A Multiband Mobile Communication System for Wide Coverage and High Data Rate

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***Abstract*— This paper studies a multiband mobile communication system to support both high data rate services and wide service coverage, using high and low frequency resources with different propagation characteristics. In the multiband system, multiple frequency bands are managed by a base station and one of the frequency bands is adaptively allocated to a terminal. By limiting the low frequency resources to a terminal not covered by the higher frequencies, the presented multiband system can provide wide coverage area for many terminals, as if all radio resources have low frequency. The numerical results show that the multiband system can support wide coverage for much larger number of terminals. It is also found that an appropriate balance of bandwidths in multiple frequencies is essential for high capacity.**

I. Introduction

The demand for high data rate communications is growing intensively and fourth generation (4G) mobile system is expected to provide high data rate services in excess of 100Mbps. The final goal of the 4G system is to satisfy the consumer's demand making successful business. To achieve this goal, efficient schemes for wireless data transmissions have been widely investigated [1][2].

In actual environments, consumers are sensitive to not only data rate but also service coverage area. A wireless system with frequent connection errors will not fascinate consumers, which results in unfavorable business condition. This tendency is seen in the past economic data between population coverage and the number of subscribers. Therefore, wide service coverage is essential to lead the 4G mobile system into success.

In fact, there are some conflicting aspects between high data rate and service coverage issues. Generally, it is known that radio wave with lower frequency is more suitable to support non-line-of-sight (NLOS) or indoor terminals, because lower frequency associated with larger wavelength has more diffraction and better propagation characteristics in NLOS locations [3]–[7]. However, most of low frequency bands, e.g. frequency below 1GHz, have been already allocated to the existing services and it seems difficult to allocate much of low frequency band to the 4G system. Therefore, it will be unavoidable to allocate higher frequency band as a main radio resource. Since the high frequency band cannot sufficiently support NLOS or indoor locations, (e.g., radio wave beyond 2GHz sometimes does not penetrate from outdoor to indoor), there is a large risk in business that consumers are not satisfied with the corresponding small coverage.

So far, a network handover between heterogeneous networks has been mainly studied to make complemental relationship of service areas [9]–[13]. Although the network handover techniques will be important for future wireless networks, there are some problems in toll collection, delay and control complexity in network management, and complicated selection of system combination for consumers. Therefore, a single wireles system supporting both high data rate and wide service coverage would be more attractive, although the network handover is still important with other networks.

In this paper, we study a multiband mobile communication system to support both wide service coverage and high data rate transmission. Apart from a traditional wireless system using a single frequency band (hereafter, singleband system)[1][8], the multiband system employs multiple frequency bands, where the frequency interval between the bands is so wide that the propagation and diffraction characteristics are different. For instance, 800MHz and 3.5GHz bands can be a set of the multiple frequency bands. In the multiband system, a terminal uses one of the frequency bands allocated by the base station according to the channel condition. Normally, the higher frequency band is allocated to a terminal if the frequency covers the terminal, otherwise the next higher frequency band is allocated. Differently from the singleband system, the multiband system limits the low frequency resources only to terminals which cannot use the other frequencies. Although the low frequency resources are small compared to the high frequency resources, the presented system can support wide service coverage as if all frequency resources have low frequency.

It should be noted that literatures [14][15] initially presented multiband system architecture from view point of efficient terminal's power consumption, cost, and management of a wide range of data rates. This paper studies different advantages of wide service coverage and high data rate support in the multiband system. Since multiband system can be applied to both uplink and downlink, we will describe the multiband system without specifying the link.

II. Multiband mobile communication system

A. Basic Concept

The multiband mobile communication system employs multiple frequency bands, where frequency interval between the bands is normally so wide that the propagation and diffraction

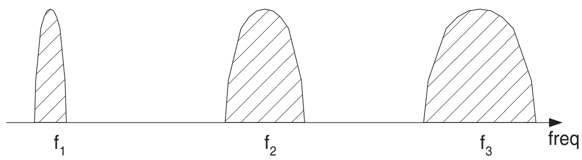

Fig. 1. Multiple frequency bands in a multiband mobile communication system.

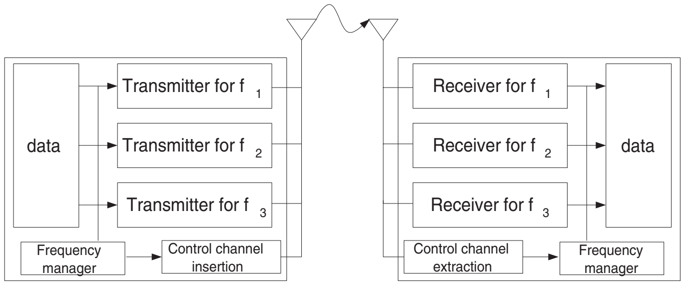

Fig. 2. Tranceiver structure in a multiband mobile communication system.

