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Research Article

Investigation of Cooperation Technologies in Heterogeneous Wireless Networks

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Heterogeneous wireless networks based on varieties of radio access technologies (RATs) and standards will coexist in the future. In order to exploit this potential multiaccess gain, it is required that different RATs are managed in a cooperative fashion. This paper proposes two advanced functional architecture supporting the functionalities of interworking between WiMAX and 3GPP networks as a specific case: Radio Control Server- (RCS-) and Access Point- (AP-) based centralized architectures. The key technologies supporting the interworking are then investigated, including proposing the Generic Link Layer (GLL) and researching the multiradio resource management (MRRM) mechanisms. This paper elaborates on these topics, and the corresponding solutions are proposed with preliminary results.

1. Introduction

In the near future, multitude of wireless communication network based on a variety of radio access technologies (RATs) and standards will emerge and coexist. The availability of multiple access alternatives offers the capability of increasing the overall transmission capacity, providing better service quality and reducing the deployment costs for wireless access. In order to exploit this potential multiaccess gain, it is required that different RATs are managed in a co-operative fashion. In the design of such a co-operative network, the main challenge will be bridging between different networks technologies and hiding the network complexity and difference from both application developers and subscribers and provide the user seamless and QoS guaranteed services. The trend will also bring about a revolution in almost all fields of wireless communications, such as network architecture, protocol model, radio resource management, and user terminal.

There are always plenty of prior researches on the cooperation of heterogeneous RATs, including a number of IST FP projects [1]. However, in the view of this paper, two technologies play an important and foundational role in efficient cooperation between different radio technologies, including: *Generic Link Layer (GLL) and Multiradio Resource Management (MRRM)*.

The generic link layer and multiradio resource management are firstly discussed in Ambient Networks Project [2]. The GLL may be identified as a toolbox of link layer functions, which is designed with the capabilities of universal link layer data processing and reconfiguration to enable different radio access networks to cooperate on the link layer. GLL not only can offer the lossless and efficient solution for intersystem handover, but also make the possibility of multiradio transmission (or reception) diversity and multiradio multi hop. Multiradio Transmission Diversity (MRTD), implies the sequential or parallel use of multiple RAs for the transmission of a traffic flow. Multiradio Multihop (MRMH) implies link layer support for multiple RAs along each wireless connection over a multi-hop communication route. Moreover, in the heterogeneous relay network, in order to provide the better end-to-end QoS guarantee a unified expression or evaluation of QoS capability through a transmission link is needed. QoS Mapping is used to translate QoS guarantee provided by the next hop into their effects on the previous hop (sender).

MRRM is a control-plane functionality designed to manage all the available radio access resources in a coordinated manner, such as load balance, radio access selection, and mobility management. (In other papers, the MRRM item may be replaced by Joint Radio Resource Management (JRRM) and Common Radio Resource Management sometimes.) The aim of introducing MRRM is to efficiently use the radio resources in a multiaccess network, it is important to provide optimum radio resource management functionalities between the different RATs in the RAN.

In the following, these aforementioned issues will be elaborated, respectively. This paper is organized as follows. Firstly, in Section 2 we propose advanced interworking networks architecture by taking WiMAX and 3GPP long-term evolution networks as a specific case. The GLL adopted in the protocol architecture is introduced, and the investigation of several novel concepts of GLL is presented in Section 3. Section 4 discusses the key functionality and mechanisms of MRRM, especially for load balance and RA selection. Section 5 concludes this paper.

2. Interworking Architecture Based on Multiradio Access

It is important to note that having a well-defined interworking architecture, which is a very challenging task to researchers, will accelerate the creation of enriched services through the co-operation of networks. In this paper, we focus in particular on an interesting use case: the integration of mobile WiMAX within 3GPP LTE networks. This integration is facilitated by the evolved packet network architecture, which has recently been standardized by 3GPP in the context of Release 8 specifications [3].

After the introduction of the IP transport in R4 and R5, 3GPP TSG RAN group studied the UTRAN architecture evolution items [4, 5] to improve the radio performance and transport layer utilization; this work continues in release 8 [3]. In [4], several UTRAN architecture enhancement proposals are presented based on: separation of control and user plane, redefinition of UTRAN nodes functionalities, and separation of functional entities for cell, multicell, and user related functions. Another aspect in the scope of this work is the functionality increase of nobe B, which moves parts of the RNC functionalities to an evolved node B(iNodeB) including cell specific radio resource management, soft HO management and radio processing (MAC, RLC, and PDCP), and user data handling.

In [6], it provides some approaches to co-operation between multiple RATs in a multiradio environment which are investigated in the work package “multiradio access” (MRA) of the Wireless World Initiative—Ambient Networks project. A multiradio access (MRA) interworking architecture is also proposed in [6], and different levels of co-operation have been studied based on two concepts: generic link layer and multiradio resource management in order to exploit the potential multiaccess gain.

Herein we adopt these ideas and clues [3–7] and propose two architectures of WiMAX and LTE interworking with necessary logical nodes and interfaces. The two architectures are designed on the basis of different levels of interworking, and each of them can combine several RATs within a single RAN and allow a flexible deployment of network nodes and the interconnecting transport network. They not only combine common functions of different RATs but also are build on a Generic Link Layer (GLL) [6] which generalizes some common link layer functions for different RATs, such as queuing of data packets, higher layer header compression, segmentation and retransmission functionality and an enhanced Radio Resource Control (RRC) layer which adds the Multiradio resource management (MRRM) [6] functionalities.

2.1. Radio Control Server- (RCS-) Based Centralized Architecture. Figure 1 shows a proposal of WiMAX and LTE interworking architecture that consists of the following logical nodes and networks.

(i) User Terminal (UT): this logical node consists of all functionalities necessary for an end user to access either WiMAX or LTE network.

(ii) Relay Node (RN): it consists of forwarding functionality in order to extend the network’s coverage area and simplify the network planning.

(iii) Base station (BS): it is a pure WiMAX Access Point (AP).

(iv) Radio Control Server (RCS): the one in WiMAX network controls the BSs with associated UTs and the one in LTE controls Node Bs with associated UTs.

(v) Multiradio Control Server (MRCS): this node is defined to control and coordinate some RCSs for interworking.

(vi) Bearer Gateway (BG): this node acting as Access Router (AR), assigns IP address, and so forth, and consists of GLL and WiMAX and LTE RATs specific user plane functions.

In this proposed architecture, WiMAX and LTE RANs co-operate in a loose mode based on the RCSs and MRCSs. The evolutional RAN architecture of 3 G as aforementioned is adopted with an evolved node B and separation of user and control plane. The new introduced RCSs and MRCSs will play an important role in the cooperation of the two different RATs. Actually, MRCS and BG are two different logical nodes, but they can be located in the same communication entity. MRCS is used to complete the functionalities in the control plane, while BG domains the user plane.

