A Framework Design for the Next-Generation Radio Access System

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***Abstract*—Extensive use of the Internet and huge demands for multimedia services via portable devices require the development of packet-based radio access systems with high transmission efficiency. Advanced radio transmission technologies have recently been proposed to achieve this challenging task. However, few researches have been reported on the design of an integrated system that can efficiently exploit the advantages of these transmission technologies. This paper considers the design of a packet-based cellular system for next-generation radio access. We propose a novel system framework that can incorporate various advanced transmission technologies such as link adaptation, opportunistic packet scheduling, channel coding, and multiantenna techniques. For efficient use of these technologies together, we first investigate the interoperability between these technologies by proposing a so-called *cause and effect analysis*. Based on this investigation, we design a differentiated-segments-based orthogonal frequency-division multiplexing system, called *DiffSeg*, to accommodate heterogeneous operating conditions in a seamless manner. Simulation results show that the proposed DiffSeg system can provide a nearly optimum performance with flexible configuration in a wide range of wireless channel conditions.**

***Index Terms*—Air-interface, orthogonal frequency-division multiplexing (OFDM) system, seamless operation.**

I. Introduction

MASSIVE USE OF the Internet has forced worldwide use of the Internet protocol (IP)-based networks to be indispensable. With the increasing use of IP networks, many efforts have been made to enhance the operation of IP such as quality-of-service (QoS) architecture, IPv6, and mobile IP. As a consequence, the IP network has become one of the most promising candidates for future core mobile networks. In fact, ITU-R WP8F envisaged in [1] that future networks for the next-generation [further noted as fourth-generation (4G)] system will include a variety of potential interworking access systems [e.g., second-generation (2G) mobile, IMT-2000, wireless local area network (WLAN), and wireline broadband access] based on an all-IP-based core network. Therefore, air interface for the 4G mobile access system should be designed with a *pure* packet-based approach to meet these network requirements [3].

A number of researches have been reported on the design of packet-based air interface. The cdma2000-1xEvDO system is the one that can coexist with conventional cdma2000-1x networks [4]. It employs a proportional fair (PF) packet scheduler to provide increased spectral efficiency, as well as user fairness for data services [5]. The user data is adaptively modulated and encoded according to the channel condition, and then transmitted in a packet mode using a time-division multiplexing (TDM) method. A hybrid automatic repeat request (HARQ) technique is also employed in combination with adaptive modulation with coding (AMC) for further performance improvement. Since it is only optimized for data services, it may not be suitable for other types of traffic such as voice or traffic with heterogeneous QoS requirements.

Orthogonal frequency-division multiplexing (OFDM) is known as one of the best transmission techniques in broadband wireless environments. It was applied to WLAN systems such as IEEE802.11a [6] for high-speed data services in fixed wireless environments. However, since these systems employ media access control (MAC) of a carrier sense multiple-access/collision avoidance (CSMA/CA) type, they do not fully exploit the efficient sharing of multiuser resources with the use of centralized control. Flash OFDM employs an OFDMA technique and an IP-centric structure for efficient sharing of resources and core networks [7]. It adopts a fast frequency hopping (FH) technique to provide performance robust to fading and interference, while supporting a single frequency network. However, it still does not fully utilize the wireless channel resources due to the nature of FH-based homogeneous air-interface structure. NTT DoCoMo proposed an OFDM-based 4G system, called variable spreading factor-orthogonal frequency code-division multiplexing (VSF-OFCDM), in combination with multicarrier CDMA (MC-CDMA) [8]. It can adaptively accommodate isolated-cell or multicell environments with a single air-interface structure. It employs a two-dimensional spreading technique, where the spreading factor and domain are adaptively changed in time- or frequency-domain according to the channel environment. Except for the adaptive spreading technique, it rather adopts a single combination of transmission technologies such as the AMC, HARQ, maximum-likelihood (ML) detection with QR decomposition and M-algorithm, and MC-CDMA.

Recently, significant efforts have been made to design packet-based mobile access systems for the 4G radio network. However, most of the efforts have been concentrated on the enhancement of core transmission technologies such as multi-input–multi-output (MIMO) antenna, link adaptation with AMC or HARQ, opportunistic packet scheduling, and channel coding techniques. Although these techniques have been developed to an acceptable level, they still have perfor-

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mance variation problems associated with operating conditions. Moreover, some techniques may not work well with other techniques, yielding undesired performance. On the other hand, a certain combination of these technologies work very well, yielding a synergy effect. Therefore, access systems should be designed to utilize these technologies in a constructive manner. For this purpose, we need to carefully investigate the interoperability between these technologies, taking account of their strengths and weaknesses.

In this paper, we consider a packet-based wireless access system that can provide data transmission rates of up to several hundred megabytes per second in various operating environments, envisaged in [2]. We consider the design of a radio access system that can seamlessly support both real-time (RT) and nonreal-time (NRT) traffic, and can also support universal frequency reuse (i.e., single frequency network) in mobile environments. To facilitate the design process, we first analyze the interoperability of advanced core technologies for wireless packet transmission, and then present a design approach. As a design example, we propose a novel system framework that can efficiently integrate various advanced transmission technologies to support seamless operation in a wide range of operating conditions. Finally, the performance of the proposed system is verified by computer simulation.

II. Interoperability Analysis

There are too many possible combinations of core transmission technologies for the 4G system, making it impractical to thoroughly investigate the interoperability between these core technologies. For ease of investigation, we set up a design criterion based on so-called *cause and effect* analysis. We first consider the fundamental causes that significantly affect the performance of these core technologies in wireless environments. By examining the causality of the fundamental cause on each transmission technology, we can efficiently clarify their interoperability in terms of the synergy effect.

Since the wireless is the most influencing term in radio access systems, we first define the wireless channel as a fundamental cause. Radio propagation is often characterized by three independent phenomena; path-loss attenuation, slow log-normal shadowing and fast multipath fading [9]. The path-loss and shadowing effect can be considered as location-dependent factors, and the multipath fading as a time-dependent factor since the signal quality is highly time-variant in multipath fading channels. Thus, we consider location-dependent and time-dependent signal characteristics as the major causes of the wireless channel.

A. Location-Dependent Signal Characteristics

The quality of location-dependent signals mainly depends on the distance between the base station (BS) and the mobile station (MS). It can also be affected by environmental factors such as building structures and foliage. We investigate the *location-dependent effect* for the clarification of interoperability between core transmission technologies.

