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Platform for Inter-Radio System Switching with Cognitive Radio

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1. Introduction and background

Frequencies below the 6 GHz band are well known to be suitable for mobile communication systems; hence, many wireless communication systems such as 3rd generation cellular systems and wireless LANs are assigned within this frequency band in Japan. As a consequence, there are not enough spare bands for future wireless broadband systems. In this situation, there is a need to use these frequencies, which are "finite resources," in a more efficient manner, including the utilization of multiple wireless communication systems with intelligence. Many technologies related to efficient utilization of multiple wireless communication systems have been researched. Cognitive radio is also one of the most effective technologies to resolve this issue..

There are two trends in cognitive radio especially in Japan. One trend is the so-called "Multiple Systems," which switches wireless communication systems according to the radio conditions. The other trend is the so-called "Dynamic Spectrum Access," which recognizes spare frequencies of a primary system and allocates them to be used for communication of a secondary system to such an extent that the primary system would not be affected.

Japanese regulations assign a unique frequency band to a particular wireless system both for licensed and unlicensed bands; therefore era of "Multiple Systems" comes earlier than "Dynamic Spectrum Access" system that needs more changes in the regulations. From time-to-market point of view, we focus on "Multiple Systems" approach here.

Based on the "Multiple systems" concept, the MIRAI architecture had already been proposed as one of the network architectures to support multiple systems. In MIRAI architecture, all access points of wireless communication systems are connected to a CCN (Common Core Network) and switching between systems is executed via mobile IP. The mobile IP protocol supports mobility transparently above the IP level and allows nodes to change their location. Mobile IP is generally adopted as a macro-mobility solution. In general, a few seconds is taken for system handover by using the mobile IP protocol, so that is less well suited for fast system handover in which an environment of mobile terminals changes dynamically.

From a terminal point of view, SDR (Software Defined Radio) terminals that support multiple wireless systems have been proposed. Mobile terminals can measure radio information and report that to the base station, and the base station decides whether to switch to other systems according to this report from the mobile terminal. However, that is not sufficient for maximizing system capacity and satisfying requirements for user communication quality because system load and information that can be acquired from the network (e.g., the number of terminals that connect to an access point) are not taken in account.

We have studied a cognitive radio system that covers multiple wireless communication systems from the network point of view. The main difference from conventional system switching technologies like MIRAI architecture is using radio information that is acquired in the physical layer and system load that is acquired in the MAC and higher layers for system switching. As a result, system throughput is enhanced with efficient frequency utilization.

In our system, a control node is newly set inside a cognitive base station to support fast system switching and multiple transmissions, and one local IP address is assigned to the terminal regardless of the number of wireless communication systems that the terminal communicates with. The radio environment, system load, and information that can be acquired from network side are taken into account to maximize system capacity.

In this chapter, we describe the architecture of the cognitive radio system and then, the simulator and the testbed system built based on the proposed architecture. In section 2, we describe the approach and system concept of our cognitive radio system. In section 3, we describe the system architecture. In section 4, we show some simulation results. In section 5, we show the experimental results obtained from the testbed system.

2. Concept of cognitive radio

2.1 Overview of cognitive radio

Japanese regulations assign a unique frequency band to a particular wireless system both for licensed and unlicensed bands. However, the time ratio of frequency utilization varies widely according to location, time, day of week, wireless communication system, and communication carrier company, for example. By using these spare radio resources adaptively, the time ratio of frequency utilization can be increased.

The concept of cognitive radio based on "Multiple Systems" approach is shown in Fig. 1. In this figure, the concept is expressed using both the frequency domain and time domain.

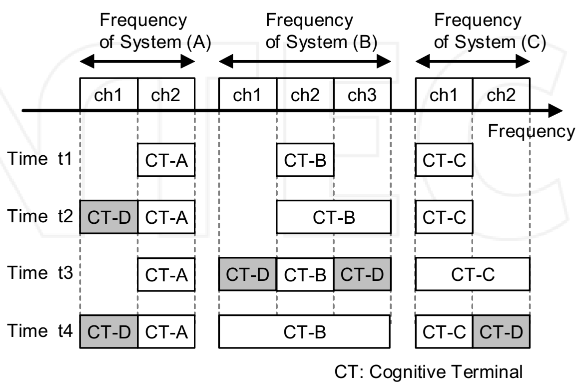


Fig. 1. Concept of Cognitive Radio.

For example, we assume we can communicate with three systems: A, B and C.
In this figure, when the current time is t2, cognitive terminal (CT) D communicates using the frequency of System A, and when the current time becomes t3, terminal D changes the wireless communication system from System A to System B to communicate using the frequency of System B. As shown in Fig. 1, the number of wireless communication systems used simultaneously is not limited to one, and the cognitive system can transmit and receive data with multiple wireless communication systems simultaneously.
Furthermore, terminals of the cognitive radio system (cognitive terminal) switch the wireless communication system frequently according to the radio conditions as stated. Therefore, in cognitive radio, the corresponding node need not know which wireless system is being used.
Based on this concept, we provide two requirements to achieve cognitive radio below:

1. system architecture for fast system handover, which can reflect radio environments that change dynamically, and system load and information that can be acquired from the network.
2. assignment of one local IP address to the terminal regardless of the number of wireless communication systems that the terminal communicates with.

2.2 System concept of cognitive radio

Provided that EV-DO (cdma2000 1x Evolution Data Optimized) is system A, WiMAX (Worldwide Interoperability for Microwave Access) is system B and wireless LAN is system C in Fig. 1, terminal D can communicate with EV-DO, wireless LAN, and WiMAX adaptively according to the radio conditions. However, terminal D can use different radio systems, as shown in Fig. 1, only when terminal D is located in the area where EV-DO, WiMAX, and wireless LAN are in service. The service areas of each system differ from each other due to the difference in frequency performance and difference in service (carrier, bit rate, and charge, for example), so we need to consider the architecture of the cognitive base station.
When we set up a cognitive BS (Base Station) that supports multiple wireless systems like that shown in Fig. 2, only the center area of the base station, which is covered by all kinds of wireless communication systems, can satisfy the conditions shown in Fig. 1. This architecture is simple and easy to construct; however, an area where cognitive radio can be adopted is narrow and limited. Actually, WiMAX access points are not always located in the same place where EV-DO access points are located; therefore, this architecture is not suitable and it would seem that the realization probability of the architecture is low.

