Multiband Mobile Communication System for Wide Coverage and High Data Rate

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SUMMARY 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 depending on his channel quality. By limiting the low frequency resources to a terminal not covered by the higher frequencies, the presented multiband system can accommodate many terminals providing wide coverage area, as if all radio resources have low frequency. From numerical results, the multiband system can provide wide service coverage area for much larger number of terminals than conventional systems. It is also found that an appropriate balance of multiple frequency resources is essential to achieve high capacity.

key words: mobile communications, wireless access, multiband, radio resource control, blocking probability

1. 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 100 Mbps. The final goal of the 4G mobile system is to satisfy the consumer’s demand under successful business. For this purpose, efficient schemes for wireless data transmissions have been widely investigated [1], [2].

In actual environments, consumers are sensitive to not only data transmission 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 can be seen in the past economic data of relationship between population coverage and the number of subscribers. Therefore, wide service coverage is an essential factor 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 or indoor locations [3]–[7]. However, most of low frequency bands, e.g., frequency below 1 GHz, have been already allocated to the existing services and, considering that the 4G mobile system requires wide bandwidth to support high data rate services, it seems difficult to allocate much of low frequency band to the 4G mobile system. Therefore, it will be inevitable to allocate higher frequency band as main radio resource. Since the high frequency band cannot sufficiently support NLOS or indoor locations, (e.g., radio wave beyond 2 GHz sometimes does not penetrate from outdoor to indoor), there is a large risk in business that consumers are not satisfied with the corresponding small service coverage.

So far, system handover between different systems has been widely studied to make complementary relationship of service areas [8]–[12]. While the system handover will be developed in future wireless networks, it is also required that a single mobile system supports wide coverage area alone. There are many kinds of 4G concepts from one mobile system to heterogeneous networking aspects to provide wireless communications everywhere. Among them, we focus our research on a single mobile system.

In this paper, we study a multiband mobile communication system to support both wide service coverage and high data rate transmission. Apart from the traditional system using a single frequency band (hereafter, singleband system) [1], [13], 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, 800 MHz and 3.5 GHz bands can be a set of the multiple frequency bands. In the multiband system, a terminal sends signals using 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 allocates 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 previous 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 the multiband system can be applied to both uplink and downlink, we will describe the multiband system without specifying the link.

This paper is organized as follows. Section 2 demonstrates the system concept of the multiband mobile commu-
2. Multiband Mobile Communication System

2.1 System Concept

The multiband mobile communication system employs multiple frequency bands, where the frequency interval between the bands is normally so wide that the propagation and diffraction characteristics are different. Figure 1 shows an example of the multiple frequency bands used in the multiband system and Fig. 2 shows the transceiver structure. It is not necessarily required to have the same transmission scheme in 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 allocation 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. As the channel condition changes, an intra-cell frequency handover (FHO) is performed for the terminal.

The presented system supports wide coverage area by allocating the high frequency resources to most terminals and the low frequency resources only to a few terminals 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.

2.2 Difference from Conventional Technologies

Traditionally, handover among multiple systems has been investigated to make complementary relationship of service coverages [8]–[12]. Although the multiple systems could have different frequencies, the presented system is different from the conventional systems in terms of networking structure. Figure 4 shows the structures of the conventional and presented systems. In the conventional systems, a single wireless system uses one frequency band and a handover is performed between the systems. Therefore, a system handover is needed, which requires large complexity for system registration, authentication, and location update [8], [10], [12].

As different researches, overlaid cell structures, where microcellular base stations support hot spot areas in one macrocell, have been also investigated [16]–[19]. Although the overlaid cells could have different frequencies, the handover delay between different base stations is usually more than several 10 ms, due to timing synchronization and networking delay.

