Differentiated Segments Based OFDM system for the Next-Generation Radio Access System

June Moon, Jae-Yun Ko and Yong-Hwan Lee
School of Electrical Engineering and INMC, Seoul National University
Kwanak P. O. Box 34, Seoul 151-600, Korea

Abstract—**Extensive use of Internet and huge demand for multi-media services via portable devices require the development of packet-based radio access systems with high transmission efficiency. Various advanced transmission technologies have recently been proposed to achieve this challenging goal. However, few researches have been reported on the design of an integrated system that can efficiently accommodate these transmission technologies. This paper considers the design of a packet-based cellular system for the next-generation radio access. We propose a novel system framework that can incorporate various transmission technologies such as link adaptation, opportunistic packet scheduling, channel coding and multi-antenna techniques. By analyzing the interoperability between these transmission technologies, we design a differentiated segments-based OFDM system, called *DiffSeg*, that can support heterogeneous operating conditions in a seamless manner. Simulation results show that the proposed DiffSeg system can provide near optimum performance in a wide variation of wireless channel condition.**

Index Terms—**4G system, OFDM, Differentiated segment.**

I. INTRODUCTION

Explosive use of Internet access has made worldwide use of Internet protocol (IP) based networks indispensable. In fact, the ITU-R WP8F envisaged in [1] that the future network for the next-generation (we will call 4G) system will include a variety of potential interworking access systems (e.g., 2G mobile, IMT-2000, WLAN and wireline broadband access) based on an all-IP based core network. Thus, air interface for the 4G mobile system should consider the use of *pure* packet-based approach to meet these network requirements.

Orthogonal frequency division multiplexing (OFDM) is known as one of the most promising transmission techniques in broadband wireless environment. It was applied to wireless local area network (WLAN) systems such as HiperLAN2 and IEEE802.11 for high-speed data services in fixed or nomadic wireless environment. Recently, Flash OFDM system has been proposed to support the users even in high-mobility environment [2]. It employs an IP-centric structure with packet-based air interface. It also adopts a fast frequency hopping (FH) technique to provide performance robust to fading and other-cell interference (OCI), enabling a universal frequency reuse. However, it still does not fully utilize the wireless channel resources due to the nature of an 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) [3]. It adopts multi-carrier CDMA (MC-CDMA) as the basic multiple access scheme. It can adaptively accommodate isolated-cell or multi-cell environment with a single air-interface structure that uses an adaptive spreading technique in the time and frequency domain. Due to the nature of a homogeneous transmission structure, however, it may also have performance problem in certain operating condition in spite of using many advanced transmission technologies such as adaptive modulation and coding (AMC), hybrid ARQ (HARQ), and fast cell site selection.

Recently, significant efforts have been devoted to the design of packet-based mobile access systems for the 4G radio network. However, most of efforts have concentrated on the enhancement of core transmission technologies without deep investigation of the interoperability with other core technologies. As a result, some techniques may not work well with other techniques, yielding undesirable performance. Therefore, it is desirable to design an access system that can utilize these technologies in a collaborative manner. For this purpose, it is necessary to carefully investigate the interoperability between these technologies, taking account of their strength or weakness in wireless packet transmission. Based on this investigation, we propose a novel system framework that can support seamless operation in a wide variation of operating conditions, by efficiently utilizing these core technologies. As an example, we design an OFDM scheme, called *DiffSeg*, that utilizes these techniques based on differentiated segments associated with operating condition. Finally, the performance of the designed DiffSeg system is verified by computer simulation.

II. INTEROPERABILITY ANALYSIS: CAUSE AND EFFECT

There are too many possible choices for combined use of core transmission technologies, making it impractical to thoroughly investigate the interoperability between these core technologies. For ease of investigation, we propose a design criterion based on so-called *cause and effect* analysis. We first consider fundamental causes significantly affecting the performance in wireless environment. By examining the causality of the fundamental cause on each transmission technology, we evaluate the interoperability in terms of the synergy effect.

Since the *wireless* is the most influencing term in radio access systems, we consider the wireless channel as the fundamental cause. Radio propagation is often characterized by three independent phenomena; path-loss attenuation, slow log-normal shadowing and fast multi-path fading. The path-loss and shadowing effect can be considered as a location-dependent factor, and the multi-path fading as a time-dependent factor since the signal quality is highly time-variant in multi-path fading channel.

A. Location-dependent signal characteristics

Location-dependent signal quality mainly depends on the distance between the base station (BS) and mobile station (MS). Therefore, we can classify the users into two groups; the users in the cell center area and in the cell boundary area.