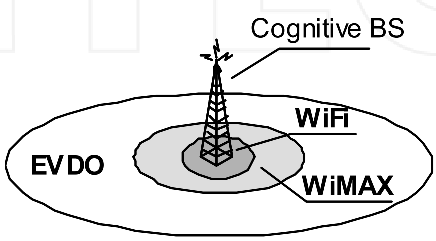


Fig. 2. Cognitive Base Station with Multiple Radio Systems.

To expand the area that satisfies the conditions shown in Fig. 1, we newly define the cognitive base station as described below:

1. The area of the cognitive base station is equivalent to the area in which access points of a cellular system are covered, which is the widest area among the access points of other wireless systems.
2. A cognitive base station has the function of access points of a cellular system, the function of access points of WiMAX and wireless LAN in the cognitive base station area, and a control node to integrate these functions.

The concept of a cognitive BS (base station) based on this definition is shown in Fig. 3.

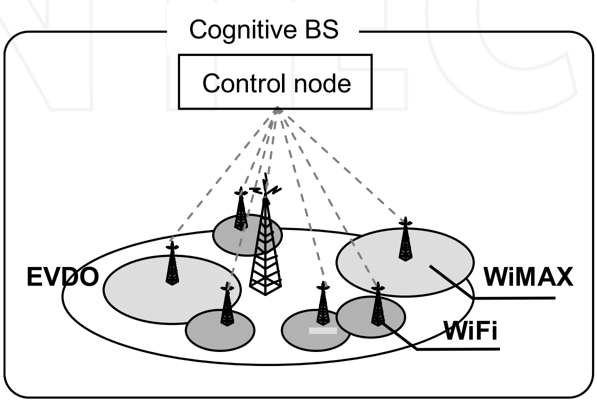


Fig. 3. Concept of Cognitive Base Station.

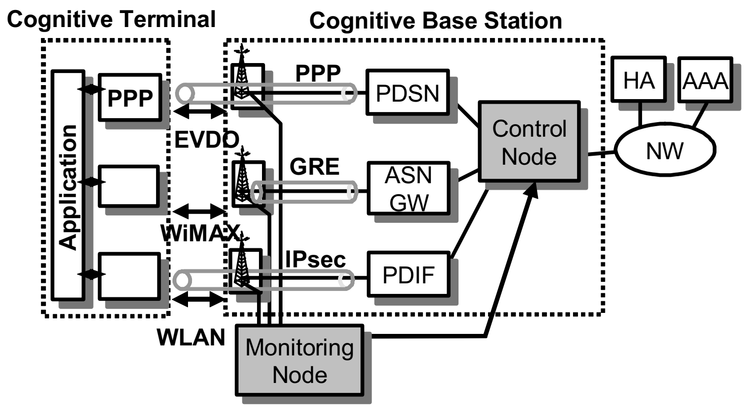
From this definition, the area that satisfies the conditions shown in Fig. 1 can be expanded. Actually, WiMAX access points are not always located in the same place where the EV-DO access point is located; therefore, this architecture is more realistic. Moreover, placing a control node inside the cognitive base station is one characteristic. The control node controls these systems below the IP layer. Thus, converging multiple access points of multiple systems inside the cognitive base station enables us to treat the radio resources spread throughout the cognitive base station area as an "internal" radio resource of the cognitive base station. Consequently, that is expected to achieve fast system handover.

3. System architecture

3.1 System architecture

Based on the concept described in section 2, we propose a system architecture of our cognitive radio system as shown in Fig. 4. Cognitive base station consists of PDSN (Packet Data Serving Node) to integrate an EV-DO access point to the cognitive base station, ASN-GW (Access Service Network Gateway) to integrate multiple WiMAX access points, PDIF (Packet Data Interworking Function) to integrate multiple wireless LAN access points, control node, monitoring node in addition to multiple access points of multiple radio systems. The monitoring node collects radio information and system load from each access

point and information that can be acquired from network side and recognizes radio condition. Based on the information from the monitoring node, the control node switches the communication system in a packet-by-packet basis. Moreover, location of control node is not above each access point, but above PDSN, ASN-GW and PDIF. PDSN terminates PPP (Point-to-Point Protocol) session to the EV-DO terminal function, ASN-GW controls multiple WiMAX access points, and IPSec (Security Architecture for Internet Protocol) tunnel is established between PDIF and the terminal, and PDIF controls multiple access points of wireless LAN. Therefore, it is reasonable for future system migration to locate control node above PDSN/ASN-GW/PDIF.
To place control node to converge wireless systems inside the cognitive base station and its location above PDSN, ASN-GW and PDIF are major characteristics of our system and these are main difference from MIRAI architecture.
Cognitive terminal consists of EV-DO terminal module, WiMAX CPE (Customer Premises Equipment) module, wireless LAN access terminal module and control node (application) to integrate the data received from these modules.



PDSN: Packet Data Serving Node
ASN-GW: Access Service Network Gateway
PDIF: Packet Data Interworking Function
HA: Home Agent
AAA: Authentication, Authorization and Accounting

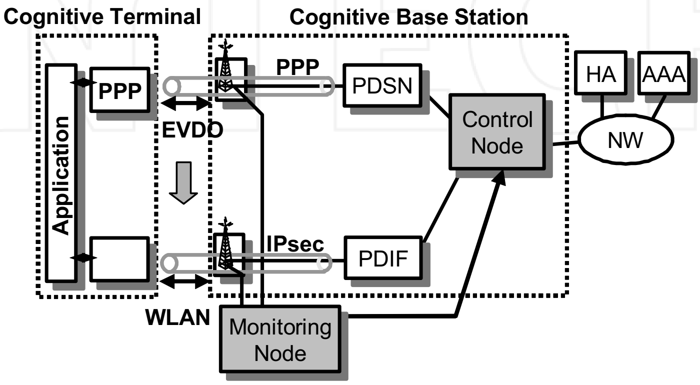
Fig. 4. System Architecture of Cognitive Radio

3.2 IP address assignments

As described previously, wireless communication system are switched dynamically according to radio environment in cognitive radio system, therefore it is desirable the corresponding node does not need to know which wireless system is being used. Unconscious switching nodes to node are achieved with mobile IP, however mobile IP is generally adopted to macro-mobility solution; in general, it takes a few seconds for system handover by using mobile IP protocol, therefore it will be not enough for fast system handover, in which an environment of mobile terminal changes dynamically.

