

Improving Handover and Drop-off Performance on High Speed Trains with Multi-RAT

Yi-Bing Lin, *Fellow, IEEE*, Shun-Neng Yang, and Chien-Ting Wu

Abstract—Provisioning commercial mobile telecommunications service on high speed train (HST) faces several challenges. In particular, when a HST quickly passes through the radio coverage of the base stations, frequent handovers may result in serious communication interruption. Methods such as the hierarchical two-hop (HTH) network and the seamless dual-link handover scheme were proposed to address these challenges. This paper proposes the multiple radio access technology (multi-RAT) to resolve the HST handover issue, which allows the HST to simultaneously connect to two or more heterogeneous mobile networks (e.g., Universal Mobile Telecommunications System (UMTS) and Long Term Evolution (LTE)). With this approach, the handover process can be improved by keeping multiple heterogeneous network links of the HST at the same time and maintaining the connection through one link during the handover process of the other link. We show that multi-RAT can effectively enhance HST communications by reducing the impact of handover failure. This approach can work together with other solutions such as the dual-link scheme to further enhance the performance of the HST communications.

Index Terms—handover, hierarchical two-hop (HTH), high speed train (HST), multiple radio access technology (Multi-RAT)

I. INTRODUCTION

Today, most telecommunications services for rail transport are provisioned by commercial mobile telecommunications systems such as Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), Code Division Multiple Access 2000 (cdma2000), and Long Term Evolution (LTE). In these systems, a mobile subscriber carrying user equipment (UE; see Fig. 1 (a)) to communicate with the mobile core

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network (Fig. 1 (b)) through a base station (BS; see Fig. 1 (c)). The radio coverage of a base station (or a sector of the base station) is called a *cell*. When the user equipment UE 1 moves from BS 1 to BS 2 (Fig. 1 (d)), the wireless connection of UE 1 is switched from BS 1 to BS 2. This process is called *handover*.

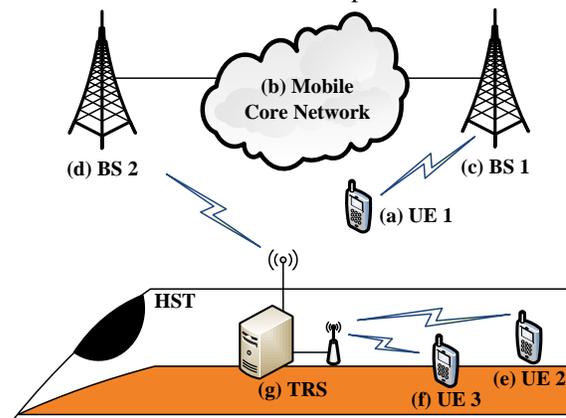


Fig. 1. Hierarchical Two-Hop (HTH) Network for HST

Although the commercial mobile telecommunications systems serve non-high speed trains well, utilizing these commercial systems on high speed trains (HSTs) faces several challenges. The issues include wireless signal degradation because of the Faraday cage characteristics, frequent handovers and drop-offs due to high speeds of trains and relatively small cell sizes in broadband wireless systems, synchronization of orthogonal frequency-division multiplexing (OFDM) against Doppler effect, and so on. In particular, when a HST quickly passes through the cells, frequent handovers may result in serious communication interruption. Some methods such as hierarchical two-hop (HTH) network (or dual-layer network), radio-over-fiber (RoF), moving cells and prediction based handover schemes were proposed to address these challenges (see [1], [2] and the references therein). Among them, the HTH network approach was widely adopted where all UEs in a HST (e.g., Fig. 1 (e) and (f)) communicate with a Train Relay Station (TRS; Fig. 1 (g)), and the TRS relays the UE connections to a BS (Fig. 1 (d)). The TRS typically supports Wi-Fi connections to the UEs in the HST, and communicates with the BSs by an “external” antenna outside the HST. Although the HTH network can effectively eliminate the handover overheads of individual UEs in the HST, it is still possible that the wireless connection to the TRS is interrupted during handover (to be elaborated in Section 3).

Following this HTH network approach, some studies [3]-[5]

described a novel dual-link handover scheme for seamless wireless connectivity in a HST (abbreviated as the *dual-link* scheme), which reduced the communication interruption during TRS's handover. Specifically, two external antennas are deployed at the front and the rear of a HST. The TRS selects the antenna that can connect to the BS with better signal quality. When the front antenna is involved in the handover process, the rear antenna can still connect with the old BS to avoid communication interruption. If the handover process with the front antenna is successful, the rear antenna simply switches the frequency to that of the new BS. On the other hand, if the previous handover failed, another handover process is executed with the rear antenna again. Implementation of this scheme needs to modify the standard 3rd Generation Partnership Project (3GPP) handover procedure [6]. When the HST moves through the railway tunnels, this two-antenna scheme can still work by using the coverage-extension technology of RoF [7].