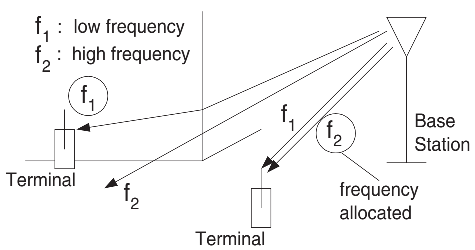

Fig. 3. Image of frequency utilization in a multiband mobile communication system.

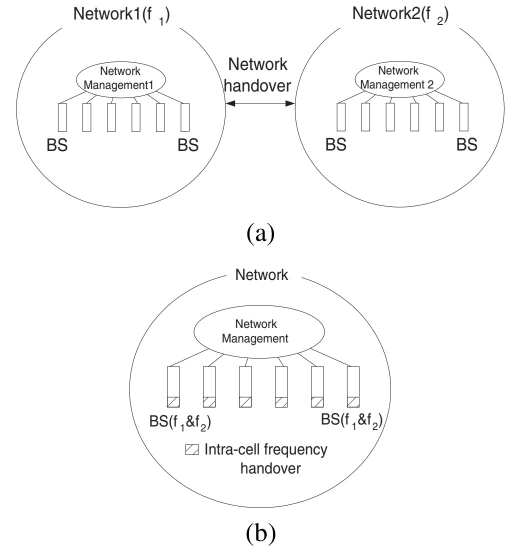

Fig. 4. Block diagram of wireless networks (a) conventional networks (b) multiband system.

characteristics are different. Figure 1 shows an example of the multiple frequency bands used in the multiband system and figure 2 shows the transceiver structure. It is not necessarily required to have the same transmission scheme in the different frequency bands, such as code division multiple access (CDMA), time division multiple access (TDMA), and orthogonal frequency division multiple access (OFDMA).

The base station allocates one frequency band suitable to a terminal according to the terminal's channel condition. Figure 3 shows an image of frequency utilization in the multiband system. Basically, higher frequency band is allocated to the terminal if the higher frequency covers the terminal, otherwise the next higher frequency band is allocated. When the channel condition changes, an intra-cell frequency handover is performed for the terminal.

The presented system supports wide coverage area by allocating the higher frequency resources to most of the terminals and by limiting the lower frequency resources to a terminal which cannot use the other frequencies. Consequently, the multiband system has advantages to support both wide coverage area and high data transmission, while consumers are not aware of frequency difference.

B. Difference From Conventional Networks

Traditionally, network handover among multiple networks has been investigated to make complemental relationship of service coverage[9]–[13]. Although the multiple networks could have different frequencies, the presented system is completely different from the conventional networks in terms of network structure. Figure 4 shows the structures of the conventional and presented networks. In the conventional networks, a single wireless network uses one frequency band and a handover is performed between the networks. Therefore, a network handover is necessary, which requires large complexity such as system registration, authentication, and location update [9][11][13]. On the contrary, the presented system changes frequency bands in one base station, where all handover process is performed in medium access control (MAC) and physical (PHY) layers. Therefore, a network handover is not necessary, which enables lower complexity and much quicker frequency change. The presented system can perform a precise allocation of frequency bands considering traffic situations and radio resources. Furthermore, the presented system can utilize the sub-millimeter wave efficiently, which cannot compose a mobile system alone.

C. Technical Requirements

The multiband system requires a multiband transceiver for each terminal. Practically, the following techniques are important to be developed:

- Multiband radio-frequency (RF) module
- Multiband radio resource control.

Multiband RF module is an important hardware issue, which becomes more realistic recently according to the development of heterogeneous networks [10]. In future, multiband RF modules are expected to have lower cost. Meanwhile, multiband radio resource control will be achieved using the

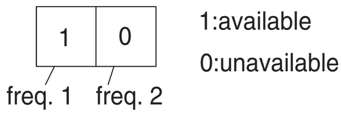

Fig. 5. Format of channel quality indicator.

current technology level. Therefore, the multiband system is a promising scheme, provided low cost multiband RF module is available.

III. System Model

In this section, system model of the multiband mobile communication system is presented.