1) Other-Cell Interference (OCI): The dynamics of OCI can significantly be affected by the distance between the BS and the MS. The instantaneous carrier-to-interference ratio (CIR) can be expressed as

$$\gamma_{\text{CIR}} = \frac{G(d_0)P_0}{\sum_{i=1}^{B} G(d_i)\chi_i P_i} \tag{1}$$

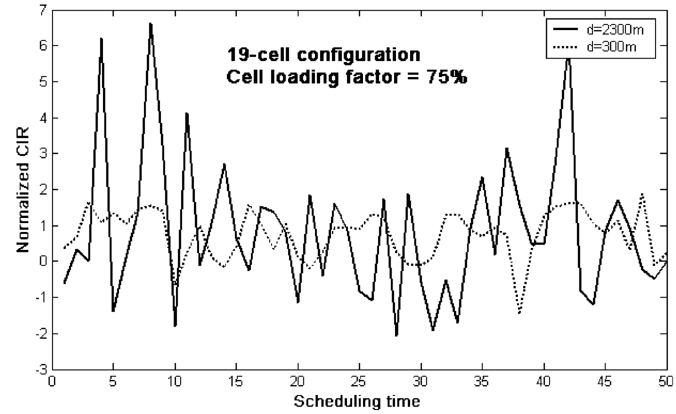


Fig. 1. Snap shot of instantaneous CIR with different distance d.

where B, d_i, and P_i, respectively, denote the number of interfering BS's, distance, and transmit power, χ_i is a random variable indicating the cell loading result of the ith BS, and $G(d)$ represents the amount of power attenuation at distance d from the BS. Here, we assume that the target user is in service by the BS in the zeroth cell (i.e., $i = 0$) and that the background noise can be ignored in interference-limited environment. Note that χ_i can be approximated as a Bernoulli random variable taking a value of 1 with probability λ_i representing the loading factor of the ith BS. Fig. 1 depicts the instantaneous CIR normalized with respect to its average CIR as a function of the normalized scheduling time (i.e., the time instant normalized with respect to the resource allocation interval) when $d = 300$ and 2300 m, corresponding to the users in the cell center and boundary area, respectively. It is assumed that there are 19 hexagonal cells with a same cell radius of 2.5 km, where all the BSs have the same transmission power and frequency band with a loading factor of 0.75. Here, we also assume that the signal power from the target cell is kept steady during the scheduling interval. It can be seen that the CIR near the cell boundary shows larger variation than near the cell center because the user near the cell boundary is mostly affected by one or two BSs nearby, making it difficult to accurately estimate the instantaneous interference. Therefore, it may not be easy to employ an opportunistic scheduling or fast AMC scheme that needs accurate instantaneous CIR information. Instead, it may be useful to employ an OCI averaging scheme that can smooth out the interference variation.

2) Channel Delay Spread: Multipath fading makes the transmitted signal dispersed into the time-domain. The coherence bandwidth of a fading channel depends on the amount of delay spread. The larger the delay spread, the narrower the coherence bandwidth, yielding a highly frequency-selective fading channel. In this case, it may be desirable to employ frequency diversity schemes that can fully exploit abundant diversity sources in the frequency domain. The root mean squared (rms) delay spread $\widehat{\tau}$ of a fading channel can be approximated as a log-normal random variable [11]. The relationship between the median value $\widehat{\tau}_{\text{med}}$ of the rms delay spread and the distance can be represented as

$$\widehat{\tau}_{\text{med}} = \widehat{\tau}_1 d^{\varepsilon} \tag{2}$$

where $\widehat{\tau}_1$ denotes the median value of the rms delay spread when $d = 1$ km and ε denotes a constant associated with the operating environment (e.g., the urban, suburban, or rural area). It can be seen that the rms delay spread increases as the distance increases, which means that the use of a frequency diversity scheme can be more effective for users near the cell boundary than near the cell center. The effect of frequency diversity becomes substantial as ε increases.

3) Spectral Efficiency: Since multiple user signals are jointly transmitted using different transmission power in the CDMA system, the use of power control is an efficient and simple way for link adaptation, resource management and fading mitigation. The use of advanced transceiver techniques such as enhanced channel estimation and multiuser detection enables the receiver to provide desired performance at a reduced signal-to-interference ratio (SIR) condition, thus increasing the system capacity. For example, consider the use of an improved transceiver that requires an SIR 3 dB less than the conventional one for the same bit-error rate (BER). Then, we can approximately double the number of users in service.[1] However, this fact does not hold in a packet-based system because the link adaptation is performed based on the rate adaptation, not on the power control.

In the packet-based system, the spectral efficiency C can be expressed as

$$C = \log_2(1 + \eta \cdot \gamma) \tag{3}$$

where η denotes a system loss factor due to implementation. It can be seen that the spectral efficiency roughly increases by 1 b/s/Hz if the SIR increases by 3 dB when $\eta\gamma \gg 1$.

Proposition: For a given $\zeta > 0$, it can be shown that

$$\frac{\log_2(1+\eta\zeta\gamma_1)}{\log_2(1+\eta\gamma_1)} > \frac{\log_2(1+\eta\zeta\gamma_2)}{\log_2(1+\eta\gamma_2)} \tag{4}$$

where $\gamma_1 < \gamma_2$.

Proof: Let $T(z) = \log_2(1+z)$. Then, $T(z)$ is a monotonically increasing function of z and its derivative $T'(z)$ is a monotonically decreasing function. Thus, it can be seen that

$$\begin{aligned}\frac{T(\eta\zeta\gamma_1)}{T(\eta\gamma_1)} &= \frac{T(\eta\gamma_1) + \int_{\eta\gamma_1}^{\eta\zeta\gamma_1} T'_z(z)dz}{T(\eta\gamma_1)} \\ &= 1 + \frac{\int_1^{\zeta} T'_t(\eta\gamma_1 t)dt}{T(\eta\gamma_1)} > 1 + \frac{\int_1^{\zeta} T'_t(\eta\gamma_2 t)dt}{T(\eta\gamma_2)} \\ &= \frac{T(\eta\gamma_2) + \int_{\eta\gamma_2}^{\eta\zeta\gamma_2} T'_z(z)dz}{T(\eta\gamma_2)} = \frac{T(\eta\zeta\gamma_2)}{T(\eta\gamma_2)} \end{aligned} \tag{5}$$

where $T'_z(\cdot)$ and $T'_t(\cdot)$ denote the derivative of T with respect to variables z and t, respectively. □

Fig. 2 depicts the normalized spectral efficiency defined by $T(\zeta \cdot \gamma)/T(\gamma)$ as a function of SIR, where ζ denotes the amount of SIR improvement. It can be seen that the performance improvement due to the SIR improvement is not noticeable when the SIR is high, but it is significantly large when the SIR is low. This implies that the use of improved transceiver algorithms may not be effective for users in a good environment where the spectral efficiency is already near the saturated region of the logarithmic-shaped performance curve. In this case, it may be rather wise to increase the system capacity by employing a parallel transmission scheme such as spatial multiplexing (SM) techniques (e.g., singular value decomposition (SVD) [12] and Bell Lab layered space–time coding (BLAST) [13] schemes). On the other hand, the use of enhanced transceiver algorithms can lower the required SIR, which might be quite effective for users in the cell boundary area. Spatial diversity (SD) techniques (e.g., space–time block coding (STBC) and space–time trellis coding (STTC) schemes) can provide the array gain (using multiple receive antennas), as well as the spatial diversity gain, considerably reducing the required SIR.