Unlike the above studies [3]-[5], we propose to resolve the TRS handover issue by using the multiple radio access technology (multi-RAT) [8]. The multi-RAT technique is widely used in data offloading and network load balancing [9][10]. With multi-RAT, this paper proposes a new soft handover concept, where the TRS of a HST can simultaneously connect to two or more heterogeneous networks (e.g., UMTS and LTE) [9], and the handover process can be improved by keeping multiple heterogeneous network links of the TRS at the same time and maintaining the TRS connection through one link during the handover process of the other link [10]. In this paper, we show how multi-RAT can effectively enhance HST communications by reducing the impact of handover failure. This approach can work together with other solutions such as the dual-link scheme to further enhance the performance of the HST communications. The paper is organized as follows. Section 2 proposes the multi-RAT soft handover approach. Section 3 studies the HTH network and the dual-link scheme. Section 4 evaluates the performance of the multi-RAT soft handover scheme. Finally, conclusions are given in Section 5.

II. MULTI-RAT SOFT HANDOVER

Most existing mobile devices are equipped with more than one network interfaces such as LTE, UMTS, High Speed Packet Access Plus (HSPA+), Enhanced Data rates for GSM Evolution (EDGE), Worldwide Interoperability for Microwave Access (WiMAX), and so on [11]. Since a geographic location is typically covered by BSs of multiple *tiers* of mobile telecommunications systems (multi-mode or multi-band heterogeneous networks), through multi-RAT, a UE may connect to two or more networks simultaneously to increase the throughput for wireless transmission.

As we point out in the previous section, frequent handovers are the main issue for wireless communications of HST. Rapidly passing through overlap areas of cells leads to high handover failure rate. With multi-RAT, we propose to perform *soft handover* at the application level (i.e., Internet Protocol or IP) to reduce the communication interruption of HST caused by handovers. In our approach, multi-RAT feature is implemented in the TRS by including multiple wireless modules with

different Universal Subscriber Identity Module (USIM) cards and antennas. For example, suppose that the TRS is multi-RATed with two tiers, UMTS and LTE, then it will have two external antennas connecting to both Wideband Code Division Multiple Access (WCDMA) / High Speed Packet Access (HSPA; for UMTS) and LTE base stations. In normal operation, the TRS maintains both UMTS and LTE links (i.e., link (a)-(b)-(c)-(d)-(e) and link (a)-(f)-(g)-(d)-(e) in Fig. 2). Both links are merged at the Multi-Connection Manager (MCM; Fig. 2 (d)) that routes the UE connections to their destinations in the Internet or the mobile networks [12]. When a link is not available due to handover, the data connection between the TRS and the MCM is switched to the other link. That is, once a link is detected as unavailable (e.g., low link quality or link failure), the TRS can quickly switch (within 10 ms) the data stream of the unavailable link to the other available link for continuous connectivity. We name this approach as multi-RAT soft handover (abbreviated as multi-RAT). Our idea is similar to the "radio" soft handover of HSPA where a UE can connect up to 6 HSPA BSs [11]. However, there are three major differences between these two soft handover approaches. First, in HSPA soft handover, the UE connects to the homogeneous HSPA BSs while in multi-RAT soft handover, the UE connects to multiple heterogeneous BSs (e.g., one HSPA BS and one LTE BS as illustrated in Fig. 2). Second, HSPA soft handover is exercised at the radio layer while multi-RAT soft handover can be exercised at the application (IP) layer. Third, all HSPA links connected to a UE deliver the same data stream while multi-RAT links deliver different data streams (and therefore increase the transmission capacity of the UE). Implementation of multi-RAT does not need to modify any 3GPP procedures, and the details are described in [12].

