Enhanced handover scheme with shared-relay stations in GSM-R network

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Abstract: In order to improve the successful handover probability of GSM-R (GSM for railway) system, an enhanced handover scheme with shared-relay stations was put forward. In the scheme, shared-relay stations were applied to improve the signal quality of target base stations in the signal overlapping region among adjacent base stations and to separate the received mixed signals from different base stations, which could decrease the handover misjudgment resulted from signal fluctuation. Simulation result shows that the scheme can trigger handover appropriately in advance about 500 m, so that there is longer distance for completing handover process when train is traversing through the overlapping region. Because of better signal quality, ping-pong effect eliminates, handover failure probability reduces to \(10^{-6}\), thereby, successful handover probability increases. Meanwhile, considering the system interference, shared-relay stations can not be used in the network with the less reuse factor than 2. 2 tabs. 9 figs. 13 refs.

Key words: train-ground wireless communication; signal transmission quality; GSM-R; shared-relay station; interference; successful handover probability

0 Introduction

The increasing construction of worldwide high-speed railway requires to provide the robust information communication technologies between train and railway dispatch control center. GSM-R...
is an international wireless communication standard for railway communication and application. In high-speed environment, handover needs less time-consuming and more accurate triggering time. In GSM-R, handover operation mainly consists of triggering, scanning, selecting and executing. Normally, the time delay cost for triggering and selecting can be ignored and both processes are completed in BSS (base station subsystem). Handover time delay mainly comes from two parts: scanning and executing. Scanning delay is the delay that MS (mobile station) and BS (base station) handle measurement reports, which depends on the amount of measurement data. Executing delay can be divided into two sub-parts: target cell channel activate time and MS access target time, which depend on the complexity of signaling processes and the network equipment capacity. Recently, most literatures focus on reducing the amount of measurement data and triggering handover in advance. (CI, TA) directional coordinate algorithm and TA directional coordinate algorithm were proposed in reference[1], in which CI (cell indicator) and TA (time advance) in GSM-R were used to determine train moving direction. Then train could handover to target cell. Based on reference[1], Wu et al proposed a location-based assisted handover algorithm. GPS (global positioning system) was used to acquire location information and train moving speed, and to send the information with measurement report to BSS[2]. Then BSS decided whether or not to trigger handover in advance. In both algorithms, the determination process of the target is optimized. Xiang et al introduced relay stations in GSM-R network to improve the signal quality in signal overlapping region, which can reduce ping-pong effect and improve handover successful probability[3]. The algorithm only improves the signal quality in overlapping region. The concept of shared-RS was put forward to separate received mixed signals and to perform interference suppression before forwarding transmission to mitigate inter-cell interference[4]. Authors propose an enhanced handover scheme with shared-RS (relay station) in GSM-R to improve the handover performance for high-speed railway. Shared-RS improves the signal quality of target BS in overlapping region, and handover can be triggered in advance so that there is longer distance for completing handover process when train is traversing through overlapping region.

1 System model

1.1 Topology

In existing GSM-R system, the cell radius is relatively small, and the distance between two neighboring BSs is around 1.8-5.0 km[5-6]. Fig. 1 shows the linear coverage topology of GSM-R network. During a call, train probably moves across multiple cells, and may handover several times. The BS makes periodic measurement and assessment of MS signal. When BS detects the decrease of signal quality from moving MS, it immediately reports to BSC (base station controller). Then, BSC will search for a new target cell for MS, and will trigger handover process. The process must complete in overlapping region. In high-speed environment, train stays in overlapping region only a few seconds, which may be shorter than handover completion time. From the perspective of distance, the moving distance of train in handover process is longer than the span of overlapping region, which satisfies the conditions of handover. Therefore, handover will be failure. The required distances for train to complete handover are shown in Tab. 1. Because of signal fluctuation and the existing handover mechanism, the problem cannot be solved by expanding the overlapping region. The real distance for completing handover is still less than the span of

![Fig. 1 GSM-R network topology](image)

Authors propose an enhanced handover scheme with shared-RS (relay station) in GSM-R to improve the handover performance for high-speed railway. Shared-RS improves the signal quality of target BS in overlapping region, and handover can be triggered in advance so that there is longer distance for completing handover process when train is traversing through overlapping region.
overlapping region. Fig. 2 shows that handover probably occur at point $A$, $B$ or $C$ due to the signal fluctuation. If handover occurs at $A$, there is enough distance or time for train to complete handover process. Thus, handover successful probability is higher. If handover occurs at $B$, the distance for handover operation is less than the required distance. Then, handover successful probability is low. However, when handover occurs at $C$, there is little distance for train to complete handover. Thus, handover will be failure\textsuperscript{[1-10]}. From the above analysis, point $A$ has the highest handover successful probability. Therefore, a way should be found to make train trigger handover at $A$ as much as possible.

\begin{table}[h]
\centering
\caption{Required distances for train completing handover}
\begin{tabular}{|c|c|}
\hline
Speed $(\text{km} \cdot \text{h}^{-1})$ & Distance/m \\
\hline
200 & 46 \\
\hline
250 & 58 \\
\hline
360 & 83 \\
\hline
500 & 115 \\
\hline
\end{tabular}
\end{table}

The average handover time-consuming is 0.834 s\textsuperscript{[8]}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{handover_triggering_positions.png}
\caption{Handover triggering positions}
\end{figure}

1.2 Shared-RS

Multiple BS-shared relay stations (RSs) with multiple antennas in overlapping region are used to improve handover performance. Shared-RS is an advanced RS with multiple antennas, which is configured to connect multiple neighboring BSs. Shared-RS is able to separate the received mixed signals from different BSs, because different BSs work at different frequency bands\textsuperscript{[12]}.