A. Pilot Signals and Channel Quality Indicator

The base station transmits a pilot waveform in each frequency band. A terminal measures the strength of the pilot signals in the multiple frequency bands and reports the channel quality to the base station periodically, or non-periodically. Figure 5 shows an example of frame format to be reported as a channel quality indicator (CQI). The indicator shows the availability of the corresponding band using a few feedback bits.

B. Allocation of Frequency Band

The base station manages the multiple frequency bands and the active terminals. When the base station receive an access request signal from a new terminal, the base station allocates a suitable frequency band to the new terminal considering both radio resources and channel conditions of the new and active terminals. Overall access and handover procedure is described as follows:

1) When a new terminal intends to have an access, the new terminal sends an access request signal to the base station with the channel quality indicator.
2) The base station selects a suitable frequency band based on the radio resource algorithm and report the selected frequency to the new terminal. The terminal starts access using the reported frequency band.
3) When the channel condition changes to poor during the communication, the active terminal sends a frequency handover request to the base station with the channel quality indicator.
4) When the base station receives the frequency handover request, the base station selects a new frequency band and reports it to the active terminal. The active terminal changes the frequency band according to the instruction.
5) At the end of the communication, the active terminal or the base station reports the end of access to the other side. Both sides terminate the communication.

In this procedure, there are many types of radio resource control algorithms to allocate a frequency band to a new terminal or to an active terminal requesting frequency handover.

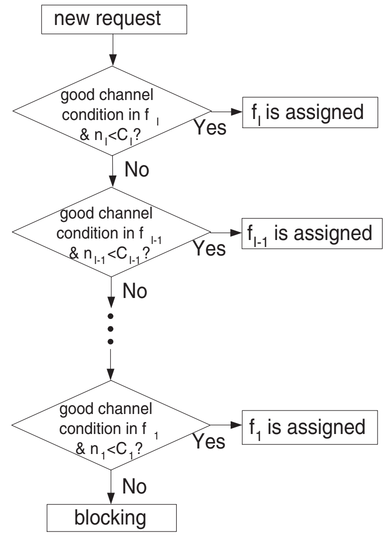

Fig. 6. Access procedure in multiband mobile communication system.

C. Radio Resource Control

We presents a simple and efficient radio resource control algorithm for a new terminal. Let us consider a multiband system with I frequency bands, where the i-th frequency f_i ($f_i < f_{i+1}$) can accommodate maximum C_i active terminals. Figure 6 shows a flow chart of the radio resource control algorithm presented here.

When the base station receives a new access request, availability of highest frequency f_I is first checked and if it is not available, availability of the next highest frequency f_{I-1} is checked. In this manner, the availability of frequency f_i is checked in order of f_I, f_{I-1}, ..., and f_1 until an available frequency is found. If an available frequency f_i is found, the frequency is selected and the selected frequency is reported to the new terminal on downlink. Otherwise, the new terminal is blocked. It is noteworthy that the i-frequency f_i is available when the frequency f_i has less than C_i active terminals and covers the new terminal.

IV. Traffic analysis

Multiband communication systems are analyzed for the case of two and three frequency bands. In the analysis, we derive blocking probabilities for the multiband systems.

A. System Description

Let us consider one base station employing I frequency bands in cellular environments, where the i-th frequency has constant resources C_i. Each terminal has a constant high data rate transmission and no mobility. Although the effect of the terminals' mobility and variable C_i are important issues to be studied in future, this paper assumes no mobility and constant C_i to get insight into the basic performance. The analysis assumes intra-cell frequency handover from f_i to f_{i+1} for a terminal covered by f_i and f_{i+1}, which happens when the resource of frequency f_{i+1} becomes available.

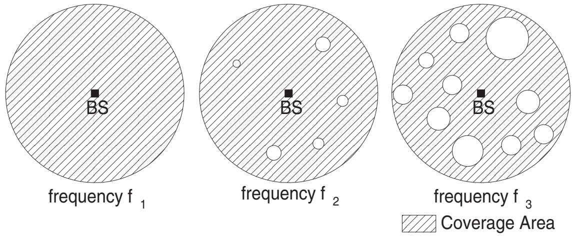

Fig. 7. Coverage areas in different frequencies.

A new terminal arises based on geometrically Poisson process with uniform density of the offered load ρ[erl]. Actually, the base station cannot support all the new terminals, due to coverage problem of radio wave or due to full accommodation. To examine the effect of coverage on system performance, we define the rate of coverage area for frequency f_i as R_i $(1 \geq R_i \geq R_{i+1})$. Figure 7 shows an example of coverage areas in different frequencies. It should be noted that the coverage area of frequency f_{i+1} is always covered by lower frequency f_i. The blocking probability is defined as the probability that a new terminal is blocked due to coverage problem or due to full accommodation.

