CONTROL AND DATA SIGNALING DECOUPLED ARCHITECTURE FOR RAILWAY WIRELESS NETWORKS

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ABSTRACT

Current implementations of narrowband Global System for Mobile Communications for railway systems are facing significant challenges in meeting the emerging massive capacity demands of passenger services. To extend the capacity, this article presents a control and data signaling decoupled architecture, namely, C/U-plane decoupled architecture for railway wireless networks, in which the relatively important C-plane of passenger services is kept on high-quality lower frequency bands to handle mobility, while the corresponding U-plane is moved to higher frequency bands to gain broader spectra. In this railway wireless network with C/U-plane decoupled architecture, the U-plane and C-plane handovers are also physically decoupled. To achieve the seamless and soft U-plane handover, we introduce a handover scheme based on coordinated multi-point transmission and reception and bi-casting. In addition, channel mappings and physical layer frames are redesigned to facilitate the design. Our study has demonstrated that by decoupling the C/U planes, the network performance is greatly enhanced, leading to a more effective way to provide high speed communications for railway systems.

INTRODUCTION

Since the momentous extension from GSM to GSM-R (GSM for railway) was achieved in 1995, GSM-R, being responsible for trains' communications and control, has been globally adopted by many countries including Germany, France, and China. The typical data rate of GSM-R is 9.6 kb/s, which can barely meet the basic capacity demands of the train control system. Nevertheless, with rapid development of the railway system and wireless access technologies, more and more wireless data need to be transmitted between the train and wayside eNodeBs (eNBs). In order to ensure the train's operational safety, more security methods such as security monitoring and maintenance, which generate tremendous traffic, have been introduced to the train control system. Considering the revenue return, no public mobile network operator would offer full coverage for most sparsely-populated railway scenarios. Moreover, due to the severe challenges in railway scenarios, such as drastic Doppler effect and large penetration loss, it is hard for ordinary user terminals (UEs) to maintain a dependable connection with wayside eNBs directly through public mobile networks. According to the evolution of wireless communications technologies, a novel unified railway wireless communication network is needed to carry passenger services to ensure a better user experience. Inside the train, passenger equipments connect to the wireless access point (AP, e.g. WiFi), and then their services are forwarded to wayside eNBs via the onboard mobile relay (MR) [1]. It is estimated that in the future, wireless traffic could be as high as 65 Mb/s per train [2]. Hence, a new type of network architecture is urgently needed to extend the transmission capacity for future railway wireless networks.

To meet the increasing capacity demands of public mobile networks, the spectrum extension of 5G (Generation) communications are envisaged at higher frequency bands with broader available spectra, including frequency bands higher than 5 GHz, up to 300 GHz, since spectrum below 2.5 GHz is already fully utilized [3, 4]. Unfortunately, larger propagation loss of these bands severely limits the transmission range and thereby results in small cells, which implies more frequent handovers and poor transmission reliability. A potential solution is to use lower frequency bands, such as existing cellular bands of macro cells, to provide basic coverage, and to use higher frequency bands in small cells to provide high-speed data transmissions, which forms a heterogeneous network. In traditional wireless communication networks, the C-plane (control plane) and U-plane (user plane) are tightly coupled. However, such coupling architecture starts to show its disadvantages as the network deployment becomes denser to meet the increasing capacity demands. For instance, in conventional heterogeneous networks with lots of small cells overlaid within a macro cell, a large number of UEs will be at cell edges due to the smaller coverage of small cells. Therefore, handovers will be triggered frequently and many redundant control signaling interactions between macro and small cells will be generated, which is a huge burden for networks and UEs [5].

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As CoMP could be a technology that allows the train to receive signals from both adjacent eNBs when the train travels through the handover overlapping area, it is employed to establish the U-plane of the target small cell in advance [10]. In this way, a seamless and soft U-plane handover is achieved to improve the QoE of passengers.

There are two planes for a UE to establish communications with a serving eNB: the C-plane and the U-plane. One of the most important design principles in LTE (Long Term Evolution)/SAE (System Architecture Evolution) networks is to split design space into C-plane and U-plane between the MME (mobility management entity) and gateway functionally. The user dedicated data are transmitted on the U-plane from or to the SGW (serving gateway), while the control signaling designed for network access provisioning, such as handover signaling and random access signaling, is carried out on the C-plane from or to the MME. As aforementioned, we can see that if the C-plane is used to handle the mobility and the U-plane is used to increase capacity, the system capacity and mobility support can be balanced. As in current LTE networks, the C-plane and the U-plane are only separated in the upper layers; the redundant control signaling in heterogeneous networks is still hard to handle. Based on this observation, 5G communications further exploit U-plane and C-plane physically decoupled architecture to solve this issue [6, 7]. This article applies this decoupled architecture to future railway wireless networks to extend the transmission capacity. Correspondingly, channel mappings and physical layer frames are redesigned to accomplish this design.