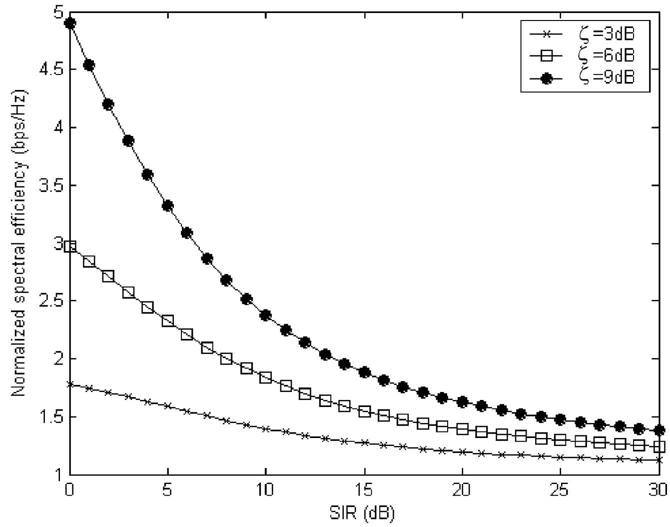


Fig. 2. Normalized spectral efficiency due to SIR improvement.

4) Link Adaptation: In CDMA-based cellular systems, link adaptation can be achieved by controlling the transmit power in a channel-inversion manner so that the SIR is maintained to guarantee the required BER. Although the power control can mitigate the fast fading effect, it may be contradictory to Shannon's theory that suggests the allocation of more power to users in better conditions for the maximization of channel capacity. In fact, it was shown that the use of power control could be worse than the use of rate adaptation [20]. Thus, most of the packet-based wireless systems consider the use of rate adaptation for the link adaptation. Two types of rate adaptation schemes, AMC and HARQ, are often employed considering the implementation.

The AMC scheme adapts the rate by adjusting the modulation level and coding rate according to the channel condition. The performance of AMC can significantly be degraded in the presence of channel estimation error and/or measurement delay. Thus, the use of AMC may not be efficient in high-speed mobile environments where the channel estimation accuracy suffers from large measurement delays, or in cell boundary environments where accurate channel estimation is impractical due to large interference.

[1]This argument holds in the uplink. In the downlink, however, the capacity may not be doubled exactly due to the orthogonality factor.

The HARQ scheme can also support the rate adaptation by means of retransmission. It combines the channel coding and ARQ to make retransmissions more reliable [21]. The use of HARQ with chase combining (CC) or incremental redundancy (IR) techniques enables the receiver to softly combine the previous packets in decoding failure with new packets in an ML decoding manner. It adapts the effective code rate according to the channel condition using acknowledgment (ACK) signaling. Since the HARQ does not require the CSI at the transmitter, it can provide stable performance even in the presence of channel measurement error. However, since it involves a large latency due to the retransmission, it may require careful consideration when applying to the transmission of delay-constrained traffic. This problem can be alleviated by carefully designing the signal timing offset between the uplink ACK and downlink traffic channel in the frequency-division duplex (FDD) system. In practice, the number of retransmissions should be adjusted by taking account of the maximum allowable delay requirement of the traffic.

B. Time-Dependent Signal Characteristics

Multipath fading, also called small-scale fading, is largely classified into two types, Rayleigh and Rician fading, depending on the existence of a line-of-sight (LOS) path. Packet-based wireless systems often handle the fading problem in two approaches; fading mitigation and the fading exploitation.

1) Fading Mitigation Approach: Conventional cellular systems usually mitigate the fading by using diversity and/or power control techniques. A packet-based OFDM system may not utilize the temporal diversity because it transmits the packet data in a burst mode for a short-time interval. Instead, it can utilize the frequency-domain as the main diversity source. When the OFDM system uses multiple antennas, it can additionally achieve a spatial diversity effect by employing an SD technique. Since the diversity gains achieved from each domain are mutually multiplicative, it is desirable to utilize the diversity sources from as many domains as possible.

FH and code-division multiplexing (CDM) techniques are widely employed to obtain a frequency diversity gain. Since they can also provide an interference-averaging effect, they are quite useful for users near the cell boundary. However, they provide the diversity gain in a different manner. The FH needs powerful channel coding to combine multiple symbols spread in the frequency-domain. Thus, it may not easily achieve a large frequency diversity gain with the use of high rate codes. On the other hand, the CDM spreads the symbols in the frequency-domain using orthogonal spreading codes. It can achieve the frequency diversity gain from inherent despreading processes. However, it may suffer from a so-called intercode interference (ICI). The user location can also affect the performance of FH and CDM. When a low-level modulation is used in the cell boundary area, the CDM can outperform the FH with the use of high rate codes [22]. The CDM can also efficiently smooth out the OCI effect regardless of the channel coding, yielding a synergy effect for the operation in the cell boundary area. However, when a high-level modulation is used in the cell center area, the performance of CDM is significantly limited by the ICI, becoming inferior to that of FH [23].

2) Fading Exploitation Approach: The packet-based wireless system transmits the user data in a burst mode when the channel condition is at a local peak, enabling the improvement of spectral efficiency. As the number of users increases, the probability of users in good channel condition increases as well. Consequently, as the number of users increases, fading exploiting schemes can increase the multiuser diversity (MUD) gain, achieving a spectral efficiency higher than the fading mitigation scheme and even higher than that in a static channel with the same average CIR [24]. Thus, the opportunistic scheduling technique plays a key role in the fading exploitation approach.

Consider a TDM system where N users have the same average SIR by slow power control in a flat Rayleigh fading channel. The channel vector can be represented as

$$\mathbf{\Gamma} = \bar{g}[\gamma_1 \quad \gamma_2 \quad \gamma_3 \quad \cdots \quad \gamma_N]^T \tag{6}$$

where $\bar{g}$ denotes the average CIR and γ_n denotes the instantaneous CIR of the nth user, which can be approximated as an independent and identically distributed exponential random variable with probability density function (pdf) $f_\gamma(z) = e^{-z}$ [9]. The average spectral efficiency of the system can be expressed as

$$\Lambda = E\left\{\log_2\left(1 + \eta\bar{g} \max_{i=\{1,\ldots,N\}}\{\gamma_i\}\right)\right\}. \tag{7}$$

By Jensen's inequality, it can be shown that

$$\begin{aligned}\Lambda &\le \log_2\left(1 + \eta\bar{g}E\left\{\max_{i=\{1,\ldots,N\}}\{\gamma_i\}\right\}\right)\\ &= \log_2\left(1 + \eta\bar{g}\sum_{k=1}^{N}\frac{1}{k}\right).\end{aligned} \tag{8}$$

Thus, the MUD gain can be considered as an SIR improvement by a factor of $\sum_{k=1}^{N} k^{-1}$, which is significantly noticeable when the CIR is low. However, it may be a challenging task to use the opportunistic scheduling in the cell boundary area because of large OCI fluctuation and inaccurate channel measurement. Moreover, the MUD gain can noticeably be diminished in the presence of delay due to the channel measurement and/or feedback signaling (e.g., in high mobility environment).