The radio interface protocol stack in the control plane is described as shown in Figure 2. Note that UT not only can directly communicate with BS/Node B, but also can communicate via RN. The GLL is defined above (or within) the L2 and below Radio Resource Control (RRC) layer. It needs to notice that the GLL entity in BS/node B is optional in the loose cooperation scenario. In RRC layer, the MRRM controls the radio connection and management of radio resource for different RATs and different hops, by cooperation between different MRRM entities in MRCS,

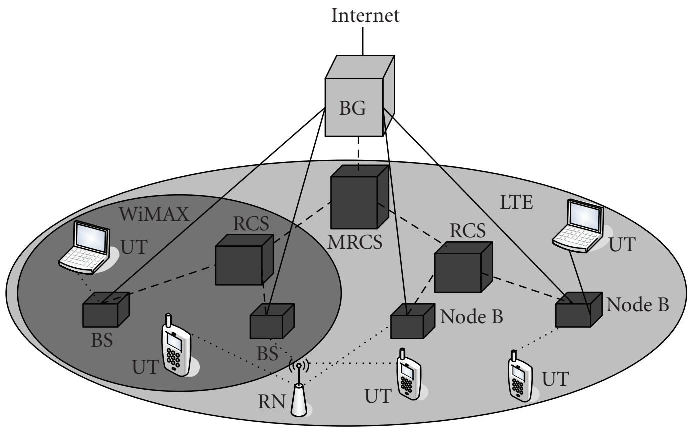

Figure 1: RCS based centralized architecture.

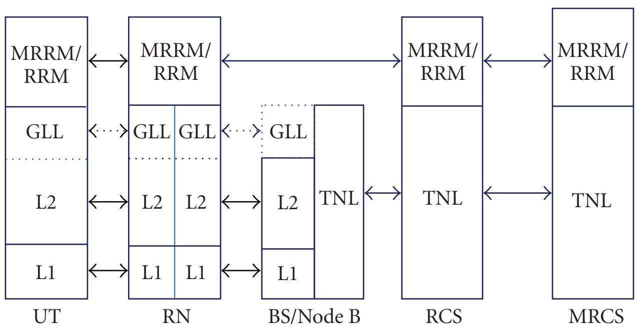

Figure 2: Interface protocol architecture in the control plane.

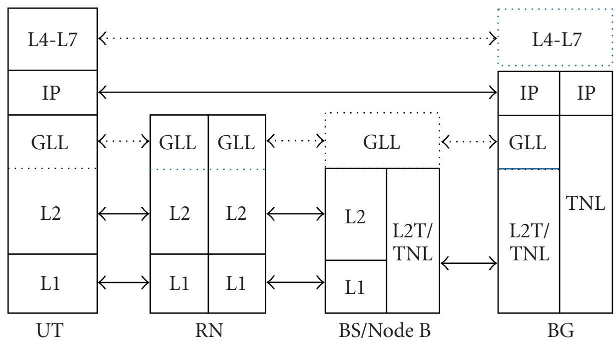

Figure 3: Interface protocol architecture in the user plane.

RCS, RN, and UT. TNL which means Transport Network Layer is used to carry the radio interface protocols between infrastructure nodes.

The radio interface protocol in the user plane is described as Figure 3. The interface between different communication entities in the user plane is the same as that in the control plane. However, RCS and MRCS are not concerned here as user and control planes are separate. But Bearer Gateway (BG) is needed to convey different data formats, respectively, from LTE or WiMAX to the IP core network and vice versa. Therefore GLL should be involved in this node. IP packets are transmitted between the BG and the Node B/BS via some layer two tunnels (L2Ts) based on some specific tunnelling protocol.

2.2. Access Point- (AP-) Based Centralized Architecture. Figure 4 shows another proposal of WiMAX and LTE interworking architecture that consists of the following logical nodes.

(i) User Terminal (UT): this logical node consists of all functionalities necessary for a terminal user to access either WiMAX or LTE at least.

(ii) Relay Node (RN): it consists of retransmission in order to extend coverage area.

(iii) Radio Access Technology Access Point (RAT AP): it is a combined WiMAX and LTE Access Point in one node with GLL features.

(iv) Radio Control Server (RCS): this is a general controller of RAT AP which performs both RRM and MRRM functions.

(v) Access Router (AR): the Access Router assigns IP address and carries out routing functions which depends on route parameters, and so forth. It may include or not include GLL because all RAT APs provide an identical format of data (all IP packets).

In this proposed architecture, WiMAX and LTE RANs co-operate in a tight mode based on the RCSs and ARs. The evolutional RAN architecture of 3G as aforementioned is adopted with an evolved node B and separation of user and control plane. RAT-AP supports both WiMAX and LTE access technologies, and Access Router (AR) is independent of any RATs and needed for routing functionalities. Therefore GLL should not be involved in AR and RCS.

3. Generic Link Layer

Generic link layer as an additional communication layer that provides universal link layer data processing for multiple radio access technologies may be identified as a toolbox

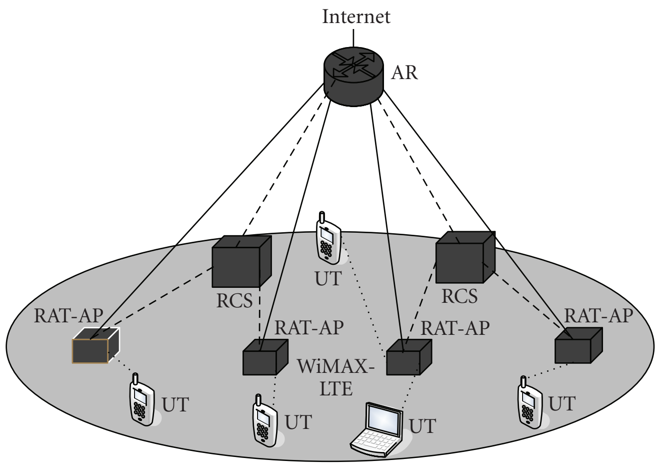

Figure 4: AP-based centralized architecture.

of link layer functions that can be readily adapted to the characteristics of both legacy and new (as yet unforeseen) radio access technologies. Figures 2 and 3 depict reference protocol model of generic Link Layer in heterogeneous networks. In these figures, both the RAN and terminal have installed the GLL logical architecture to support the efficient cooperation between different radio access technologies.

One of the important functions of introducing GLL is to enable lossless and efficient intersystem handover. Considering an intersystem handover process without GLL, a mobile terminal dynamically selects one of the two available radio access networks. During the lifetime of a session, an intersystem handover from RAN A to RAN B is executed in the case of the movement of the terminal or a change of the radio link quality, the radio link in RAN A is torn down and a new radio link is established in RAN B. In consequence, all buffers in the old link layer of RAN A are flushed and all data stored for transmission is discarded. Consequently, such an intersystem handover can lead to a significant amount of packet losses. The motivation for a generic link layer is to overcome this problem by making radio access networks cooperate on the link layer. If the radio link layers are compatible, the old radio link layer state can be handed over to the new radio link layer that continues the transmission in a seamless way, where the generic link layer is used for both radio links in the different radio access networks with different configurations.