To realize the single local IP address on a cognitive terminal, we propose IP configuration and control sequence, as depicted for the case of switching wireless system from EV-DO to wireless LAN as shown in Fig. 5.

When the terminal communicates with EV-DO for the first step, PPP (Point-to-Point Protocol) is established between the terminal and PDSN, and then it is authenticated with PAP/CHAP (PAP: Password Authentication Protocol, CHAP: Challenge Handshake Authentication Protocol). After finishing the authentication process, PDSN transmits an access request message to AAA (Authentication, Authorization and Accounting). AAA assigns an IP address and sends it back to PDSN along with the information of HA (Home Agent), and PDSN relays these information to the terminal.



PDSN: Packet Data Serving Node
ASN-GW: Access Service Network Gateway
PDIF: Packet Data Interworking Function
HA: Home Agent
AAA: Authentication, Authorization and Accounting

Fig. 5. System Architecture of Cognitive Radio.

When the terminal moves to the wireless LAN area, terminal authentication is established between the terminal and PDIF with IKEv2 (Internet Key Exchange version 2). After finishing authentication, PDIF transmits access request message to AAA (Authentication, Authorization and Accounting).

In the present system, AAA of wireless LAN system is independent of that of cellular system, but in our proposal, AAAs of wireless LAN and cellular system would be unified or have cooperation with each other. When one communication operator (carrier) operates multiple systems, unified AAA is easy to construct. When plural communication operators cooperate with each other to achieve cognitive system shown in Fig. 5, cooperation of AAAs is needed to identify the terminals and to assign one local IP address to them. This is also one characteristic of our system. Before assigning a IP address to the terminal, AAA identifies whether access request message is sent from the terminal that has same product number or USIM number. If the access request message is sent from the terminal that has same product number or USIM number, AAA assigns the same IP address that is already assigned using EV-DO system (Fig. 6). In this sense, AAAs are needed to be unified or have cooperation with each other.

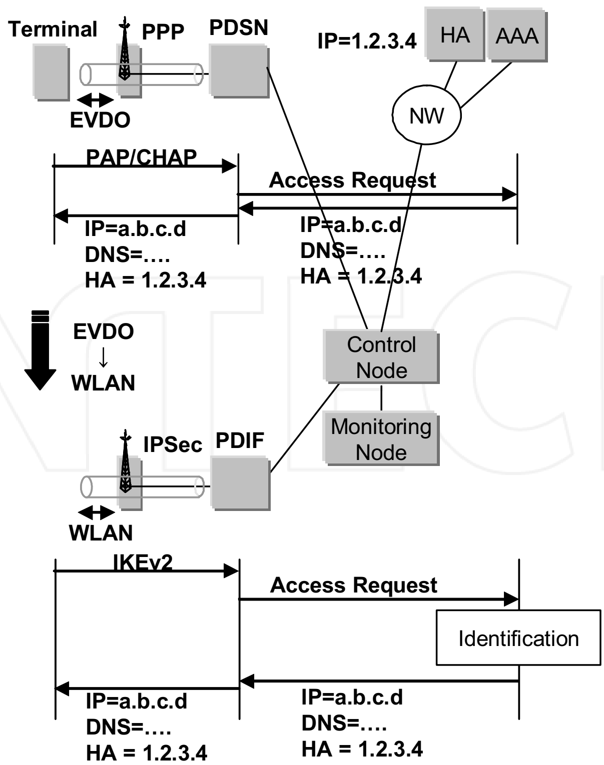


Fig. 6. Control Sequence for IP Address Assignments

3.3 Controls for system switching

To achieve the single local IP address on a terminal, control node acts as a Foreign Agent to the Home Agent, and acts as Home Agent to the PDSN/PDIF at the same time. These relationships are shown in Fig. 7. Control node has the table that relates between IP address of cognitive terminal and IP address of Foreign Agent. To relate multiple IP addresses of Foreign Agents with one cognitive terminal is one major characteristic of our proposed system and cognitive terminal keeps multiple sessions during data transmission. Due to this characteristic, system switching can be done by packet-by-packet basis and expected system switching delay can be a few milliseconds.

Regarding IP packet format, there are many approaches to realize transfer of IP packets to the nodes (PDSN/PDIF). We adopt IP capsulation, because the process of header replacement can be done by the hardware implementation and high speed switching could be expected.

