# Adaptive Sub-band Nulling for OFDM-Based Wireless Communication Systems

Bang Chul Jung, Young Jun Hong, Dan Keun Sung, and Sae-Young Chung
CNR Lab., School of EECS., KAIST, 373-1,
Guseong-dong, Yuseong-gu, Daejeon, 305-701, KOREA
Email: bcjung@cnr.kaist.ac.kr; yjhong@cnr.kaist.ac.kr; dksung@ee.kaist.ac.kr; sychung@ee.kaist.ac.kr

***Abstract*— In this paper, we propose an adaptive sub-band nulling technique in order to improve the performance of orthogonal frequency division multiplexing (OFDM)-based wireless communication systems. It excludes some sub-bands experiencing deep-fading and the transmission power for the excluded sub-bands is reallocated for the remaining sub-bands. We compute the optimal number of nulled sub-bands in order to maximize the capacity. Water-filling is one well-known optimal resource allocation scheme. However, it has tremendous complexity at the transmitter and requires full channel state information from the receiver. We compare the performance of the proposed scheme with that of the water-filling scheme and the result shows that the performance of the proposed scheme is similar to that of the water-filling in a wide range of signal-to-noise ratio (SNR) values. Furthermore, the proposed adaptive sub-band nulling can be used as an enhanced distributed transmission mode in future OFDM-based wireless communication systems after a small modification in the frame structure.**

## I. Introduction

OFDM is one of the most promising techniques for high-speed data transmissions over frequency selective fading channels [1] and a number of multiple access schemes with OFDM techniques have been proposed, including OFDM-TDMA, OFDM-FDMA, OFDM-CDMA, and FH-OFDMA [2].

Recently, a number of OFDM-based wireless systems have been proposed. The IEEE 802.16-2004 standard was published for fixed access in October 2004 [3]–[6]. The standard has been updated and extended to the IEEE 802.16e standard for mobile access, Mobile WiMAX, as of October 2005. The IEEE 802.16e system exploits the OFDMA with a fast Fourier transform (FFT) size of $1024$. The OFDMA is also being considered as a physical layer technique for the Evolved-UTRA [7] and the IEEE 802.20 standard (mobile bradband wireless access, MBWA) [8].

There are two transmission modes in OFDM-based wireless communication systems: a time and frequency diversity (TFD) mode and a frequency domain scheduling (FDS) mode. Since the TFD mode is a very useful scheme for averaging intercell interference and avoiding deep fading by selecting subcarriers pseudo-randomly, it is expected to be suitable for users with high mobility and/or low signal-to-interference-plus-noise ratio (SINR) values. The TFD mode uses the same modulation and coding scheme (MCS) over subcarriers and only changes the MCS level over time. In this mode, since it requires the averaged channel state information over frequency domain from the receiver, it can reduce the signaling overhead for indicating the packet location in the physical frame and the MCS level.

On the other hand, the FDS groups adjacent subcarriers into a sub-band and multiple sub-bands are allocated to users. In the FDS, the channel response of each sub-band can be considered as a flat fading channel. Thus, the FDS can make better use of multiuser diversity in frequency domain, while the TFD can only exploit the multiuser diversity in time domain. However, the FDS requires a large amount of feedback information for indicating the channel state information over frequency domain and signaling overhead for indicating the packet location in the physical frame. If a large number of users demand low-rate data services with low channel activities, then a BS should transmit a large amount of signaling information, which includes subcarrier allocation, modulation and coding format, pending data to specific users, in order to maintain the connections. Furthermore, it may not operate correctly in rapidly varying channel environments. Thus, the FDS is expected to be suitable for users with low mobility and/or high SINR values [9], [10].

In summary, though the TFD mode makes the system operation simple, it has a demerit that the subcarriers with low channel qualities may be allocated. The FDS mode has a merit that multiuser diversity is achieved in frequency domain and time domain at the cost of complexity. In this paper, we propose an adaptive sub-band nulling technique as a compromise between the TFD and FDS modes. It basically operates like the TFD mode after it excludes sub-bands with low SINR values. The remainder of this paper is organized as follows: In Section II we introduce the proposed adaptive sub-band nulling technique. In Section III, we analyze the optimum number of nulled sub-bands to maximize the system capacity. In Section IV, the performance of the proposed technique is evaluated in terms of throughput for varying SNR values by computer simulation. Finally, conclusions are presented in Section V.