In the presence of delay, the channel gain of a scheduled user at the transmission time can be represented as

$$\tilde{\alpha}_{n_Q} = \rho\alpha_{n_Q} + \sqrt{1-\rho^2}\alpha_\delta \tag{9}$$

where $\alpha_{n_Q}\alpha_{n_Q}^* = \max_{i=\{1,\ldots,N\}}\{\gamma_i\}$, α_δ is a zero-mean complex Gaussian random variable with $E\{\alpha_\delta\alpha_\delta^*\} = 1$, and ρ denotes the correlation coefficient of the channel gain. By Jake's model [9], ρ can be represented as

$$\rho = J_0(2\pi f_d \tau)$$

where $J_0(\cdot)$ is the zeroth order Bessel function of the first kind, f_d is the maximum Doppler frequency, and τ denotes the amount of time delay between the time instant of channel measurement and transmission. Thus, it can be shown that

$$\begin{aligned}\Lambda &\le \log_2\left(1 + \eta\bar{g}E\left\{\tilde{\alpha}_{n_Q}\tilde{\alpha}_{n_Q}^*\right\}\right)\\ &= \log_2\left(1 + \eta\bar{g}\left\{1 + \rho^2\sum_{k=2}^{N}k^{-1}\right\}\right).\end{aligned} \tag{10}$$

Thus, the MUD gain is directly associated with the Doppler frequency and channel measurement delay. Note that (10) is derived assuming perfect rate adaptation, which may not be achievable in practice. This implies that the user mobility can seriously deteriorate the performance of opportunistic scheduling and rate adaptation.

The MUD gain is closely related to the tail probability of γ_i since the system throughput is directly associated with the largest value of γ_i. Thus, the MUD gain essentially benefits from large signal fluctuation. Since fading mitigation schemes are incompatible with fading exploitation schemes, it is desirable to reduce the link-level diversity when an opportunistic scheduling scheme is employed.

C. Consideration on the Interoperability

Investigation on the *location-dependent effect* elucidates that the user location could be the most influencing factor affecting the efficiency of core transceiver technologies. It was shown that some core technologies are very effective in the cell center area, while some others are effective in the cell boundary area.

Consider the signal transmission to users in the cell center area. It was shown that the amount of channel delay spread increases in proportion to the distance between the BS and the MS. Thus, the use of diversity techniques may not be effective in the cell center area where the channel delay spread is not relatively large. In addition, the use of interference-averaging schemes may not be effective in this area where the OCI effect is not significant. This suggests that the use of FH or CDM techniques may not provide noticeable performance improvement in this area. Instead, the use of an opportunistic scheduling technique may be effective by achieving a large MUD effect from large signal fluctuation. The use of the AMC technique may also be useful for fine rate adaptation because the CIR can be estimated accurately in this area. Shannon's channel capacity theory implies that the spectral efficiency may not be increased by the SIR improvement. Since the SIR is high enough in this area, it may be useful to increase the overall capacity by employing a parallel transmission scheme such as the SM scheme, rather than improving the SIR. Although the SM scheme does not provide spatial diversity effects, it can provide a synergy effect when combined with an opportunistic scheduling scheme.

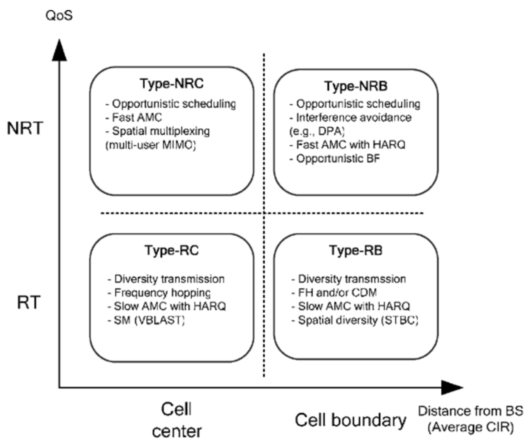
Next, consider the signal transmission to users in the cell boundary area. The signal transmission is affected by high frequency selective fading characteristics due to large channel delay spread in this area. Thus, the use of diversity techniques may be effective in this area. The use of interference averaging schemes may also be effective in this area where the OCI is highly time-varying. As a result, the use of an opportunistic scheduling technique may not be effective with the use of diversity and interference averaging techniques. Besides, large CIR estimation errors may significantly degrade the performance of opportunistic scheduling, as well as the performance of AMC. This problem can be alleviated by using an HARQ technique that can work without explicit channel information. Unlike in the cell center area, the system capacity can be enhanced by improving the CIR in this area. Thus, it may be desirable to employ a multiantenna technique that can provide a large link-level diversity effect.

Investigation on the *time-dependent effect* suggests that the fading effect is the major factor for the improvement of transceiver performance. The fading exploitation scheme treats the fading as an opportunity for the improvement of spectral efficiency, while the fading mitigation scheme just reduces the fading effect to provide robust performance. It is required for the transmission of RT traffic to consider the QoS, as well as the channel condition. Thus, fading exploitation techniques may not easily be applicable to the RT traffic because of the latency involved in the opportunistic scheduling. Rather, it may be desirable for the RT traffic to employ a diversity scheme that can guarantee average performance in various fading conditions. On the other hand, when the channel variation is rather slow, the use of a fading exploitation scheme can be effective for the transmission of traffic that does not require strict transmission latency. If the channel condition cannot be exploited appropriately, the use of fading mitigation scheme may be better than the use of fading exploitation scheme. Thus, it is desirable to employ a scheme that can adaptively employ a proper fading handling technique according to the operating condition.