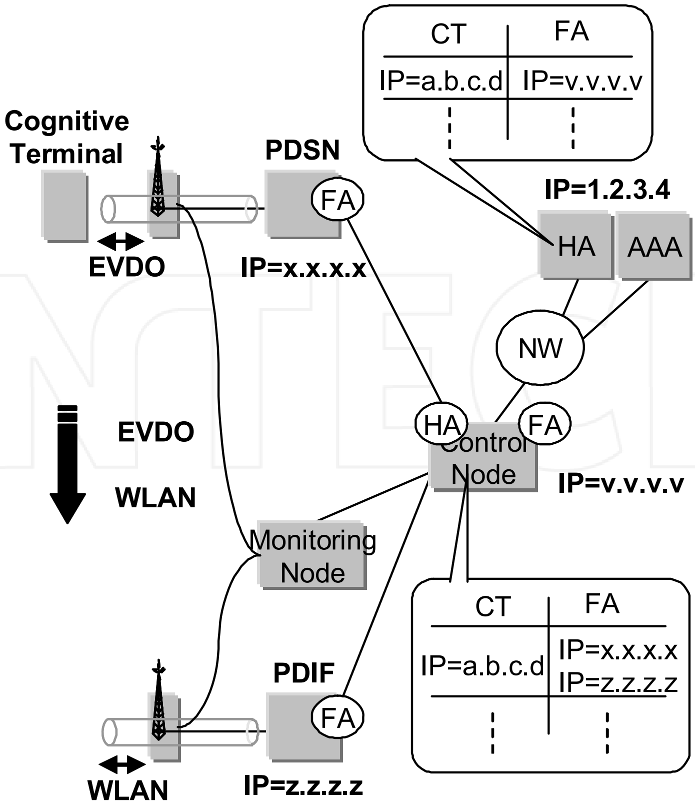


Fig. 7. Function of Control Node

4. Simulations

4.1 Preliminary simulator overview

Based on the architecture described in section 3, we have developed a preliminary simulator that supports both WiMAX and wireless LAN.

As described in section 3, cognitive node switches the wireless system to communicate with according to the radio condition and system load. In scenario 1, monitoring node monitors RSSI (Received Signal Strength Indicator) value of wireless LAN and based on this value, control node switches the system, because WiMAX service is provided in all area of the simulator. In scenario 2, adding to scenario 1, system load is taken into account.

Simulator overview is shown in Fig. 8, and system parameters of each wireless system for this simulator are shown in Table 1.

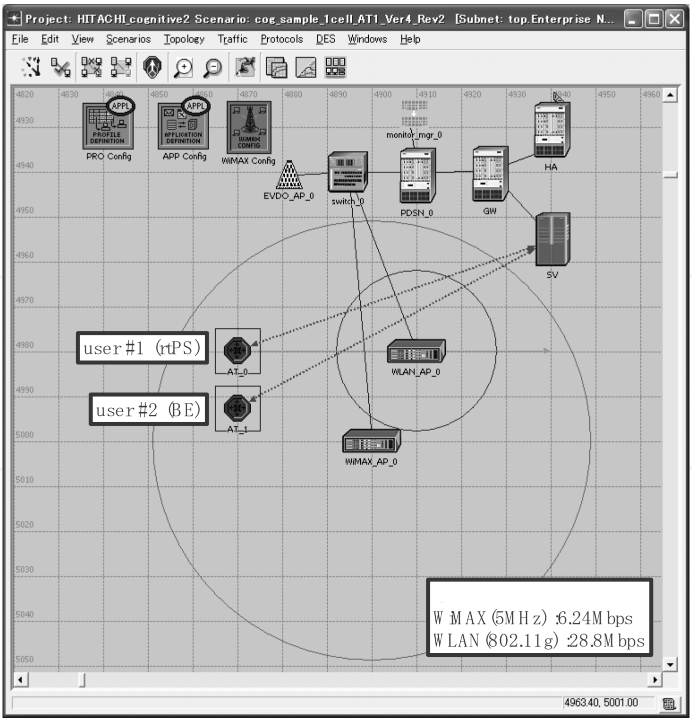


Fig. 8. Overview of Preliminary Simulator.

Item	Specifications	
WiMAX	Based on	IEEE802.16e
	Bandwidth	5 MHz
	QoS Mode	User #1: rtPS User#2: BE
Wireless LAN	Based on	IEEE802.11g
	Bandwidth	20 MHz
	Radio information	RSSI Level
Data	UDP	User #1: 4.8Mb/s User #2: 28.8Mb/s

Table 1. Preliminary Simulator Specifications.

4.2 Scenario 1: Switching based on RSSI level

In scenario 1, we assume two terminals. The terminals move along a line in cognitive base station area. For the first step, these terminals connect with WiMAX, and then, the terminals can use either WiMAX or wireless LAN area in the overlapped area as shown in Fig. 8.

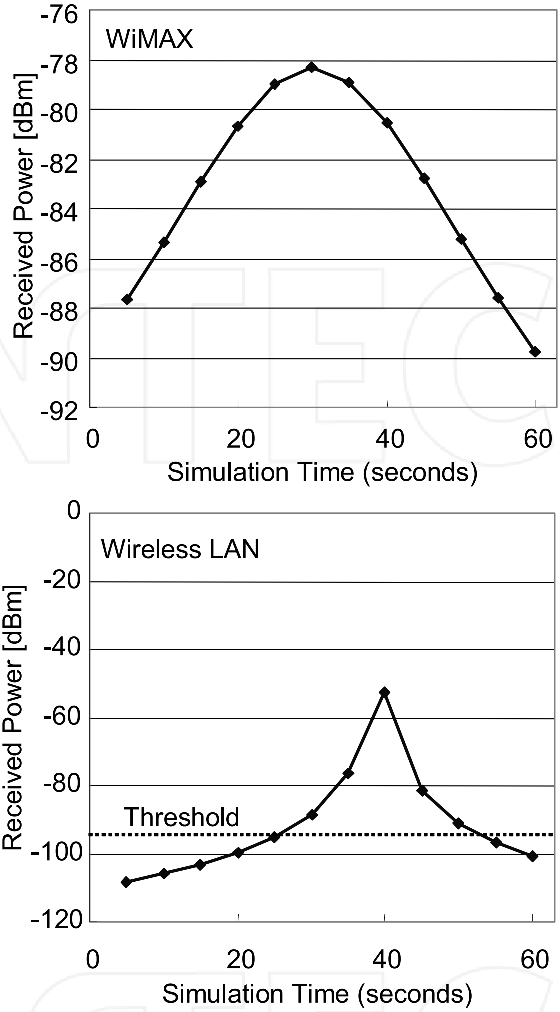


Fig. 9. RSSI Level of Each System.

To realize the system switching between two systems, we set the threshold to switch the wireless system according to RSSI value of wireless LAN. RSSI of each system is shown in Fig. 9. The terminal can connect with wireless LAN when the RSSI level exceeds -95dBm, therefore the threshold level is set to -95dBm.