B. Case of Two Frequency Bands

Let us consider the multiband system with two frequency bands. We refer to the area covered only by frequency f_1 as area A and that covered by both frequencies f_1 and f_2 as area B. Assume the mean arrival rates λ_A and λ_B of a new access request and the mean access holding times $1/\mu_A$ and $1/\mu_B$ of an active terminal, in area A and in area B, respectively. Since the mean holding time is identical in all areas, we have $\mu_A = \mu_B = \mu$. For the performance analysis, let $P[n_A, n_B]$ be the probability of n_A and n_B active terminals in area A and in area B, respectively. The probability $P[n_A, n_B]$ satisfies

$$\lambda_A P[n_A - 1, n_B] = n_A \mu P[n_A, n_B] \quad (1)$$

$$\lambda_B P[n_A, n_B - 1] = n_B \mu P[n_A, n_B]. \quad (2)$$

Therefore, we have [16]

$$P[n_A, n_B] = (\rho_A^{n_A}/n_A!)(\rho_B^{n_B}/n_B!)P(0,0) \quad (3)$$

$$\rho_A = \lambda_A/\mu, \quad \rho_B = \lambda_B/\mu,$$

where ρ_A and ρ_B are the regional offered loads in areas A and B, respectively. Using the total offered load ρ, the regional offered loads are given by

$$\rho_A = (R_1 - R_2)\rho, \qquad \rho_B = R_2\rho. \quad (4)$$

The number of active terminals must be less than C_1 in area A and less than $C_1 + C_2$ in areas A and B. Assuming an intra-cell frequency handover from f_1 to f_2 for an active terminal, the multiband system can always support (n_A, n_B) active terminals if and only if $n_A + n_B \leq C_1 + C_2$ and $n_A \leq C_1$. Accordingly, $P[n_A, n_B]$ satisfies

$$\sum_U P[n_A, n_B] = 1$$

$$U = \{n_A, n_B | n_A + n_B \leq C_1 + C_2, n_A \leq C_1\}.$$

Then, it follows that

$$P[n_A, n_B] = \frac{(\rho_A^{n_A}/n_A!)(\rho_B^{n_B}/n_B!)}{\sum_U (\rho_A^{n_A}/n_A!)(\rho_B^{n_B}/n_B!)}. \quad (5)$$

Considering that blocking of a new terminal occurs in case of $n_A = C_1$ in area A, or in case of $n_A + n_B = C_1 + C_2$ in areas A and B, the blocking probability is given by

$$P_b = (1 - R_1) + (R_1 - R_2)\sum_{n_B=0}^{C_2-1} P[C_1, n_B] + R_1 \sum_{n_B=C_2}^{C_1+C_2} P[C_1 + C_2 - n_B, n_B]. \quad (6)$$

C. Case of Three Frequency Bands

We can extend the analysis to the case of three frequency bands, where the i-th frequency $f_i (i = 1, 2, 3)$ can accommodate maximum C_i terminals. In the similar manner with the case of two frequency bands, the blocking probability for the multiband system with three frequency bands is given by

$$\begin{aligned} P_b &= (1 - R_1) \\ &+(R_1 - R_2)\sum_{n_B=0}^{C_2-1}\sum_{n_C=0}^{C_3+C_2-n_B-1} P[C_1, n_B, n_C] \\ &+(R_1 - R_3)\sum_{n_B=C_2}^{C_2+C_3}\sum_{n_C=0}^{C_3-1} P[C_1 + C_2 - n_B, n_B, n_C] \\ &+R_1 \sum_{n_A=0}^{C_1}\sum_{n_B=0}^{C_1+C_2-n_A} P[n_A, n_B, C_1 + C_2 + C_3 - n_A - n_B] \end{aligned} \quad (7)$$

with

$$P[n_A, n_B, n_C] = \frac{(\rho_A^{n_A}/n_A!)(\rho_B^{n_B}/n_B!)(\rho_C^{n_C}/n_C!)}{\sum_U (\rho_A^{n_A}/n_A!)(\rho_B^{n_B}/n_B!)(\rho_C^{n_C}/n_C!)} \quad (8)$$

$$\begin{aligned} \rho_A &= (R_1 - R_2)\rho \\ \rho_B &= (R_2 - R_3)\rho \\ \rho_C &= R_3\rho. \\ U &= \{n_A, n_B, n_C | n_A + n_B + n_C \leq C_1 + C_2 + C_3, \\ &\quad n_A + n_B \leq C_1 + C_2, n_A \leq C_1\}. \end{aligned}$$

V. Numerical Results

The performance of the multiband mobile communication system is evaluated by analysis and computer simulations.

