A Novel Predictive Dynamic Channel Allocation Scheme for Improving Power Saving and Mobility in Broadband Wireless Access Networks

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***Abstract*— The radio spectrum of the IEEE 802.16 medium access control (MAC) protocol ranges from 2 to 66 GHz, which is one of potential solutions for broadband wireless access (BWA) or beyond third generation (B3G)/4G networks. However, with the characteristic of radio propagation, the maximum transmission distance is proportioned inversely to the frequency which the mobile subscriber station (MSS) carries. According to this property, the channel allocation can be based on how far the distance between the SS and the base station (BS) in a cell. Therefore, in this paper, we first propose a new channel allocation model for BWA in the macrocell and investigate the relations between the signal propagation and the distance as well as propose a signal-aware dynamic channel allocation (SDCA) scheme for dynamic channel allocation (DCA) in BWA networks (BWANs). The SDCA enables the BS to allocate appropriate channels to MSSs according to the received signal-to-noise ratio (SNR) value from the MSSs. Besides, according to the frequency, the SDCA can estimate a minimum power for MSS to communicate. The SDCA not only increases the capacity of the system but saves the overall power consumption of the system well. We also present a new out-of-service prevention scheme for supporting mobility in the system. Simulation results show that the proposed SDCA increases the channel utilization by up to 89% over the original IEEE 802.16 standard specifications.**

***Index Terms*— Algorithm, channel allocation, MAC, OFDM, spectrum.**

I. INTRODUCTION

The method of frequency allocation includes a fixed channel allocation (FCA) and a dynamic channel allocation (DCA) in the IEEE 802.16 wireless metropolitan area network (WMAN) standard. The FCA follows the initial characteristics of the subscriber station (SS), e.g., decaying, multipath fading, frequency enhanced ratio, and power etc. [14], to allot each SS an exclusive channel in advance. Some performance issues for FCA are studied in [30], [41]. Comparing with FCA, DCA does not reserve an exclusive channel for SSs beforehand, but stands on and follows the characteristics of SSs to offer proper channels [11]. Nevertheless, the possible implementation of DCA schemes has been attracting some interest for years due to the need for larger capacities and more flexibility than those achievable through FCA. Nowadays many DCA schemes are investigated and proposed in various wireless networks [8], [9], [10], [29], [38], [40]. It is well known that the DCA algorithms based on the measurement of actual interference, i.e., interference adaptive DCA (IA-DCA), perform better than those based on traffic assessment.

Broadband wireless access (BWA) has received much more attentions in recent years [17], [18], [27], [42]. Work towards specification of "beyond third generation" (B3G) or fourth generation (4G) is ongoing [7], [19], [32]. On the path toward 4G, it has to be seen as the next-generation communications system, which may include new wireless access technologies, but in any case will be able to provide an acceptable broadband access. It can be foreseen that the demand on high bandwidth transmission follows a large number of multimedia applications [25], [37] in wireless communications will be inevitable in the near future.

Fixed BWA systems, such as the local multipoint distribution service (LMDS), provide multimedia services to a number of discrete subscriber sites with IP and offer numerous advantages over wired IP networks. This is accomplished by using base stations (BSs) to provide network access services to subscriber sites based on the IEEE 802.16 WirelessMAN® standard [13]. First published in April 2002, the IEEE 802.16 standard has recently been updated to IEEE 802.16-2004 [20] (approved in June 2004). The standard focuses on the "first-mile/last-mile" connection in WMANs. Its purpose is to facilitate the optimal use of bandwidth from 2 to 66 GHz, as well as interoperability among devices from different vendors. Typical channel bandwidth allocations are 20 or 25 MHz (United Stats) or 28 MHz (Europe) in 10 to 66 GHz, or various channel bandwidths among 1 to 30 MHz in 2 to 11 GHz [21]. The progress of the standard has been fostered by the keen interest of the wireless broadband industry to capture the emerging WiMAX (worldwide interoperability for microwave access) market, the next-wave wireless market that aims to provide wireless broadband Internet services. The WiMAX Forum, formed in 2003, is promoting the commercialization of IEEE 802.16 and the European Telecommunications Standard Institute's (ETSI's) high performance radio MANs (HyperMANs). It provides one of potential solutions to B3G/4G architecture [28], [35].