Consider the signal transmission to users in cell center area. It was shown that the amount of channel delay spread increases in proportion to the distance between the BS and MS [4]. Thus, the use of diversity techniques may not be effective in the cell center area due to low channel delay spread. In addition, the use of an interference-averaging scheme may not be effective since the other-cell interference (OCI) effect does not significant in this area. This implies that the use of FH or code division multiplexing (CDM) techniques may not provide substantial performance improvement in this region. Instead, the use of opportunistic scheduling technique may be effective because it can achieve the multi-user diversity (MUD) effect by exploiting the large signal fluctuation. The use of AMC techniques may also be useful for fine rate adaptation because the carrier to interference ratio (CIR) can accurately be estimated in this region. The Shannon's channel capacity theorem implies that additional SIR improvement may not be helpful for the increase of spectral efficiency in this region because the SIR is high enough to be in performance saturated region of the logarithmic-shaped capacity curve. Therefore, it is quite useful to employ a parallel transmission scheme such as the singular value decomposition (SVD) [5] and vertical Bell Laboratory layered space time code (VBLAST) [6]. Since the use of a spatial division multiplexing (SDM) scheme does not provide spatial diversity effect, it can provide a synergy effect when combined with the opportunistic scheduling.

Next, consider the signal transmission to users in the cell boundary area. The channel has highly frequency selective fading characteristics due to large channel delay spread in this region. Thus, the use of diversity techniques may be effective in this region. The use of an interference averaging scheme may also be effective in this area. As a result, the use of opportunistic scheduling technique may not be practical with the use of diversity and interference averaging techniques, because large link-level diversity is not helpful for achievement of MUD gain. Besides, large CIR estimation error may significantly degrade the performance of opportunistic scheduling. It can also seriously degrade the performance of AMC. This problem can be alleviated by using an HARQ technique that does not require explicit channel information. Unlike in the cell center region, it is very desirable to increase the CIR to enhance the system capacity in this region. Thus, the use of multi-antenna techniques such as space-time block coding (STBC) may be quite useful in this region, while achieving a large link-level diversity order.

B. Time-dependent signal characteristics

Multi-path fading, 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. This fading problem is often handled in the packet-based wireless system by two approaches; fading mitigation and fading exploitation approach.

Conventional cellular systems usually mitigate the fading by using diversity and/or power control techniques. However, packet-based OFDM systems may not utilize the temporal diversity because they transmit the data in a burst mode for a short time interval. Instead, they can exploit the frequency domain as the main diversity source. When they employ a multi-antenna scheme, called multi-input multi-output (MIMO), they can additionally achieve a spatial diversity gain by using a space-time coding (STC) technique [7]. 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. The packet-based wireless system needs to mitigate the fading especially for the transmission of real-time (RT) traffics that may require strict quality of service (QoS) as in circuit connection. They can easily obtain the diversity gain using the FH and CDM techniques. Note that these techniques are quite applicable to users in the cell boundary because they can also provide an interference averaging effect.

On the other hand, the packet-based wireless system can improve the spectral efficiency by transmitting the user signal in the local peak channel condition. The larger the number of users, the higher the probability of users in good condition enough for the transmission. As a result, as the number of users increases, the fading exploiting scheme can increase the MUD gain, achieving a spectral efficiency higher than the fading mitigation scheme and even higher than in static channel with the same average CIR. [8]. Thus, the opportunistic scheduling plays a key role in the fading exploitation approach. The MUD gain is closely related to the tail probability of fading channel gain since the system throughput is directly associated with the largest value of the channel gain. The use of link-level diversity technique can significantly reduce the signal gain fluctuation, reducing the MUD gain. Since the fading mitigation and exploitation schemes are incompatible, it is desirable to reduce the link-level diversity when the opportunistic scheduling is employed. The use of fading exploitation technique may involve a latency problem since the user should wait until the channel condition becomes favorable enough to achieve the desired spectral efficiency. This latency problem may inhibit the use of an opportunistic scheduling scheme for the transmission of RT traffics. Thus, the fading exploitation techniques are quite suitable for the transmission of non-real time (NRT) traffics.

III. DESIGN OF A PACKET-BASED WIRELESS ACCESS SYSTEM

Next-generation mobile access systems should be able to support heterogeneous multi-media traffics with various types of QoS, while providing high system capacity in a single frequency network. To meet these requirements, the system framework should be designed so as to utilize these core technologies in different operating conditions in a seamless manner. Since the OFDM can provide fine resource granularity in the time and frequency domain, we define the *segment* by a basic transmission unit comprising $N_t \mu N_f$ modulation symbols in the 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. The orthogonality between the subcarriers and the insertion of a cyclic prefix in the OFDM symbol ensure no multiple access interference between the segments.