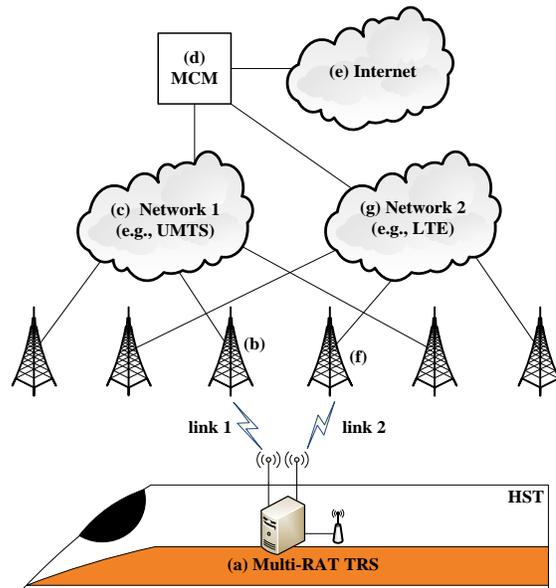


Fig. 2. Multi-RAT Soft Handover

III. PERFORMANCE OF HST COMMUNICATIONS WITH HIERARCHICAL TWO-HOP NETWORK

This section conducts analytic and simulation modeling to

investigate the performance of HST communications with hierarchical two-hop (HTH) network. With the HTH network approach, only the TRS needs to involve in handover. Suppose that the handover time for the TRS is t , a random variable with the density function (pdf) $f(t)$. The 3GPP standard specifies that $E[t] < 300$ ms, and our measurements indicate that $E[t] \approx 100$ ms. This paper assumes $E[t] = 100$ ms.

Let T_o be the time interval for the HST to pass through the overlap area of two consecutive cells. Then the TRS must complete the handover process and switch from the old cell to the new cell within T_o . Assume that the HST speed is around 360 Km/h, and the average overlap area of two consecutive cells is around 300 meters, then $E[T_o] \approx 3$ seconds. During handover, the TRS is successfully switched from the old cell to the new cell if $t < T_o$. Suppose that T_o is a random variable with the density function $g_o(T_o)$ and the Laplace transform

$$g_o^*(s) = \int_{T_o=0}^{\infty} e^{-sT_o} g_o(T_o) dT_o.$$

If the random variable t is exponentially distributed with the rate λ , then $f(t) = \lambda e^{-\lambda t}$. Thus the probability that the handover of the TRS is successful when the HST passes through a cell is

$$\begin{aligned} \Pr[t < T_o] &= \int_{T_o=0}^{\infty} \int_{t=0}^{T_o} \lambda e^{-\lambda t} g_o(T_o) dt dT_o \\ &= \int_{T_o=0}^{\infty} (1 - e^{-\lambda T_o}) g_o(T_o) dT_o = 1 - g_o^*(\lambda), \end{aligned} \quad (1)$$

while the probability that the TRS fails to hand over to the new cell is

$$p_{h,1} = g_o^*(\lambda). \quad (2)$$

We have developed a simulation model which is validated by (1) with Exponential t and Gamma T_o distributions. The experiments indicate that the discrepancies between the analytic and simulation results are within 0.1%. Then we extend the simulation model to accommodate Gamma t distribution. The Gamma distributions are considered because this distribution is widely used in telecom modeling (see [13], [14] and the references therein). The Laplace transform for Gamma T_o is

$$g_o^*(s) = \left(\frac{E[T_o]}{sV_o + E[T_o]} \right)^{\frac{E[T_o]^2}{V_o}},$$

where V_o denotes the variance of Gamma T_o distribution.

The HTH network performance has been investigated in

terms of data rate [15], which proved that through the TRS, the power consumption of UEs in the HST could be saved. Through simulation experiments we investigate the handover performance in a HST with the HTH network.

The performance of the HTH network approach can be improved by the dual-link scheme [3]-[5]. When the HST moves across the boundary of two cells, the TRS of the dual-link scheme has the opportunity to conduct handover twice (one for the front antenna and one for the rear antenna). Theoretically, the dual-link scheme can be extended to accommodate multiple antennas. Practically, multiple antennas may not be feasible for the following reason. In the dual-link scheme, the handover processes for the antennas are executed sequentially. Therefore the antennas must be placed “far” apart or the time allowed for the rear antenna to perform handover is shorter than that for the front antenna. In [4], the distance between two antennas is $X_1 = 200$ meters. In Fig. 3, the overlap area of two cells is $X_2 = 300$ meters in diameter. The front antenna conducts handover to switch from BS 1 to BS 2 when it travels through this 300-meter overlap area. If the front antenna fails to switch to BS 2 when it passes the boundary of the overlap area (see point (A) in Fig. 3), the rear antenna already entered the overlap area for $X_2 - X_1 = 100$ meters (see point (B) in Fig. 3), and only 200 meters left for this antenna to perform handover before it leaves the overlap area. In other words, if $X_2 > X_1$, then the rear antenna can only perform handover during the time period when it travels for the distance X_1 . If the time budget for the front antenna to perform handover is T_o , then approximately, the time budget for the rear antenna is εT_o , where

$$\varepsilon = \begin{cases} X_1 / X_2, & \text{for } X_2 > X_1 \\ 1, & \text{for } X_2 \leq X_1 \end{cases}.$$