## II. Adaptive Sub-band Nulling Technique

Fig. 1 shows the block diagram of a TFD mode. Users transmit their data through the distributed subcarriers which are selected pseudo-randomly. Data symbols of each user in a frame experience fading and it results in varying SINR values at the receiver. Thus, a channel coding technique is required to achieve a good TFD mode. A single modulation and coding

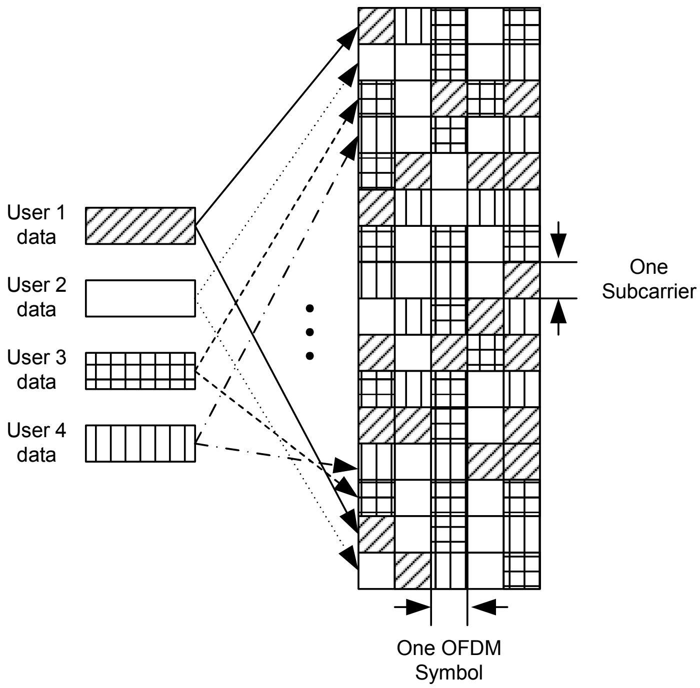


Fig. 1. Block diagram of a TFD mode

scheme is used in the frequency domain in the TFD mode and it is adapted according to the averaged channel gain in frequency domain.

Fig. 2 shows the block diagram of an FDS mode. Users transmit their data through sub-band(s) each of which consists of adjacent subcarriers in the FDS mode. The number of subcarriers in a sub-band is here assumed to be two. If a wireless channel is frequency-selective, then each sub-band has a different channel gain and the favorable sub-band of a specific user may be different from those of other users. If users can transmit their data through their favorable sub-bands, then the system throughput can be improved through multi-user diversity. In Fig. 2 there exist $8$ sub-bands and user 1 uses the first and the sixth sub-bands from the top. User 2 uses the fourth and the fifth sub-bands from the top.

Fig. 3 shows the block diagram of the proposed adaptive sub-band nulling (ASN) mode. The ASN mode is similar to the TFD mode except that some sub-bands are excluded in data transmission. For example, user 3 does not use the third sub-band from the top and user 4 does not use the sixth sub-band. The excluded sub-bands vary according to users since the wireless channel characteristics of each user are independent. Thus, when the proposed ASN mode is applied in a cell, adjacent cells still experience the averaged interference characteristics over frequency domain, while the FDS mode induces bursty interference characteristics to adjacent cells. The transmission power which is supposed to be allocated to the nulled sub-bands can be reallocated to the remaining sub-bands. The proposed ASN mode exploits time and frequency diversities since it basically transmits data in a distributed manner. It also achieves a multiuser diversity because it does