A. System Parameters

In the performance evaluation, the system model described in **IV. A** is employed. An exception is that simulations does not consider intra-cell frequency handover from frequency f_i to f_{i+1}, which is assumed in the analysis. Instead, the allocated frequency is held on during communications.

First, we study the case of two frequency bands $(I = 2)$ for the multiband system, assuming the coverage rates $(R_1, R_2) = (0.9999, 0.97)$. Note that the coverage rates are supposed as

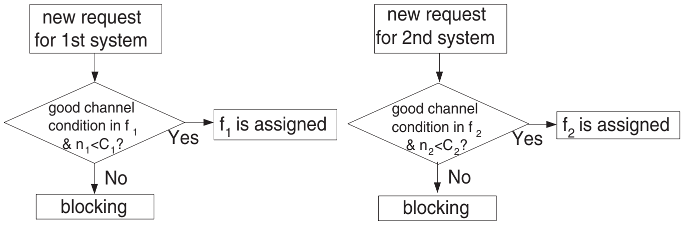

Fig. 8. Access procedure in two independent systems.

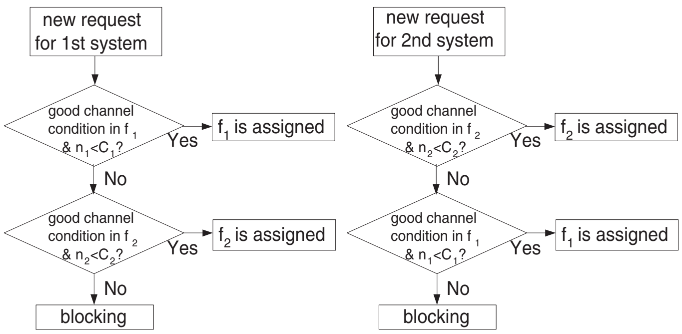

Fig. 9. Access procedure in dual systems.

an probable example to show the usefulness of the multiband system.

B. System Configurations for Comparison

For comparison purpose, we present two other types of system configurations using the same frequency bands with the multiband system, as follows:

1) Independent systems : which include two independent systems in the base station where the i-th system $(i = 1, 2)$ has frequency f_i and accommodates maximum C_i terminals. Figure 8 shows the corresponding access procedure. When a new terminal requests to access the i-th system, availability of the i-th frequency is checked. If the frequency is available, the new terminal is accepted, otherwise blocked.

2) Dual systems: which include two systems with a joint resource management, where the i-th system $(i = 1, 2)$ has frequency f_i and accommodates maximum C_i terminals. Figure 9 shows the corresponding access procedure. When a new terminal requests to access the i-th system, availability of the own frequency band f_i is initially checked. If it is not available, availability of the other frequency band is checked. If an available frequency is found, the new terminal is accepted, otherwise blocked.

In the simulations, the offered load ρ_i for the i-th system is proportional to the maximum resources as

$$\rho_1 = \frac{\rho C_1}{C_1 + C_2}, \quad \rho_2 = \frac{\rho C_2}{C_1 + C_2}. \tag{9}$$

For the above systems, the blocking probability is defined as the probability that a new terminal requesting to access the first or the second system is blocked.

C. Blocking Probability

Figure 10 shows the blocking probability versus the offered load ρ for the multiband system along with independent systems and dual systems under $(C_1, C_2) = (5, 150)$. The simulations are performed by 300, 000 new access requests. The theoretical results for the multiband system and independent systems are given by (6) and (14) (see appendix I) , respectively. In the independent systems, the blocking probability is always poor, since the 2nd system $(i = 2)$ blocks more than 3% of the new terminals due to coverage problem. In the dual systems, the blocking probability is much decreased by joint resource control of high and low frequencies. The multiband system further improves the performance by limiting the low frequency resources to terminals which are not covered by the high frequency.

Thus, the blocking probability is much improved by an appropriate resource management of high and low frequencies. In the multiband system, most of active terminals are accommodated by high frequency f_2, while a small number of terminals which is not covered by frequency f_2 are supported by low frequency f_1. Statistically, all terminals have wide coverage area and less connection errors.