A simple scenario of a GSM-R system with shared-RS is depicted in Fig. 3. A shared-RS with multiple antennas is deployed in the center of overlapping region. The above analysis shows that train 1 should handover at point $A$, and train 2 should handover at point $C$. To achieving the goal, the signal quality from target BS is improved to make handover occur in advance. So shared-RS always amplifies the signal from target BS. For example, in overlapping region, train 1 receives the signal from BS 2 (target BS) that is amplified by shared-RS, and train 2 receives the signal from BS 1 (target BS) that is amplified by shared-RS. Shared-RS can use beam-forming technique to avoid mutual interference.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{shared-rs_usage.png}
\caption{A simple scenario of shared-RS usage}
\end{figure}

2 Performance analysis

In order to verify the proposal, a mathematical model is built, and MATLAB is used to do a series of simulation and analysis.

2.1 System parameter setting

System parameters are set referred to\textit{GSM-R Procurement Guide} of UIC (International Union of Railways). Cell radius is 3 km. Overlapping region's span is 1200 m. BS transmitting power is 43 dBm (20 W). Shared-RS transmitting power is 33 dBm (2 W). The path loss model is Hata-Okumura model. Tab. 2 shows the coverage requirement of the network.

\begin{table}[h]
\centering
\caption{Coverage requirement of GSM-R network}
\begin{tabular}{|c|c|c|}
\hline
Speed $V$ $(\text{km} \cdot \text{h}^{-1})$ & Coverage power dBm & Coverage rate/\% \\
\hline
$V \leq 220$ & -95 & 95 \\
\hline
220 $< V \leq 280$ & (-95, -92) & 95 \\
\hline
$V > 280$ & -92 & 95 \\
\hline
\end{tabular}
\end{table}

2.2 Propagation model

Path loss, shadow and Doppler effect are only considered, and engineering margin is reasonably set to meet the coverage requirement. The following equation is the basic path loss $L$

\begin{equation}
L = 69.55 + 26.16 \lg (f) - 13.82 \lg (h_{at}) - \alpha (h) + [44.9 - 6.55 \lg (h_{at})] \lg (d)
\end{equation}

The valid range of $f$ is 150-2000 MHz, the valid
range of \( d \) is 1-20 km, the valid range of \( h_a \) is 30-200 m, and the valid range of \( h \) is 1-10 m. \( a(h) \) is varying with the specific environment. For a suburban environment, \( a(h) \) is calculated as follows
\[
a(h) = 4.78 \cdot 10^{\lg(f)} + 18.33 \cdot \lg(f) + 40.94 \quad (2)
\]

Fig. 4 is the intensity of received signal and the overlapping span varies from 1 800 m to 3 000 m. Source BS is at (0, 0), and target BS is at (4 800, 0). The minimum intensity of received signal from source BS is \(-86.91 \, \text{dBm}\), and the minimum intensity of received signal from target BS is \(-85.69 \, \text{dBm}\). Both values have 5 dB margin compared with the coverage requirement. Doppler effects and multipath propagation effects in the system will not exceed the margin. From Fig. 4, it is difficult to clearly distinguish the mixed signals. Signal fluctuations greatly impact handover, and it is likely to cause handover too late.

If train is moving from left to right, its handover is at point \( A \), and shared-RSs are installed in existing GSM-R network, the received signal intensities is shown in Fig. 5. In overlapping region, the signals from different BSs are clearly distinguished according to received signal intensities. Handover is ahead of schedule, and ping-pong effect reduces.

Fig. 6 is the simulation result of handover triggering location. Handover location is ahead of schedule approximately 500 m. With speed upgrade, handover location continuously postpones. Because wireless measurement cycle is fixed at 480 ms in GSM-R system, wireless measurement distance is 480 (ms) * \( V \) (km * h\(^{-1}\)).

It is obvious that the wireless measurement distance varies with moving speed.