Existing licensed lower frequency bands such as the legacy bandwidth of evolving GSM-R are stringently regulated, with explicit limitations on interference level and coverage to enable dependable service quality and efficient mobility support. In the proposed C/U-plane decoupled architecture for railway wireless networks, to enable reliable transmission and efficient mobility support, the relatively important C-plane of passenger services is kept in macro cells using these high-quality frequency bands. More precisely, in addition to the C-plane of passenger services, some other low-rate services with strict requirements for transmission reliability, e.g. the train control information, can also be fully distributed to these frequency bands. As for the major capacity demander, the U-plane of passenger services is moved to small cells operating at higher frequency bands to gain broader spectra.

Actually, in the proposed network architecture, with the C-plane and the U-plane separately transmitted in different physical nodes, the C-plane and U-plane handovers are physically separated. The U-plane handover takes place between two adjacent small cells, which is also called inter-small cell handover. Within a macro cell, the C-plane is always kept on-line without handovers. Consequently, the redundant control signaling due to inter-small cell handovers of coupled heterogeneous networks is solved. As the coverage of small cells is severely limited, frequent inter-small cell handovers will degrade the QoE (quality of experience) of passengers. Hence, it is necessary to design a seamless and soft U-plane handover scheme. Based on this requirement, the CoMP and bi-casting techniques are used to establish the U-plane of the target small cell in advance, so that the U-plane is not interrupted in the following handover process. Generally, during the joint transmission of CoMP, the coordinating eNB just transmits the U-plane data at the same time-frequency resource as that of the serving eNB, and the UE only receives the C-plane from the serving eNB [8]. However, in conventional networks the C-plane and the U-plane are coupled in the physical layer frame, and much signaling is required to be exchanged between the coordinating and serving eNBs so that these two eNBs can exactly align their transmission resources. Obviously, the conventional coupled architecture badly affects the flexibility of CoMP. This issue is fortunately avoided in the decoupled architecture. Since the U-plane is thoroughly separated from the C-plane and moved to higher frequency bands, it is much easier for the coordinating and serving eNBs to precisely align their U-plane transmission resources. As for the C-plane handover, it happens between two adjacent macro cells, which is also called inter-macro cell handover. As mentioned before, during the handover of conventional LTE networks, the U-plane is interrupted all the time. That is, the handover is equivalent to the C-plane handover. Thanks to the efficient coverage of macro cells, the C-plane handover of the proposed network can achieve the same performance as that of the conventional coupled network. Hence, the detailed C-plane handover will not be redundantly discussed in this article.

As a final note, we want to point out that the idea of using different frequency bands to support control and data transmissions has demonstrated superior performance in multi-hop IEEE 802.11 networks. In [9], Zhai, Wang, and Fang showed that by shifting control signals to a different frequency band, severe collision on data frames caused by control frames can be mitigated and tremendous throughput performance can be obtained. The current article demonstrates how to improve network performance by taking channel quality into consideration.

The rest of this article is organized as follows. The decoupled architecture and inter-small cell handover process are presented next. Channel mappings and frame structures are redesigned following that. Performance evaluations are then discussed. The final section concludes this article.

Network Architecture

This section presents the C/U-plane decoupled architecture for railway wireless networks. As CoMP could be a technology that allows the train to receive signals from both adjacent eNBs when the train travels through the handover overlapping area, it is employed to establish the U-plane of the target small cell in advance [10]. In this way, a seamless and soft U-plane handover is achieved to improve the QoE of passengers.

C/U-plane Decoupled Architecture for Railway Wireless Networks

In traditional wireless communication networks, the control signaling and user dedicated data are tightly coupled. For such voice-oriented homogeneous networks, the method of capacity extension is normally to reduce the frequency reuse distance such as cell splitting. However, the capacity gain is severely limited by the high inter-cell interference. As various wireless connected mobile devices with various capability increase dramatically in our daily life, heterogeneous network deployment with various kinds of communication infrastructures is commonly used to enhance the capacity locally. Heterogeneous networks, such as mico-cell, pico-cell, and femtocell networks, exploit interference management techniques to address inter-cell interference in homogeneous networks. However, the significantly increased control signaling due to network access poses tremendous challenges to the traditional tightly coupled architecture as the network density is getting higher. For clarity, the performance results of different network architectures are listed in Table 1 [11–13].