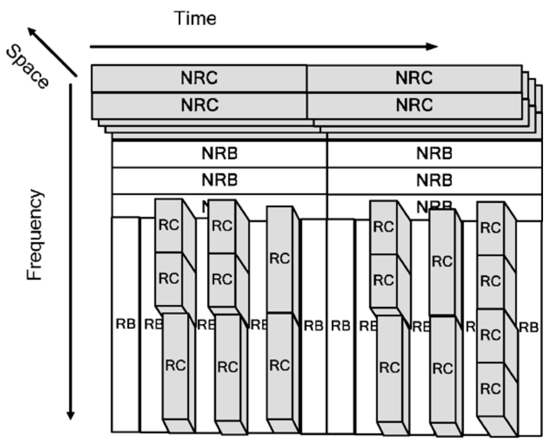
III. Design of a Packet-Based Wireless Access System

Next-generation mobile access systems should be able to support heterogeneous multimedia traffic with various types of QoS, and to provide high system capacity in a single frequency network. To meet these requirements, the system framework should be designed to utilize these core technologies in various operating conditions in a seamless manner. From the aforementioned *cause and effect* analysis, it was shown that the use of a single combination of transmission technologies might not be sufficient to cover up a wide range of operating conditions. It was also shown that the user's location and traffic types were the most influencing factors requiring different combinations of transmission technologies.

Based on the interoperability analysis, we propose an OFDM-based multiple access wireless system, called *DiffSeg*, that can accommodate various operating requirements by using differentiated segments in a seamless manner. We define the *segment* by a basic transmission unit comprising $(N_t \times N_f)$ modulation symbols in two-dimension, where N_t and N_f are the number of OFDM symbols and subcarriers in each dimension, respectively. Note that the subcarriers in each segment are not necessarily concatenated since they can be chosen arbitrarily for a special purpose such as FH. As an example, Fig. 3 illustrates a basic structure of the DiffSeg system that considers the use of four differentiated segments for the ease of implementation. Four segments are for the NRT traffic near the cell center (NRC), NRT traffic near the cell boundary (NRB), RT traffic near the cell center (RC), and RT traffic near the cell boundary (RB). Each segment utilizes different combinations of transmission technologies. The proposed DiffSeg can accommodate the best combination of transmission technologies in a seamless manner by means of segment differentiation associated with the operating environment. Fig. 3(b) illustrates an example of the corresponding resource map of the traffic channel, where each segment has a different configuration for proper accommodation of the associated transmission technologies.



(a) Differentiated segments



(b) Resource map

Fig. 3. A design example of the proposed DiffSeg system.

A. *Differentiated Segments for Traffic Channel*

1) Type-NRC Segment: The type-NRC segment is for the transmission of NRT traffic in the cell center area where the channel condition is good. The opportunistic scheduling can be employed in this segment since the SIR can be estimated accurately and the transmission latency is not important. In addition, it is also possible to transmit the signal in parallel to increase the system capacity by employing an SM scheme such as the VBLAST. To fully exploit the MUD gain, this segment comprises a small number of subcarriers and occupies only a single spatial subchannel as illustrated in Fig. 3(b). Thus, it can be possible to provide a large amount of signal gain fluctuation in the time domain. Since the segments of this type are distinguishable in the spatial domain, they can maximize the MUD gain using a multiuser MIMO technique [18]. It is desirable to employ a multiuser MIMO scheme that can provide the MUD and spatial multiplexing gain simultaneously. Such a scheme was recently proposed by collaboratively combining the opportunistic scheduling and spatial multiplexing scheme using multiple random beams [19]. As mentioned before, this type segment does not consider the use of a diversity scheme such as FH and CDM, which is incompatible with the opportunistic scheduling.

Each segment needs to have a certain amount of symbols to achieve a desirable coding gain. Thus, this type segment has a large N_t due to the use of a small N_f value. This may cause the increase of the loop latency with the use of HARQ. However, this issue may not be serious unless the HARQ plays an important role. When accurate CIR information is available, the proposed DiffSeg can achieve desired rate adaptation by employing an AMC scheme without heavily relying on the HARQ. However, when the user mobility is high (i.e., the CIR estimate is inaccurate) it may not be practical to use an opportunistic scheduling technique even in this type segment. This issue may suggest further consideration of additional parameters such as the user's mobility and power allocation for the segment differentiation, in addition to the two aforementioned major parameters (i.e., the traffic type and channel condition).

2) Type-RC Segment: The type-RC segment is mainly for the transmission of RT traffic in the cell center where the channel condition is good. Since the RT traffic requires deterministic (or regular) transmission opportunities to meet the latency requirement, fading exploitation techniques may not be applicable to this type segment. Instead, we consider the use of fading mitigation techniques. To fully exploit the frequency diversity, the transmission symbols are spread into the whole frequency band in combination with FH. Thus, this type segment has a structure with a large N_f, as shown in Fig. 3(b). An SD scheme can be employed to obtain an additional spatial diversity. However, it may be preferable to employ an SM scheme that can provide parallel spatial subchannels because the transmission performance is nearly in the saturation region due to good channel condition. Unlike the type-NRC segment, it may be desirable to allocate all the spatial subchannels to a single user to obtain additional spatial diversity, making up the lack of frequency diversity sources available in the cell center area. Thus, this type segment has a three-dimensional (3-D) structure, as shown in Fig. 3(b).

Slow AMC can be employed to adjust the data rate in response to large-scale variation due to the path loss and shadowing. It can be combined with diversity techniques that can mitigate the signal gain fluctuation due to fast multipath fading. The HARQ can be applied to the RT traffic for fast recovery of errors due to residual signal gain fluctuation after imperfect diversity processing. In practice, the HARQ can also be useful for fine rate adaptation to minimize the portion of resources occupied by the RT traffic. Considering the latency requirement for the RT traffic, this type segment should have a small N_t to minimize the retransmission latency with the use of HARQ.

3) Type-NRB Segment: The type-NRB segment is for the transmission of NRT traffic in the cell boundary area where the channel condition is poor. Although the opportunistic scheduling can improve the performance for the NRT traffic, it may not be effective when combined with an interference-averaging scheme such as FH and CDM. Therefore, it is desirable to use an interference-avoidance scheme (e.g., dynamic packet assignment [25]) to fully exploit the advantages of opportunistic scheduling. This type segment can employ an opportunistic beamforming (BF) technique [26] that can provide an interference nulling effect as well as the MUD gain. However, the opportunistic BF technique can provide high-spectral efficiency only when the number of users is large. The transmission strategy for this type segment may need further study for optimization.

TABLE I
BASIC SYSTEM PARAMETERS

Parameters	
Carrier frequency	5.8 GHz
Bandwidth	100 MHz
FFT duration	20.48usec
CP duration	5 μsec (500 sample)
Number of sub-carriers	2048
Tolerable frequency synchronization error	0.16 ppm
Modulation	Up to 64QAM

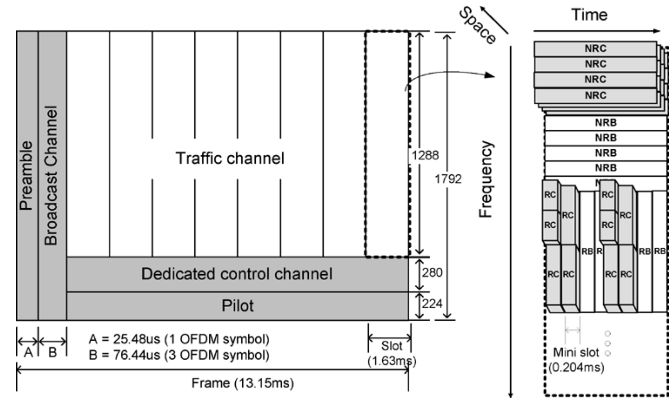


Fig. 4. Frame structure of the designed DiffSeg system.