Apart from the conventional technologies, the pre-
sented system changes frequency bands in medium access control (MAC) and physical (PHY) layers of one base station. Applying the common timing synchronization to different frequency bands [20], the frequency change can be performed quickly, in principle, in less than 1 ms. This fast frequency change enables continuous use of hybrid-automatic repeat request (H-ARQ) and quality of service (QoS) control without initialization. Also, the base station can change the frequency band for high-mobility terminals frequently with reasonable complexity. Furthermore, the presented system can use the sub-millimeter wave efficiently as one of multiple frequency bands, which cannot compose a mobile system alone.

From viewpoints of traffic researches, many papers have investigated cellular planning for overlaid cellular architectures [16]–[19]. Among them, strategy to allocate small coverage resources prior to wide coverage resources is also effective in the multiband system. Using the radio resource allocation strategy, this paper studies different topic to design multiple frequency resources for one base station. In specific, effective amount of radio resources of small coverage is clarified on the constraint of scarce radio resources of wide coverage.

2.3 Technical Requirements

The multiband system requires 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 [9]. In future, multiband RF modules are expected to have lower cost. Meanwhile, multiband radio resource control will be achieved using the current technology level. Therefore, the multiband system is a promising scheme, provided low cost multiband RF module is available.

3. System Model

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

3.1 Pilot Signals and Channel Quality Indicator

The base station transmits pilot signal in each frequency band. A terminal measures the strength of pilot signals in 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 report the channel quality indicator (CQI). The CQI shows availability of the corresponding band using a few feedback bits.

Usually, the strength of pilot signals is measured by averaging the received power in time and frequency domain within each frequency band [20]. Then, the multipath fading effect is reduced by the averaging process over coherent time or bandwidth of multipath channels. Therefore, the CQI mainly indicates channel gain due to propagation loss and shadowing including diffraction effect. Correspondingly, the base station controls the radio resources, according to the terminal’s propagation loss and shadowing.

3.2 Initial Access

Figure 6 shows overall control procedures between the base station and a terminal. When a new terminal arises, the base station allocates a frequency band to the new terminal, according to the following initial access procedures.

- When a new terminal intends to have an access, the new terminal sends an access request signal to the base station with the CQI.
- The base station selects a suitable frequency band based on the radio resource algorithm and reports the selected frequency band to the new terminal. The terminal starts access using the reported frequency band.

Here, we consider a simple and efficient radio resource control algorithm to select the suitable frequency band. Figure 7 shows the radio resource control algorithm for the multiband system with \( I \) frequency bands, where the \( i \)-th frequency band \( f_i \) \( (f_i < f_{i+1}) \) can accommodate maximum \( C_i \) active terminals. In Fig. 7, \( n_i \) denotes the number of active terminals being accommodated by the \( i \)-th frequency band \( f_i \).

In the radio resource control algorithm, availability of highest frequency band \( f_I \) is first checked and if it is not available, availability of the next highest frequency band \( f_{I-1} \) is checked. In this manner, the availability of frequency
band \( f_i \) is checked in order of \( f_1, f_{i-1}, \ldots, f_1 \) until an available frequency band is found. If an available frequency band \( f_i \) is found, the frequency band is selected and reported to the new terminal on downlink. Otherwise, the new terminal is blocked. It should be noted that the \( i \)-frequency band \( f_i \) is available, when the \( i \)-th frequency band \( f_i \) supports less than \( C_i \) active terminals and covers the new terminal.

### 3.3 Intra-Cell Frequency Handover

As active terminal’s channel condition changes, the base station performs intra-cell frequency handover (hereafter, referred to as FHO-I) as follows:

- When the channel condition changes, the active terminal sends updated CQI to the base station.
- If the base station finds a more suitable frequency band, the base station instructs the active terminal to change the frequency band to the more suitable one.

The more suitable frequency band is selected by the same radio resource control algorithm to the initial access shown in Fig. 7. When the channel condition becomes poor, the frequency band of the terminal is changed to the lower frequency band. When the terminal has good channel condition in higher frequency band, the frequency band is changed to the higher frequency band.