Network architecture	System capacity	Mobility	Interference	Control signaling
Macro cell	Low	Good	High	Low
Cell splitting	High	Medium	High	Low
Micro cell	High	Medium	High	High
Pico cell	High	Bad	Low	High
Femto cell	Low	Bad	Medium	High
C/U-plane decoupled	Extremely high	Good	Low	Low

Table 1. Performance comparisons.

According to the above analysis, the 5G C/U-plane decoupled architecture is applied to future railway wireless networks to extend the transmission capacity as shown in Fig. 1. In this network, passenger equipment inside the train first connects to the AP, and then their services are forwarded to wayside eNBs via the onboard MR. To gain broader spectra, the U-plane of passenger services, which is the major consumer for capacity, is moved to small cells operating at higher frequency bands. To enable efficient mobility management, the relatively important C-plane is kept in macro cells operating at high-quality lower frequency bands. More precisely, some low-rate services with strict requirements for transmission reliability, e.g. train control information, can also be entirely distributed to macro cells without decoupling. In the future train control system, more security equipments will be employed, which will generate more data to transmit between the train and wayside eNBs. To fulfill these capacity demands, less critical data, such as security monitoring data, can also be transmitted with the U-plane moved to higher frequency bands as the passenger services. As small cells are only responsible for the U-plane, they are just connected to the SGW while not to the MME, as shown in Fig. 1. The control signaling for managing small cells is handled by macro cells via interface X3 [6]. To provide other services with strict requirements for transmission reliability, in addition to the MME, macro cells are also connected to the SGW. Since small cells and macro cells operate at different frequency bands, there is no co-channel interference between them.

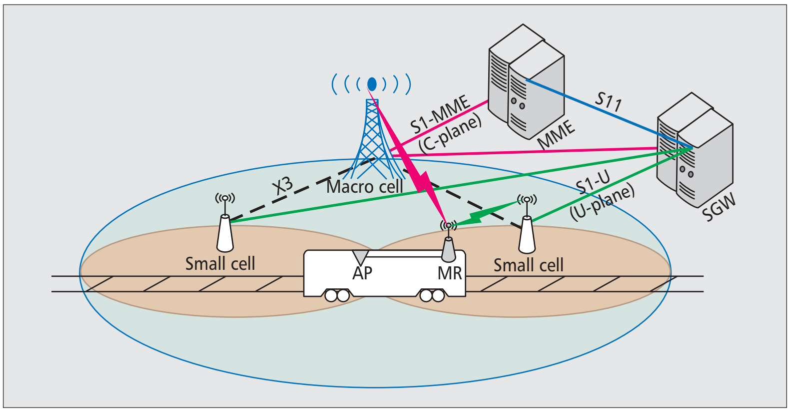


Figure 1. The C/U-plane decouple architecture for railway wireless networks.

Inter-Small Cell Handover

Because of the severe path loss of higher frequency bands, the coverage of small cells is very limited, which causes more frequent inter-small cell handovers. To achieve seamless and soft U-plane handover, the CoMP and bi-casting techniques are employed to establish the U-plane transmission of the target small cell in advance. Since the macro cell controls all control functionalities in the network, the entire inter-small cell handover process is under the control of the macro cell. Furthermore, this concentrated management can facilitate fast coordination between the two small cells [7]. As shown in Fig. 2, the whole process of the CoMP and bi-casting based handover can be divided into three operational phases: CoMP and bi-casting triggering; U-plane handover; and CoMP and bi-casting exit. Before the train runs into the overlapping area, if the signal strength of the source small cell is lower than a threshold, CoMP will be triggered. As the source and target small cells are both connected to the SGW, the macro cell asks SGW to directly bi-cast the U-plane data to these two small cells. Then, under the control of the macro cell, these two small cells begin to transmit the same U-plane data on the same time-frequency resources. In the overlapping area, as the signal strength of the source small cell further reduces, the inter-small cell handover is triggered. Thanks to the decoupled architecture, within a macro cell, the C-plane is always kept on-line without handovers. The otherwise intensive C-plane handover signaling, such as the signaling of RRC reconfiguration and non-contention random access, can be saved, thereby simplifying the inter-small cell handover. Thus, the above described issue in heterogeneous networks is greatly mitigated. Moreover, with the CoMP technique, the U-plane is always kept connected without interruption during the whole handover process, which achieves seamless and soft U-plane handover. At the last phase, upon receiving the handover confirmation, CoMP and bi-casting are terminated.