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 accommodate a wide
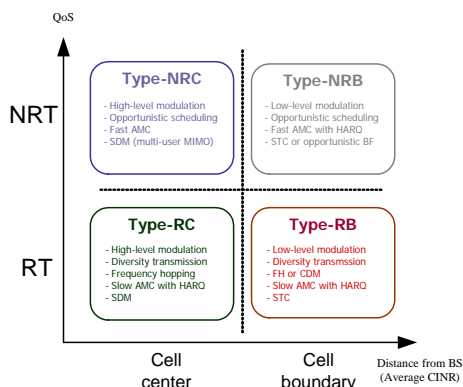
(a) Differentiated segments
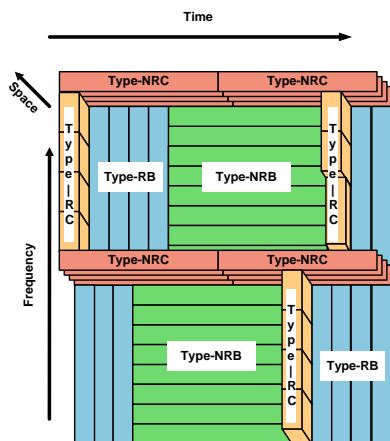
(b) Resource map

Figure 1. Design parameters of the DiffSeg system

variation of operating conditions. It was also shown that the user location and traffic type are the most influencing factors that may require different combinations of transmission technologies. Thus, we design an OFDM-based *DiffSeg* system that can accommodate various operating environments by using differentiated segments in a seamless manner. Figure 1 (a) illustrates a proposed DiffSeg system that uses four types of differentiated segments for ease of implementation. The segments are for the NRT traffic in the cell center (NRC), NRT traffic in the cell boundary (NRB), RT traffic in the cell center (RC) and RT traffic in the cell boundary (RB). By means of segment differentiation, the proposed DiffSeg can optimally utilize the combination of transmission technologies associated with the operating environment. Figure 1 (b) illustrates an example of the resource map of the traffic channel for the proposed DiffSeg system. Note that each segment has a different shape for proper accommodation of transmission technologies associated with the operating condition. Note also that other operation parameters such as the user mobility can further be considered for adoption of additional differentiated segments.

A. Type-NRC segment

Type-NRC segment is for the transmission of NRT traffics in the cell center area, *i.e.,* when the channel condition is good. The opportunistic scheduling can be employed in this segment since the CIR 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 spectral efficiency by employing an SDM 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 Figure 1 (b). Thus, it may be possible to make the signal has large gain fluctuation in the time domain. Since the type-NRC segments are distinguishable in the spatial domain, they can maximize the MUD gain using a multi-user MIMO technique [9]. It may be desirable to use a multi-user MIMO scheme that can provide the MUD and spatial multiplexing gain simultaneously. Such a scheme was recently proposed by collaboratively combing the opportunistic scheduling and spatial multiplexing scheme using multiple random beams [10].

As mentioned before, this type segment does not consider the use of a diversity scheme such as the FH and CDM, which is not compatible with the opportunistic scheduling. Each segment needs to have a certain amount of symbols to achieve a proper coding gain, requiring the use of a large value of N_t due to the use of a small value of N_f. This may cause the increase of loop latency with the use of HARQ. However, it may not be serious unless the HARQ plays an important role.

When accurate CIR information is available, the proposed DiffSeg can achieve desirable rate adaptation performance using 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 the opportunistic scheduling even in this segment. This issue may require to use additional parameters such as the user mobility and power allocation for the segment differentiation. However, simulation results show that the use of additional parameters for the segment differentiation does not yield significant performance improvement, compared to huge increase of the implementation complexity and feedback signaling burden.

B. Type-RC segment

Type-RC segment is mainly for the transmission of RT traffics in the cell center where the channel condition is good. Since RT traffics require regular transmission opportunity to meet the latency requirement, we consider the use of fading mitigation techniques instead of fading exploiting 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 Figure 1 (b). An STC scheme can be employed to obtain an additional spatial diversity. However, it may be preferable to employ an SDM scheme that can provide parallel spatial subchannels because the transmission performance is near in the saturation region due to good channel condition. Unlike the type-NRC segment, all the spatial subchannels are assigned to a single user in order to obtain an additional spatial diversity gain, making up the lack of frequency diversity sources. Thus, this type segment has a three-dimensional structure as shown in Figure 1 (b).