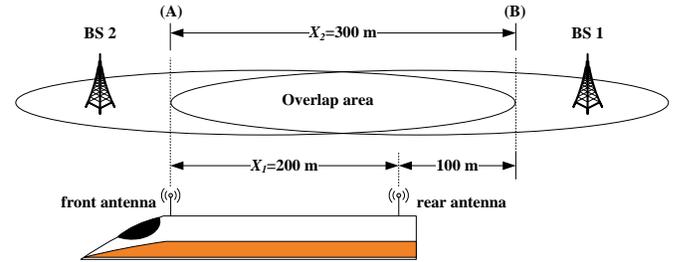


Fig. 3. The overlap area for handover in the dual-link scheme

Assume that εT_o has the same distribution as T_o except that $E[\varepsilon T_o] = \varepsilon E[T_o]$ and its Laplace transform is denoted as $g_{o,\varepsilon}^*(s)$. Let $p_{h,2}$ be the probability that the TRS of the dual-link scheme fails to hand over to the new cell. Then from (2), $p_{h,2}$ is expressed as

$$p_{h,2} = g_o^*(\lambda) g_{o,\varepsilon}^*(\lambda). \quad (3)$$

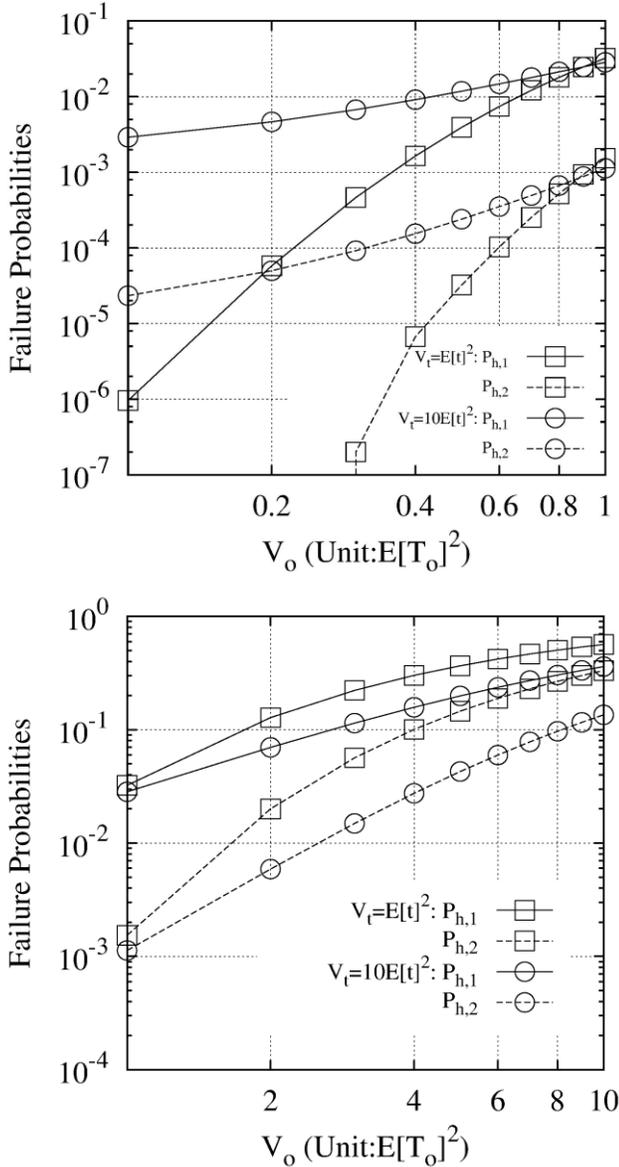


Fig. 4. The $p_{h,m}$ performance for the TRS ($E[t] = 1/\lambda = 100$ ms, $E[T_o] = 3$ seconds)

Equation (3) is consistent with the results in [4]. Fig. 8 of [4] shows that, for example, if we place the two antennas 200 meters away in the HST, and the HST travels for 300 meters to cross the cell overlap area, then the dual-link scheme can improve handover failure performance over the HTH network approach from $p_{h,1} \approx 0.03$ to $p_{h,2} \approx 0.0014$. This result is consistent with (3) for $V_t = E[t]^2, V_o = 0.9775E[T_o]^2$ (V_t denotes the variance of Gamma t distribution), and $\varepsilon = 2/3$. By using (3), we have $p_{h,1} = 0.03, g_{o,\varepsilon}^*(\lambda) = 0.0454$ and $p_{h,2} = 0.001362$.

