Short Papers

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 a high-speed train (HST) faces several challenges. In particular, when an 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 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., the Universal Mobile Telecommunications System and Long Term Evolution). 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) network, 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 the Global System for Mobile Communications (GSM), the Universal Mobile Telecommunications System (UMTS), code division multiple access 2000 (CDMA 2000), and Long Term Evolution (LTE). In these systems, a mobile subscriber carries user equipment [UE, see Fig. 1(a)] to communicate with the mobile core network [see Fig. 1(b)] through a base station [BS, see Fig. 1(c)]. The radio coverage of a BS (or a sector of the BS) is called a *cell*. When UE 1 moves from BS 1 to BS 2 [see Fig. 1(d)], the wireless connection of UE 1 is switched from BS 1 to BS 2. This process is called *handover*.

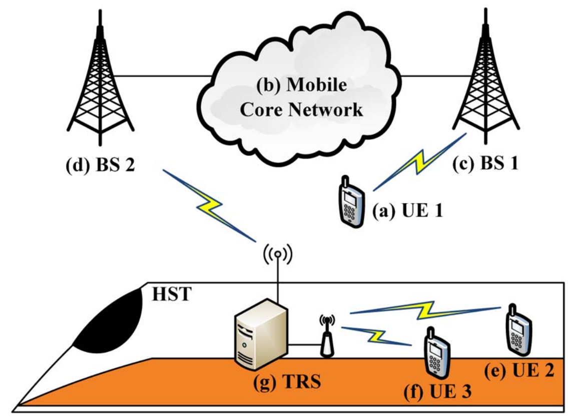

Fig. 1. HTH network for the HST.

Although commercial mobile telecommunications systems serve nonhigh-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, the synchronization of orthogonal frequency-division multiplexing against the Doppler effect, and so on. In particular, when an HST quickly passes through the cells, frequent handovers may result in serious communication interruption. Some methods such as the 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] and [2], and the references therein). Among them, the HTH network approach was widely adopted, in which all the UE in an HST [e.g., see Fig. 1(e) and (f)] communicates with a train relay station [TRS, see Fig. 1(g)], and the TRS relays the UE connections to a BS [see Fig. 1(d)]. The TRS typically supports Wi-Fi connections to the UE 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 UE in the HST, it is still possible that the wireless connection to the TRS is interrupted during handover (to be elaborated upon in Section III).

Following this HTH network approach, some studies ([3]–[5]) described a novel dual-link handover scheme for seamless wireless connectivity in an HST (abbreviated as the *dual-link* scheme), which reduced the communication interruption during the TRS's handover. Specifically, two external antennas are deployed at the front and the rear of an 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

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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. The implementation of this scheme needs to modify the standard Third 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 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, in which the TRS of an 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. This paper is organized as follows. Section II proposes the multi-RAT soft handover approach. Section III studies the HTH network and the dual-link scheme. Section IV evaluates the performance of the multi-RAT soft handover scheme. Finally, the conclusion is given in Section V.

II. Multi-RAT Soft Handover

Most existing mobile devices are equipped with more than one network interface 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 the BSs of multiple *tiers* of mobile telecommunications systems (multimode or multiband heterogeneous networks), through multi-RAT the UE may simultaneously connect to two or more networks to increase the throughput for wireless transmission.

As we noted in the previous section, frequent handovers are the main issue for wireless communications of an HST. Rapidly passing through the overlap areas of cells leads to a high handover failure rate. With multi-RAT, we propose to perform *soft handover* at the application level [i.e., Internet Protocol (IP)] to reduce the communication interruption of an HST caused by handovers. In our approach, the 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, i.e., UMTS and LTE; then, it will have two external antennas connecting to both Wideband CDMA (WCDMA)/HSPA (for UMTS) and LTE BSs. In a normal operation, the TRS maintains both the 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, see 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 call this approach *multi-RAT soft handover* (abbreviated as multi-RAT). Our idea is similar to the "radio" soft handover of HSPA in which the UE can connect up to six 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, whereas in multi-RAT soft handover, the UE connects to

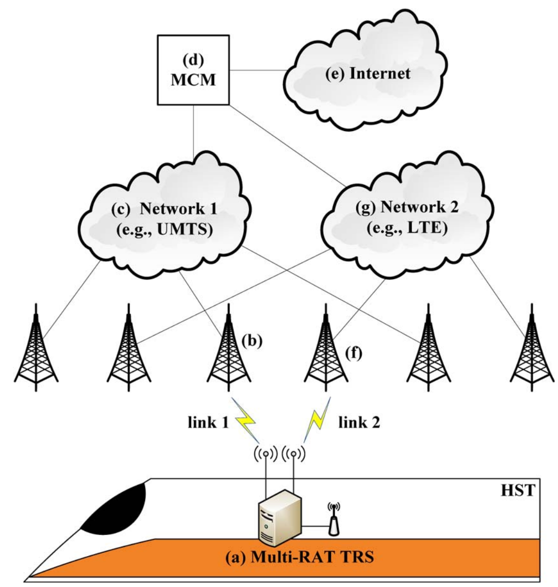

Fig. 2. Multi-RAT soft handover.