4) Type-RB Segment: The type-RB segment is for the transmission of RT traffic in the cell boundary area where the channel condition is poor. The segment structure is similar to that of the type-RC segment since the principle transmission strategy is to mitigate the fading effect. Since the CIR improvement is important in the cell boundary area, the use of SD is preferred to that of SM. In addition, the CDM can improve the transmission performance by providing a large amount of frequency diversity and interference-averaging effect. The link adaptation strategy can be designed in a similar manner to that of the type-RC segment.

B. Design of a DiffSeg System

The DiffSeg concept can be applied to OFDM-based wireless access systems. We consider the design of an FDD-based DiffSeg downlink system. The basic system parameters are summarized in Table I, which can be considered as typical system parameters for the next-generation radio access system [2]. With the use of 100 MHz bandwidth, it is suggested to provide a peak data rate of up to 1 Gb/s with the use of a MIMO configuration in fixed wireless and nomadic environment. Since the frequency band is expected to be allocated below 6 GHz, we consider the use of 5.8 GHz carrier frequency as a conservative design. The length of cyclic prefix (CP) for the OFDM signaling is set to 5 μs to support the channel delay spread even in macrocell environment. The FFT duration is set to 20.48 μs, resulting in 19% CP redundancy. Note that the OFDM symbol duration is minimized to support a large Doppler frequency, while taking the CP redundancy into account. For possible QPSK transmission even in the worst Doppler condition, the maximum Doppler frequency normalized with respect to the OFDM symbol duration is set to 0.07.[2] This enables signal transmission to users in a movement of up to 600 km/h. It is important for the design of an OFDM system to check out the feasibility of frequency synchronization requirements. The SNR loss can be calculated as a function of frequency offset normalized with respect to the subcarrier spacing [27]. Unless the normalized frequency offset exceeds $10^{-1.7}$, the SNR loss due to the frequency synchronization error is less than 0.1 dB for QPSK (at 10 dB SNR), and 1.0 dB even for 64-QAM (at 22 dB SNR). This requirement corresponds to a maximum frequency synchronization error of 0.16 ppm with respect to the BS, which may easily be achievable considering a maximum allowable error of 0.1 ppm in the 3G cellular system. Note that the use of an FDD scheme enables fast signaling exchange between the BS and the MS.

Fig. 4 illustrates the frame structure of the designed DiffSeg system. The frame comprises 1792 subcarriers with a duration of 13 ms, comprising a preamble, broadcast, pilot, dedicated control, and traffic channel. The preamble channel is mainly for the purpose of initial synchronization and cell search. The dedicated control channel (DCC) transmits the control information such as the resource assignment, uplink acknowledgment, and AMC parameters. Note that the DCC is separated from the traffic channel in an FDM manner to enable fast signaling exchange between the BS and MS. The DCC signal is transmitted using a low-level modulation with FH for reliable transmission. The traffic channel consists of eight slots comprising 1288 subcarriers. Each slot is divided into eight mini-slots and comprises four different types of segments unlike in conventional packet-based systems. Since the type-NRC and -NRB segments do not use FH, they are allocated at a fixed frequency position, while occupying the whole slot time. On the other hand, the type-RC and -RB segments employ fast FH on a symbol-by-symbol basis, while occupying a mini-slot time interval. In fact, the slot and mini-slot can be considered as a basic unit for the packet scheduling of NRT and RT traffic, respectively.

We consider the use of M_T antennas in the BS and M_R antennas in the MS. Since the type-RC segment can have M_R spatial layers in parallel (assuming $M_T \geq M_R$), it can also have different 3-D shapes according to the number of MS antennas. Note that the type-NRC segment can always have M_T spatial sublayers regardless of M_R by employing a multiuser MIMO technique such as the multiuser diversity and multiplexing (MUDAM) in [19]. Fig. 5 depicts the transmitter structure of the designed DiffSeg system. Each type segment can be allocated to different subcarriers, making it possible to easily adopt different technologies as in the MIMO-OFDM system.

The DiffSeg system can have a MAC-layer structure similar to a conventional packet-based cellular system except for the protocol related to the control and management of four different types of traffic segments. The segment type is mainly determined by the traffic type and user's location (or channel condition). For better determination, the BS can consider additional parameters such as the number of antennas, mobile speed, and antenna correlation. To change the segment type,

[2]This value is deduced assuming that the ICI power does not exceed 10% of the total noise power level.

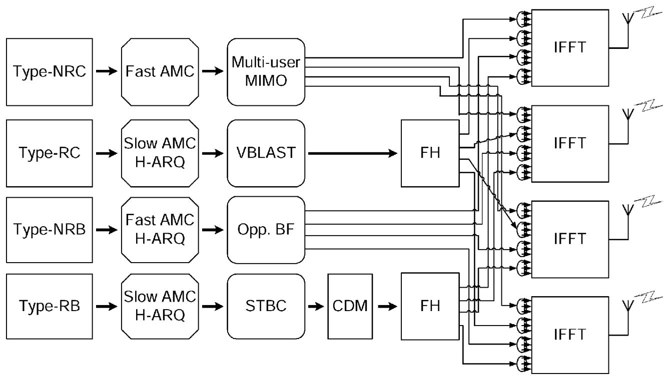


Fig. 5. Basic structure of the designed DiffSeg transmitter.

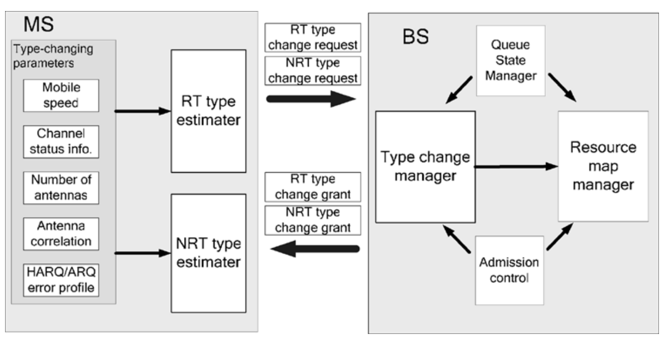


Fig. 6. Mobile-assisted classification of the segment type.