For the multi-RAT approach, it is not appropriate to be evaluated through the handover performance due to its application-level soft handover nature. Suppose that I tiers of mobile systems are available in the moving path of a HST. In Taiwan, for example, LTE, HSPA+, EDGE and WiMAX may

co-exist in the HST environment, and $I = 4$. If the BSs of these I tiers are deployed independently, then the handover processes for these tiers are not likely to perform simultaneously. We will investigate the multi-RAT performance through availability of connection in the next section.

Fig. 4 shows that the dual-link scheme (the dashed curves) outperforms the HTH network approach (the solid curves) for various V_o and V_t values. However, when both V_o and V_t are large, poor $p_{h,2}$ performance may still be observed. For example, if $V_o = 10E[T_o]^2$ and $V_t = 10E[t]^2, p_{h,2} = 0.1354562$. If the TRS fails the handover process, then it needs to re-establish the wireless connection again, and during connection setup, wireless communications in the HST may be seriously degraded. In the next section we show how connection setup affects the performance of the HTH network and the dual-link scheme, and how multi-RAT soft handover can resolve this issue.

IV. CONNECTION PERFORMANCE OF HTH WITH AND WITHOUT MULTI-RAT

Let t_s be the time for the TRS to set up the connection after a handover failure, which is a random variable with the pdf $f_s(t_s)$. Following the 3GPP standard and our measurements, we assume that $E[t_s] = 5$ seconds. Let $T_{n,j}$ be the time period for a HST to travel through the non-overlap area of a cell j . We assume that the HST speed is 360Km/h, the non-overlap area of a cell is 6 Kms, and $E[T_{n,j}] = 1$ minute.

If we observe the behavior of the TRS for a long period when the HST moves across the cells, then we will see consecutive handover events if the TRS successfully hands over to the consecutive cells. If the TRS fails to hand over to a cell, then we will observe one or more connection setup events before the next handover occurs. Therefore the observed period can be partitioned into “time cycles” by the handover events. Fig. 5 illustrates a time cycle T_c between two handovers of the TRS.

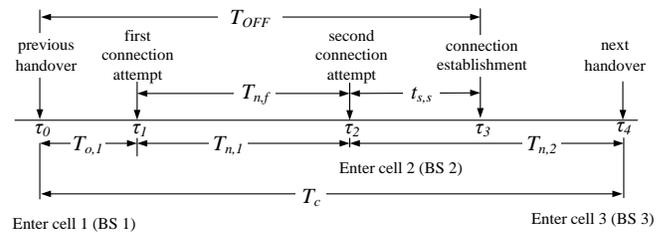


Fig. 5. The timing diagram for the events occurring between two handovers

In this figure, the HST enters cell 1 at τ_0 , and leaves the cell overlap area at τ_1 . If the TRS fails to complete the handover process by τ_1 , it needs to conduct a standard 3GPP connection setup to BS 1. The HST moves to cell 2 at τ_2 , and the time to pass through the non-overlap area of cell 1 is $T_{n,1} = \tau_2 - \tau_1$. If

the TRS fails to connect to BS 1 before τ_2 (i.e., $t_s > T_{n,1}$), then it must establish the connection with BS 2 again. If the reconnection is successful at the j -th connection attempt, then $T_c = \sum_{l=1}^j (T_{o,l} + T_{n,l})$ where $T_{o,l}$ is the time period for the HST to travel through the overlap area between the $(l-1)$ -th and l -th cells. Note that j is the number of BSs visited by the HST during the T_c cycle. In Fig. 5, after the TRS has connected to BS 2 at τ_3 , it moves to cell 3 at τ_4 . That is, after the TRS has conducted the previous handover at τ_0 , the next handover occurs at τ_4 . In this scenario, $T_c = \tau_4 - \tau_0$ and $j = 2$. Since $T_{o,j} \ll T_{n,j}$ in general (e.g., $E[T_{o,j}] = 3$ seconds and $E[T_{n,j}] = 1$ minute), we simplify the T_c equation as

$$T_c = \sum_{l=1}^j T_{n,l} \quad \text{for } j \geq 1. \quad (4)$$

Assume that the connection setup time t_s is exponentially distributed with the rate μ . Let $T_{n,j}$ be i.i.d. random variables, then notation $T_{n,j}$ can be simplified as T_n , which is a random variable with the pdf $g_n(T_n)$, the cdf $G_n(T_n)$ and the Laplace transform $g_n^*(s) = \int_{T_n=0}^{\infty} e^{-sT_n} g_n(T_n) dT_n$. Let p_s be the probability that the TRS successfully re-establishes the connection. Then similar to (2),