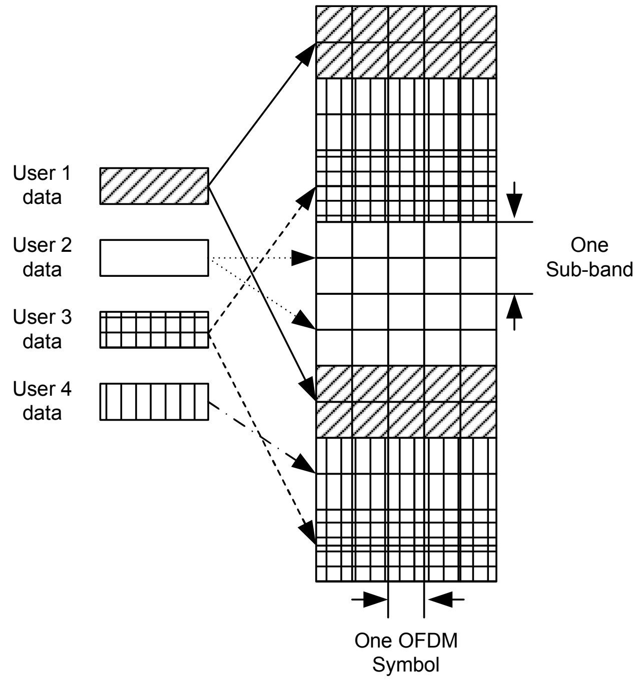


Fig. 2. Block diagram of an FDS mode

not use the unfavorable sub-bands of each user. In the proposed ASN mode, the averaged SINR values of each user can be improved by excluding the unfavorable sub-bands and it has a multiuser diversity gain over frequency domain intrinsically. A single MCS is used over the frequency domain and it requires simple signalling.

Fig. 4 shows the operation procedure of the proposed ASN mode between a base station (BS) and a mobile station (MS). At first, a BS transmits a pilot signal and an MS estimates the wireless channel based on the received pilot signal. It determines the number of sub-bands nulled according to a given criterion. Then, the MS informs the BS of its channel characteristics, which include the indexes of the excluded sub-bands and the averaged SINR values of the remaining sub-bands. The BS decides an appropriate MCS level according to the received averaged SINR value and allocates the resources (subcarriers) to the MS. The BS transmits the user data and the signaling information about the resource allocation. The MS receives the data and transmits the ACK/NACK signaling to the BS. The MS estimates its channel characteristics and computes the averaged SINR value of the remaining sub-bands. If the channel varies and the nulled sub-bands change, then the MS determines the nulled sub-bands again and transmits the indexes of the nulled sub-bands.

## III. Optimum Number of Nulled Sub-bands in the ASN mode

In Section II we introduced the proposed ASN mode which excludes some sub-bands with low SINR values. Now, a natural question is that how many sub-bands should be excluded in transmission or what the minimum SINR level of the remaining sub-bands is. We assume that the channel gain

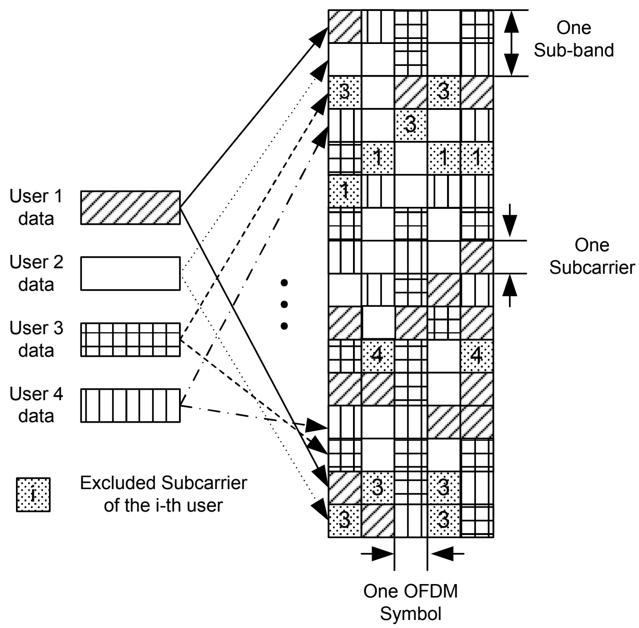


Fig. 3. Block diagram of the proposed adaptive sub-band nulling mode

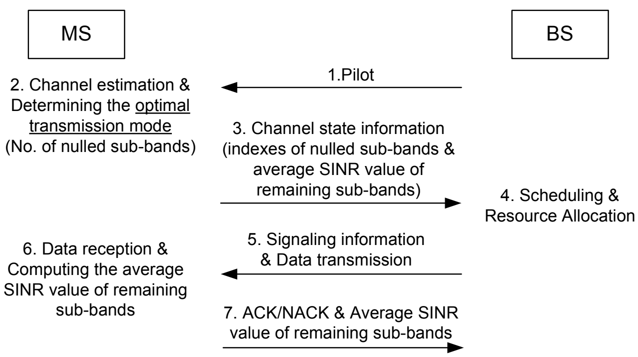


Fig. 4. Procedure of the proposed adaptive sub-bands nulling mode

of subcarriers in a sub-band is identical, that is, the bandwidth of a sub-band is smaller than the coherence bandwidth. In this section, we assume that MSs know channel coefficients through the pilot signal from a BS. Then, determining the optimum number of the nulled sub-bands for maximizing capacity is to solve the following optimization problem:

$$C_{N_{SB}} := \max_{x_1,\ldots,x_{N_{SB}}} \sum_{n=1}^{N_{SB}} \log_2 \left( 1 + \frac{P_T |H_n|^2}{N_0 B} \cdot \frac{x_n}{\sum_{i=1}^{N_{SB}} x_i} \right) \quad (1)$$

subject to

$$x_n \in \{0, 1\},$$

where $N_{SB}$ and $P_T$ denote the total number of sub-bands and the total power allocated to each OFDM symbol, respectively. $|H_n|^2$ and $B$ represent the channel gain of the $n$-th sub-band and the bandwidth of a sub-band, respectively. To find an optimal solution with exhaustive search, it requires $O(2^{N_{SB}})$ steps. However, if we know $\sum_{i=1}^{N_{SB}} x_i = K$ at the optimal solution, then the original problem is reduced as:

$$\max_{x_1,\ldots,x_{N_{SB}}} \sum_{n=1}^{N_{SB}} \log_2 \left( 1 + W_n \cdot x_n \right), \quad (2)$$

where $W_n = P_T |H_n|^2 / (N_0 K B)$. Since a logarithm function is a monotonically increasing, finding an optimal solution is equivalent to setting $x_n$ to 1 with the highest-$K$ values of $W_n$. The term $K$ ranges from 1 to $N_{SB}$. Now, we know that the original problem in Eq. (1) is changed into an ordering problem which takes $O(N_{SB} \log(N_{SB}))$ steps. Fig. 5 shows an algorithm for determining the optimal number of remaining sub-bands of the proposed ASN for given channel coefficients. After obtaining the optimal number of sub-bands used, the MS transmits the indexes of the excluded sub-bands and the averaged SINR value for the remaining sub-bands to the BS through a feedback channel. If we use a water-filling (WF) method [11], then the MS needs to send the channel gain values of all sub-bands, $|H_n|^2$, to the BS and the feedback signaling overhead becomes much larger than that of the proposed ASN mode.

Order the channel gain of each sub-band ($|H_n|^2$)
**For** $K$=1,...,$N_{SB}$
- Select the largest-$K$ values of $|H_n|^2$: $\{|\tilde{H}_1|^2,...,|\tilde{H}_K|^2\}$
- Compute and save the corresponding capacity: $C_K = \sum_{n=1}^{K} \log_2 \left( 1 + \frac{P_T |\tilde{H}_n|^2}{N_0 K B} \right)$

**End**
Obtain the optimal $K$ value
$K^* = \arg_K \max\{C_1, C_2, ..., C_{SB}\}$

Fig. 5. Algorithm for determining the optimal number of remaining sub-bands

Intuitively, a sub-band with a high channel gain yields a high capacity. Thus, if we fix the number of remaining sub-bands after nulling some sub-bands, then we should use the sub-bands with high channel gains. In other words, we exclude a required number of sub-bands with lower channel gains first. The proposed ASN mode boosts the power allocated to the remaining sub-bands so that the averaged power allocated to all the remaining sub-bands is the same as the conventional TFD mode.