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, whereas multi-RAT soft handover can be exercised at the application (IP) layer. Third, all the HSPA links connected to the UE deliver the same data stream, whereas multi-RAT links deliver different data streams (and therefore increase the transmission capacity of the UE). The implementation of multi-RAT does not need to modify any 3GPP procedures, and the details are described in [12].

III. Performance of HST Communications With HTH Network

This section conducts analytic and simulation modeling to investigate the performance of HST communications with the HTH network. With the HTH network approach, only the TRS needs to be involved in the handover process. Suppose that the handover time for the TRS is t, which is a random variable with density function [probability 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 that $E[t] = 100$ 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 m; then, $E[T_o] \approx$ 3 s. 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 density function $g_o(T_o)$ and 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 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

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

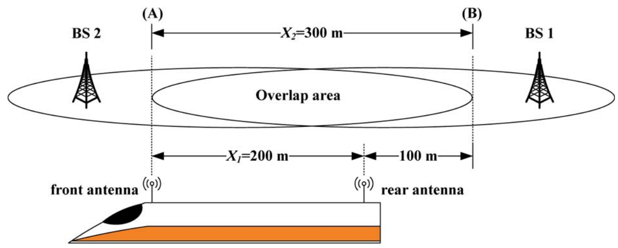

Fig. 3. Overlap area for handover in the dual-link scheme.

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

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

We have developed a simulation model that 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 the gamma t distribution. The gamma distributions are considered because this distribution is widely used in telecom modeling (see [13] and [14], and the references therein). The Laplace transform for gamma T_o is

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

where V_o denotes the variance of the gamma T_o distribution.

The HTH network performance has been investigated in terms of the data rate [15], which proved that, through the TRS, the power consumption of the UE in the HST could be saved. Through simulation experiments, we investigate the handover performance in an 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 $X_1 = 200$ m. In Fig. 3, the overlap area of two cells is $X_2 = 300$ m in diameter. The front antenna conducts handover to switch from BS 1 to BS 2 when it travels through this 300-m 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 $X_2 - X_1 = 100$ m (see point (B) in Fig. 3), and there is only 200 m 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 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

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

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 by $g_{o,\varepsilon}^*(s)$. 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

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

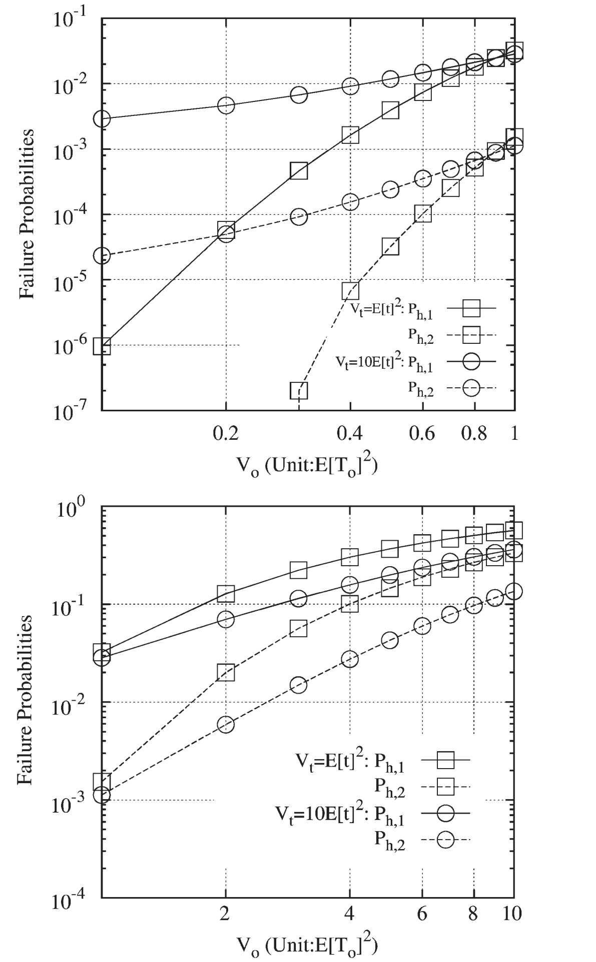

Fig. 4. $p_{h,m}$ performance for the TRS ($E[t] = 1/\lambda = 100$ ms, $E[T_o] = 3$ s).