The IEEE 802.16 [20], ranging from 10 to 66 GHz, has the maximum transmission distance around 1.6–4.8 kilometers and the maximum data rate up to 120 Mb/s. It provides a framework of the BWA backbone network based on various BSs. In IEEE 802.16a [21], the transmission distance is expended to 6–10 kilometers and the data rate is up to 75 Mb/s. It supports nonline-of-sight (NLOS) communications and thus fits in the urban environment, which may have a lot of hindrances. Moreover, for the need of mobility in different radio access networks (RANs), the IEEE 802.16e [22] is established for roaming of mobile SSs (MSSs) and operates in the frequency below 6 GHz. The supplied data rate is approximately 15 Mb/s if the channel bandwidth is 5 MHz.

In recent year, a huge number of papers in the literature dealing with the proposal and/or the performance evaluation of DCA schemes, but only a small number of them are applied for the BWA networks (BWAN) correspondingly. With the characteristic of radio propagation, a longer distance will cause fading signal and losing path conspicuously [43] and the signal arriving the BS from the subscriber station (SS) with lower frequency will take a longer distance than that of higher frequencies [5]. According to above mentions, with the wide range of spectra (2–66 GHz), thousands of channels will be able to be allocated for access in a cell of the BWAN, which we will call a *macrocell* hereafter, if each channel has bandwidth of 20 MHz. How to organize these available channels efficiently to increase the maximum capacity of MSSs has become very important [1], [16]. Thus, in this paper, we first point out the problem of how to efficiently distribute channels (or frequencies) to MSSs according to distances between the MSSs and the BS, and then propose a new macrocell channel arrangement model for BWA's cellular system.

Based on this model, we design a signal-aware DCA (SDCA) scheme to coordinate MSS's channel allocation according to the received signal-to-noise ratio (SNR) value of signal arriving the BS from the MSS. One major benefit of this scheme is that, without global positioning system (GPS) [31], SDCA can estimate the distance of the MSS to the BS by only using the SNR value whether in urban or suburban area. Furthermore, the MSS will be informed by the BS to reduce its transmission power so that the overall power consumption is minimized. Finally, considering the mobility of MSSs in the macrocell, SDCA also supports MSS in various velocities and movements in different directions without out of radio service. We also show that the proposed SDCA not only increases the capacity of the system and the capability of MSS's mobility in the BWAN but reduces the call blocking probability by allocating an appropriate channel for MSSs.

The remainder of this paper is organized as follows. Section II takes an overview of the mechanism of the IEEE 802.16 MAC protocol. In Section III, we illustrate the relationship of the measured SNR and the maximum transmission distance in detail. Section IV introduces a new macrocell channel arrangement model and the SDCA for the IEEE 802.16 networks. In Section V, we give the performance evaluations of the SDCA and show the impact of the SDCA to the IEEE 802.16 networks. Finally, some concluding remarks are discussed in Section VI.

II. The IEEE 802.16 MAC Protocol

This section briefly summarizes the medium access control (MAC) protocol as standardized by the IEEE 802.16 Working Group, which provides system access, bandwidth allocation, connection establishment, and connection maintenance in detail. For a more complete and detailed presentation, refer to the IEEE 802.16 standards [20], [21], [22]. The IEEE 802.16 physical (PHY) layer requires equally radio link control (RLC), which is the capability of the PHY to transition from one burst profile to another. RLC begins with periodic BS broadcast of the burst profiles that have been chosen for the uplink and downlink. The particular burst profiles used on a channel are chosen based on a number of factors, such as rain region and equipment capabilities [27]. For ongoing ranging and power adjustments, the BS may transmit unsolicited ranging using ranging response (RNG-RSP) messages commanding the MSS to adjust its power or timing.

During initial ranging, the MSS also requests to be served in the downlink via a particular burst profile by transmitting its choice of downlink interval usage code (DIUC) to the BS. The BS commands the SS to use a particular uplink burst profile simply by including the appropriate burst profile Uplink Interval Usage Code (UIUC) with the SS's grants in UL-MAP messages. After initial determination of uplink and downlink burst profiles between the BS and a particular SS, RLC continues to monitor and control the burst profiles. The SS can use the ranging using ranging request (RNG-REQ) message to request a change in downlink burst profile.The channel measurements report request (REP-REQ) message shall be used by a BS to request SNR channel measurement reports. The channel measurement report response (REP-RSP) message shall be used by SS to respond to the channel measurements listed in the received REP-REQ.