More specifically, GLL should have the following functions [6]: (1) provides a unified interface to the upper layers, acting as a multi-RAT convergence layer, hiding the heterogeneity of the underlying multi-RAT environment, (2) controls and maybe complement the RLC/MAC functionalities supported by the multiple RATs in order to maximize the application layer performance while utilizing the radio resources allocated by the MRRM, (3) provides a modular architecture that readily caters for the integration and co-operation of different types of legacy and future RATs, (4) provides support for novel concepts such as dynamic scheduling of user packets across multiple RATs selected by the MRMM and other forms of multiradio macro diversity, (5) provides link layer context information to the higher layers for supporting efficient inter-RAT mobility management.

The proposed GLL facilitates two novel applications. The first one, named Multiradio Transmission Diversity, implies the sequential or parallel use of multiple RAs for the transmission of a traffic flow. The second one, termed Multiradio Multi-Hop networking, implies link layer support for multiple RAs along each wireless connection over a multi-hop communication route.

3.1. Multiradio Transmission Diversity (MRTD). Multiradio transmission diversity (MRTD) is defined as a well-defined split of a data-flow (on IP or MAC PDU level) between two communicating entities over more than one RAT. The transmitting entity may select one or more RATs among the available ones to achieve the gain of multiradio diversity. Different MRTD schemes are possible. When referring to the scheme of selecting the multiple RAs at any given time for transmission of user data, MRTD is classified as well two schemes: switched (sequential) and parallel MRTD [8].

For switched MRTD, user's data, equivalent in size to the payload of MAC PDUs, is transmitted via only one RA PHY layer at any given time. Successive MAC PDUs may be transmitted via different RA physical layers. The paper [9] studies packet scheduling algorithms in order to exploit multiradio transmission diversity in multiradio access networks, where the packet scheduling process is viewed as a combination of user scheduling and radio access allocation. In [10], the authors address the problem of multiuser scheduling with multiradio access selection, it shows that performance gains are possible and come from multiuser diversity as well as multiradio diversity while both the best user and the best radio access were selected. Parallel MRTD is implemented by simultaneously transmitting the copies of same data over multiple RAs, in other word different RAs are allowed to serve the same entity, so as to increase the robustness. At the reception, the received packets from different radio accesses can be combined based on some

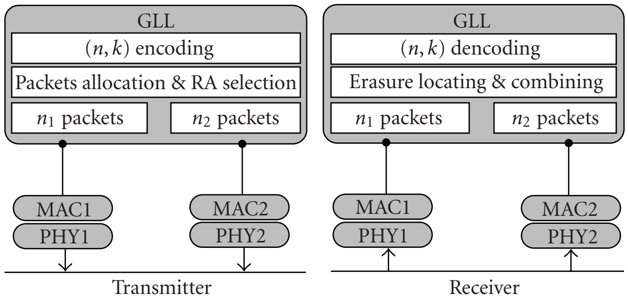

FIGURE 5: MRTD based on Packet level FEC.

strategies to achieve the gain of MRTD. The researching of parallel MRTD schemes is still scare up to now.

Both switched and parallel MRTD can provide considerable performance gain, but there are also some constraints for them. For switched MRTD, it supposes every selected radio access can provide enough bandwidth or data rate serving for the user, but which is not always possible. For parallel MRTD, the transmission efficiency is decreased due to that the reduplicate packets need to be transmitted simultaneously. Therefore, in this paper, a novel MRTD scheme based on packet level FEC (MRTD-PFEC) is proposed, which both considers the constraints of maximum data rate of each RA for the user on the one hand and integrates with packet level FEC to achieve better transmission efficiency than parallel MRTD scheme. The brief idea of the scheme is described as follow: the source packets (original information packets) will be firstly coded at generic link layer for the enhanced capability of error correction, then the coded packets are allocated over different RAs according to the specified selection algorithm, in order to minimizing the probability of irrecoverable loss at receiver side. At the reception, the source packets can be recovered based on combined decoding procedure at GLL.

We firstly assume that the sender with multi-mode has more than one ($l > 1$) available radio accesses (RAs) for simultaneous transmission, and these l radio access networks (RANs) are interworking in a cooperated fashion. Moreover, the terminal is designed with the functionality of MRRM and GLL. For simplicity, the number of available RAs is assumed as two ($l = 2$) in the following analysis, but it can be extended to the case with $l > 2$.

Figure 5 give a modal structure of the proposed MRTD scheme. The implementation procedure of MRTD-based packet level FEC scheme consists of four steps: *packet level encoding, channel measurement, packets allocation, and receiving and decoding* sequentially. As the most important step, the packet allocation process will be elaborated in the following.

3.1.1. Packet Level Encoding. At the sender, the data from upper layer (e.g., IP) are segmented into packet with fixed length L (bits) at GLL. The GLL packets are sequentially buffered and the continuous k packets are coded into n packets by using the (n, k) packet level forward error correction.

Different from bit level correction strategies, packet level correction operates on sequences of packets and deals with straight packet losses, while bit level correction operates on sequences of bits and deals with unpredictable bit error. For packet level FEC, one of advantages is that the decoder can know where the errors are by use of a Cyclic Redundancy Check (CRC), while the CRC field exists in each packet. These known error locations are called erasures, with which the decoder can correct more errors than that without the information of error locations. A (n, k) block erasure code takes k source packets and produces n encoded packets in such a way that any subset of k encoded packets (and their identity) allows the reconstruction of the source packets in the decoder and can recover from up to $n-k$ losses in a group of n encoded blocks.

When using the *Vandermonde code* [11] as the erasure code, the coding process can be represented as

$$y_{(n)} = G_{(n\times k)} \times x_{(k)}. \tag{1}$$

where $x = x_0 \cdots x_{k-1}$ are the source data, G is an $n \times k$ encoding matrix with rank k and consists in using coefficients of the form

$$g_{ij} = x_i^{j-1}. \tag{2}$$

It should be pointed out that the redundancy level $n - k/n$ is determined by the requirement of tolerant error rate for the service.

3.1.2. Channel Measurement. We assume that the instantaneous channel state of one RA link between sender and receiver is available sender through specific feedback and measurement mechanism, which is beyond the scope of this paper and would not be detailed here. Then, the average channel signal-to-noise ratio (SNR) can be calculated as

$$\gamma = \alpha\gamma_t + (1-\alpha)\overline{\gamma}, \tag{3}$$

where γ_t is the instantaneous channel, SNR, $\overline{\gamma}$ is the average channel SNR before the time t, and α is a constant. The average channel SNR will be used in the following step.

3.1.3. Packets Allocation. The goal of packets allocation is adaptive to the capability and reliability of the available transmission channels (i.e., RAs) in order to exploit the maximum gain of MRTD. Herein, we give an allocation strategy with the goal of minimizing the probability of irrecoverable loss at receiver.

In Section 2, we mention that a (n, k) block erasure code takes k source packets and produces n encoded packets in such a way that any subset of k encoded packets (and their identity) allows the reconstruction of the source packets in the decoder and can recover from up to $n - k$ losses in a group of n encoded blocks. Therefore, the probability of irrecoverable loss equals the probability of more than $n - k$ lost packets out of n packets sent via the two RAs.