Equation (3) is consistent with the results in [4]. [4, Fig. 8] shows that, for example, if we place the two antennas 200 m away in the HST and the HST travels for 300 m to cross the cell overlap area, then the dual-link scheme can improve the 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 $V_t = E[t]^2$, $V_o = 0.9775\mathrm{E}[T_o]^2$ (V_t denotes the variance of the 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 an HST. In Taiwan, for example, LTE, HSPA+, EDGE, and WiMAX may coexist 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 be performed simultaneously. We will investigate the multi-RAT performance through the 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 $V_o = 10\mathrm{E}[T_o]^2$ and $V_t = 10\mathrm{E}[t]^2$, $p_{h,2} = 0.1354562$. If the TRS fails the handover process, then it needs to reestablish the wireless connection again, and during the connection setup, wireless communications in the HST may be seriously degraded. In the next section, we show how the connection setup affects the performance of the HTH network and the dual-link scheme, and how multi-RAT soft handover can resolve this issue.

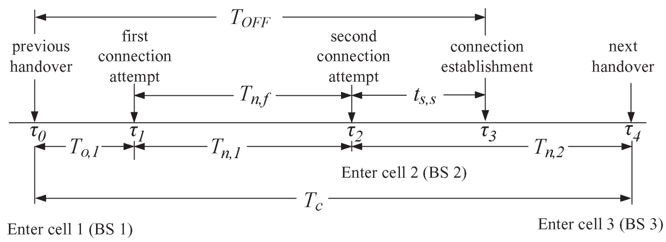

Fig. 5. Timing diagram for the events occurring between two handovers.

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 pdf $f_s(t_s)$. Following the 3GPP standard and our measurements, we assume that $E[t_s] = 5$ s. Let $T_{n,j}$ be the time period for an HST to travel through the nonoverlap area of a cell j. We assume that the HST speed is 360 km/h, the nonoverlap area of a cell is 6 km, and $E[T_{n,j}] = 1$ min.

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.

In Fig. 5, 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 nonoverlap 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 jth 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 lth 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., $E[T_{o,j}] = 3$ s and $E[T_{n,j}] = 1$ min), we simplify the T_c equation as

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

Assume that connection setup time t_s is exponentially distributed with rate μ. Let $T_{n,j}$ be independent identically distributed random variables; then, notation $T_{n,j}$ can be simplified as T_n, which is a random variable with pdf $g_n(T_n)$, cumulative distribution function $G_n(T_n)$, and 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 reestablishes the connection. Then, similar to (2), we have

$$p_s = 1 - g_n^*(\mu). \tag{5}$$

If the connection reestablishment fails, then travel time $T_{n,f}$ to pass the nonoverlap 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

$$E[T_{n,f}](1-p_s) = \int_{T_n=0}^{\infty} \int_{t_s=T_n}^{\infty} T_n \mu e^{-\mu t_s} g_n(T_n) dt_s \, dT_n$$

$$= \int_{T_n=0}^{\infty} T_n g_n(T_n) e^{-\mu T_n} dT_n$$

$$= -\left.\frac{dg_n^*(s)}{ds}\right|_{s=\mu}. \tag{6}$$

Let $t_{s,s}$ be the setup time for a successful reconnection, 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

$$E[t_{s,s}]p_s = \int_{t_s=0}^{\infty} \int_{T_n=t_s}^{\infty} t_s \mu e^{-\mu t_s} g_n(T_n) dT_n \, dt_s$$

$$= E[t_s] - \int_{t_s=0}^{\infty} \mu t_s e^{-\mu t_s} G_n(t_s) dt_s$$

$$= E[t_s] + \mu \left.\left\{ \frac{d\left[g_n^*(s)/s\right]}{ds} \right\}\right|_{s=\mu}$$

$$= \frac{1 - g_n^*(\mu)}{\mu} + \left.\frac{dg_n^*(s)}{ds}\right|_{s=\mu}. \tag{7}$$