$$p_s = 1 - g_n^*(\mu). \quad (5)$$

If the connection re-establishment fails, then the travel time $T_{n,f}$ to pass the non-overlap area is T_n under the condition that $t_s > T_{n,f}$. In Fig. 5, the TRS attempts to connect to cell 1 at τ_1 , but cannot complete the connection setup process before the HST moves to cell 2 at τ_2 . Therefore, $T_{n,f}$ for this connection attempt is $T_{n,f} = \tau_2 - \tau_1$. $E[T_{n,f}]$ is derived as

$$\begin{aligned} E[T_{n,f}](1 - p_s) &= \int_{T_n=0}^{\infty} \int_{t_s=T_n}^{\infty} T_n \mu e^{-\mu t_s} g_n(T_n) dt_s dT_n \\ &= \int_{T_n=0}^{\infty} T_n g_n(T_n) e^{-\mu T_n} dT_n \\ &= - \left. \frac{dg_n^*(s)}{ds} \right|_{s=\mu}. \end{aligned} \quad (6)$$

Let $t_{s,s}$ be the setup time for a successful re-connection; i.e., $t_{s,s}$ is t_s under the condition that $t_{s,s} < T_n$. In Fig. 5, the HST

enters cell 2 at τ_2 and the TRS successfully connects to this cell at τ_3 . Therefore, $t_{s,s} = \tau_3 - \tau_2$. We derive $E[t_{s,s}]$ as

$$\begin{aligned} E[t_{s,s}]p_s &= \int_{t_s=0}^{\infty} \int_{T_n=t_s}^{\infty} t_s \mu e^{-\mu t_s} g_n(T_n) dT_n dt_s \\ &= E[t_s] - \int_{t_s=0}^{\infty} \mu t_s e^{-\mu t_s} G_n(t_s) dt_s \\ &= E[t_s] + \mu \left. \left\{ \frac{d[g_n^*(s)/s]}{ds} \right\} \right|_{s=\mu} \\ &= \frac{1 - g_n^*(\mu)}{\mu} + \left. \frac{dg_n^*(s)}{ds} \right|_{s=\mu}. \end{aligned} \quad (7)$$

Let T_{OFF} be the time interval that the TRS's wireless connection is not available in the time cycle T_c . Clearly, during connection setup, the TRS cannot provide communications between the UEs and the network, and the $T_{n,f}$ and the $t_{s,s}$ periods contribute to T_{OFF} . In Fig. 5, $T_{OFF} = \tau_3 - \tau_0$. Let α_m be the probability (or the portion of the time) that the wireless connection is not available to a HST for the HTH network approach ($m=1$) or for the dual-link scheme ($m=2$). Then α_m can be expressed as

$$\alpha_m = \frac{E[T_{OFF}]}{E[T_c]}. \quad (8)$$

Consider T_c expressed in (4). For $j=1$, there are two cases. If the previous handover is successful (with probability $1 - p_{h,m}$), then $E[T_c] = E[T_n]$ and $T_{OFF} = 0$. If the previous handover fails and the first connection setup (with BS 1) is successful (with probability $p_{h,m}p_s$), then $E[T_c] = E[T_n | T_n > t_s]$ and $E[T_{OFF}] = E[t_{s,s}]$, where

$$\begin{aligned} E[T_n | T_n > t_s]p_s &= \int_{T_n=0}^{\infty} \int_{t_s=0}^{T_n} T_n \mu e^{-\mu t_s} g_n(T_n) dt_s dT_n \\ &= \int_{T_n=0}^{\infty} T_n (1 - e^{-\mu T_n}) g_n(T_n) dT_n \\ &= E[T_n] + \left. \frac{dg_n^*(s)}{ds} \right|_{s=\mu}. \end{aligned} \quad (9)$$

For $j \geq 2$ in (4), $E[T_c] = E[T_n | T_n > t_s] + (j-1)E[T_{n,f}]$ and $E[T_{OFF}] = E[t_{s,s}] + (j-1)E[T_{n,f}]$ with probability $p_{h,m}(1 - p_s)^{j-1}p_s$. Therefore,

$$\alpha_m = \frac{p_{h,m} \{ p_s^2 \mathbb{E}[t_{s,s}] + (1-p_s) \mathbb{E}[T_{n,f}] \}}{(1-p_{h,m}) p_s \mathbb{E}[T_n] + p_{h,m} \{ p_s^2 \mathbb{E}[T_n | T_n > t_s] + (1-p_s) \mathbb{E}[T_{n,f}] \}} \quad (12)$$

$$\begin{aligned} \mathbb{E}[T_c] &= (1-p_{h,m}) \mathbb{E}[T_n] + p_{h,m} p_s \\ &\times \left\{ \mathbb{E}[T_n | T_n > t_s] + \sum_{j=1}^{\infty} (j-1) \mathbb{E}[T_{n,f}] (1-p_s)^{j-1} \right\} \\ &= (1-p_{h,m}) \mathbb{E}[T_n] + p_{h,m} p_s \\ &\times \left\{ \mathbb{E}[T_n | T_n > t_s] + \left(\frac{1-p_s}{p_s^2} \right) \mathbb{E}[T_{n,f}] \right\}. \end{aligned} \quad (10)$$