Fig. 10 shows the history of user throughputs with using WiMAX and wireless LAN. User #1 and user #2 move same way with same speed.

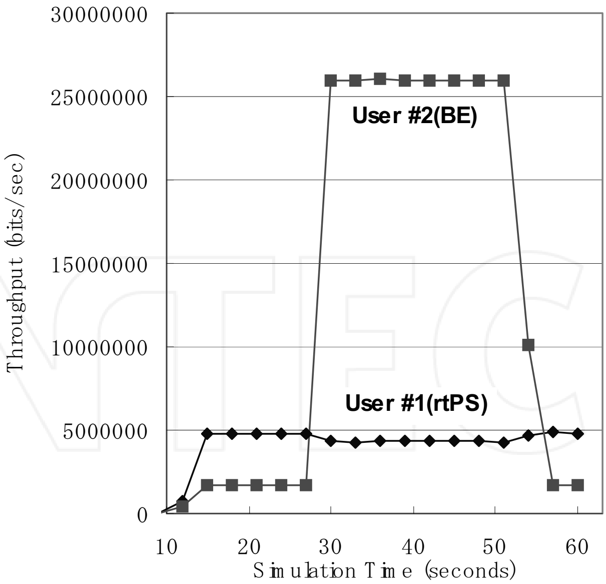


Fig. 10. Throughputs of Scenario 1.

When both users are in WiMAX area, due to QoS function of WiMAX, user #1, that has higher priority than user #2, can communicate with required bit rate, and user #2 communicates with vacant bandwidth.
When both users come near an access point of wireless LAN, RSSI level of wireless LAN becomes higher, therefore based on RSSI level, both user #1 and user #2 switch the system from WiMAX to wireless LAN.
However, wireless LAN cannot support 33.6Mb/s (that equals a sum of the data rates of user #1 and user #2), throughput performance degradation occurred.
In this scenario, we have found that not only radio condition, but also system load is taken into account to switch radio systems.

4.3 Scenario 2: Switching based on RSSI level and load balancing

In scenario 2, the terminal communicates with WiMAX area first, and then moves to wireless LAN area as shown in Fig. 8, and switches wireless system according to not only the RSSI of wireless LAN and but also system load or users' QoS, etc.
In this case, QoS of user #1 is set to rtPS (Real Time Packet Service), and QoS of user #2 is set to BE (Best Effort), so user #1 has more priority.
rtPS class ensures the real time transmission and user's required bandwidth. On the contrary, BE class uses the rest bandwidth, so there are no guarantee regarding transmission rate and throughput.
The result is shown in Fig. 11. When both users are in WiMAX area, due to QoS function of WiMAX, user #1 that has higher priority than user #2, can communicate with required bit

rate, and user #2 communicates with vacant bandwidth. Performance of this area is same as that of scenario 1.

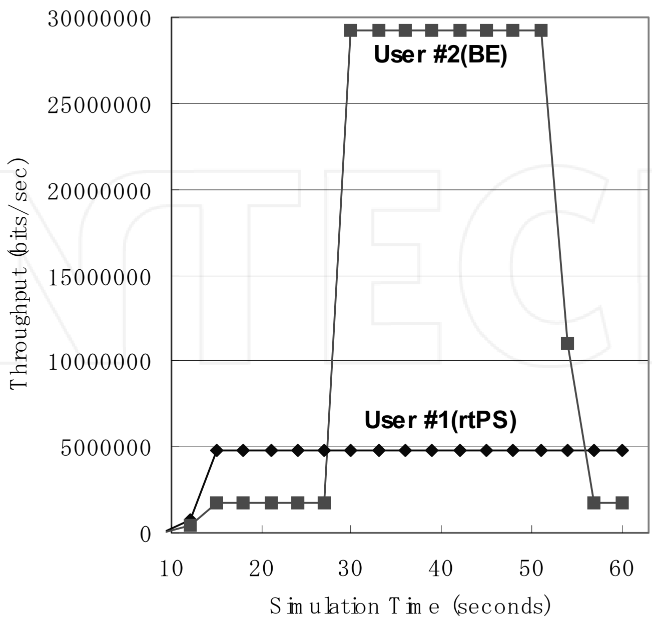


Fig. 11. Throughputs of Scenario 2.

When both users come near an access point of wireless LAN, RSSI level of wireless LAN becomes higher. User #1 has a priority, therefore control node decide that user #1 continues communication with WiMAX (not switching to wireless LAN). On the contrary, user #2 does not have priority, therefore based on RSSI level and control nodes' decision of user #1, user #2 switches the system from WiMAX to wireless LAN.
As a result, any performance degradation can not be seen in both user #1 and user #2 transmission.

4.4 Simulator that supports EV-DO, WiMAX and wireless LAN

Based on the architecture described in section 3, we have also developed a simulator that supports EV-DO, WiMAX and wireless LAN. Simulator overview is shown in Fig. 12, and system parameters of each wireless system for this simulator are shown in Table 2.
In this simulator, cognitive node switches the wireless system to communicate with according to the radio condition and system load.

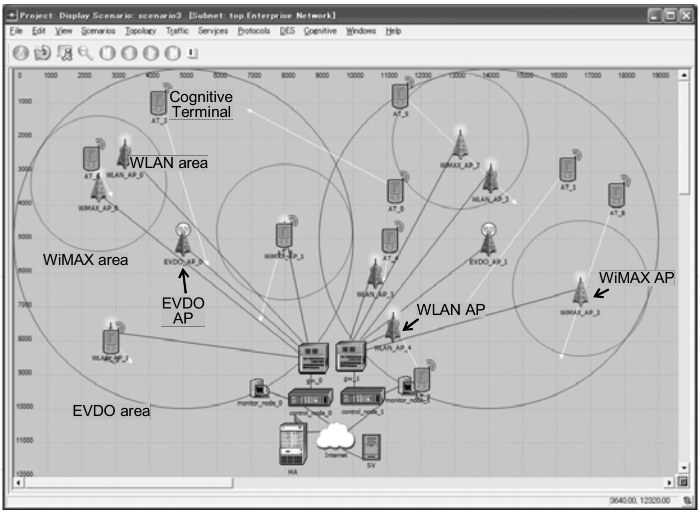


Fig. 12. Simulator Overview.