We divide the n packets into two groups with the length of n_1 and n_2, respectively, and the process of separation satisfies the following condition:

$$n = n_1 + n_2. \tag{4}$$

Assuming the transmission via different RAs is independent, according to the separation, the probability of irrecoverable loss at the receiver can be expressed as

$$C(k, n_1, n_2) = \sum_{j=n-k}^{n} \sum_{i=0}^{j} P_1(i, n_1) P_2(j - i, n_2), \tag{5}$$

Subjected to (5), $n_1 L/T_1 < B_1, n_2 L/T_2 < B_2$, where $P_1(i, n_1)$ represents the fact that there are i packets lost out of n_1 packets sent via RA 1, $P_2(j - i, n_2)$ represents the fact that there are $j - i$ packets lost out of n_2 packets sent via RA 2. $C(k, n_1, n_2)$ is the probability that total more than $n - k$ packets are lost out of a total $n_1 + n_2$ packets sent by both senders. T_l is the total time duration of sending n_l packets via RA l, and B_l is the constraint of maximum data rates $(l = 1, 2)$.

The goal of the allocation algorithm is to select the optimized value of n_1, n_2 to minimize the probability of irrecoverable loss:

$$(n_1, n_2) = \arg\min_{n_1, n_2} C(k, n_1, n_2). \tag{6}$$

The process of searching for n_1, n_2 is fast since only n comparisons are required for the senders.

3.1.4. Receiving and Decoding. At the receiver, both the two parts of received packets from RA 1 and 2 are collected. The packets detected by CRC with error are discarded firstly. If there are more than k packets without error, recovery of original data is possible by solving the linear system

$$\underline{y}' = G' \underline{x} \Longrightarrow \underline{x} = G'^{-1} \underline{y}', \tag{7}$$

where $\underline{x}$ is the source data, $\underline{y}'$ is a subset of k components of $\underline{y}$ available at the receiver, and matrix G' is the subset of rows from G corresponding to the components of $\underline{y}'$.

Otherwise, the retransmitting strategy will be triggered to retransmit some of the error packets until more than k packets are received without error. The retransmitting process is also beyond the scope of this paper and will not be described in detail.

The simulation works have been carried out to investigate the performance of our proposed MRTD-FEC scheme based on the last section. Three types of MRTD scheme are compared together.

Switched MRTD. The packet at GLL is sent via the selected RA, where the maximum throughput RA selection strategy proposed in [9] is used.

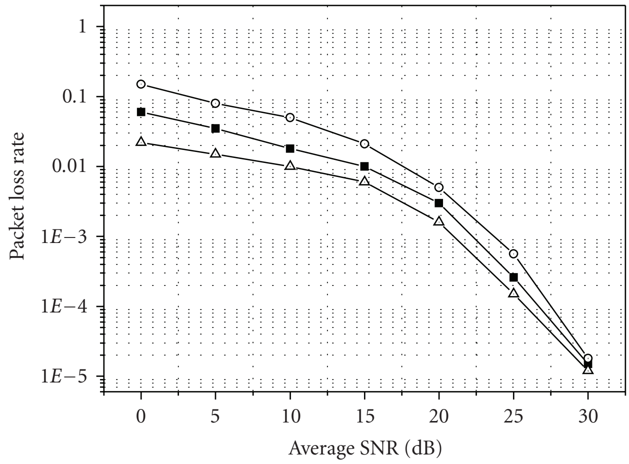

Figure 6: Packet loss rate versus average SNR.

Parallel MRTD. The packet at GLL is duplicated and sent via both the RAs. And the proposed *MRTD-PFEC* isin the paper.

To assess the performance of the proposed scheme clearly, Figure 6 shows the packet loss rate versus different average signal noise ratio. (Herein, we adopt the same average SNR for the user on the two RAs because the instantaneous SNR on different RAs are different at a time.) From the figure, it can be seen that the least packet loss rate happens in the MRTD-PFEC strategy, especially in the cases of lower average SNR. When the SNR is increasing and above certain value, all of the MRTD schemes have almost the close performance. That can be explained when the channel state was favorable with high robustness, the diversity and error correction strategies will be needed rarely and not contribute the correction of packet losses sufficiently.

Figure 7 depicts the average expected goodput versus different average SNR. We can observe when the channel state is in a bad condition that the MRTD-PFEC can provide the best expected goodput among the three strategies. When the SNR increases and the channel condition changes better, the switched MRTD outperforms MRTD-PFEC and parallel MRTD strategies since the needs of error correction and diversity are reduced but the pain of increased overhead introduced by MRTD-PFEC outstands. When combining with the results of packet loss rate, we can conclude that the MRTD-PFEC performs well especially when the channel states of the available RAs are in a bad condition as well.

3.2. Multiradio Multihop. From the multiradio access perspective, the scenarios that need to be targeted are quite different from the ones that have been traditionally associated to ad hoc (multi-hop) networks. Multi-hop communications are thought to be an extension of the current wireless communications paradigm, characterized by having, in most of the cases, a single hop between the end user and the point of attachment to the network. In contrast with this, multi-hop extensions appear as an appropriate way of extending coverage in a quick and efficient manner, so as to serve punctual increases of traffic demand. This can be achieved either by having dedicated relaying nodes, usually deployed by the operators, or working at unlicensed bands or even by letting end users to become forwarding nodes.

In WINNER project [12], the same concept of heterogeneous relay node is proposed. A heterogeneous relay node is a network element that is wirelessly connected to another relay node or a BS by means of a given radio access technology, and it serves another relay node or a UT using a different radio access technology. Figure 8 illustrates the scenario with a heterogeneous relay node, in which a subscriber can connect to both RAN1 BS and RAN2 BS through the relay node.

There are a number of interest issues and potential solutions with regards to the realization of MRMH networks.

(1) Multi-Hop ARQ as a unified error recovery protocol spanning over the complete multi-hop route may be described in terms of a two-stage error recovery process with respect to different radio access technologies.

(2) A special issue that needs to be addressed is that of different Layer 2 segmentation sizes per hop in cases where different RATs are used along the multi-hop route. This causes a problem that no common sequence numbering scheme can be used along the route.

(3) The capacity of a multi-hop route is typically determined by the bottleneck hop or "weakest link." Therefore, it is not realistic to have more data in flight on the multi-hop route than being required for utilizing the bottleneck capacity (or some anticipated variations thereof). A further advantage of a common multi-hop ARQ layer is that a bottleneck node can use a flow control mechanism in order to avoid extensive data buffering. This reduces the amount of data that needs to be recovered in cases where the route changes. To facilitate the prioritization of certain types of packets (e.g., ARQ signaling), a priority-based queuing discipline is required.

(4) MRMH can be combined with MRTD. Henceforth two-route selection mechanisms can be identified: one addresses the problem within the route (i.e., at the relay nodes) and another addresses it from the edge-nodes of the network (i.e., infrastructure nodes or user terminals).