Slow AMC can be employed to adjust the data rate in response to large-scale variation due to the path-loss and shadowing, in combination with the diversity technique that can mitigate the signal gain fluctuation due to fast multi-path fading. The HARQ can be applied to the RT traffic for fast recovery of errors due to the signal fluctuation unhandled by the diversity processing. In practice, the HARQ can also be useful for fine rate adaptation to minimize the portion of the resource occupied by the RT traffic. Considering the latency requirement for the RT traffic, this type segment should have a
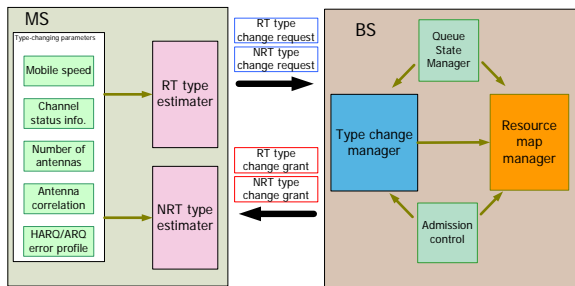
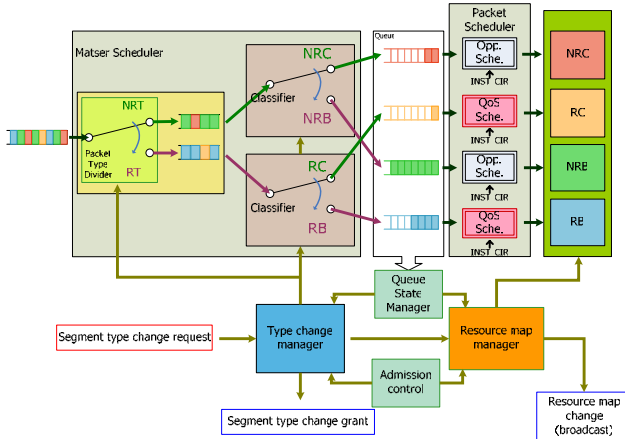**Figure 2. Selection of the segment type**

Figure 3. Segment allocation in the DiffSeg system

small N_t to minimize the retransmission latency with the use of HARQ.

C. Type-NRB segment

Type-NRB segment is for the transmission of NRT traffics 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 the FH and CDM. Therefore, it is desirable to use an interference-avoidance scheme such as dynamic packet assignment (DPA) to fully exploit the advantages of opportunistic scheduling techniques [11]. This type segment can employ an opportunistic beamforming (BF) technique [12] that can provide an interference nulling effect as well as the MUD gain. However, the BF technique can achieve high spectral efficiency only when the number of users is large. The transmission strategy for this type segment may need further study.

D. Type-RB segment

Type-RB segment is for the transmission of RT traffics 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. Note that the CIR improvement is important in the cell boundary area. Thus, the use of STC is preferred to that of SDM to achieve large spatial diversity gain. In addition, the CDM can improve the transmission performance by providing large frequency diversity and interference-averaging effect. The link adaptation strategy can be designed in a similar manner to that of the type-RC segment.

TABLE I
AMC PARAMTERS FOR SIMULATION

| Modulation	Initial code rate	Code block length	HARQ max. retransmission	Effective spectral efficiency
QPSK	3/8	336	2	0.25~0.75
QPSK	3/4	672	2	0.5~1.5
16-QAM	9/16	1008	2	0.75~2.25
16-QAM	3/4	1344	2	1.0~3.0
64-QAM	5/8	1680	2	1.25~3.75

E. Transmission strategy for the DiffSeg system

In addition to the user location and traffic type, additional operation parameters such as the mobile speed can be considered to determine the segment type. If the BS determines the segment type for each user, it needs these parameters continuously, which may require heavy signaling burden. To alleviate this problem, we consider the use of a mobile assisted type change (MATC) protocol as illustrated in Figure 2. The MATC protocol allows the MS to determine the segment (i.e., operation) type based on its own estimate. When the BS receives a request for segment type change from the MS through an uplink control channel, the type change manager in the BS changes the segment type taking account of queue status of each segment, cell load, and resource map. If the BS decides to change the operation type, it sends a type change grant message to the user via a broadcast channel.

Figure 3 illustrates a transmission and segment allocation strategy for the DiffSeg system. The segment type of each user is classified according to the MS request, and then each packet is fed into the corresponding queue. Finally, the user packets are handled by a packet scheduler optimized for each segment type. There may be a load unbalancing problem between the segments when the amount of traffic demanding a certain segment type increases to an unacceptable level with the use of resource map. As a result, packets can be dropped out due to overflow in the queue even though other queues are not in overflow. In this case, the type change manager adjusts the load of segments using the queue state information. However, when the loads are severely unbalanced, the BS may change the resource map to alleviate the load unbalancing. Since the load distribution is not rapidly changed in a short time interval, the amount of additional signaling burden for the change of resource map is negligible compared to the system complexity.