In the figure, the analytical results are very close to the simulation results. Although the analysis assumes intra-cell frequency handover while the simulation does not, the similar results in the two approaches shows that the frequency handover happens rarely and has little effect on the performance.

D. Capacity

We evaluate the capacity, which is defined as the maximum allowable offered load at blocking probability of 0.01. Figure 11 shows the capacity under $C_1 = 5$ and variable C_2. It is noted that the independent systems have zero capacity, because the blocking probability is always higher than 0.01.

As seen in the figure, both the multiband system and the dual systems achieve capacity more than 100 [erl] using an appropriate C_2. As is understood intuitively, the multiband system always outperforms the dual systems. The capacity of the multiband system increases proportionally to C_2 under $C_2 \leq 170$, whereas it is saturated around $C_2 = 200$ and no more increase is seen for $C_2 \geq 220$. This saturation is because most of blockings occur in area A and cannot be decreased by increasing C_2. Thus, too small C_2 loses the capacity and too large C_2 does not contribute to the capacity. Therefore, an appropriate value of C_2 is essential for high capacity and efficient use of the multiband resources. A good balanced multiband resources optimize the capacity of the multiband system.

E. Comparison with Singleband System

To get insight into the behavior, we compare the multiband system with a singleband system using frequency f_1 and accommodating maximum $C_1 + C_2$ terminals. The blocking

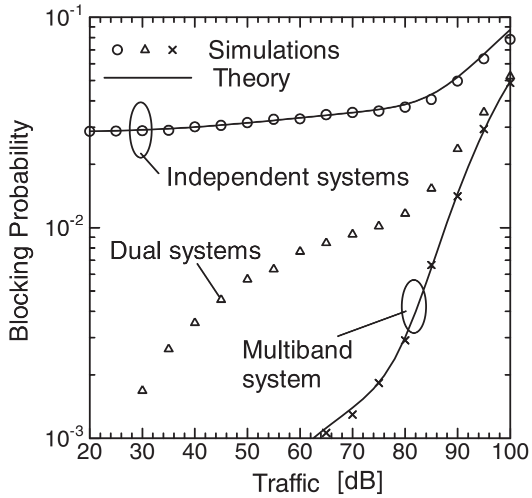

Fig. 10. Blocking probability for multiband mobile communication system with two frequency bands under $(C_1, C_2) = (5, 150)$.

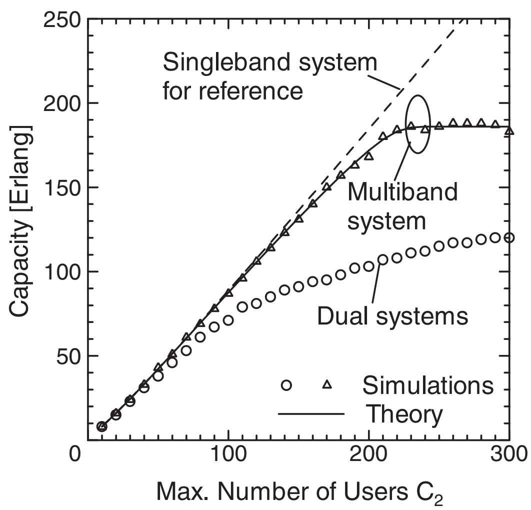

Fig. 11. Capacity for multiband systems with two frequency bands under $C_1 = 5$.

probability of the singleband system is given by

$$P_b = (1 - R_1) + R_1 \frac{(R_1\rho)^{C_1+C_2}}{(C_1+C_2)!} \left\{ \sum_{n=0}^{C_1+C_2} \frac{(R_1\rho)^n}{n!} \right\}^{-1} \quad (10)$$

The capacity can be obtained by $P_b = 0.01$ and is shown in figure 11. It is seen that the singleband system and the multiband system have almost the same capacity under $C_2 \leq 140$.

In the multiband system, if frequency f_1 has enough resources to support the offered load in area A, the number of the active and new terminals in area A rarely exceeds C_1. Then, the blocking occurs mainly when the total number of active and new terminals in areas A and B exceeds $C_1 + C_2$ or when the new terminal arises in no coverage area. This blocking condition is the same with the singleband system. Therefore, the multiband system has the similar capacity with the singleband system, if frequency f_1 has enough resources for the offered load in area A.