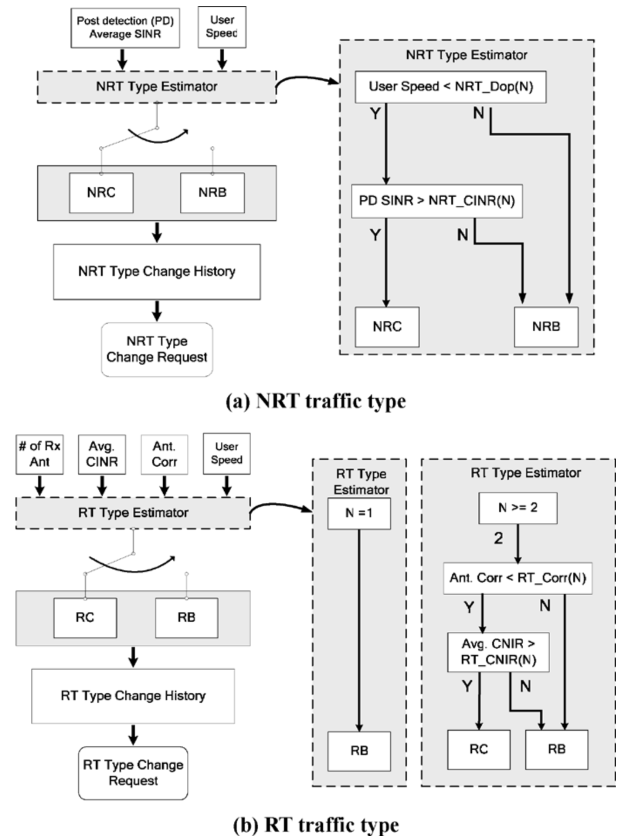


Fig. 7. Identification of the segment type.

the BS needs a large amount of information from the MS, which may require a heavy feedback signaling burden. To alleviate this problem, we consider the use of a mobile-assisted method for the change of segment type, as illustrated in Fig. 6. The MS first determines whether the segment type needs to be changed by estimating the related parameters. If necessary, the MS requests a type-change to the BS through the uplink control channel. The BS makes a final decision on the change of segment type by taking account of the transceiver status such as the queue status of each segment, user priority, cell load, and resource map. Finally, the BS notifies an admission to the MS through the broadcast channel.

Fig. 7 illustrates the procedure for the identification of segment type in the MS. The MS can identify the NRT-type traffic based on the average SINR and user's mobility information available from the CSI estimator. The MS can make unnecessarily frequent changes of the segment type, which can be alleviated by using a hysteresis-type decision rule. Note that the type-NRC segment employs the opportunistic scheduling and multiuser MIMO techniques which are sensitive to the user's mobility. If the user's mobility is high, the NRT traffic is classified as a type-NRB segment. For the RT-type traffic, all the spatial sublayers are assigned to a single user in order to obtain the SD effect, as shown in Fig. 7(b). Thus, the number of spatial sublayers is equal to the number of receiver antennas if $M_T \geq M_R$. The type RC segment can provide multiple spatial sublayers with the use of a VBLAST or double space–time transmit diversity (D-STTD) scheme [28] for users equipped with multiple receive antennas. Users equipped with a single receive antenna are always classified as a type-RB segment. The performance of a single-user SM technique can seriously be degraded in the presence of antenna correlation. This factor should be taken into account for the identification of RT traffic.

Fig. 8 shows the segment allocation structure in the DiffSeg system, where each segment type has its own queue. The master scheduler stores the user packet into an appropriate queue. The data in each queue is handled by a packet scheduler optimized for each segment type. However, the user packet in a queue can be dropped out due to an overflow caused by a temporary load unbalancing. To avoid this problem, the DiffSeg employs a type-change manager that adjusts the load between the segments based on the queue state information. However, when the load is seriously unbalanced, the resource map manager in the BS needs to change the resource map based on the load distribution. The change of resource map is notified to all the users through the broadcast channel. Since the resource map is not changed in a short time interval, the amount of additional signaling burden for the change of the resource map is negligible compared to the whole system complexity.

C. Performance Evaluation

To verify the validity of the proposed scheme, we evaluate the performance of a four-segment-based DiffSeg system with (2×2) MIMO configuration in a 19-hexagonal cell configuration environment by computer simulation. We assume that all the base stations use the same frequency band and the users are uniformly distributed in the cell. We consider the use of rate

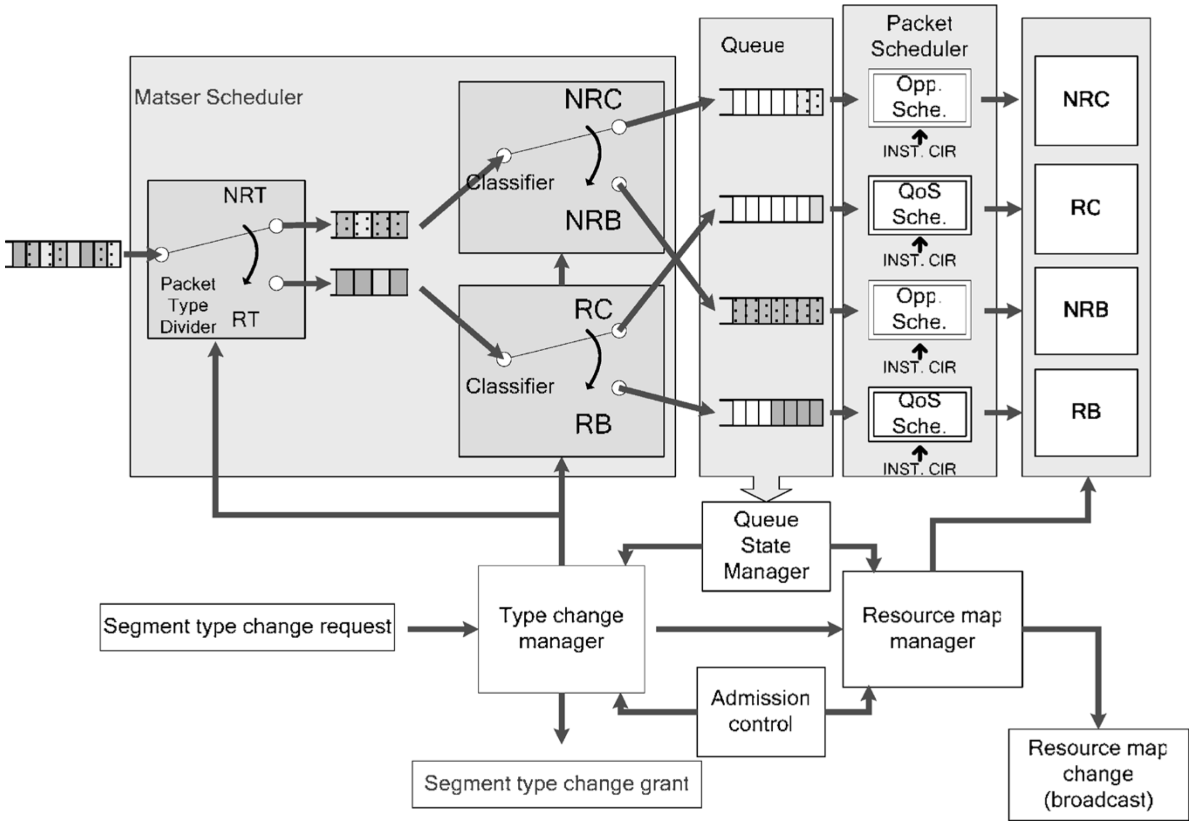


Fig. 8. Segment allocation in the designed DiffSeg system.