In the decoupled architecture, the C-plane and U-plane of passenger services are separately managed by different physical nodes. As a consequence, channel mappings and physical layer frames need to be redesigned. To facilitate the presentation, we use LTE for the baseline study.

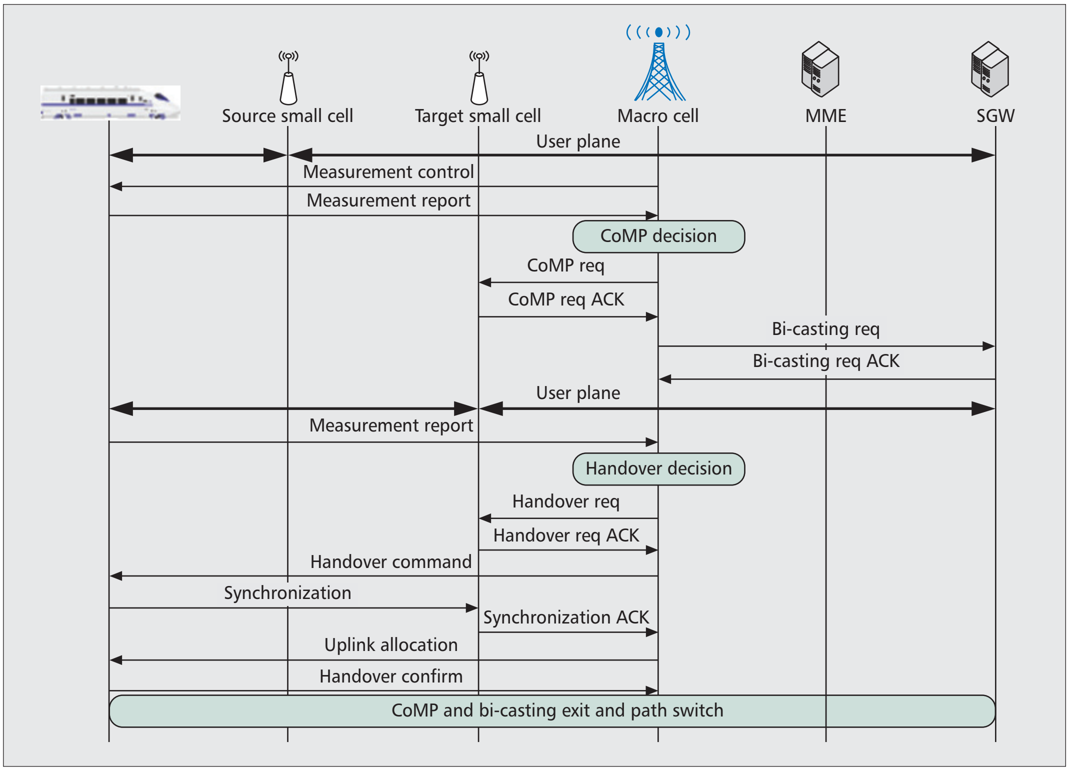


Figure 2. CoMP and Bi-casting based U-plane handover process.

Channel Mappings and Frame Structure

In the decoupled architecture, the C-plane and the U-plane of passenger services are separately managed by different physical nodes. As a consequence, channel mappings and physical layer frames need to be redesigned. To facilitate the presentation, we use LTE for the baseline study.

Channel Mappings

In conventional LTE networks, channel mappings include the mapping from logical channels to transport channels and from the transport channels to physical channels. A logical channel is defined by the type of information it carries and classified as control channel or traffic channel, which includes [14]:

- PCCH (paging control channel), used for paging.
- CCCH (common control channel), used for the transmission of control signaling in conjunction with random access.
- DCCH (dedicated control channel), used for individual configuration such as handover messages.
- BCCH (broadcast control channel), used for the transmission of system information from the network to all users in a cell.
- MCCH (multicast control channel), used for the transmission of control information required for reception of the MTCH.
- DTCH (dedicated traffic channel), used for the transmission of user data to/from a terminal.
- MTCH (multicast traffic channel), used for the downlink transmission of MBMS (multimedia broadcast multicast service).