Now, let us study a condition that the multiband system has almost the same capacity with the singleband system. First, let us consider a specific condition of

$$\frac{\rho_A}{C_1} = \frac{\rho_A + \rho_B}{C_1 + C_2}, \quad (11)$$

which is reduced to

$$\frac{R_1 - R_2}{C_1} = \frac{R_1}{C_1 + C_2}. \quad (12)$$

Under (11), an event that the number of active and new terminals exceeds C_1 in area A is likely to an event that the number of active and new terminals exceeds $C_1 + C_2$ in areas A and B. The former should be less probable than the latter by some degrees, so that the multiband system has the same capacity with the singleband system. Therefore, we consider the condition of

$$\frac{R_1 - R_2}{C_1} \leq \frac{\alpha R_1}{C_1 + C_2}. \quad (13)$$

where α (< 1) is the traffic moderating factor.

Using our simulation parameters, (12) yields $C_2 = 161$. Although $C_2 = 161$ gives high capacity, there is a small gap of capacity between the multiband and singleband systems. Empirically, we find that the two systems have almost the same capacity under $\alpha = 0.9$, which corresponds to $C_2 \leq 145$. Here, (13) shows a strict sense condition and larger C_2 can be also applied to the multiband system if we accept a capacity different from the singleband system. The condition of (13) is useful to design the bandwidths of multiple frequencies keeping the same performance with the singleband system. Consequently, the multiband system can support active terminals as if all resources $C_1 + C_2$ have low frequency f_1 under (13).

F. Performance in Case of Three Frequency Bands

Next, we evaluate the case of three frequency bands for the multiband system ($I = 3$), assuming the coverage rates $(R_1, R_2, R_3) = (0.9999, 0.97, 0.70)$. Figure 12 shows the blocking probability for the multiband system under $(C_1, C_2) = (5, 70)$ and $C_3 = 50, 150, 250$. The analytical results obtained by (7) are very close to the simulation results, so it is verified that the analysis is also useful in three frequency bands. Figure 13 shows the capacity of the multiband system under $C_1 = 5$ and various C_2 and C_3. The capacity of the singleband system which has frequency f_1 and accommodates maximum $C_1+C_2+C_3$ terminals is also shown in the figure. It is seen that the capacity of the multiband system is saturated around $C_2 = 70$ and $C_2 + C_3 = 200$. Under $C_2 \geq 50$ and $C_2 + C_3 \leq 160$, the multiband system has similar capacity with the singleband system.

Thus, the frequency f_2 can be further replaced by higher frequency f_3 maintaining same capacity. Sub-millimeter wave such as 19GHz can be a candidate of the high frequency f_3. Therefore, the multiband system enables efficient use of the

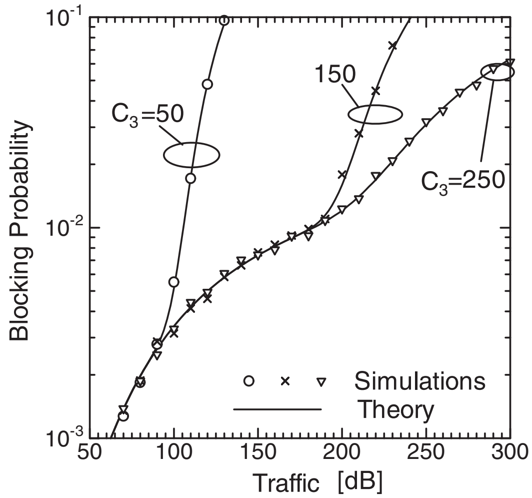

Fig. 12. Blocking probability for multiband system with three frequency bands under $(C_1, C_2) = (5, 70)$.

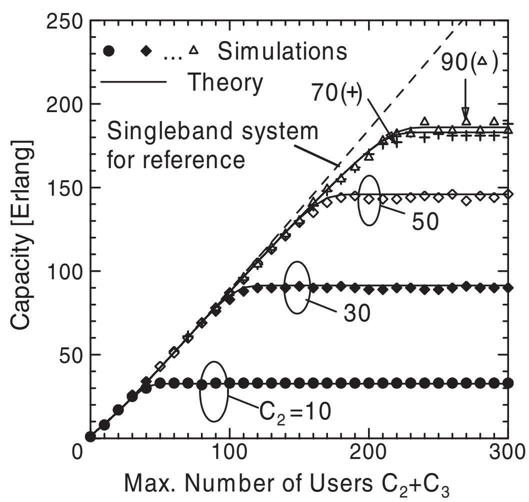

Fig. 13. Capacity for multiband mobile communication systems with three frequency bands under $C_1 = 5$.

sub-millimeter wave as a part of radio resources in the mobile communication system. Thus, the multiband system ($I = 3$) with appropriate (C_1, C_2, C_3) can support active terminals as if all resources $C_1 + C_2 + C_3$ have low frequency f_1. Thus, appropriate bandwidths in three frequencies is essential for high performance of the multiband system.