Figure 6 illustrates the capacities of the proposed ASN technique and the optimal WF technique. The channel coefficients of a sub-band are assumed to be Rayleigh-distributed and independent of each other. The total number of sub-bands is set to 20. The proposed ASN technique has a similar capacity to that of the WF technique in a wide range of SNR values. The proposed ASN technique operates according to the algorithm shown in Fig. 5. It is important that the optimum number of nulled sub-bands is chosen in the proposed ASN technique. If we fix the number of nulled sub-bands in the ASN technique, then the capacity of the ASN technique decreases. Fig. 7 shows the capacity of the ASN technique with three different

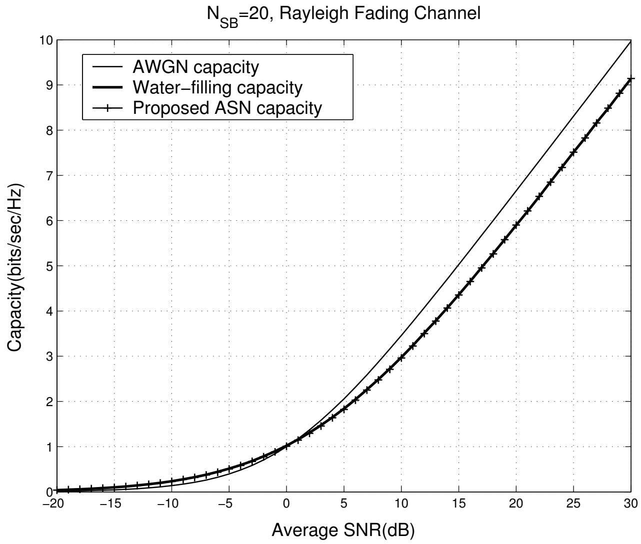


Fig. 6. Capacity comparison between the proposed ASN technique and the optimum water-filling technique

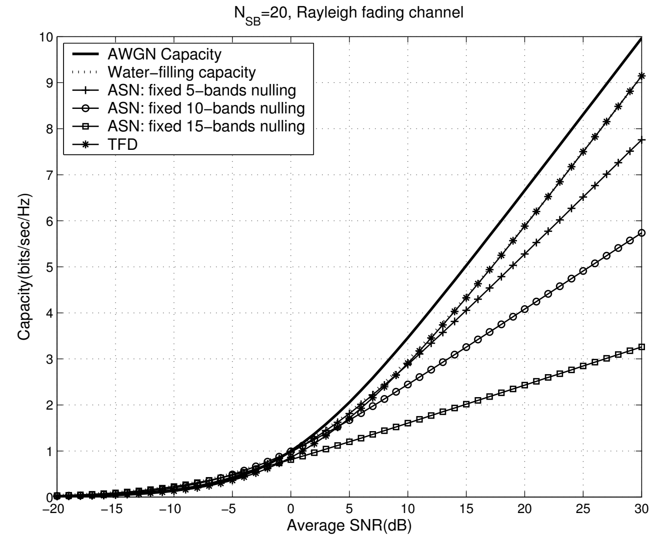


Fig. 7. Capacity of the ASN technique with three different numbers of nulled sub-bands

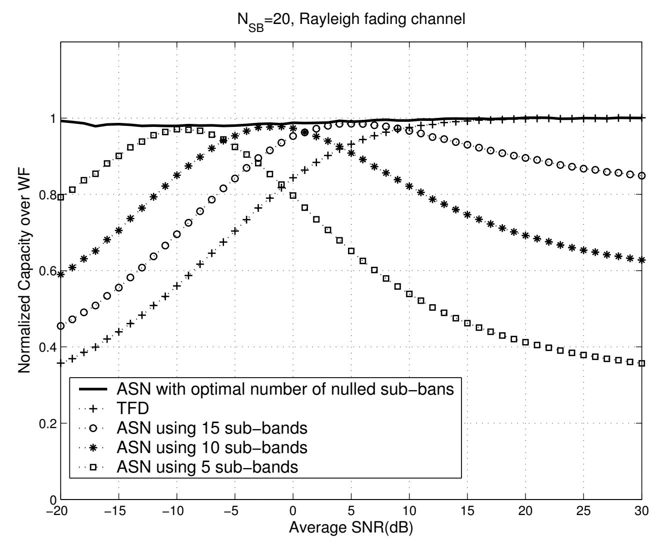


Fig. 8. Normalized capacities of the ASN technique over the WF technique

numbers of nulled sub-bands. As the SNR values increase, the capacity of the TFD mode approaches to the WF capacity. The optimal power allocation strategy is to allocate the power equally over the frequency sub-bands when the received SNR values are very high [12]. On the contrary, the optimal power allocation strategy is to allocate all the power to a sub-band with the highest SNR value when the received SNR values are very low. Thus, excluding more sub-bands with low SNR values is better when the SNR values are low. In Fig. 7, if we use $15$ good sub-bands among $20$ sub-bands, then the capacity of the ASN technique is equal to $7.8$ bits/sec/Hz at an SNR value of $30$dB, while the capacity of the ASN technique using $10$ good sub-bands is equal to $5.8$ bits/sec/Hz at the same SNR value. However, when the received SNR values are low, the capacity of the ASN technique using $10$ good sub-bands is equal to $0.0236$ bits/sec/Hz, while that of the ASN technique using $15$ good sub-bands is equal to $0.0182$. Thus, it is important to dynamically change the number of nulled sub-bands according to varying channel gains in the ASN technique.