Obviously, BCCH and MCCH are cell-dedicated control channels that carry system level information. While for the user-dedicated control channels PCCH, CCCH, and DCCH, the signal they transmit is specific to some user, inclusive of paging, handover, and random access. In LTE networks these two kinds of control channels are responsible for the C-plane signaling process. The U-plane data are carried by the traffic channels DTCH and MTCH, of which DTCH is designed for the user-dedicated service and MTCH is used for the cell-dedicated traffic. From the perspective of logical channels, the C-plane and U-plane are split actually. However, after the logical channels are mapped to the transport and physical channels, these two planes are mixed up as shown in Fig. 3a. Conversely, in the decoupled architecture, the C-plane and the U-plane of passenger services are managed via different nodes. Therefore, the control and traffic channels are always separated during all channel mappings. Based on this, channel mappings of the C/U-plane decoupled architecture are redesigned as shown in Fig. 3b. Since PCCH, CCCH, and DCCH are all user-dedicated control channels, all of them are mapped to the transport channel CCH (control channel), and then to the physical channel CPDCCH (converged physical downlink control channel). Although both of BCCH and MCCH are cell-dedicated control channels, they carry different types of system information, thereby being separately mapped to the transport channels BCH (broadcast channel) and MCH-C (multicast channel for the C-plane), and then to the physical channels PBCH (physical broadcast channel) and PMCCH (physical multicast

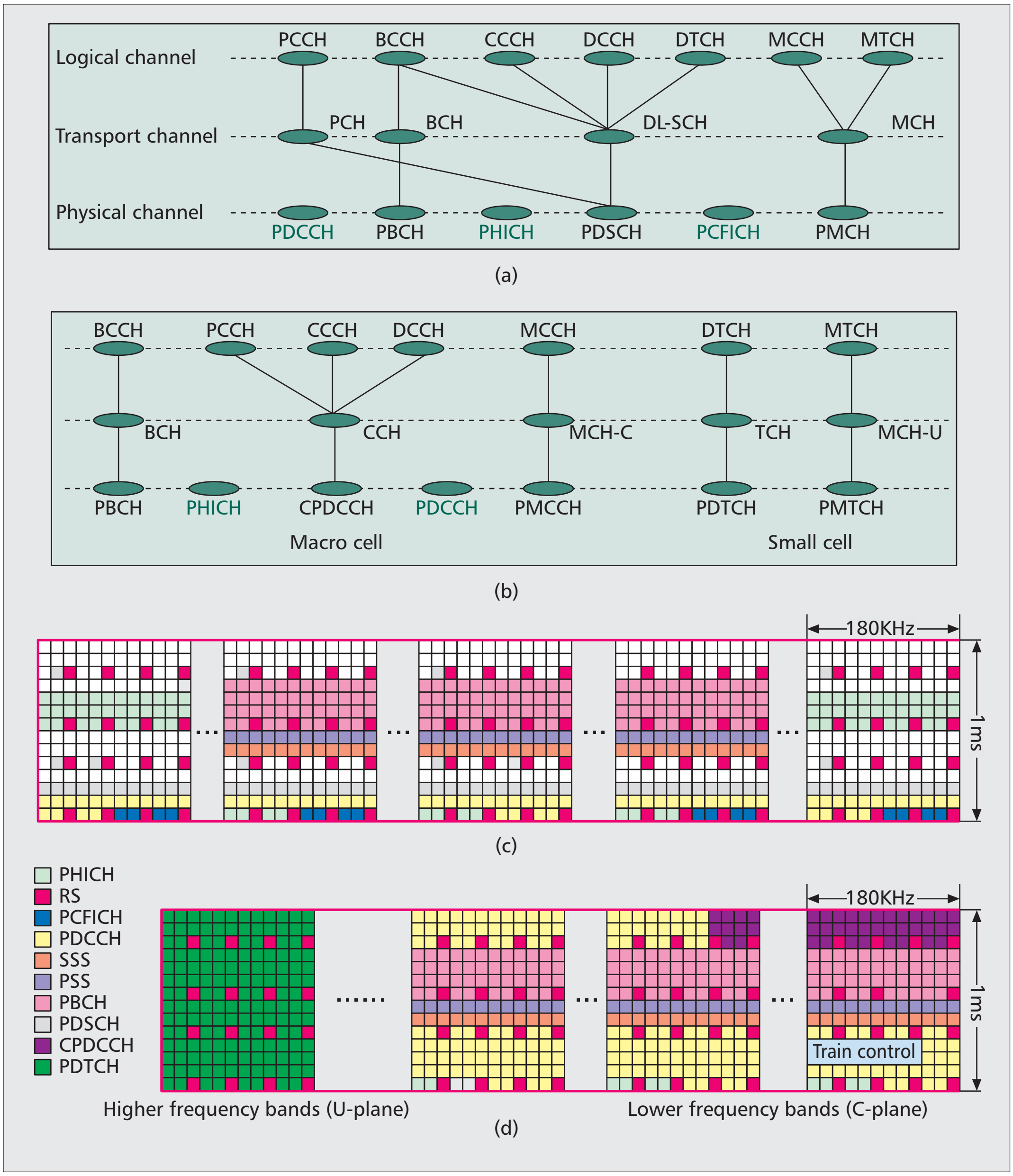


Figure 3. Channel mappings and frame structure: a) channel mappings in conventional LTE networks; b) newly redesigned channel mappings; c) frame structure in conventional LTE networks; d) newly redesigned frame structure.