3.3. QoS Mapping. Providing a seamless and adptive QoS in a heterogeneous network is a key issue. The research work of QoS has been mainly in the context of individual system, and much less process has been in addressing the issue of QoS guarantee in the heterogeneous networks. In [13], the author proposes a QoS framework integrating a three-plane network infrastructure and a unified terminal cross-layer adaptation platform for heterogeneous environment.

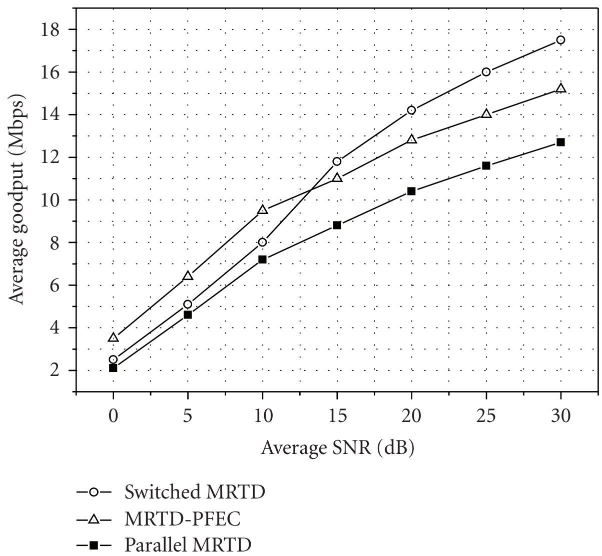

Figure 7: Expected goodput versus average SNR.

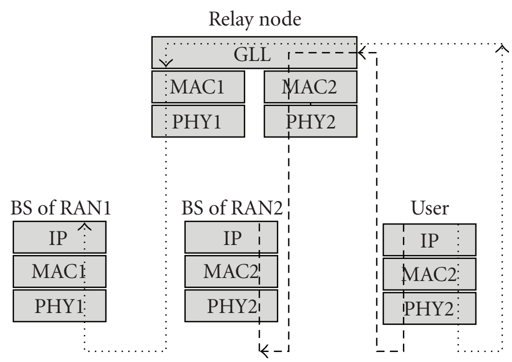

Figure 8: Heterogeneous relay.

However, there are no research results considering the end-to-end QoS guarantee over multiradio multi-hop link, so here we give a possible solution based on QoS mapping mechanism.

QoS mapping is usually referred for cross-layer of the protocol stack [14], herein which is needed to translate QoS guarantee provided by the next hop into their effects on the previous hop (sender), in order to give a unified evaluation of QoS capability of the end-to-end link. We can illustrate mapping process with some preliminary results related to segmentation and reassembly.

Considering a specific multiradio multi-hop scenario showed by Figure 9, there is a relay node connecting RAT-1 BS and RAT-2 UT. When the downlink RAT-1 MAC PDUs (denoted as RAT-1 PDU) pass through the relay node, each of them will be processed through the General Link Layer in relay node. In GLL, RAT-1PDUs will be segmented and reassembled in several RAT-2 PDUs, then the overall packet losses and delay are determined not only by RAT-1 link but also by RAT-2 link. In the following, the packet loss probability in the second hop with consideration of

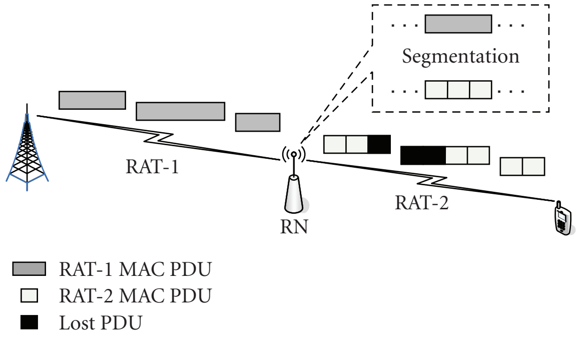

Figure 9: Segmentation and reassembly in MRMH link.

segmentation and reassembly are derived and mapped to the first link or sender (BS).

For simplicity, assuming a RAT-1 PDU can be divided into $N(N > 1)$ RAT-2 PDUs, which are labeled from 0 to $N - 1$. The loss probability of the ith RAT-2 PDU is independent of others, defined as p_i. Then, we can obtain the probability of successful transmission, which contains transmission of N RAT-2 PDUs and indicates the successful transmission probability of the corresponding RAT-1 PDU in the second hop

$$P_W = 1 - \prod_{i=0}^{N-1} 1 - p_i. \tag{8}$$

Because of the related fading characters of wireless channel, the loss of each PDU is relative with the previous PDU, a Markovian model is adopted where the probability of a packet loss depends only on whether the previous packet was also lost. Let M_i represent the event that the ith RAT-2 PDU is lost, then we have

$$P[M_i \mid M_{i-1}] = \alpha p, \tag{9}$$

$$P\left[M_i \mid \overline{M_{i-1}}\right] = p, \tag{10}$$

where $\alpha > 1$ and $0 < \alpha p < 1$, and α represents the relativity of the channel conditions in the time intervals for the transmission of two continuous RAT-2 PDUs. The larger α is, the more similar the channel conditions are.

Then, the probability of the ith RAT-2 PDU delivering correctly can be calculated as

$$\begin{aligned} P\left[\overline{M_i}\right] &= P\left[\overline{M_i} \mid M_{i-1}\right]P[M_{i-1}] + P\left[\overline{M_i} \mid \overline{M_{i-1}}\right]P\left[\overline{M_{i-1}}\right] \\ &= (1-\alpha p)P[M_{i-1}] + (1-p)P\left[\overline{M_{i-1}}\right]. \end{aligned} \tag{11}$$

The steady-state probability that a RAT-2 PDU is delivered correctly can be derived from (9), denoted by β,

$$\beta = \frac{1-\alpha p}{1+p-\alpha p}. \tag{12}$$

Finally, according to (6), the overall packet loss probability can be obtained

$$P_W = 1 - \beta^N. \tag{13}$$

That is the capability of packet losses provided by the second hop, which is actually the effect on the previous hop. The investigation of delay mapping can be analyzed in a similar way. Based on the result of QoS mapping, the unified expression of QoS capability through a multiradio multi-hop link is achieved, which can be used in resource allocation and scheduling for specific service to provide a better QoS guarantee, which is beyond the scope of this paper.

4. Multiradio Resource Management

To use the radio resources efficently in a multiaccess network, it is important to provide optimum radio resource management functionalities between the different RATs in the RAN. MRRM can operate at system, session, and flow level. At the system level, MRRM performs, for example, spectrum, load, and congestion control across two or more RAs. At the session level, MRRM coordinates decisions on different associated flows, where MRRM operations can be triggered either by system level operations or directly by session/flow level events, for example, session arrivals, or MRRM works through the establishment and maintenance of different RA.