System	Specifications	
EV-DO	Based on	cdma2000 1x EV-DO Rev.0 (simplified model)
	Frequency	2.0GHz
	Maximum Rate	2.4Mb/s
	Maximum Tx Power	10W
WiMAX	Based on	IEEE802.16e based (OFDMA/TDD)
	Frequency	2.5 GHz
	Maximum Rate	6.2Mb/s (downlink)
	Maximum Tx Power	27dBm
WirelessLAN	Based on	IEEE802.11g
	Frequency	2.4 GHz
	Maximum Rate	28.8Mb/s
	Maximum Tx Power	17 dBm

Table 2. Simulator Specifications.

4.5 Scenario 3: Average throughput evaluation

In this simulator, ten terminals moves randomly in the simulation area and required rate of each user is set to 400kb/s. We assumed web browsing and small size streaming as an application.

For example, we picked up the performance of user #5 out of ten users.

In this simulation, user #5 started from EV-DO area for the first time, and then moved into WiMAX area and moved into wireless area, and finally moved into EV-DO area again.

Simulation result of user #5 is shown in left side of Fig. 13. From Fig. 13, performance of user #5 is improved by switching to other systems according to RSSI level of each system.

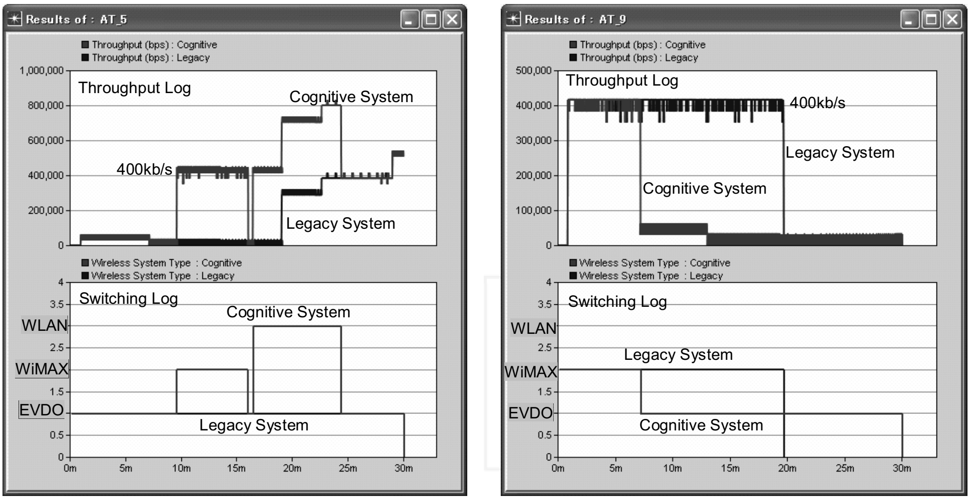


Fig. 13. Simulation results of user #5 (left), user #9 (right).

On the contrary, we picked up user #9 as another case. User #9 started from WiMAX area for the first time, and then moved into EV-DO area. Simulation Result of user #9 is shown in right side of Fig. 13. In this case, legacy system keeps connection with WiMAX until simulation time = 20minutes and then is disconnected due to long distance between WiMAX access point and user terminal, however proposed cognitive system decides to switch system from WiMAX to EV-DO when simulation time = 7minutes and then keep connection with EV-DO until user #9 is in EV-DO area. From Fig. 13, user throughput improvement is NOT seen by switching from WiMAX to EVDO.

The reason is WiMAX has wider bandwidth than EVDO, and expected throughput of WiMAX is faster than that of EV-DO. When user's required rate becomes higher, using WiMAX as long as possible gives better throughput performance as a total. Right side of Fig. 13 is one example that proposed system cannot achieve better performance than legacy system.

As a total, average throughput of ten terminals of both legacy system and proposed cognitive system is shown in Table 3. Regardless the example such as right side of Fig. 13, we have proved that throughput enhancement can be achieved by using proposed architecture.

System	Average Throughput
Legacy System	135.4kb/s
Cognitive System	230.9kb/s

Table 3. Average Throughput Comparison.

5. Experiments with testbed system

5.1 Preliminary testbed system

Based on the system architecture described in section 3, we have developed a preliminary testbed system that supports both WiMAX and wireless LAN. An overview of the testbed system is shown in Fig 14. In the preliminary testbed system, we connect the base station and the terminal via RF cables with fading simulators and variable attenuators inserted in the middle to emulate wireless radio propagation. The attenuation level of each system can be changed independently, manually and continuously, simulating the fluctuation of radio conditions.

In our experiments, we prepare two terminals just like as preliminary simulation scenario, that is, an application of user #1 is set to data streaming, and an application of user #2 is set to file downloading. .

System parameters of each wireless system for this experiment are shown in Table 4.

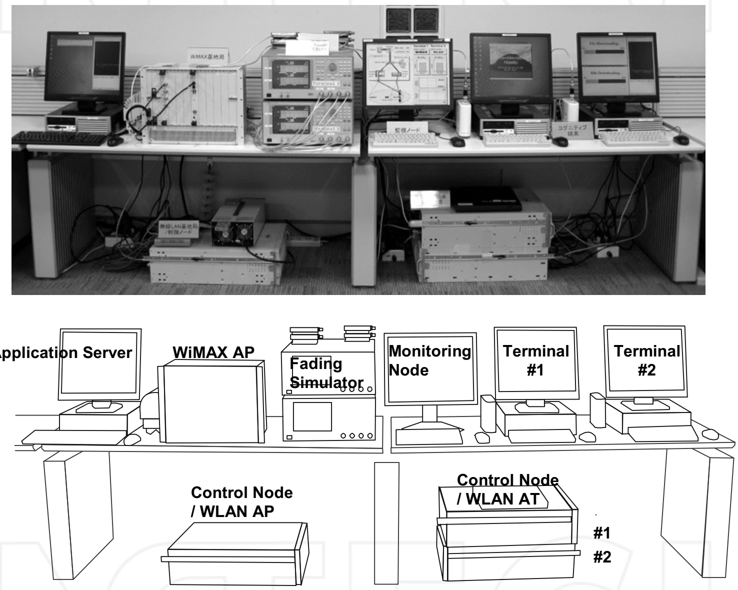


Fig. 14. Overview of Preliminary Testbed System.