IEEE 802.16 supports a frame-based transmission, in which the frame can adopt variable lengths. The frame structure for the orthogonal frequency division multiple access (OFDMA) PHY in time division duplex (TDD) mode as shown in Fig. 1. Each frame consists of a DL-subframe and an UL-subframe [24]. A DL-subframe consists of DL frame prefix to specify the modulation/coding (PHY mode), length of the DL-burst-1 and the broadcast MAC control messages i.e. DL and UL channel descriptor (DCD, UCD) define the characteristic of the physical channels. The DL-MAP defines the access to the DL channel, and the UL-MAP allocates access to the UL channel. The FCH is followed by one or multiple DL-bursts, which are ordered by their PHY mode. While the most robust one is transmitted first, the last burst has the highest PHY mode. Thus, the whole MAC frame is specified by the FCH and/or the DL-burst-1. The UL-subframe consists of contention intervals scheduled for initial ranging and bandwidth request purposes and one or multiple UL PHY transmission bursts, each transmitted from a different subscriber station (SS). Each UL PHY transmission burst contains only one UL-burst and starts with a preamble. The DL-MAP defines the access to the DL channel, and the UL-MAP allocates access to the UL channel.

The investigated IEEE 802.16a PHY uses OFDM with a 256 point transform, designed for NLOS operation in the 2–11

GHz frequency bands, both licensed and license exempt. TDD and FDD variants are defined. Typical channel bandwidths vary from 1.25 to 28 MHz. There are more optional air interface specifications, e.g. based on OFDMA with a 2048-point transform or based on single-carrier modulation [6], [39]. The finalization of the IEEE's 802.16-2004 standard improves the OFDM technology, which splits a given frequency into subcarriers. This lets operators transmit more signals over a given frequency with less likelihood of interference, a key factor in opening up unlicensed spectrum. IEEE 802.11 has a 64 OFDM physical layer, while IEEE 802.16 features a 256 OFDM architecture.

IEEE 802.16e [22], the mobility of cell selection refers to the process of an MSS scanning and/or ranging one or more BS in order to determine suitability, along with other performance considerations, for network connection or hand-over etc. MSS may incorporate information acquired from a MOB-NBR-ADV message to give insight into available neighbor BS for cell selection consideration [2], [23]. If currently connected to a serving BS, an MSS shall schedule scanning intervals or sleep-intervals to conduct cell selection for the purpose of evaluating MSS interest in hand-over to potential target BS [33].

However, IEEE 802.16 standard defines DL-subframe and UL-subframe that determine the downlink and uplink channel allocation, described above such as DL-MAP and UL-MAP, but it does not define how to allocate these huge channels efficiently for enhancing the maximum capacity of SS and MSSs. In WMAN we will consider the whole above facts and the mobility of each handset to prevent it out of service. In the next section we will investigate how the SDCA affects network performance in the IEEE 802.16 WMAN.

III. The Signal Estimation

As we discuss above, the maximum transmission distance is proportioned inversely to the frequency which the MSS carries. By a pre-planned channel allocation model based on this property, the BS can assign a proper channel to a MSS for communication according to the distance between the BS and the MSS. The distance can be obtained by using the well-known global positioning system (GPS) [31]. However, applying the GPS will cost the prime cost of the implementation of the mobile communication devices and reduce the possibility of implementation to market. Besides, more important, the obtained distance is not sufficient to determine an appropriate channel for allocation since the system still lacks the environment parameters such as the path loss, the multipath fading, the figure noise, and the antenna gain etc. To overcome this problem, we propose a signal-aware dynamic channel allocation (SDCA) scheme based on the received SNR value of signal arriving the BS from the MSS, which is a measured value from the PHY, to estimate how far the MSS to the BS and select a proper channel to allocate to the MSS.

The power received from a transmitter at a separation distance d directly impacts the SNR, which the desired signal level is represented in received power P_r and is derived by

$$P_r = \frac{P_t G_t G_r}{\mathrm{PL}(d) L} \ [\text{Valid if } d \gg 2D^2/\lambda], \tag{1}$$