The MRRM concept is divided into two logical parts on the basis of already existing intrinsic RRM functions. (1) RA coordination functions: the scope of these generic functions spans over the available RAs and typically includes functions such as dynamic RA addition and removal, inter-MRRM communication, RA selection, inter-RA handover, congestion control, load sharing, adaptation of the allocated resources in a coordinated manner across several available RAs, and so forth. (2) Network-complementing RRM functions: these technology-specific functions are particularly designed for one or more RAT(s). However, these functions do not replace the existing RRM functions of RAT(s) but rather complement them. These functions may provide missing, or complement inadequate RRM functions of an underlying RAT, for example, providing admission control, congestion control, intra-RAT handover. They are responsible for the RAT-specific interaction of the RA coordination functions and act as an adaptation function towards the network-intrinsic RRM functions. Hence, they appropriately translate format/terminology or commands into supporting effective interaction.

A nonexhaustive list of the most important RRM issues in multiradio access networks will be presented as follows.

4.1. Radio Access Network (RAN) Selection. Future devices can incorporate more than one access method to enjoy the seamless and variable services. The technological solutions should be transparent to the end user and one automatic means of evaluating the optimum choice to satisfy a set of services. Therefore, one of the principle research challenges involved in heterogeneous networks is the network selection to determine the appropriate radio accesses from those available RAs for the users. A perfect RA selection scheme should not only benefit from being able to access his/her subscribed services anywhere and anytime with high QoS and less cost, but also can improve overall efficiency of spectrum utilization.

At present, many researches aiming at this issue have been done, and they have put forward some fundamental algorithms for the heterogeneous systems. In the traditional methods such as [15], only the radio signal strength (RSS) threshold and hysteretic values are considered and processed in a fuzzy logic-based algorithm. However, in such a multiradio access environment, the traditional algorithm is not sufficient to make a handoff decision, since they do not take the current context or user's preference into account. When considering more handoff decision factors, a number of two-dimension cost functions such as [16] are developed. In one dimension, the function reflects the types of services requested by the user; while in the second dimension, it represents the cost of the network according to specific parameters. However, this method is not flexible for variable scenario, and the considered factor is not enough to describe the requirements in the RA selection process.

Herein we propose an optimized cost function-based RA selection algorithm. The purpose of the RAN selection algorithm is to optimize a predefined cost function including minimizing the consumed resources and/or "minimal price" for the session, guarantee the required QoS, and increase the overall spectrum efficiency. The algorithm is flexible for many scenarios by through parameters weight regulation. The implementation of the algorithm can be divided into three stages (depicted as Figure 10): Trigger and information collection, parameters processing, and RA selection.

In the first stage, the selection process will be triggered by several conditions, such as a new service generated, user profiles changed, or a new available access point detected. Next, some parameters used in the RAN selection procedure are collected. These parameters consist of radio propagation conditions, load situation in each RAN, required QoS level by the application, achievable level of QoS per RAN, consumed resources the corresponding charge per RAN, and so forth. In this scheme these parameters can be divided into two parts.

In the second stage, it is to calculate the weights of each parameter in the predefined cost function. The weight factors reflect the dominances of the particular requirements with respect to the user. AHP [17] as a mathematical-based technology to analyze complex problems and assist in finding the best solution by synthesizing all deciding factors is adopt to derive the weights of QoS parameters on the basis of user's preference and service application. Then we should normalize these parameters. Because these parameters have different characters, the normalization of the data is performed through two methods: larger the better, or smaller the better.

Larger the better:

$$x_i^*(j) = \frac{x_i(j) - l_j}{u_j - l_j}. \tag{14}$$

Smaller the better

$$x_i^*(j) = \frac{u_j - x_i(j)}{u_j - l_j}, \tag{15}$$

where $u_j = \max\{x_1(j), x_2(j), \ldots, x_n(j)\}$, $l_j = \min\{x_1(j), x_2(j), \ldots, x_n(j)\}$.

In the last stage, based on the prepared parameters and information, the cost function can be calculated for each user-network pair. The cost function for ith user on kth radio access is predefined as

$$\begin{aligned} F(i,k) &= W_{\text{se}} \times \text{SE} + W_c \times \text{Cost} \\ &\quad + W_\alpha \times \alpha + W_\beta \times \beta + W_\gamma \times \gamma, \end{aligned} \tag{16}$$

where SE is the spectrum efficiency and Cost represents the cost of a specific network per data unit. α and β are the required bit rate and BER of specific service respectively. γ is a required Grade Of Service (GOS) of a specific network. The spectrum efficiency can be configured out by this expression

$$\text{SE} = \frac{\text{ErlangsPerCell} \times \text{Bitrate} \times \text{Activity Factor}}{\text{System Bandwidth} \times \text{Cell Area}}, \tag{17}$$

where Activity Factor is the weight attributed to different service. Based on the results, the K_i network with the maximum value of the cost function will be selected for ith user to access

$$K_i = \arg\max_k F(i,k). \tag{18}$$

Figures 11 and 12 are the simulation result. In the simulation, we compare the performance of the Resource Utilization and Percentage Of Satisfied Users between using AHP selection and Random selection algorithm. Resource Utilization can be defined as the ratio of used bandwidth and the total system bandwidth. Percentage Of Satisfied Users can be defined as the ratio of the user number which get the service which they want and the total user number. Through these two figures, it is very clear that the system performance get improvement.

4.2. Load Balancing. Balancing the load between multiple systems allows for a better utilization of the radio resource as a whole and an improvement of the systems' capacity. Many intelligent algorithms have been proposed to balance the load between different radio technologies, but few researches address the theoretical analysis for the load balance strategies. Reference [18] analyzes multiple bearer services allocation onto different subsystems in multiaccess wireless systems.

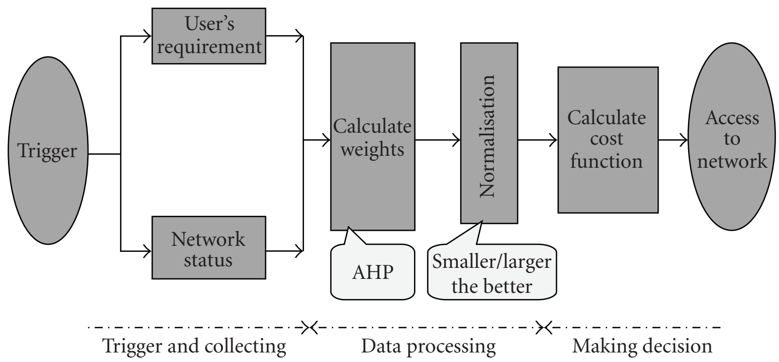

Figure 10: Cost function-based RA selection scheme.

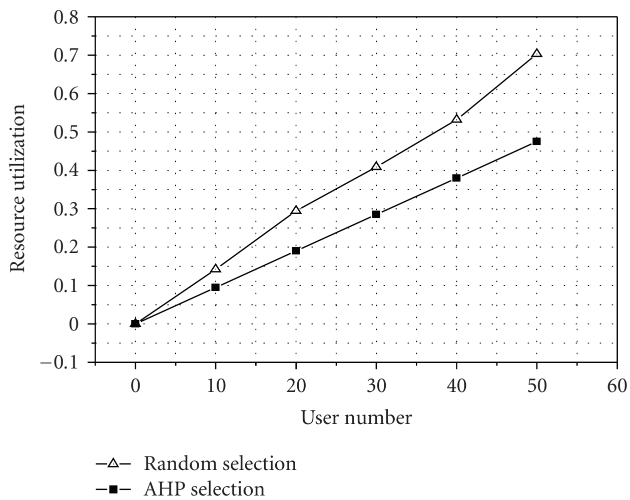

Figure 11: Resource utilization.