RSSI level of wireless LAN can be adjusted by using fading simulators. Streaming data (equivalent to rtPS priority) is transmitted from the streaming server shown on the left of Fig. 14, to the cognitive terminal #1 shown in the right of Fig. 14, and at the same time, file download data (equivalent to Best Effort priority) is transmitted from the server shown on the left of Fig.14, to the cognitive terminal #2 shown in the right of Fig.14.

Moreover, overview of monitoring node is shown in Fig. 15. Lines in the left side shows the links that the terminals connect with, and RSSI value and its history are shown in the right side of the screen. Monitoring node has GUI interface to change the algorithm for system switching. Concretely, we can choose whether RSSI level is used or not and whether load balancing is taken into account or not. These GUI interface is located on the center top of the screen.

Item	Specifications	
WiMAX	Based on	IEEE802.16e (OFDM/TDD)
	Bandwidth	5 MHz
	Freq. Band	2.5 GHz
	Max Tx Power	30 dBm
	QoS Mode	rtPS / BE
Wireless LAN	Based on	IEEE802.11g
	Bandwidth	20 MHz
	Max. rate	54 Mb/s
	Freq. Band	2.4 GHz
	Max Tx Power	16 dBm
Data		Streaming / File Download

Table 4. Preliminary Testbed System Specification.

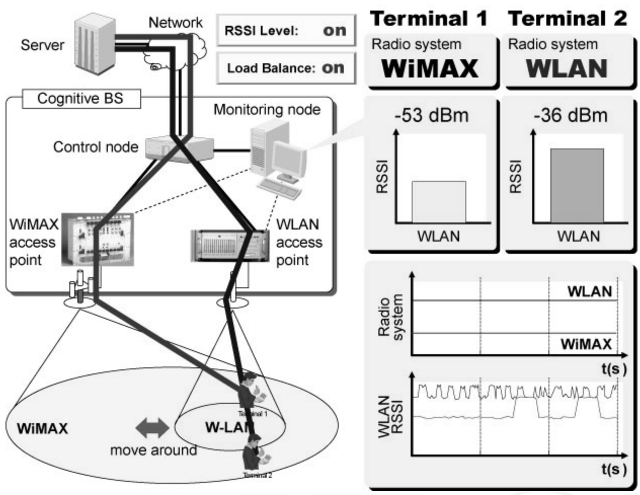


Fig. 15. Overview of Monitoring Node.

And also, the monitoring node has a function to set propagation loss of the fading simulators according to the terminal location located at the bottom of the screen (terminal location is same as the picture of standing men).
When both users are in WiMAX area, due to QoS function of WiMAX, user #1 that has higher priority than user #2, can communicate with required bit rate, and user #2 communicates with vacant bandwidth. Performance of this area is same as that of scenario 1 and 2 of the simulation (see the period (1) in Fig.16).
When both users come near an access point of wireless LAN, RSSI level of wireless LAN becomes higher. Provided that we switch the system based on both RSSI level of wireless LAN, both user #1 and user #2 switch to wireless LAN (see the period (2) in Fig.16). Provided that we switch the system based on both RSSI level of wireless LAN and also system load, control node decide that user #1 continues communication with WiMAX (not

switching to wireless LAN). On the contrary, user #2 does not have priority, therefore based on RSSI level and control nodes' decision of user #1, user #2 switches the system from WiMAX to wireless LAN.
As a result, any performance degradation can not be seen in both user #1 and user #2 transmission with the testbed system. User #1 can enjoy streaming service without any block noise or delay, and User #2 can download the files faster (see the period (3) in Fig.16). These performance enhancements are same as that of scenario 2 of the simulation.
Screenshot of the experiment is shown in Fig.16.

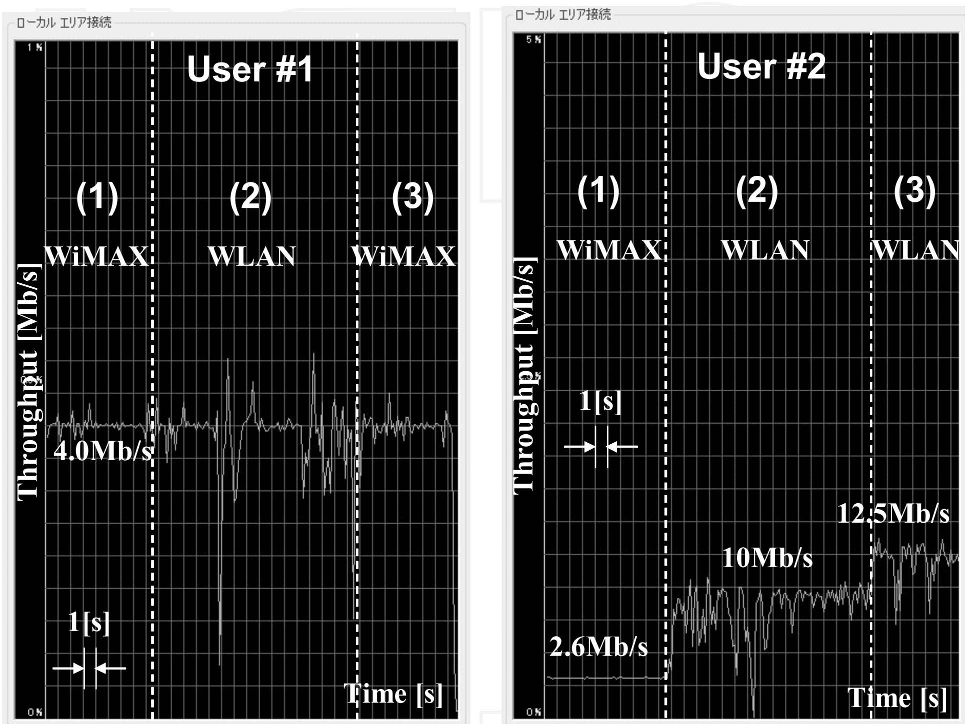


Fig. 16. Screenshot of the experiment.