Similar to the derivation for (10), we have

$$\begin{aligned} \mathbb{E}[T_{OFF}] &= p_{h,m} p_s \left\{ \mathbb{E}[t_{s,s}] + \sum_{j=1}^{\infty} (j-1) \mathbb{E}[T_{n,f}] (1-p_s)^{j-1} \right\} \\ &= p_{h,m} p_s \left\{ \mathbb{E}[t_{s,s}] + \left(\frac{1-p_s}{p_s^2} \right) \mathbb{E}[T_{n,f}] \right\}. \end{aligned} \quad (11)$$

Substitute (10) and (11) into (8) to yield (12) at the top of this page. From (6), (7), and (9), (12) is re-written as

$$\begin{aligned} \alpha_m &= \frac{p_{h,m} \left\{ p_s \left[\frac{1-g_n^*(\mu)}{\mu} + \frac{dg_n^*(s)}{ds} \Big|_{s=\mu} \right] - \frac{dg_n^*(s)}{ds} \Big|_{s=\mu} \right\}}{(1-p_{h,m}) p_s \mathbb{E}[T_n] + p_{h,m} \left\{ p_s \left[\mathbb{E}[T_n] + \frac{dg_n^*(s)}{ds} \Big|_{s=\mu} \right] - \frac{dg_n^*(s)}{ds} \Big|_{s=\mu} \right\}} \\ &= \frac{p_{h,m} \left\{ p_s \left[\frac{1-g_n^*(\mu)}{\mu} \right] - (1-p_s) \left[\frac{dg_n^*(s)}{ds} \Big|_{s=\mu} \right] \right\}}{p_s \mathbb{E}[T_n] - p_{h,m} (1-p_s) \left[\frac{dg_n^*(s)}{ds} \Big|_{s=\mu} \right]}. \end{aligned} \quad (13)$$

Substitute (5) into (13) to yield

$$\alpha_m = \frac{p_{h,m} \left\{ \frac{[1-g_n^*(\mu)]^2}{\mu} - g_n^*(\mu) \left[\frac{dg_n^*(s)}{ds} \Big|_{s=\mu} \right] \right\}}{\mathbb{E}[T_n] - g_n^*(\mu) \left\{ \mathbb{E}[T_n] + p_{h,m} \left[\frac{dg_n^*(s)}{ds} \Big|_{s=\mu} \right] \right\}}, \quad (14)$$

where $m=1$ for the HTH network approach, and $m=2$ for the dual-link scheme.

Consider the multi-RAT soft handover approach. Suppose that I tiers of mobile systems are available in the moving path of a HST. For $1 \leq i \leq I$, let $p_{i,h,m}$, $g_{i,n}^*(s)$, μ_i , $T_{i,n}$ be the $p_{h,m}$, $g_n^*(s)$, μ , T_n values for tier i . Let $\alpha_{I,m}$ be the α_m measure for multi-RAT soft handover approach with I tiers. Since the TRS connects to each tier independently, the TRS is disconnected from the network if its links to all tiers are disconnected at the same time. Therefore, from (14) we have

$$\alpha_{I,m} = \prod_{i=1}^I \frac{\left\{ p_{i,h,m} \left[\frac{[1-g_{i,n}^*(\mu_i)]^2}{\mu_i} - g_{i,n}^*(\mu_i) \left[\frac{dg_{i,n}^*(s)}{ds} \Big|_{s=\mu_i} \right] \right\}}{\mathbb{E}[T_{i,n}] - g_{i,n}^*(\mu_i) \left\{ \mathbb{E}[T_{i,n}] + p_{i,h,m} \left[\frac{dg_{i,n}^*(s)}{ds} \Big|_{s=\mu_i} \right] \right\}}. \quad (15)$$

Without loss of generality, we assume that the tiers are homogeneous, and (15) can be simplified as

$$\alpha_{I,m} = \frac{\left\{ p_{h,m} \left[\frac{[1-g_n^*(\mu)]^2}{\mu} - g_n^*(\mu) \left[\frac{dg_n^*(s)}{ds} \Big|_{s=\mu} \right] \right\}^I}{\mathbb{E}[T_n] - g_n^*(\mu) \left\{ \mathbb{E}[T_n] + p_{h,m} \left[\frac{dg_n^*(s)}{ds} \Big|_{s=\mu} \right] \right\}}. \quad (16)$$

If T_n has a Gamma distribution, then $g_n^*(s)$ in (16) is expressed as

$$g_n^*(s) = \left(\frac{\mathbb{E}[T_n]}{sV_n + \mathbb{E}[T_n]} \right)^{\frac{\mathbb{E}[T_n]^2}{V_n}},$$

where V_n denotes the variance of Gamma T_n distribution.