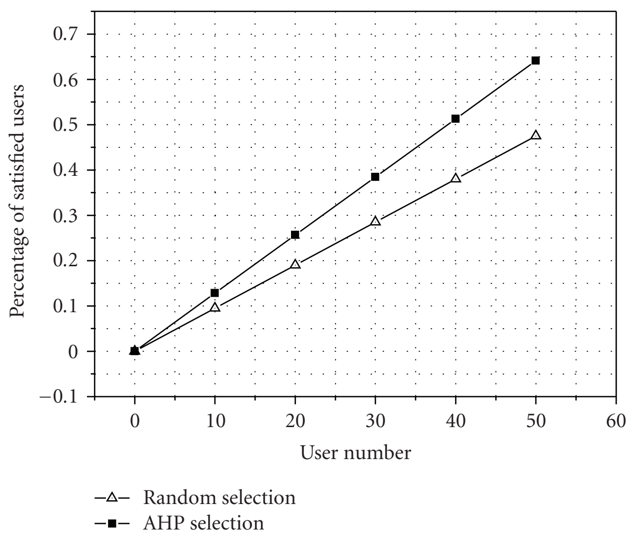

Figure 12: Percentage of satisfied users.

Considering subsystem's multi-service capacities and capacity constraints, near-optimum subsystem service allocations that maximize combined multi-service capacity are derived from simple optimization procedures. However, this work cannot be applied to give a theoretical evaluation for certain load balance strategies. In order to solve this problem, we put forward a theoretical framework, which can be used to evaluate the performance of dynamic load-balancing strategies.

In our analysis, for simplicity a scenario with two kinds of RATs overlapped is considered, we also suppose that two networks have the same capacity C, and each service utilizes the single unit of resource in TDMA. Based on certain load balance strategy, the user or service of one overloaded network or cell can be transferred to the light-load network or cell. We also assume that call requests arrive according to a Poisson process and call arrival rates in RAN 1 and RAN 2 are λ_1 and λ_2, respectively, and service times in both networks are exponentially distributed with parameter μ. By applying the multidimensional Markov chain to model the load state of both the two networks, the blocking probability between the two inter-working networks can be derived in a simple way.

Assuming that $P(0,0)$ is the idle-state probability and $s(i_1; i_2)$ are the states which the two networks experienced, so the probabilities of all the states are derived and satisfied

$$\begin{aligned} &P[s(i_1 \leq c;\ i_2 \leq c)] \\ &\quad + P[s(i_1 > c;\ 0 \leq i_2 \leq 2c - i_1) \\ &\qquad \cap\ s(0 \leq i_1 \leq 2c - i_2;\ i_2 > c)] \\ &\quad + P[s(i_1 \leq c;\ i_2 \geq 2c - i_1 + 1) \\ &\qquad \cap\ s(i_1 \geq 2c - i_2 + 1;\ i_2 \leq c)] = 1. \end{aligned} \tag{19}$$

The expression of each element of the formulation will depend on the certain load balance strategy. When a "simple borrowing" load balance scheme [19] is employed, the probabilities of all the states are given as

$$
\begin{aligned}
&P[s(i_1 \leq c;\ i_2 \leq c)] \\
&\quad = P(0,0)\sum_{i_1=0}^{c}\sum_{i_2}^{c}\frac{T_1^{i_1}T_2^{i_2}}{i_1!i_2!}, \\
&P[s(i_1 > c;\ 0 \leq i_2 \leq 2c-i_1),\ s(0 \leq i_1 \leq 2c-i_2;\ i_2 > c)] \\
&\quad = P(0,0)\sum_{i_1=c+1}^{2c}\sum_{i_2=0}^{2c-i_1}\frac{T_1^{i_1}T_2^{i_2}+T_2^{i_1}T_1^{i_2}}{i_1!i_2!}, \\
&P[s(i_1 > c;\ i_2 > c)] \\
&\quad = P(0,0)\frac{c^c}{c!}\sum_{i_1=c+1}^{\infty}\left(\frac{T_1}{c}\right)^{i_1}\times\frac{c^c}{c!}\sum_{i_2=c+1}^{\infty}\left(\frac{T_2}{c}\right)^{i_2}, \\
&P[s(i_1 \leq c;\ i_2 \geq 2c-i_1+1),\ s(i_1 \geq 2c-i_2+1;\ i_2 \leq c)] \\
&\quad = P(0,0)\sum_{i_2=0}^{c}\sum_{i_1=2c-i_2+1}^{\infty}\frac{(2c-i_2)^{2c-i_2}}{(2c-i_2)!} \\
&\qquad \times\left[\left(\frac{T_1}{2c-i_2}\right)^{i_1}\frac{T_2^{i_2}}{i_2!}+\left(\frac{T_2}{2c-i_2}\right)^{i_1}\frac{T_1^{i_2}}{i_2!}\right],
\end{aligned} \tag{20}
$$

where $T_1 = \lambda_1/\mu$ and $T_2 = \lambda_2/\mu$ are the *traffic intensities* of networks 1 and 2, respectively, so $P(0,0)$ can be calculated from the above relation.

The call blocking probability of network i ($i = 1$), denoted by Pb_i, is given as

$$
\begin{aligned}
Pb_i = P(0,0)\Bigg\{&\frac{c^c}{c!}\sum_{i_1=c}^{\infty}\left(\frac{T_1}{c}\right)^{i_1}\times\frac{c^c}{c!}\sum_{i_2=c}^{\infty}\left(\frac{T_2}{c}\right)^{i_2} \\
&+\sum_{i_2=0}^{c}\sum_{i_1=2c-i_2}^{\infty}\frac{(2c-i_2)^{2c-i_2}}{(2c-i_2)!}\left(\frac{T_1}{2c-i_2}\right)^{i_1}\frac{T_2^{i_2}}{i_2!} \\
&-\frac{T_1^c}{c!}\frac{T_2^c}{c!}\Bigg\}.
\end{aligned} \tag{21}
$$

The call blocking probability of network 2 can be calculated similarly.

In contrast to interworking, the probability of one network without interworking can also be calculated as

$$
Pb_s = P(0)\frac{c^c}{c!}\sum_{i_1=c}^{\infty}\left(\frac{T_1}{c}\right)^{i_1}, \tag{22}
$$

where $P(0)$ can be derived from the following relation:

$$
P(0)\left[\sum_{i_1=0}^{c-1}\frac{T_1^{i_1}}{i_1!}+\frac{c^c}{c!}\sum_{i_1=c}^{\infty}\left(\frac{T_1}{c}\right)^{i_1}\right] = 1. \tag{23}
$$

When the two networks have the same capacity 12 ($C = 12$), Figures 13 and 14 show the blocking probability of RAN 1 in both interworking and non-interworking case, with the constant traffic intensity of RAN 2 (T_2= 8, T_2= 10). It may be observed that the blocking probability is eased in the interworking case, and the profit is more evident when the traffic became more heavy.