We evaluate the performance of a 4-segment based DiffSeg system with a 2x2 MIMO configuration in a 19-hexagonal cell configuration environment by computer simulation. We consider spatially uncorrelated environment where five resolvable multi-path have exponentially decaying power. As a channel variation in the time domain, we assume Jake's model with maximum Doppler frequency of 300Hz and 30Hz for RT and NRT traffic transmission, respectively. 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 adaptation based on AMC and HARQ with incremental redundancy (IR). The AMC parameters are summarized in Table I.

Figure 4 (a) depicts the link-level performance for the RT traffic, when the VBLAST and Alamouti scheme [7] are used
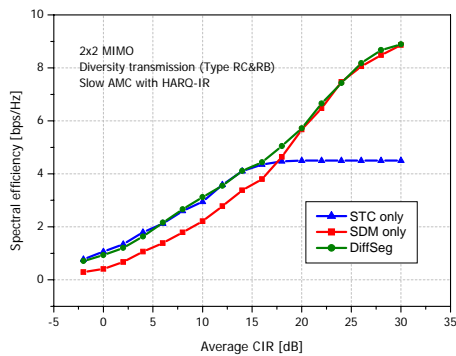
(a) Performance of RT traffic
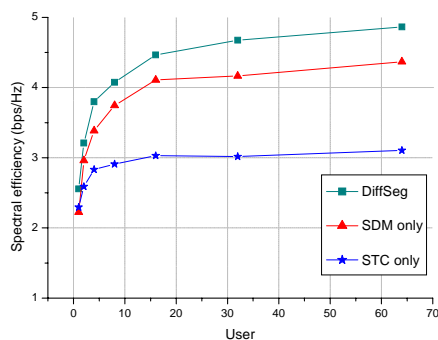
(b) Performance of NRT traffic

Figure 4. Performance of the DiffSeg system with a 2x2 MIMO

as the SDM and STC technique, respectively. Note that the average CIR can be considered as the distance between the BS and MS. It can be seen that, when the CIR is low, the STC outperforms the SDM. On the other hand, when the CIR is high, the SDM provides better spectral efficiency than the STC. It can also be seen that the proposed DiffSeg system seamlessly provides near optimum performance in a wide range of channel condition.

Figure 4 (b) depicts the average spectral efficiency as a system-level performance measure for the NRT traffic, when the VBLAST and Alamouti scheme are used for the type-NRC and –NRB, respectively. Note that, unlike for the RT traffic, each spatial layer is allocated to different users to maximize the MUD gain. A proportional fair scheduler is used for the scheduling of user packets and the rate is adapted by fast AMC and HARQ-IR. For comparison, the performance of conventional SDM and STC scheme is also depicted. We make the segment differentiation between the NRC and NRB based on the average CIR. It can be seen that the system performance improves as the number of users increases due to the MUD effect providing larger gain on the SDM than on the STC. However, since the STC outperforms the SDM in the cell boundary area, the DiffSeg system provides better performance than the use of a single MIMO technique. Thus, we can obtain a synergy effect by utilizing multiple core technologies so that they work optimally in each segment condition, significantly improving the overall system capacity. The performance of the DiffSeg system can further be improved with the use of advanced core technologies. For example, the use of a new

MIMO scheme called MUDAM in [10] can significantly improve the spectral efficiency over the use of conventional SDM scheme for NRT in the cell center.

IV. CONCLUSIONS

In this paper, we have proposed a new air interface framework for the next generation mobile access system. For this, we have investigated the interoperability between the core transmission technologies by proposing a so-called *cause and effect* analysis. The investigation has elucidated that the user location (or channel condition) and traffic type are the most influencing parameters on the performance in mobile multi-access environment. Based on this investigation, we have proposed a new air interface framework, called *DiffSeg*, that can accommodate heterogeneous operating environments in a seamless manner. As an example, a DiffSeg system was designed using four types of differentiated segments associated with the user location and traffic type. It was also illustrated how the proposed DiffSeg system differently utilizes core technologies in heterogeneous operating environments. Simulation results show that the DiffSeg system outperforms conventional systems that employ a single combination of transmission technologies in wide range of operating condition. The proposed DiffSeg system illustrates the superiority of a single unified air interface approach for the next generation wireless system, over the conventional evolution approaches with backward compatibility that may need multiple air interfaces to accommodate heterogeneous operating environments.

V. REFERENCES

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