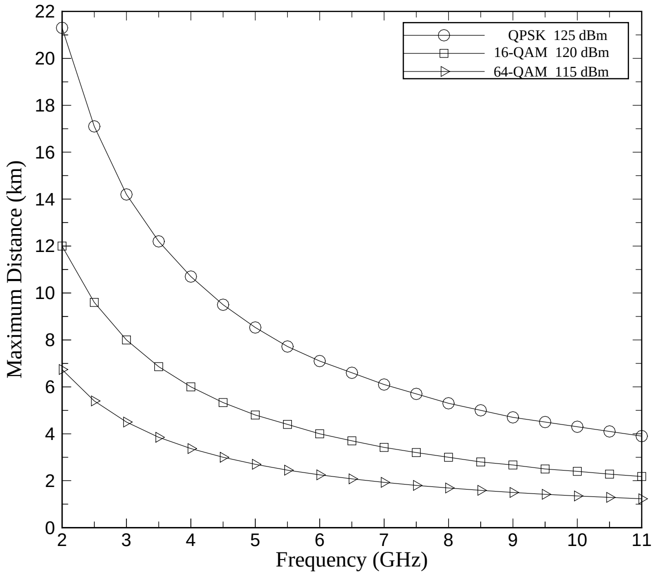

Fig. 1. Maximum transmission distance versus frequency domains from 2 GHz to 11 GHz in OFDM with different modulation schemes.

where P_t is the transmitted power, G_t and G_r are the transmitter and receiver antenna gains, $\mathrm{PL}(d)$ is the path loss (PL) with distance d, L is the system loss factor ($L \geq 1$, transmission lines etc., but not due to propagation), D is the maximum dimension of transmitting antenna, and λ is the corresponding wavelength of the propagating signal [36]. The measurement unit of P_r is milliwatt (mW). The antenna gain G is equal to $4\pi A_e/\lambda^2$; A_e is the effective aperture of antenna. The length of λ can be obtained by $c/f = 3 \times 10^8/f$ in meters where f is the frequency the signal carries. Besides, the P_r can be represented in dBm units as

$$\begin{aligned} P_r[\text{dBm}] &= 10\log(P_r[\text{mW}]) \\ &= P_t + G_t + G_r - \mathrm{PL}(d) - L. \end{aligned} \tag{2}$$

In the free space propagation model, the propagation condition is assumed idle and there is only one clear line-of-sight (LOS) path between the transmitter and receiver. On unobstructed LOS path between transmitter and receiver, the PL can be evaluated as

$$\mathrm{PL}(d) = \frac{(4\pi)^2 d^2}{\lambda^2} \tag{3}$$

or when powers are measured in dBm units

$$\mathrm{PL}(d) = 92.4 + 20\log(f) + 20\log(d). \tag{4}$$

From equation (3), we can get the desired T-R separation distance in meters

$$d = \frac{\lambda}{4\pi}\sqrt{\mathrm{PL}(d)} = \frac{c}{4\pi f}\sqrt{\mathrm{PL}(d)}. \tag{5}$$

However, different modulation schemes such as quadrature phase shift keying (QPSK), 16 quadrature amplitude modulation (16-QAM) or 64-QAM have different maximum PL values [35]. These values are 125 dB for QPSK, 120 dB for 16-QAM and 115 dB for 64-QAM and will impact the calculations of distance. Fig. 1, calculated from equation (4), shows the relation of the frequency and the distance between two isotropic antennas with different modulation schemes in detail. We can see that a higher frequency will lead to a shorter transmissible distance and vice versa. Furthermore, a higher modulation scheme such as 64-QAM requires lower PL ratio and thus achieves an overall shorter transmission distances than lower modulation schemes if the transmission power is fixed.

Nevertheless, this equation can not be applied in street canyon scenario or urban environment. A general PL model that has been demonstrated through measurements uses parameter σ to denote the rule between distance and received power [3]. The $\mathrm{PL}(d)$ in realistic environment can be expressed as

$$\mathrm{PL}(d) = \mathrm{PL}(d_0) + 10\rho\log(\frac{d}{d_0}) + X_\sigma + C_f + C_h; \quad d \geq d_0, \tag{6}$$

where the term $\mathrm{PL}(d_0)$ is for the free-space PL with a known selection in reference distance d_0, which is in the far field of the transmitting antenna (typically 1 km for large urban mobile system, 100 m for microcell systems, and 1 m for indoor systems) and is measured by $\mathrm{PL}(d_0) = 20\log(4\pi d_0/\lambda)$. The term X_σ denotes a zero-mean Gaussian distributed random variable (with units in dB) that reflects the variation in average received power that naturally occurs when PL model of this type is used [15]. The ρ is the path loss exponent, where $\rho = 2$ for free space, and is generally higher for wireless channels. It can measured by $\rho = (a - bh_b + c/h_b)$, where a, b and c are constants for each terrain category. The numerical values for these constants is studied in [14] where h_b is the height of the base station and is 10 m $\leq h_b \leq$ 80 m. The term C_f is the frequency correction factor, accounts for a change in diffraction loss for different frequencies which a simple frequency dependent correction factor C_f due to the diffraction loss, and measured by $C_f = 6\log(f/1900)$ [12]. The C_h is the receiver antenna height correction factor and h is the receiver antenna height. The $C_h = -10.7\log(h/2)$ when 2 m $\leq h \leq$ 8 m. This correction factor closely matches the Hata-Okumura mobile antenna height correction factor for a large city [16]. The mostly NLOS conditions, doubling the receiver antenna height results in approximately 3.5 dB decrease in path loss.