### 2.3 Interference model

Typical railway’s radio channel shows the following characteristics: low multipath propagation, low delay spread and dominating direct path\(^ {13}\). The path loss \( L_i \) can be expressed as follows
\[
L_i = r_i^{n} \cdot 10^{\frac{(k+1)/10}{}} \quad (3)
\]

The signal intensity received by the onboard receiver can be expressed as follows
\[
R_i = SL_i \quad (4)
\]

The system co-channel interference can be expressed as follows
\[
I = \sum_{i=1}^{N_M} R_i \quad (5)
\]

Fig. 7 shows the carrier-interference ratios (CIR) with different cell radii and different frequency reuse factors in GSM-R with shared-RSs. When frequency reuse factor is 2, CIR is under 9 dB, which does not meet engineering requirement. Therefore, shared-RS should has higher reuse factor than 2.
2.4 Handover probability

When the received signal intensity of the BS is less than that of the neighboring BS as \( H \) (the hysteresis margin), train triggers handover to the neighboring BS. Handover probability \( P_{HO} \) can be expressed as follows:

\[
P_{HO} = P \left\{ R_j - R_i \geq H \right\} = P \left\{ L_j - L_i \geq H/S \right\}
\]

When \( P \{ \varepsilon_i = \varepsilon \} = N(0, \sigma_i^2) \), and \( \sigma_i \) is the standard deviation of \( \varepsilon_i \), \( P_{HO} \) is expressed as follows:

\[
P_{HO} = \int_{\infty}^{-\infty} P \left\{ L_j - L_i \geq \frac{H}{S} \right\} \varepsilon_i = \varepsilon_0 \ast \\
\ast \int_{\infty}^{-\infty} \Phi \left( \frac{10\lg \left| \frac{R_i}{r_j} \right|^4 - \frac{H}{S}}{\sigma_i} \right) \frac{1}{\sqrt{2\pi} \sigma_i} e^{-\frac{\varepsilon_0^2}{2\sigma_i^2}} d\varepsilon_0
\]

2.5 Handover failure probability

If the ratio of signal to interference plus noise of the MS is less than a threshold \( \gamma_h \), handover will be outage. The probability of handover outage \( P_{OT} \) can be defined as:

\[
P_{OT} = P \left\{ S_{INR} < \gamma_h \right\}
\]

\[
S_{INR} = \frac{R_i}{1 + N_0W_B}
\]

Due to \( I \gg N_0W_B \), equation (8) can be expressed as follows:

\[
P_{OT} = P \left\{ \lg(R_i) - \lg(I) < \lg(\gamma_h) \right\}
\]

Thus, handover failure probability \( P_{FL} \) occurring after handover is

\[
P_{FL} = P_{HO} P_{OT}
\]

3 Simulation result analysis

In the simulation, the radius of BS coverage is 3 km, the overlapping region span is 1.2 km, and train speed is 350 km/h. Fig. 8 shows the relationship between handover occurring probability and train location. The curve with "*" indicates the cumulative distribution of traditional handover probability. For example, when the distance is 2 km, probability is 3.97%. The curve with "o" indicates the cumulative distribution of proposal handover probability. When train locates at 2 km, the proposal handover probability is larger than that of traditional scheme without shared-RS by 53.33%. It shows that handover occurs earlier.

Fig. 9 shows the relationship between handover failure probability and train location. Overlapping region span is 1.8-3.0 km. With shared-RS, handover failure probability decreases significantly. From 1.8 km to 2.0 km, the probability decreases because the signal from shared-RS varies from weak to strong. From 2.8 km to 3.3 km, the probability increases because the signal from shared-RS varies from strong to weak. When the distance is more than 3.3 km, the signal from shared-RS continues to weaken, so both lines tend to be same.

4 Conclusions

An enhanced handover scheme with shared-RS in GSM-R network for high-speed railway is
proposed to improve the handover performance of the network. In the scheme, shared-RS improves the signal quality of target BS in signal overlapping region, and train can distinguish the signals from different BSs clearly. Handover can be triggered in advance, so that there is longer distance for completing handover process when train is traversing through the overlapping region, and the misjudgment and ping-pong effect of handover caused by signal fluctuations can be avoided. However, because of the co-frequency interference, shared-RS is not suitable to be applied to the network with the reuses factor less than 2. The simulation result has confirmed the conclusion. In the next work, the network coding based on shared-RS will be introduced to improve GSM-R network’s throughput performance.

Nomenclatures:

- $f$: receiving frequency
- $d$: distance between transmitter and receiver
- $h_{\text{transmitter}}$: antenna height of transmitter
- $h$: antenna height of receiver
- $a(h)$: correction term
- $r_i$: distance between train and BS $i$
- $\varepsilon_i$: Gaussian distribution random variable with zero mean and standard deviation
- $\varepsilon_0$: a free value of $\varepsilon_i$
- $\varepsilon$: a very small constant
- $\nu$: Doppler effect factor
- $a$: path loss factor
- $S$: BS transmitting intensity
- $W_B$: system band width
- $N_0$: density of AWGN (additive white Gaussian noise)
- $\sigma_i$: standard deviation of $\varepsilon_i$
- $I$: total interference
- $S_{\text{INR}}$: ratio of signal to interference plus noise
- $R_i$: received signal intensity
- $N_{\text{RS}}$: number of BSs that generate co-channel interference
- $N_{\text{RSs}}$: number of shared-RSs that generate co-channel interference

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