Besides, another intra-cell frequency handover (hereafter, referred to as FHO-II) is performed, in case that a fully accommodated frequency band \( f_i \) becomes newly available by termination or inter-cell handover of an accommodated terminal.

- When a fully accommodated frequency band \( f_i \) becomes newly available, the base station searches an available frequency band \( f_i \) in order of \( f_1, \ldots, f_{i-1} \).
- If the active terminal is found, the base station instructs the active terminal to change the frequency band to \( f_i \).

In case that the \( i \)-th frequency band \( f_i \) is fully accommodated, there may exist an active terminal using a lower frequency band \( f_1, \ldots, f_{i-1} \), even if the terminal is covered by the \( i \)-th frequency band \( f_i \). The active terminal changes the frequency band, as soon as the the \( i \)-th frequency band \( f_i \) becomes available.

Throughout the initial access and the intra-cell frequency handovers, the radio resource control keeps low frequency resources as much as possible. For this purpose, the base station allocates the highest available frequency band to new and active terminals. 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.

### 3.4 Inter-Cell Handover

When an active terminal moves to other cells, inter-cell handover is performed by comparing the pilot signal power in the lowest frequency band \( f_1 \) from the current base station with those from near-by base stations. Based on the wide coverage of the lowest frequency band, a reliable inter-cell handover is performed. The characteristics of the inter-cell handover are the same as in the conventional singleband system using the frequency band \( f_1 \). Therefore, we focus on the performance of the initial access and the intra-cell frequency handovers for the multiband system.

### 3.5 Coverage Characteristics in Frequency Bands

In general, the propagation loss increases proportionally to square of operating frequency \( f \) [7]. Therefore, in case of large cell radius, high frequency band has difficulty in supporting the boundary with near-by base stations. Then, the high frequency band covers only a limited area near the base station.

In contrast, when base stations are so dense that the high frequency band supports the boundary with near-by base stations, each frequency band has interference-limited environments. Then, all frequency bands support the same target area inside the boundary, although high frequency band has poor locations within the target area.

Thus, there are two typical cases in the multiband system. In this paper, we investigate the case of dense base stations, aiming to show the effectiveness of the multiband system as a final goal. Based on attractive final goal, we will further study other aspects of the multiband system. For instance, we have already presented a realistic scenario to deploy base stations in [20], where the singleband system is gradually migrated to the multiband system with dense base stations, keeping low investment risk. Therefore, the purpose of this paper is to show the effectiveness of ideal multiband system with dense base stations.
4. Traffic Analysis

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

4.1 System Description

Let us consider one base station in cellular environments, employing I frequency bands, where the i-th frequency has the resources C_i. The base station provides a constant high data rate transmission to active terminals. Although the effect of variable C_i depending on outer-cell interference is interesting issue to be studied in future, this paper gives the analysis assuming constant C_i, which will be useful to get insight into the basic performance. Also, no mobility of terminals are assumed, where FHO-I does not occur, but FHO-II occurs. The effect of terminal’s mobility will be discussed later in Sect. 5.8.

In the target area, a new terminal arises based on geometrically Poisson process with uniform density of the offered load \rho_{[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 the i-th frequency band f_i as \mathcal{R}_i (1 \geq \mathcal{R}_i \geq \mathcal{R}_{i+1}). Figure 8 shows an example of coverage areas in different frequencies. In the figure, uncovered area (white hole) arises inside the target area, by the effect of obstacles, such as buildings, walls, cars, etc. It is empirically known that low frequency covers indoor or NLOS locations better than high frequency, due to larger diffraction. Therefore, it is assumed that the coverage area of high frequency f_{i+1} is always covered by low frequency f_i. It may happen that the high frequency has locally better channel condition than the low frequency due to multipath fading effect. However, since the multiband system controls the radio resources based on propagation loss and shadowing, coverage area is defined based on propagation loss and shadowing effects. For the multiband system, the blocking probability is defined as the probability that a new terminal is blocked due to coverage problem or due to full accommodation.