Based on (16), Fig. 6 plots the $\alpha_{I,m}$ values against V_t, V_o , and V_n , where $E[t] = 1/\lambda = 100$ ms, $E[T_o] = 3$ seconds, $E[t_s] = 1/\mu = 5$ seconds, and $E[T_n] = 1$ minute. To simplify our discussion, we assume that $V_t = E[t]^2$, $V_n = \beta E[T_n]^2$, and $V_o = \beta E[T_o]^2$, where $0.1 \leq \beta \leq 10$. A large β value implies a larger variance for T_o .

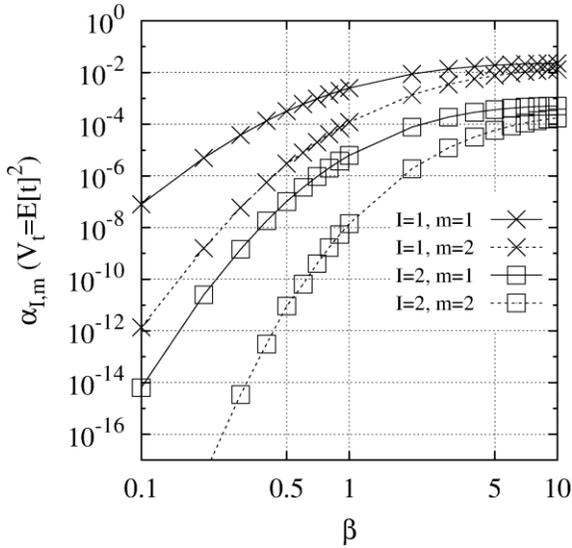
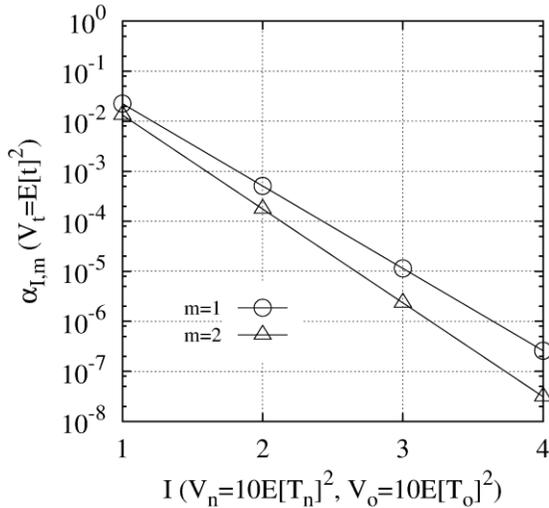
(a) $\alpha_{1,1}$ and $\alpha_{1,2}$ with different β (b) $\alpha_{1,1}$ and $\alpha_{1,2}$ with different I

Fig. 6. Probability that wireless communication is not available: $\alpha_{I,m}$ against $V_t, V_o = \beta E[T_o]^2$ and $V_n = \beta E[T_n]^2$

The figure indicates that $\alpha_{2,m} \ll \alpha_{1,m}$; i.e., the wireless connectivity for the dual-link scheme is much better than that for the HTH approach. The figure also indicates that $\alpha_{I,m}$ significantly decreases as I increases; i.e., by utilizing multi-RAT with more tiers, the wireless connectivity of the HST is significantly improved. For example, if $V_t = E[t]^2$, $V_o = 10E[T_o]^2$ and $V_n = 10E[T_n]^2$, $\alpha_{1,1} = 0.022533$ and $\alpha_{1,2} = 0.013284$ (see the \times curves). By utilizing multi-RAT with two tiers, $\alpha_{2,1} = 0.000507736$ and $\alpha_{2,2} = 0.000176465$ (see the \square curves).

V. CONCLUSIONS

This paper proposed the Multi-RAT soft handover approach to enhance wireless communications on high speed trains

(HSTs). Our study indicated that the dual-link scheme can effectively improve the handover performance for the HST. The multi-RAT soft handover approach further enhances the connection performance of the HST communications and improves the connection availability for the dual-link scheme by over 10 times under our study. To conclude, the multi-RAT effectively improves the HST's wireless connectivity. Our future work will provide experiment measurements on Taiwan High-speed Trains to test the Multi-RAT technology.

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