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

$$\alpha_m = \frac{E[T_{\mathrm{OFF}}]}{E[T_c]}. \tag{8}$$

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 $T_{\mathrm{OFF}} = 0$. 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 $E[T_{\mathrm{OFF}}] = E[t_{s,s}]$, where

$$E[T_n|T_n > t_s]p_s = \int_{T_n=0}^{\infty} \int_{t_s=0}^{T_n} T_n \mu e^{-\mu t_s} g_n(T_n) dt_s \, dT_n$$

$$= \int_{T_n=0}^{\infty} T_n \left(1 - e^{-\mu T_n}\right) g_n(T_n) dT_n$$

$$= E[T_n] + \left.\frac{dg_n^*(s)}{ds}\right|_{s=\mu}. \tag{9}$$

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

$$E[T_c] = (1 - p_{h,m})E[T_n] + p_{h,m}p_s \times \left\{ E[T_n|T_n > t_s] + \sum_{j=1}^{\infty}(j-1)E[T_{n,f}](1-p_s)^{j-1} \right\}$$

$$= (1 - p_{h,m})E[T_n] + p_{h,m}p_s \times \left\{ E[T_n|T_n > t_s] + \left(\frac{1-p_s}{p_s^2}\right) E[T_{n,f}] \right\}. \tag{10}$$

Similar to the derivation for (10), we have

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

Substitute (10) and (11) into (8) to yield (12), shown at the bottom of the page. From (6), (7), and (9), (12) is rewritten as (13), shown at the bottom of the page.

Substitute (5) into (13) to yield

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

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 an HST. For $1 \le i \le I$, let $p_{i,\,h,\,m}$, $g_{i,\,n}^*(s)$, μ_i, and $T_{i,\,n}$ be the $p_{h,\,m}$, $g_n^*(s)$, μ, and T_n values for tier i, respectively. Let $\alpha_{I,\,m}$ be the α_m measure for the 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

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

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

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

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

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

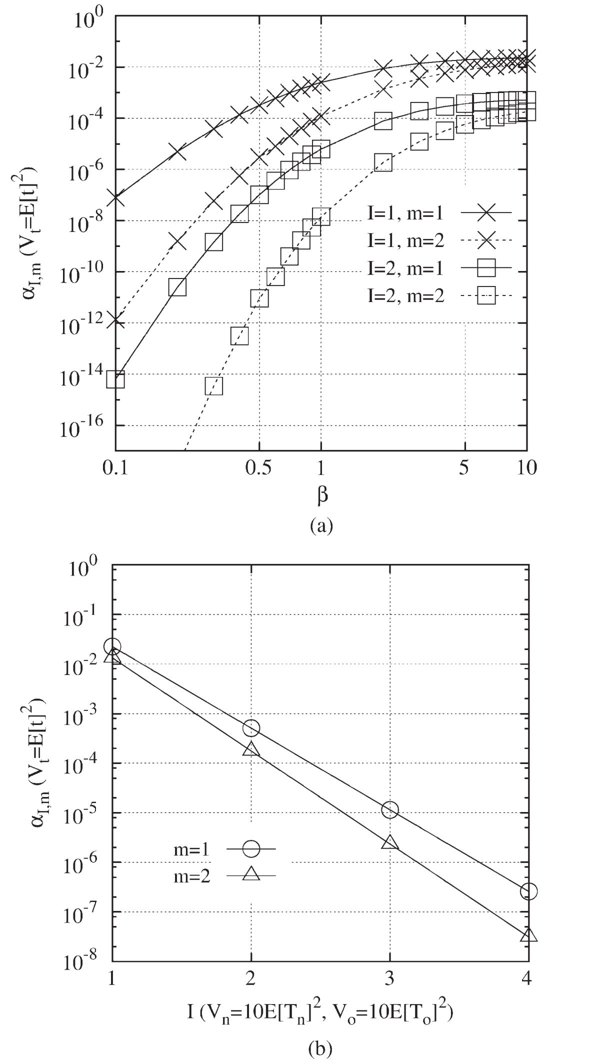

Fig. 6. Probability that wireless communication is not available. $\alpha_{I,\,m}$ against V_t, $V_o = \beta E[T_o]^2$, and $V_n = \beta E[T_n]^2$. (a) $\alpha_{I,\,1}$ and $\alpha_{I,\,2}$ with different β. (b) $\alpha_{I,\,1}$ and $\alpha_{I,\,2}$ with different I.

where V_n denotes the variance of the 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, $E[T_o] = 3$ s, $E[t_s] = 1/\mu = 5$ s,

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

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

and $E[T_n] = 1$ min. 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.

Fig. 6 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. It 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 $V_t = E[t]^2, V_o = 10\mathrm{E}[T_o]^2$, and $V_n = 10\mathrm{E}[T_n]^2$, $\alpha_{1,1} = 0.022533$, 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 $\Box$ curves).

V. Conclusion

This paper has proposed the multi-RAT soft handover approach to enhance wireless communications on 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 ten times under our study. To conclude, multi-RAT effectively improves the HST's wireless connectivity. Our future work will provide experimental measurements on Taiwanese HSTs to test multi-RAT.

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