m. As can be seen, the FSW scheme is not affected by varying U, while for the HO scheme as U decreases the HO success probability increases. The reason is that it ensures a superior P_i^S to receive the command successfully. Also, it can be seen that the FSW scheme performs better than the HO scheme for all the chosen U values. Note that in the following analysis we use CU-CU HO success probability of 0.55 which corresponds to U= -66 dBm.

B. *Inter-RAU Distance*

In this section, the maximum required inter-RAU distance D which maintains a successful FSW/HO procedure is analyzed. In order to do so, $Q(\beta - A + 10\gamma\log_{10}(d_i^T)/\sigma_i^T)$ is assumed to approach 1, for both cases in order to find d_i^T (see Fig. 6), as FSW/HO process both need to trigger the report to be initiated, where d_i^T is the maximum distance between MR and T that can achieve a successful measurement report triggering. Since the FSW scheme is not needed for RCR command transmission to have a successful FSW procedure, $Q(U - A + 10\gamma log_{10}(d_i^S)/\sigma_i^S)$ is assumed to approach zero to find d_i^S for the FSW case, where d_i^S is the maximum distance between MR and S that can achieve a successful RCR command reception. For a successful HO procedure, RCR command should be correctly received from S, so $Q(U - A + 10\gamma \log_{10}(d_i^S)/\sigma_i^S)$ should approach 1. However, since the train is moving away from S, the probability of having a successful RCR command reception will be lower resulting in higher failure probability. As a result, the coverage extension of the FSW process compared to HO process is examined against varying RCR command success probability that lies between (0.1, 1) to find d_i^S for HO case. For the HO case there will be an overlapping region between d_i^S and d_i^T of $(v \cdot T_r)$ where T_r is the time needed by CU_j and correspondingly S to respond with RCR command upon reception of the measurement report, and v is the train speed. Since $d_i^S + d_i^T \gg v \cdot T_r$, then, we will neglect this portion. Therefore, D for both cases will be approximately equal to $d_i^S + d_i^T$, as d_v is very small in our scenario. Fig. 7 shows the coverage gain for the FSW case compared to the HO case. As it can be seen from Fig. 7, the success HO probability increases as the RAU coverage gain increases compared to the case of successful FSW, reaching a coverage gain of 120 % for 100% successful HO procedure.

C. Frequency Switch/Handover Average Latency

The FSW/HO latency is a critical metric of whether the designed FSW/HO procedure is efficient. As the FSW/HO is susceptible to failure, so there are two types of latencies the first one is associated with a successful process and the other is related to the failure case. Then, the total average FSW/HO latency associated with the MR for one RAU can be found as follows

$$\mathbf{T} = \mathbf{P}_{(FSW/HO)_s} \cdot T_s + (1 - \mathbf{P}_{(FSW/HO)_s}) \cdot T_{rec}, \quad (8)$$

where $\mathbf{P}_{(FSW/HO)_s}$ denotes the probability of a successful FSW/HO procedure, T_s denotes the time required for the scheme to finish successfully (see Table I), and T_{rec} is the time required to recover from an RLF. In traditional LTE-A HO scheme, after the expiration of timer T304 an RLF is declared due to HOF. Then, MR starts timer T311 for cell reselection, after successful cell resection, the MR stops timer T311 and starts timer T301 and begins the connection reestablishment with the selected cell by sending RRC connection reestablishment. The reestablishment procedure is successful only if the MR selects a prepared cell. Consequently, T_{rec} is the accumulated times of the above timers. In FSW scheme, the RLF probability is zero since it can achieve 100% success before reaching the target RAU so there is no wasted time in such operation. Fig. 8 shows the average latency associated with FSW/HO scheme, as can be seen, the CU-CU HO represents the worst performance as the HOF probability is high due to the small coverage area between RAUs which is not sufficient to finish the HO procedures successfully resulting in a higher average delay, while the FSW scheme using the SOA as an optical switch represents the best performance as the switching time for it is very small. Note that the macro-macro success HO is derived from [5] which is 0.97 when the speed is 100 m/s.

V. Conclusion

This paper proposed a specialized DAS network for future HSR wireless communication systems. A frequency switch scheme is further proposed when a train moves from one RAU to the next one under the same CU control. The proposed scheme was evaluated analytically and our results showed that compared to HO, FSW scheme will be able to deliver application with high QoS requirement, as seamless and lossless FSW is achieved. However, CU-CU HO shows worse performance than macro-macro eNB HO as the adjacent RAUs coverage area is small and not sufficiently enough to finish successfully.

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