4.2 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 \lambda_A and \lambda_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

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

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

Figure 9 shows the corresponding markov chain. Therefore, we have [21]

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

\[\rho_A = \lambda_A / \mu, \quad \rho_B = \lambda_B / \mu, \quad \]

where \rho_A and \rho_B are the regional offered loads in areas A and B, respectively. Using the total offered load \rho, the regional offered loads are given by

\[
\rho_A = (R_1 - R_2) \rho, \quad \rho_B = R_2 \rho. \quad (4)
\]

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. Considering effect of FHO-II, the multiband system can always support \((n_A, n_B)\) active terminals on the constraint of \(n_A + n_B \leq C_1 + C_2\) and \(n_A \leq C_1\). Accordingly, \(P[n_A, n_B]\) satisfies

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

\[U = [n_A, n_B] n_A + n_B \leq C_1 + C_2, n_A \leq C_1].
\]

![Fig. 8](image-url) Coverage areas in different frequencies.

![Fig. 9](image-url) Markov chain for the prioritized frequency band allocation.
Then, it follows that
\[
P[n_A, n_B] = \frac{(\rho_A^{n_A}/n_A!)(\rho_B^{n_B}/n_B!)}{\sum_{i=0}^{n_A} (\rho_A^{n_A}/n_A!)(\rho_B^{n_B}/n_B!)}. \tag{5}
\]
A 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. Therefore, the blocking probability is given by
\[
P_B = (1 - R_1) + (R_1 - R_2) \sum_{n_B=0}^{C_2-1} P(C_1, n_B)
+ R_1 \sum_{n_A=0}^{C_1+C_2} P(C_1 + C_2 - n_B, n_B). \tag{6}
\]

### 4.3 Case of Three Frequency Bands

We can extend the analysis to the case of three frequency bands, where the \( i \)-th frequency band \( f_i \) \((i = 1, 2, 3)\) can accommodate maximum \( C_i \) terminals. In the similar manner to the case of two frequency bands, the blocking probability for the case of three frequency bands is given by
\[
P_B = (1 - R_1) + (R_1 - R_2) \sum_{n_B=0}^{C_2-1} P(C_1, n_B, n_C)
+ (R_1 - R_3) \sum_{n_C=0}^{C_3-1} P(C_1 + C_2 - n_B, n_B, n_C)
+ R_1 \sum_{n_A=0}^{C_1+C_2} \sum_{n_B=0}^{C_2} P(n_A, n_B, n_C)
+ R_1 \sum_{n_A=0}^{C_1+C_2+C_3} P(n_B, C_1 + C_2 + C_3 - n_A - n_B) \tag{7}
\]
with
\[
P[n_A, n_B, n_C] = \frac{(\rho_A^{n_A}/n_A!)(\rho_B^{n_B}/n_B!)(\rho_C^{n_C}/n_C!)}{\sum_{U} (\rho_A^{n_A}/n_A!)(\rho_B^{n_B}/n_B!)(\rho_C^{n_C}/n_C!)} \tag{8}
\]
\[
\rho_A = (R_1 - R_2)p,
\rho_B = (R_2 - R_3)p,
\rho_C = R_3p.
U = \{n_A, n_B, n_C | n_A + n_B + n_C \leq C_1 + C_2 + C_3, n_A + n_B \leq C_1 + C_2, n_A \leq C_1 \}.
\]

### 5. Numerical Results

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

#### 5.1 System Parameters

In the performance evaluation, the system model described in Sect. 4.1 is employed. First, we study the case of two frequency bands \((I = 2)\) for the multiband system. Table 1 lists the simulation parameters of radio resources and coverage rates for \( I = 2 \). Note that these coverage rates are supposed as an probable example to show usefulness of the multiband system and accuracy of our analysis. It is desirable to obtain more realistic coverage rates based on experimental results in future study.

#### 5.2 Systems for Comparison

For comparison purpose, we present the following two other types of systems using the same frequency bands.