TABLE II
AMC PARAMETERS FOR PERFORMANCE EVALUATION

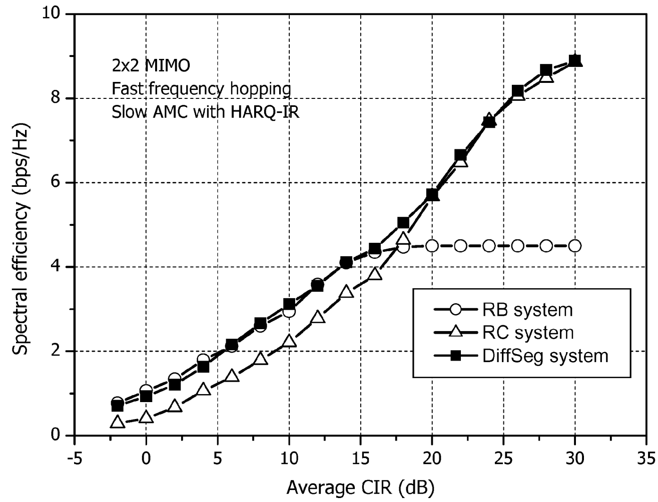
Modulation	*Initial code rate*	*Code block length*	*Max. number of retransmissions for HARQ*		
			NRC	*NRB*	*RC & RB*
QPSK	3/8	336	1	7	3
QPSK	3/4	672	1	3	3
16-QAM	9/16	1008	1	3	3
16-QAM	3/4	1344	1	1	3
64-QAM	5/8	1680	1	1	3
64-QAM	3/4	2016	1	1	3

adaptation based on the AMC and HARQ-IR. The AMC parameters are summarized in Table II. We use a concatenated ZigZag code with a mother code rate of 1/5 as the channel code [29].

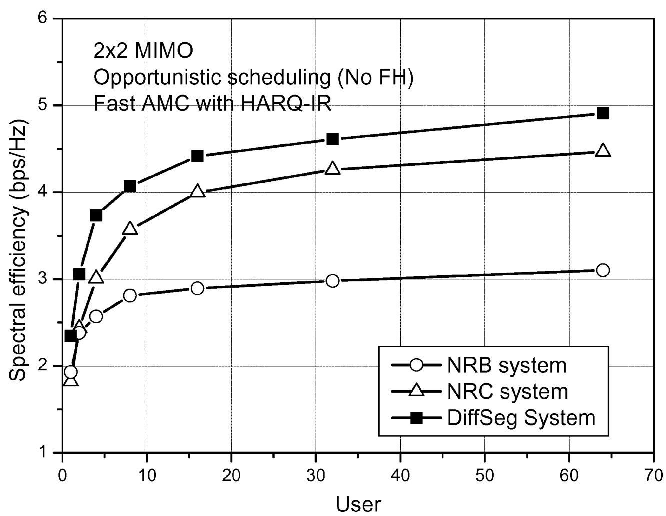
Fig. 9(a) depicts the link-level performance for the RT traffic, when a VBLAST and Alamouti scheme are used in combination with fast FH for the type-RC and -RB segment, respectively. For comparison, we also depict the performance of two systems, respectively, optimized for the type-RC and -RB. These two systems are referred to the RC and RB system, respectively. Note that when a fading mitigation technique is employed, the transmission performance for the RT traffic is not affected by the number of users and instantaneous channel condition. Rather, it is mainly related to the link-level performance associated with the average channel condition. It can be seen that the RC system outperforms the RB system when the CIR is high, and *vice versa*. On the other hand, the proposed DiffSeg system seamlessly provides near optimum performance in a wide range of channel conditions.

Fig. 9(b) depicts the system-level performance for the NRT traffic, when a multiuser MIMO in [30] and an opportunistic BF technique are employed for the type-NRC and –NRB segment, respectively. Note that, unlike for the RT traffic, each spatial layer is allocated to different users to maximize the MUD gain for the type-NRC traffic. The user packet is handled by a PF scheduler and the rate is adjusted by fast AMC and HARQ-IR. The fast FH technique is not employed for the NRT traffic. The segment type NRC and NRB are classified based on the measurement of average CIR. For comparison, we also depict the performance of two systems optimized for the type-NRC and -NRB traffic, referred to the NRC and NRB system, respectively. Note that the NRB system outperforms the NRC system in the cell boundary area and *vice versa*. It can be seen that the system performance improves as the number of users increases. This is mainly due to the MUD effect that provides a larger gain in the NRC system than in the NRB system. It can also be seen that the DiffSeg system uniformly outperforms the two systems each of which employs a single combination of transceiver techniques optimized for each condition.

The simulation results show that the proposed DiffSeg system can easily obtain a synergy effect by applying different core technologies to each segment condition, seamlessly providing near-optimum performance in a wide range of operating conditions. Moreover, new transceiver technologies can easily be applied to the DiffSeg system. For example, the performance for the NRC-type traffic can further be improved with the use of a new MIMO scheme in [19].



(a) Performance of RT traffic



(b) Performance of NRT traffic

Fig. 9. Performance of designed DiffSeg system with 2×2 MIMO.

IV. Conclusion

In this paper, we have considered a new air interface framework design for the next generation mobile access system. For this purpose, we first investigated the interoperability between the core transmission technologies through a so-called *cause and effect* analysis. The investigation elucidates that the user's location (or channel condition) and traffic type are the most influencing parameters on the performance of transmission technologies in location-dependent and time-varying wireless channel environments. Based on this analysis, we have proposed a new air interface framework, called *DiffSeg*, that can accommodate heterogeneous operating environments in a seamless manner. As an example, we have designed a DiffSeg system using four types of differentiated segments associated with two parameters; the user's location and traffic type. It was also shown how core transceiver technologies are combined in a constructive manner in presumed operating environments. The simulation results show that the DiffSeg system can provide better performance in various operation environments than conventional systems that employ a single combination of transmission technologies. The DiffSeg system shows the superiority of the proposed air interface framework approach, in comparison to conventional evolution approaches that consider the use of multiple air interfaces to accommodate heterogeneous operating environments with backward compatibility.

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