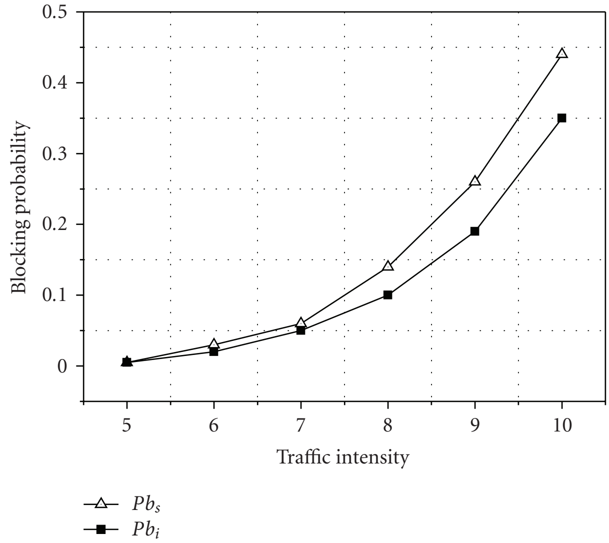

Figure 13: Blocking probability versus traffic intensity, for $C = 12$, $T_2 = 8$.

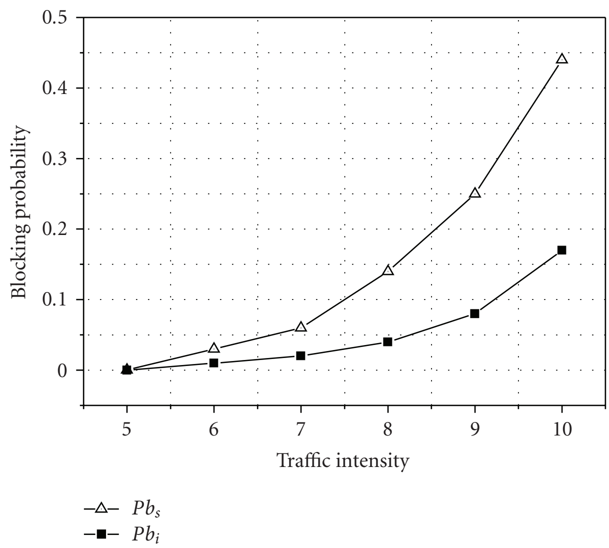

Figure 14: Call blocking probability versus traffic intensity, for $C = 12$, $T_2 = 10$.

5. Conclusion

Cooperation mechanisms between different radio access technologies in the heterogeneous network environments is one of the hot issues in the following years, which may cover most of the foundational fields of wireless communications, such as link layer protocol design, radio resource management and power saving and QoS guarantee. This paper fistly proposes two interworking network architectures to make different RATs cooperate, which makes subscribers access anywhere with the best techniques, the interworking between WiMAX and 3GPP LTE networks is taken as the specific case. Then this paper elaborates several important issues including GLL, MRRM, in order to allow efficient cooperation between different radio access technologies. The potential state-of-the-art challenges are presented for these corresponding topics. Moreover, some solutions and mechanisms are proposed with numeric results.

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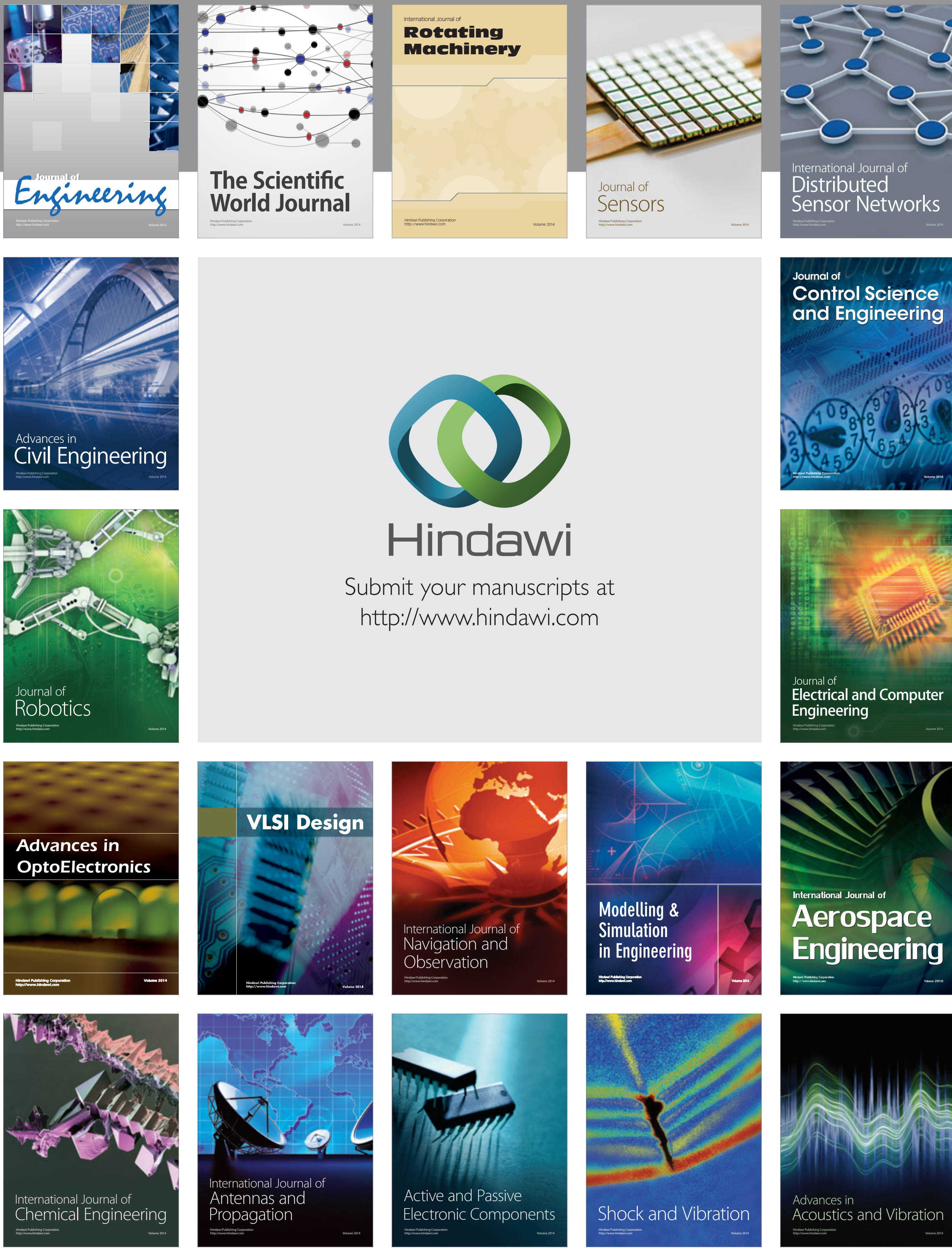
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