1. Independent systems which include two independent systems in the base station, where the \( i \)-th system \((i = 1, 2)\) uses frequency band \( f_i \) and accommodates maximum \( C_i \) terminals. Figure 10 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 band \( f_i \) and accommodates maximum \( C_i \) terminals. Figure 11 shows the corresponding access procedures. 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 $\rho_i$ for the $i$-th system is proportional to the maximum resources as

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

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

5.3 Blocking Probability

Figure 12 shows the blocking probability versus the offered load $\rho$ for the multiband system along with independent systems and dual systems under $(C_1, C_2) = (5, 100)$. 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 (A-1) (see Appendix), 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 both high and low frequencies. The multiband system further improves the performance by limiting the low frequency resources to terminals uncovered by the high frequency.

Thus, the blocking probability is much improved by an appropriate resource management of high and low frequency bands. Therefore, it is important to use an efficient radio resource algorithm for high performance. In the multiband system, most of active terminals are accommodated by the high frequency band $f_2$, while a small number of terminals uncovered by the frequency band $f_2$ are supported by the low frequency band $f_1$. Statistically, all terminals have wide coverage area and less connection errors. In the figure, the analytical results match with the simulation results. Therefore, the theoretical expression is verified by the simulation results.

5.4 Capacity

We evaluate the capacity, which is defined as the maximum allowable offered load at blocking probability of 0.01. Figure 13 shows the capacity under $C_1 = 5$ and variable $C_2$ for the multiband system and the dual systems. 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 appropriate resources $C_2$. 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 in $C_2 \geq 220$. 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, appropriate resources $C_2$ are essential for high capacity and efficient use of the multiband resources. A good balanced multiband resources optimize the capacity of the multiband system.

5.5 Comparison with Singleband System

To get insight into the behavior, we compare the multiband system with a singleband system which accommodates maximum $C_1 + C_2$ terminals using the frequency band $f_1$. Since the frequency band $f_1$ covers the target area with rate $R_1$, the blocking probability of the singleband system is given by

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

The capacity can be obtained by $P_b = 0.01$ and is shown in Fig. 13. It is seen that the singleband system and the multiband system have almost the same capacity under $C_2 \leq 140$. 

![Fig. 12](image1.png)  
Fig. 12 Blocking probability for multiband mobile communication system with two frequency bands under $(C_1, C_2) = (5, 100)$. 

![Fig. 13](image2.png)  
Fig. 13 Capacity for multiband systems with two frequency bands under $C_1 = 5$. 

![Fig. 14](image3.png)  
Fig. 14 Singleband system for reference.
Therefore, the multiband system performs as if all resources \( C_1 + C_2 = 145 \) have low frequency, although real low frequency resources are \( C_1 = 5 \). In other words, the multiband system makes the scarce low frequency resources 29 times more effective.

In the multiband system, if the frequency band \( f_1 \) 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 to the case of the singleband system. Therefore, the multiband system has the similar capacity to 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, we 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 to 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 \( \alpha \) (\( \leq 1 \)) is the traffic moderating factor.

Using our simulation parameters, (12) yields \( C_2 = 161 \). Although \( C_2 = 161 \) gives high capacity without wasting the resources of frequency \( f_2 \), 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 to 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). Using the appropriate bandwidths in multiple frequencies, the multiband system can support wide service coverage and high data rate transmission.

### 5.6 Case of Three Frequency Bands

Next, we evaluate the case of three frequency bands for the multiband system (\( I = 3 \)). Table 2 lists the simulation parameters of radio resources and coverage rates in the

<table>
<thead>
<tr>
<th>Frequency ( f_i )</th>
<th>( f_1 )</th>
<th>( f_2 )</th>
<th>( f_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage ( R_i )</td>
<td>99.99%</td>
<td>97%</td>
<td>79%</td>
</tr>
<tr>
<td>Max. terminals ( C_i )</td>
<td>5</td>
<td>( C_2 )</td>
<td>( C_3 )</td>
</tr>
</tbody>
</table>

Table 2 Coverage rates and radio resources in multiple frequency bands (\( I = 3 \)).