The results on bandwidth matching demonstrate that the decoupled architecture could offer higher capacity. The simulation results on connection outage probability reveal that the propagation diversity between higher and lower frequency bands is balanced.

control channel). With the C-plane and the U-plane separated to different frequency bands, there is no need to preserve the traditional PCFICH (physical control format indicator channel) to discriminate the boundary of the control and shared channels. However, for PHICH (physical hybrid ARQ indicator channel) and PDCCH, they are still necessary to separately bear the HARQ (hybrid automatic repeat request) feedback information and DCI (downlink control information). As to the traffic channels, DTCH and MTCH are individually mapped to the transport channels TCH (traffic channel) and MCH-U (multicast channel for the U-plane), and then to the physical channels PDTCH (physical downlink traffic channel) and PMTCH (physical multicast traffic channel).

Physical Layer Frames

As depicted in Fig. 3c, the physical layer frames of conventional LTE can be roughly divided into two segments: PDCCH and PDSCH (physical downlink shared channel). PDCCH is designed to carry the downlink control information, which can help UEs properly receive and transmit U-plane data. As mentioned above, in conventional LTE networks, control channels are mixed with traffic channels during channel mappings. Therefore, in the physical layer frame, the C-plane signaling and the U-plane data share the same time-frequency resources in PDSCH. Based on the newly redesigned channel mappings for the decoupled architecture, the C-plane and the U-plane of passenger services are supposed to be separately assigned to different frequency bands in the newly proposed frame structure as

The amount of resources employed by CPDCCH depends on users' behavior. For example, when handovers for a high speed rail system occur, lots of resources will be occupied by CPDCCH to transmit the corresponding control signaling.

described in Fig. 3d. As the U-plane of passenger services demands more capacity, its carrier PDTCH is moved to higher frequency bands to gain broader spectra. The relatively critical C-plane signaling, generated from paging, handover, and random access processes, is all converged to CPDCCH. To ensure the transmission reliability, CPDCCH is kept on lower frequency bands. In addition, other possible services with strict requirements for transmission reliability are also considered during the physical layer frame design. For simplicity, we take the train control information as an example for the following analysis. To ensure the transmission reliability of the train control information, both the C-plane and the U-plane are served on lower frequency bands without decoupling. Hence, its frame structure is the same as that of the conventional LTE. Just as in conventional LTE, other control channels such as PBCH and PHICH are still kept on lower frequency bands. Even though the above redesigned channel mappings and physical layer frames are for downlink, the same also applies to uplink.

Performance Evaluation

In this section we conduct performance evaluation for our proposed architecture in terms of bandwidth matching and connection outage probability. The results on bandwidth matching demonstrate that the decoupled architecture could offer higher capacity. The simulation results on connection outage probability reveal that the propagation diversity between higher and lower frequency bands is balanced.

Bandwidth Matching

Given the total bandwidth in the macro cell, how much bandwidth to be allocated to the small cells to support the entire system is addressed in this section. Intuitively, we can draw a qualitative conclusion that if the entire existing lower frequency band is used for the C-plane, more passengers will be accommodated and the broader bandwidth of higher frequency bands will be required to transmit the U-plane data of these passengers. Nevertheless, it is much more important to have rigorous quantitative analysis to provide a better understanding of this architecture in terms of bandwidth matching. The intuitive idea of our analysis is to set apart the resources needed to support the train control information (as mentioned above, the train control information is taken as an example of the possible services fully provided by macro cells without decoupling to guarantee the transmission reliability) , and then determine how many passengers can be supported by the remaining resources of the macro cell to support the C-plane. Given the number of passengers supported by the macro cell and the required bandwidth of the U-plane data per passenger, the bandwidth used by the small cells can be obtained.