VI. Conclusions

We have studied a multiband mobile communication system to support both high data rate services and wide coverage using high and low frequency resources. The multiband system can accommodate many terminals as if all radio resources have low frequency, under appropriate bandwidths of multiple frequencies.

Thus, by allocating a set of separated multiple frequency bands to a wireless system, the system can support higher data rate keeping wide coverage area. The multiband system is also related to the spectrum allocation policy, which will be discussed for next mobile communications. The multiband system will be a promising scheme for future mobile communications.

Appendix I
Blocking Probability for Independent Systems

The total blocking probability for the two independent systems is theoretically expressed as

$$P_b = (\rho_1/\rho)P(C_1, \rho_1, R_1) + (\rho_2/\rho)P(C_2, \rho_2, R_2) \quad (14)$$

where

$$P(C, \rho, R) = (1 - R) + R\frac{(R\rho)^C/C!}{\sum_{n=0}^{C}(R\rho)^n/n!}. \quad (15)$$

References

[1] H. Atarashi, S. Abeta, M. Sawahashi, "Variable spreading factor-orthogonal frequency and code division multiplexing (VSF-OFCDM) for broadband packet wireless access," IEICE Trans. on Commun., vol. E86-B, no. 1, pp. 291–299, Jan. 2003.
[2] Y. Kim, B. Jeong, J. Chung, C. Hwang, J. Ryu, K. Kim, Y. Kim, "Beyond 3G: Vision, requirements, and enabling technologies," IEEE Communications Magazine, vol. 41, no. 3, pp. 120-124, March 2003.
[3] Y. P. Zhang, Y. Hwang, "Measurements of the characteristics of indoor penetration loss," Proc. of IEEE VTC'94, pp. 1741–1744, June 1994.
[4] G. Durgin, T. S. Rappaport, H. Xu, "Measurements and models for radio path loss and penetration loss in and around homes and trees at 5.85 GHz," IEEE Trans. Commun., vol. 46, no. 11, pp. 1484–1496, Nov. 1998.
[5] A. F. de Toledo, A. M. D. Turkmani, J. D. Parsons, "Estimating coverage of radio transmission into and within buildings at 900, 1800, and 2300 MHz," IEEE Personal Communications, vol. 5, no. 2, pp. 40–47, April 1998.
[6] R. F. Rudd, "Building penetration loss for slant-paths at L-, S- and C-band," Proc. of IEE ICAP'03, March 2003.
[7] R. Hoppe, G. Wölfle, F. M. Landstorfer, "Measurement of building penetration loss and propagation models for radio transmission into buildings," Proc. of IEEE VTC'99, pp. 2298–2302, Sept. 1999.
[8] http://www.3gpp.org/
[9] P. D. Silva and H. Sirisena, "A mobility management protocol for IP-based cellular networks," IEEE Wireless Communications, pp. 31–37, June 2002.
[10] R. State, K. El-Khazen, G. Martinez, G. Vivier, "Service management for multi-operator heterogeneous networks," IEEE Globecom2002, vol. 21, no. 1, pp. 2080–2084, Nov. 2002.
[11] M. Inoue, K. Mahmud, H. Murakami, M. Hasegawa, H. Morikawa, "Novel out-of-band signaling for seamless interworking between heterogeneous networks," IEEE Wireless Communications, Vol. 11, Issue 2, pp. 56–63, April 2004.
[12] A. Doufexi, E. Tameh, A. Nix, S. Armour and A. Molina, "Hotspot wireless LANs to enhance the performance of 3G and beyond cellular networks," IEEE Communications Magazine, vol. 41, no. 7, pp. 58–65, July 2003.
[13] A. Salkintzis, "Interworking techniques and architectures for WLAN/3G integration toward 4G mobile data networks," IEEE Wireless Communications, vol. 11, no. 3, June 2004.
[14] M. Rinne, P. Pasanen, P. Seppinen, and K. Leppänen, "Dual bandwidth approach to new air interface," WWRF # 11 meeting, June, 2004.
[15] N. Matoba, T. Sugiyama, M. Shirakabe, and H. Yoshino, "Capacity evaluation of a system using dynamic channel allocation," IEICE Technical Report on Radio Communication System (RCS), RCS2004-277, Jan. 2005.
[16] L. Kleinrock,"Queuing systems," John Wiley and Sons, New York, 1975.