Three frequencies. Figure 14 shows the blocking probability versus the offered load \( \rho \) for the multiband system under \( (C_1, C_2) = (5, 70) \) and \( C_1 = 50, 100, 150, 200, 250 \). The analytical results obtained by (7) match with the simulation results, so it is verified that the analysis is also useful in three frequency bands. Figure 15 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 accommodates maximum \( C_1 + C_2 + C_3 \) terminals using frequency band \( f_1 \) 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 to the singleband system.

Thus, the frequency \( f_2 \) can be further replaced by the
higher frequency \(f_3\) maintaining the same capacity. Sub-millimeter wave such as 19 GHz can be candidate of the high frequency \(f_3\), although the sub-millimeter wave cannot compose the mobile communication system alone. Therefore, the multiband system enables efficient use of the sub-millimeter wave as a part of radio resources in the mobile communication system.

Now, we consider the condition that the multiband system has almost the same capacity to the singleband system. In the same manner to the case of \(I = 2\), we examine the case of

\[
\frac{R_1 - R_2}{C_1} \leq \frac{\alpha(R_1 - R_3)}{C_1 + C_2} \leq \frac{\alpha^2 R_1}{C_1 + C_2 + C_3}. \tag{14}
\]

Using \(\alpha = 0.9\), (14) corresponds to \(C_2 \leq 40 \) and \(C_3 \leq 2C_2 + 10 \leq 90\) in our system parameters. In Fig. 15, it is verified that the multiband system with the given \((C_2, C_3)\) has the same capacity to the singleband system.

Therefore, (14) is useful to design the bandwidths of three frequencies keeping the same performance to the singleband system. Indeed, the multiband system \((I = 3)\) can support active terminals as if all resources \(C_1 + C_2 + C_3\) have low frequency \(f_1\) under (14). Thus, appropriate bandwidths in three frequencies are essential for high performance of the multiband system.

### 5.7 Cases of More Frequency Bands

We further examine the cases of more frequency bands. To find the condition that the multiband system has almost the same capacity to the singleband system, we take up specific cases that the radio resources \(C_1, \ldots, C_I\) in \(I\) frequency bands satisfy

\[
\frac{R_1 - R_i}{\sum_{k=1}^{I} C_k} = \begin{cases} 
\frac{\alpha_0(R_1 - R_{i+1})}{\sum_{k=1}^{i} C_k} & i = 2, \ldots, I - 1 \\
\frac{\alpha_0 R_1^{i-1}}{\sum_{k=1}^{I} C_k} & i = I
\end{cases} \tag{15}
\]

where \(\alpha_0\) is a variable parameter. Under given coverage rates \(R_1, \ldots, R_I\) and radio resources \(C_i\) of the first frequency band, \(C_i (i = 2, \ldots, I)\) is successively determined by

\[
C_i = \begin{cases} 
\left(\frac{\alpha_0 R_1 - R_{i+1}}{R_1 - R_i} - 1\right) \sum_{k=1}^{i-1} C_k & i = 2, \ldots, I - 1 \\
\left(\frac{\alpha_0 R_1}{R_1 - R_i} - 1\right) \sum_{k=1}^{i-1} C_k & i = I.
\end{cases} \tag{16}
\]

Using the above \((C_1, \ldots, C_I)\) and \((R_1, \ldots, R_I)\), the capacity is evaluated by computer simulations under various number of frequency bands.

Figure 16 shows the capacity of the multiband systems with \(I = 2, \ldots, 6\) frequency bands under \(C_1 = 5\) and \((R_1, R_2, R_3, R_4, R_5, R_6) = (0.9999, 0.99, 0.97, 0.93, 0.85, 0.7)\). In case of \(I \leq 5\) frequency bands, the first frequency bands \(f_1, \ldots, f_I\) corresponding to coverage rates \(R_1, \ldots, R_I\) are used. The capacity of singleband system, which accommodates maximum \(C_1 + \ldots + C_I\) terminals using the frequency band \(f_1\), is also shown in the figure.