For simplicity, we only consider voice dispatch via VoIP as the train control information. Since the entire train control information is handled by the macro cell, its physical layer frame structure is the same as that of conventional LTE, that is, PCFICH, PHICH, PDCCH, and PDSCH are all kept the same. In LTE networks, one PHICH can be shared by eight users in the case of normal CP (cyclic prefix) and FDD (frequency division duplex) [14]. In order to lower the resource consumption in the macro cell, the train control information shares the same PHICH with other passengers. Considering the transmission reliability, the MCS (modulation and coding scheme) of the voice dispatch information is set to, for example, QPSK with coding rate of 1/3 and four CCEs are assigned to its PDCCH, while for passengers, the C-plane and the U-plane are handled by the macro cell and the small cells, respectively. Hence, there is no need to retain PCFICH to indicate the boundary of the PDCCH and PDSCH. To accommodate the maximum number of passengers in the macro cell, some infrequent control channels including PBCH and PMCCH are ignored. The amount of resources employed by CPDCCH depends on users' behavior. For example, when handovers for a high speed rail system occur, lots of resources will be occupied by CPDCCH to transmit the corresponding control signaling. Except for particular situations, in most common communication processes, the amount of resources consumed by CPDCCH can be neglected. Excluding the resources for the train control information, all remaining resources are assigned to the essential channels, such as PHICH, PDCCH, and RS (reference signal), to maximize the number of passengers that the macro cell can accommodate. Based on the above analysis, the results of bandwidth matching are shown in Fig. 4. With the bandwidth of 5 MHz assigned to the macro cell, 96 passengers can be supported in the duration of one sub-frame (1ms). Correspondingly, 21.2 MHz bandwidth for small cells is required to accommodate these passengers (each with a data rate of 500 kb/s), while in conventional LTE networks, only up to three OFDM (Orthogonal Frequency Division Multiplexing) symbols in the time domain of a frame can be used to transmit the essential control channels including PDCCH, PHICH, PCFICH, and RS. In a similar way, it is easy to obtain that 21 passengers can be accommodated in the conventional LTE network with 5 MHz bandwidth, which is much less than that accommodated in the proposed network architecture. Besides, the attained average data rate per user on the remaining resources is 21.2 kb/s, which can barely meet users' capacity requirements in the future. As a remedy, in the proposed network architecture, with broader available spectra in small cells, a larger data rate per user can be achieved. From the above comparison, it is shown that the decoupled architecture can offer higher capacity.

Connection Outage Probability

Without loss of generality, the channel quality in the form of SIR (signal to interference ratio) is used to evaluate the network connection performance. Connection outage happens when the SIR of the received signal is lower than a connection outage threshold. Considering the log-normal distributed shadow fading with mean 0 and standard deviation σ, the connection outage

Bandwidth of the macro cell	
Bandwidth	5MHz
Protection ratio	10%
Total (normal CP)	4200 REs
REs for train control	
VoIP data rate	12.2 Kbps
MCS	QPSK, 1/3
PCFICH	16 REs
PDCCH (4CCE)	144 REs
RS (9.52%)	19 REs
Consumption	198 REs

(a)

The number of supported passengers	
Available resources	4200-198=4002 REs
RS (9.52%)	381 REs
PHICH/8 passengers (N_g=1)	12 REs
PDCCH/passenger (1CCE)	36 REs
Number of passengers	96

(b)

Matched bandwidth of the small cell	
Data rate/passenger	500 Kbps
MCS	16QAM, 2/3
RS (9.52%)	1879 REs
Total consumption	19735 REs
Matched bandwidth	21.2 MHz

(c)

Figure 4. Bandwidth matching analysis.

Theoretical analysis and simulation results demonstrate that the decoupled architecture has the ability to offer higher capacity and balance the propagation diversity between the higher and lower frequency bands. It is expected that the proposed architecture will provide a viable solution to supporting high data rate services over future railway communications systems.