Figure 8 illustrates the normalized capacities of the ASN technique over the WF technique. The ASN technique with an optimal number of nulled sub-bands nearly achieves the WF capacity over all SNR values, while the capacity of the TFD technique approaches to the WF capacity only when the received SNR values are high. Furthermore, the ASN technique using a fixed number of nulled sub-bands achieves the WF capacity at a specific SNR value. Note that the optimal number of nulled sub-bands decreases as the received SNR values increase, which is coincident with the optimal power allocation strategy derived in [12]. The proposed ASN with a fixed power allocation strategy over the remaining sub-bands nearly achieves the capacity of the optimal power allocation strategy, WF. Thus, we can conclude that excluding some sub-bands with low SNR values is sufficient to achieve the optimal capacity and a variation in the allocation of power over the remaining sub-bands does not affect the capacity much.

## IV. Simulation Results

Table I summarizes the simulation parameters of an OFDM link-level simulator for evaluating the performance of the proposed ASN mode [13]. We group $45$ adjacent subcarriers into a sub-band. Table II lists the modulation and coding schemes. In MCS levels 1 and 2, five OFDM data units are allocated to a single user per 2ms TTI. Five sub-bands among 15 sub-bands are used for data transmission in this case and these five sub-bands per OFDM symbol are changed according to a Costas sequence [13]. For the other MCS levels, all sub-bands are used for data transmission.

TABLE I

SIMULATION PARAMETERS

| Parameters | Values |
|---|---|
| Transmission time interval (TTI) duration | 2 ms |
| FFT size (points) | 1024 |
| OFDM sampling rate ($M$samples/sec) | 6.528 |
| Guard time interval (samples, $\mu$sec) | 64, 9.803 |
| Subcarrier saparation ($k$Hz) | 6.375 |
| Number of OFDM symbols per TTI | 12 |
| OFDM symbol duration ($\mu$sec) | 166.67 |
| Number of useful subcarriers per OFDM symbol | 705 |
| OFDM bandwidth ($M$Hz) | 4.495 |
| Number of total sub-bands | 15 |

TABLE II

MODULATION AND CODING SCHEMES (MCS)

| MCS | Modulation | Data rate | Code rate | Payload size per TTI |
|---|---|---|---|---|
| 1 | QPSK | 800 kbps | 1/3 | 1600 bits |
| 2 | QPSK | 1.2 Mbps | 1/2 | 2400 bits |
| 3 | QPSK | 2.4 Mbps | 1/3 | 4800 bits |
| 4 | QPSK | 3.6 Mbps | 1/2 | 7200 bits |
| 5 | 16QAM | 4.8 Mbps | 1/3 | 9600 bits |
| 6 | QPSK | 5.4 Mbps | 3/4 | 10800 bits |
| 7 | 16QAM | 7.2 Mbps | 1/2 | 14400 bits |
| 8 | 16QAM | 10.8 Mbps | 3/4 | 21601 bits |

Figure 9 illustrates the achieved data rates of the conventional TFD mode and the proposed ASN mode. The ITU Pedestrian-B channel model is used for a wireless channel model [13]. We fix the number of nulled sub-bands in this simulation. As we mentioned in Section III, the proposed ASN mode with 5 nulled sub-bands yields a higher throughput than the conventional TFD mode when the received SNR values are low. However, the conventional TFD mode achieves the highest throughput among the schemes. Therefore, we should adapt the number of nulled sub-bands according to the received SNR values.