5.2 Testbed system

In previous section, we described the results of experiments conducted on the preliminary testbed system that supports both WiMAX and wireless LAN. In this section, we describe a testbed system that supports EV-DO (Cellular), WiMAX, and wireless LAN. Specifications of the testbed system are shown in Table 5 and testbed overview is shown in Fig. 17. We had received experimental license for the testbed, and evaluate the testbed under outdoor environment.

System	Specifications	
EV-DO	Based on	cdma2000 1x EV-DO Rev.A
	Frequency	2.0GHz
	Maximum Rate	3.1Mb/s
	Maximum Tx Power	AP: 5dBm, AT: 24dBm
WiMAX	Based on	IEEE802.16e based (OFDM/TDD)
	Frequency	2.5 GHz
	Maximum Rate	6.2Mb/s (downlink)
	Maximum Tx Power	AP: 26dBm, AT: 14dBm
WirelessLAN	Based on	IEEE802.11g
	Frequency	2.4 GHz
	Maximum Rate	28.8Mb/s
	Maximum Tx Power	18 dBm
Data Transmission	UDP Packets	

Table 5. Specifications of testbed system

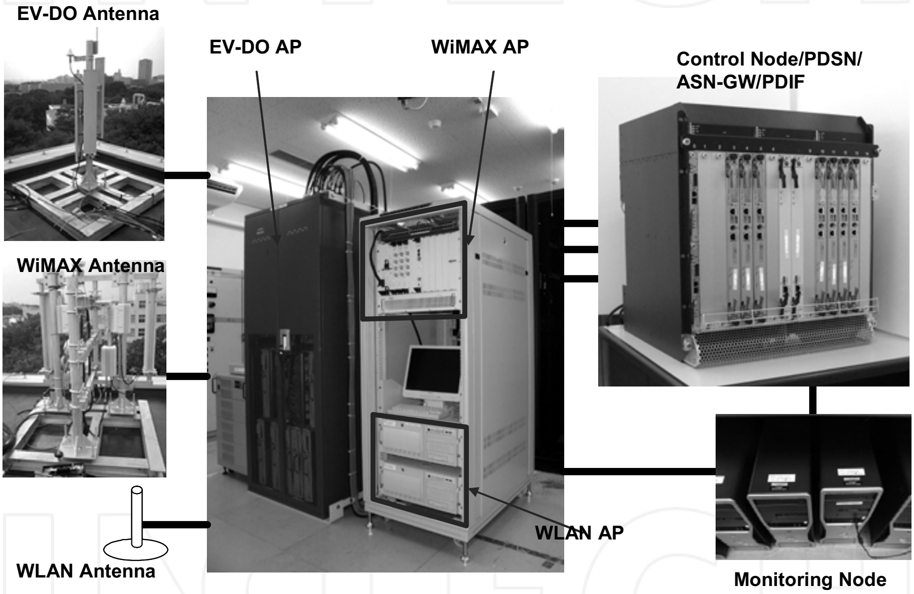


Fig. 17. Structure of Testbed System.

Outdoor experiment examples with the testbed system are shown in Fig. 18 and Fig. 19.
As shown in Fig. 18, we confirmed when received power of wireless LAN became lower, system decided to switches to EV-DO system automatically, and during system switching, connection with the terminal was continued.
Moreover, as shown in Fig. 19, we also confirmed when another terminal came into wireless LAN area, other terminal that connects with wireless LAN switches to EVDO to avoid conjestion and to achieve maximize system capacity.

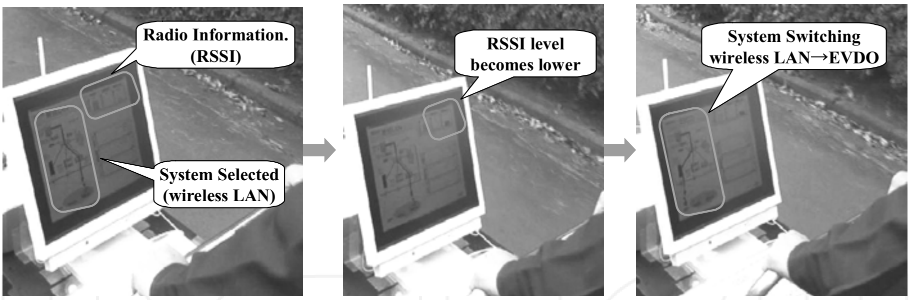


Fig. 18. System switching example under outdoor environment.

Fig. 19. System switching example under outdoor environment.

Through these experiments, we confirmed that system switching works correctly according to radio condition and system load under outdoor environment and that the system architecture described here is a reasonable architecture to achieve a convergence with plural wireless systems.

6. Conclusion

We described the architecture to integrate multiple-radio system with cognitive radio. Furthermore, we described the simulator and testbed system based on the architecture.
Through simulation and experiment with testbed system, we have proved that total system capacity was increased with using proposed architecture. These results suggest that the system architecture described here is one of reasonable platform to achieve a convergence with plural wireless systems.
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Cognitive radio is a hot research area for future wireless communications in the recent years. In order to increase the spectrum utilization, cognitive radio makes it possible for unlicensed users to access the spectrum unoccupied by licensed users. Cognitive radio let the equipments more intelligent to communicate with each other in a spectrum-aware manner and provide a new approach for the co-existence of multiple wireless systems. The goal of this book is to provide highlights of the current research topics in the field of cognitive radio systems. The book consists of 17 chapters, addressing various problems in cognitive radio systems.

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