In the figure, it is seen that the capacity with \(\alpha_0 = 0.9\) always matches with the capacity of the singleband system, irrespective of the number of frequency bands \(I\). Applying the same considerations in Sect. 5.5 to the relation between two frequencies \(f_i\) and \(f_{i+1}\) \((i = 1, \ldots, I - 1)\) successively, the multiband system has almost the same capacity to the singleband system, on the constraint of

\[
\sum_{k=1}^{I} C_k \leq \alpha \frac{R_1 - R_{i+1}}{\sum_{k=1}^{i} C_k} \leq \frac{\alpha R_1^{i-1}}{\sum_{k=1}^{I} C_k}
\]

\[
\ldots \leq \frac{\alpha^{I-2}(R_1 - R_I)}{\sum_{k=1}^{I} C_k} \leq \frac{\alpha^{I-1} R_1}{\sum_{k=1}^{I} C_k} \tag{17}
\]

with \(\alpha = 0.9\). Similarly to Sect. 5.5, (17) is a strict sense condition and larger \(\alpha\) can be applied allowing different capacity from the singleband system. It should be noted that Fig. 16 aims to find the strict sense condition and does not aim to show the capacity comparison among different \(I\) because the total radio resources \(C_{\text{total}} = C_1 + \ldots + C_I\) are variable depending on \(I\) and \(\alpha_0\). Only in case of \(\alpha_0 = 1\), the total radio resources \(C_{\text{total}}\) are constant independently of \(I\), since it holds from (15) that

\[
C_{\text{total}} = \sum_{k=1}^{I} C_k = \frac{R_1}{R_1 - R_2} C_1. \tag{18}
\]

In case of \(\alpha_0 = 1\), the capacity has a small degradation according to the increase of \(I\). Nevertheless, allowing the small capacity degradation, the frequency resources can be replaced by the higher frequency resources. Table 3 lists the radio resources used for capacity evaluation under
Table 3  Radio resources under $I$ frequency bands and $\alpha_0 = 1$ ((R1, R2, R3, R4, R5, R6) = (0.9999, 0.99, 0.97, 0.85, 0.7, 0.7)).

<table>
<thead>
<tr>
<th>$I$</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>$C_2$</td>
<td>5.0</td>
<td>10.1</td>
<td>10.1</td>
<td>10.1</td>
<td>10.1</td>
</tr>
<tr>
<td>$C_3$</td>
<td>0</td>
<td>489.9</td>
<td>20.2</td>
<td>20.2</td>
<td>20.2</td>
</tr>
<tr>
<td>$C_4$</td>
<td>0</td>
<td>0</td>
<td>469.7</td>
<td>40.4</td>
<td>40.4</td>
</tr>
<tr>
<td>$C_5$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>429.3</td>
<td>75.8</td>
</tr>
<tr>
<td>$C_6$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>354.5</td>
</tr>
<tr>
<td>$C_{total}$</td>
<td>505.0</td>
<td>505.0</td>
<td>505.0</td>
<td>505.0</td>
<td>505.0</td>
</tr>
</tbody>
</table>

$I = 2, \ldots, 6$ frequency bands and $\alpha_0 = 1$. It is seen that much low frequency resources can be replaced by the higher frequency bands, which will solve the problem of scarce low frequency bands. Currently, new spectrum in 2 to 5 GHz has been considered for future mobile systems [22], which will be further discussed in the ITU-R World Radiocommunication Conference (WRC). In future, it may be probable to use more than 3 frequency bands, including the current frequency bands located below 2 GHz and the new frequency bands.