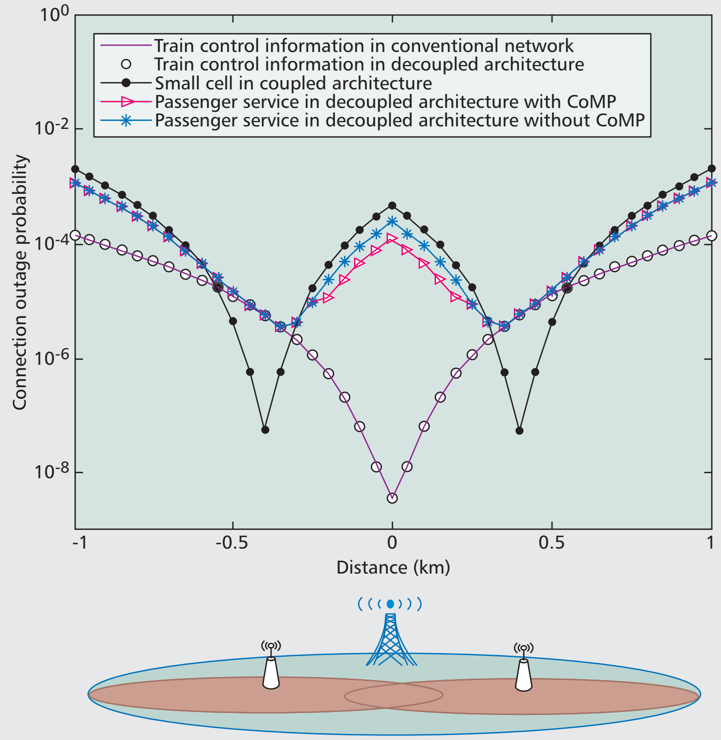
probability can be evaluated as $\Phi[(\Gamma + I + PL(d) - P_t)/\sigma]$, where P_t is the transmission power of the eNB, $PL(d)$ is the path loss at propagation distance d, I is the co-channel interference, Γ is the connection outage threshold, and Φ is the standard normal Gaussian cumulative function. Detailed mathematical and simulation models can be found in [10]. The simulation parameters and results are described in Fig. 5. As train control information is entirely kept on lower frequency bands of macro cells in the decoupled architecture, the conventional network and the decoupled network gain the same connection performance of train control information. Consequently, as shown in Fig. 5b, the curve "Train control information in conventional network" overlaps with the curve "Train control information in decoupled architecture." Suppose the connection outage probability of the macro cell and small cells is P_m and P_s, respectively. For passengers, only when the C-plane handled by the macro cell and the U-plane handled by the small cells are both connected, can they be kept on-line. Hence, the connection outage probability of passenger services can be approximately expressed as $1 - (1 - P_m)(1 - P_s)$. From this expression, we observe that the propagation diversity between the higher and lower frequency bands is balanced. For example, at the edge of the macro cell, which is also the edge of the small cell, the value of P_m is much smaller than P_s because of the higher path loss at higher frequency bands. Thus, the connection outage probability of this decoupled architecture, $1 - (1 - P_m)(1 - P_s)$, is smaller than $1 - (1 - P_s)(1 - P_s)$, which corresponds to the connection outage probability of the conventional coupled architecture (i.e. both the C-plane and the U-plane are handled at higher frequency bands). This can also be observed in Fig. 5b, where the connection outage probability of the small cells in the coupled architecture is higher than that of the decoupled architecture at the cell edge. For the area near the small cell still far away from the edge of the macro cell, because the signal quality of the macro cell is worse than that of the small cell, the connection outage probability of the coupled architecture performs better than that of the decoupled one. However, this also reflects that the decoupled architecture can balance the propagation diversity between the higher and lower frequency bands. Finally, thanks to the CoMP technique, which enables the train to simultaneously receive two U-plane signals, the received U-plane signal quality is greatly improved. Consequently, compared with the case without CoMP, the connection performance of passenger service is improved. As CoMP is applied to U-plane handovers, as shown in Fig. 5b, the performance improvement is only achieved at the overlapping area of small cells.

Conclusions

To meet the dramatically increasing capacity demands, new network architectures are being proposed in 5G cellular systems. Using small cells that operate at higher frequency bands with broader spectra is a good choice to increase the

Simulation parameters	Values
Frequency band of the macro cell	900 MHz
Radius of the macro cell	1 km
Fading model of the macro cell	Hata
Frequency band of the small cell	3.5 GHz
Radius of the small cell	0.6 km
Overlapping area of the small cell	0.4 km
Fading model of the small cell	PL(d/km)=15+36lg(d) [15]
Transmission power of the macro and small cells	43 dBm
Connection outage threshold	3 dB
Reuse factor	3
Shadow fading variance	4 dB

(a)



(b)

Figure 5. The connection outage probability comparison.

system capacity, while the transmission reliability and mobility performance are guaranteed by macro cells operating at lower frequency bands. Therefore, based on these observations, in this article we advocate a novel C/U-plane decoupled architecture for future railway wireless networks. By considering the transmission reliability and mobility management, the relatively important C-plane of passenger services is kept on the reliable lower frequency bands, while the U-plane of passenger services, which demand more capacity, is moved to higher frequency bands. The corresponding channel mappings and physical frames need to be redesigned to achieve the design goal. To address the QoE of passengers, CoMP and bi-casting are used to realize seamless and soft U-plane handover. Theoretical analysis and simulation results demonstrate that the decoupled architecture has the ability to offer higher capacity and balance the propagation diversity between the higher and lower frequency bands. It is expected that the proposed architecture will provide a viable solution to supporting high data rate services over future railway communications systems.

Acknowledgment

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