## V. CONCLUSIONS

We proposed an adaptive sub-band nulling (ASN) scheme which can be applied to a conventional TFD mode in OFDM-based wireless communication systems. Small modifications are required to inform the indexes of the nulled sub-bands, compared to the conventional TFD mode. We analyzed the optimum number of nulled sub-bands. When the received SNR values are low, more sub-bands need to be nulled. We showed that the proposed ASN mode yields a similar capacity to that of the water-filling (WF) scheme over in a wide range of SNR values, while the conventional TFD mode achieves the WF capacity only when the received SNR values are very high. Furthermore, we illustrated the link-level simulation result of the ASN mode. The proposed ASN mode can be an effective transmission mode as a enhanced mode of the conventional TFD mode in future OFDM-based wireless communication systems.

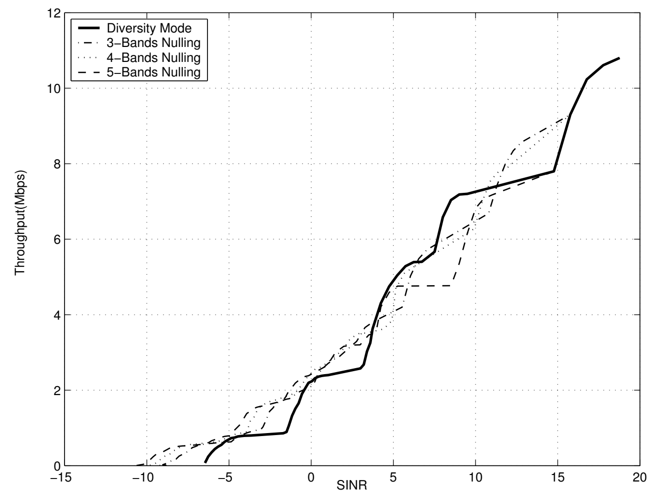


Fig. 9. Throughput comparison between the proposed ASN mode and the conventional TFD mode

## ACKNOWLEDGMENTS


This research was supported in part by BroMA IT Research Center Project.


## REFERENCES


[1] R. Van Nee and R. Prasad, *OFDM for wireless multimedia communications*, Artech House Publishers, 2000.

[2] K. Fazel and S. Kaiser, *Multi-carrier and spread spectrum systems*, Wiley, 2003.

[3] IEEE, P802.16-REVd/D5, “ Part 16: Air interface for fixed broadband wireless access systems,” May 2004.

[4] C. Eklund et al., “IEEE Standard 802.16: A technical overview of the wirelessMAN air interface for bradband wireless access,” *IEEE Commun. Mag.*, Vol. 40, No. 6, pp.98-107, Jun. 2002.

[5] I. Koffman and V. Roman, “Broadband wireless access solutions based on OFDM access in IEEE 802.16,” *IEEE Commun. Mag.*, Vol. 40, No. 4, pp.96-103, Apr. 2002.

[6] A. Ghosh et al., “Broadband wireless access with WiMAX/802.16: Current performance bandchmarks and future potential,” *IEEE Commun. Mag.*, Vol. 43, No. 2, pp.129-136, Feb. 2005.

[7] 3GPP, TR 25.814, “Physical layer aspects for Evolved UTRA (Release 7),” Nov. 2005.

[8] IEEE C802.20-05/68r1, “MBFDD and MBTDD wideband mode: Technical overview,” Jan. 2006.

[9] C. Y. Wong, R. S. Cheng, K. B. Letaief, and R. D. Murch, “Multiuser OFDM with adaptive subcarrier, bit, and power allocation,” *IEEE J. Select. Areas Commun.*, Vol. 17, No. 10, pp.1747-1758, Oct. 1999.

[10] T. Ikeda, S. Sampei, and N. Morinaga “TDMA-based adaptive modulation with dynamic channel assignment for high-capacity communication systems,” *IEEE Trans. Veh. Technol.*, Vol. 49, pp. 404-412, Mar. 2000.

[11] A. J. Goldsmith and P. P. Varaiya, “Capacity of fading channels with channel state information,” *IEEE Trans. Inform. Theory.*, Vol. 43, No. 6, pp. 1986-1992, June 1997.

[12] D. Tse and P. Viswanath, *Fundamentals of wireless communication*, Cambridge, 2005.

[13] 3GPP, TR 25.892 v.6.0.0, “Feasibility study for orthogonal frequency division multiplexing (OFDM) for UTRAN enhancement,” June 2004.