In the Fig. 16, the multiband system with $I = 2$ achieves larger capacity than that in Fig. 13, because the frequency band $f_2$ has larger coverage rate $R_2 = 0.99$. Then, the frequency $f_2$ must be lower than $f_2$ in Fig. 13 and the radio resources $C_2$ are needed in the lower frequency band $f_2$. However, using $I \geq 3$, the required radio resources in $f_2$ are reduced significantly, keeping the large capacity. In Table 3, $C_2$ is reduced from 499 to 10, as $I$ increases from 2 to 3. Thus, the use of a large number of frequency bands with small frequency interval has advantage in capacity enhancement. Also, a large number of frequency bands may be motivated by the requirement to compose a single mobile system using existing distributed spectra.

However, on the other hand, the larger number of frequency bands requires more complex RF modules and higher implementation cost. Then, coexistence of different types of terminals which deal with different number of frequency bands according to their applications may be one practical way. Thus, it is important to design the number of frequency bands, considering many aspects such as capacity enhancement, hardware cost, and coexistence of different types of terminals.

5.8 Effect of Terminal’s Mobility

Let us consider the effect of terminal’s mobility on the multiband system. In principle, the multiband system is expected to perform intra-cell frequency handover quickly in MAC & PHY layers in less than 1 ms. Since time-variance of shadowing is usually below several 10 Hz even in case of very high mobility, the intra-cell frequency handover will be applicable to high-mobility terminals using reasonable complexity.

Next, we consider the effect of mobility on the performance for the case of $I = 2$. The active terminals may move from area A (or B) to area B (or A). Then, the traffic state ($n_A, n_B$) will be changed to ($n_A + \Delta n, n_B - \Delta n$), where ($n_A, n_B$) denotes the state that $n_A$ and $n_B$ active terminals exist in areas A and B, respectively, and $\Delta n = \ldots, -1, 0, 1, \ldots$ is the number of active terminals having moved from area B to area A. In case of $\Delta n \leq 0$, it is apparent that the base station can support all terminals maintaining the constant high data rate transmission. Likewise, the blocking probability for a new terminal is maintained. Therefore, performance will not deteriorate under $\Delta n \leq 0$.

On contrary, in case of $\Delta n > 0$, the base station is required to support $n_A + \Delta n$ terminals in area A. In some cases, $n_A + \Delta n > C_1$ may happen. In order to accommodate these active terminals, it is a practical way to reduce the data rate of each terminal by $C_1/(C_1 + \Delta n)$, compared to the constant high data rate. Then, the base station can support maximum ($C_1 + \Delta n$) active terminals in area A. Since the base station can always support $C_1$ terminals which arise in area A, the blocking probability for a new terminal is maintained. Thus, the adaptive data rate control depending on $\Delta n$ will help the base station to keep the blocking probability. Although the data rate of each terminal temporary decreases, the terminal is not forcibly terminated in the high data rate communications.

From the above considerations, the multiband system can always support the constant data rate in area B. Meanwhile, adaptive data rate control is an effective technique in area A, which will help to keep the blocking probability under terminal’s mobility. The similar arguments can be applied to the case of $I(\geq 3)$ frequency bands, where adaptive data rate control is used in the frequency bands $f_i, \ldots, f_{i-1}$. Overall performance evaluation including communication quality deterioration under the adaptive data rate control will be subject for future study.

6. 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. From the numerical results, the appropriate balance of bandwidth in multiple frequencies enhances the capacity of the multiband system.

So far, a wireless communication system has been always allocated to a single frequency bandwidth. However, 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 fourth generation mobile communications.

\footnote{There may be another problem that PHY layer cannot detect the data signal well, due to high Doppler spread in high frequency band. Here, we assume ideal PHY layer, expecting progress of signal processing.}
References


Appendix: Blocking Probability for Independent Systems

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

\[
P_b = (p_1/p_2)P(C_1, p_1, R_1) + (p_2/p_1)P(C_2, p_2, R_2) \quad (A-1)
\]

where

\[
P(C, p, R) = (1 - R) + \frac{R^n (R_p)^C}{n!} \quad (A-2)
\]

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