As we know that the audio or video quality of a receiver is directly related to the SNR; the greater the SNR is, the better the reception quality is. The limiting factor on a wireless link is the SNR required by the receiver for useful reception

$$\mathrm{SNR(dB)} = P_r(\mathrm{dBm}) - N_o(\mathrm{dBm}), \tag{7}$$

where $N_o(\mathrm{dBm})$ is the noise power in dBm. Assume the carrier bandwidth is B, the receiver noise figure is F, the spectral efficiency is r_b/B, and the coding gain is G_c. Then the SNR for coded modulation with data rate r_b can be obtained by

$$\mathrm{SNR(dB)} = 10\log\left(\frac{P_r}{N_o}\cdot\frac{r_b}{B}\right) - G_c, \tag{8}$$

where

$$N_o(\mathrm{dBm}) = -174(\mathrm{dBm}) + 10\log B + F(\mathrm{dB}) \tag{9}$$

and G_c is normally considered as 5 dB. The noise might consist of thermal noise generated in the receiver, co-channel or adjacent channel interference in frequency division or time division multiple access systems, or multiple access interference in code division multiple access spread spectrum systems.

IV. The Signal-Aware Dynamic Channel Allocation Scheme

A. The Measured SNR

As we discuss the SNR value in previous section, the SNR value is affected by the transmitted power and the frequency it carries. In order to obtain a criterion measurement of the received SNR, we enforce each MSS which has packets to transmit has to use the lowest frequency to contend the channel access right during the uplink contention period with a pre-defined transmission power. The reason we consider the channel of lowest frequency as the *contention channel* is that we want to ensure that each MSS can communicate with the BS even if it is in the boundary of the macrocell since the lowest frequency can get the maximum transmissible distance.

The BS, after receiving a RNG-REQ message from the MSS, calculates the estimated distance between BS and MSS according to the received SNR value. Assume the BS needs a necessary received minimum power or sensitivity $P_{r,\min}$ from each MSS, which corresponds to a minimum required SNR value denoted as $\mathrm{SNR}_{r,\min}$, to successfully receive the signal. Then, according to equations (2) and (7), we have

$$\begin{aligned}\mathrm{SNR}_{r,\min} &= P_{r,\min} - N_o \\ &= P_t + G_t + G_r - \mathrm{PL}(d) - L - N_o.\end{aligned} \tag{10}$$

Substituting (6) in (10) leads to

$$\begin{aligned}\mathrm{SNR}_{r,\min} &= P_t + G_t + G_r - 20\log\left(\frac{4\pi d_0 f}{c}\right) \\ &\quad - 10\rho\log\left(\frac{d}{d_0}\right) - X_\sigma \\ &\quad - C_f - C_h - L - N_o \\ \Rightarrow 10\rho\log\left(\frac{d}{d_0}\right) &= P_t + G_t + G_r - 20\log\left(\frac{4\pi d_0 f}{c}\right) - X_\sigma \\ &\quad - C_f - C_h - L - \mathrm{SNR}_{r,\min} - N_o.\end{aligned} \tag{11}$$

Solving equation (11) for maximum transmission distance d denoted as $d_{\max}$, then we obtain

$$\begin{aligned}d_{\max} = d_0 \times 10\exp\bigg\{&\bigg[P_t + G_t + G_r - 20\log\left(\frac{4\pi d_0 f}{c}\right) \\ &- X_\sigma - C_f - C_h - L - \mathrm{SNR}_{r,\min} - N_o\bigg]/10\rho\bigg\}.\end{aligned} \tag{12}$$

In the following, for instance, we use the 64-QAM modulation scheme to compare the relations of the transmission power, the maximum transmission distance, and $\mathrm{SNR}_{r,\min}$, respectively. Fig. 2 shows the comparisons of the transmission power with the maximum transmissible distance in detail. We can see that the required transmission power is proportionally

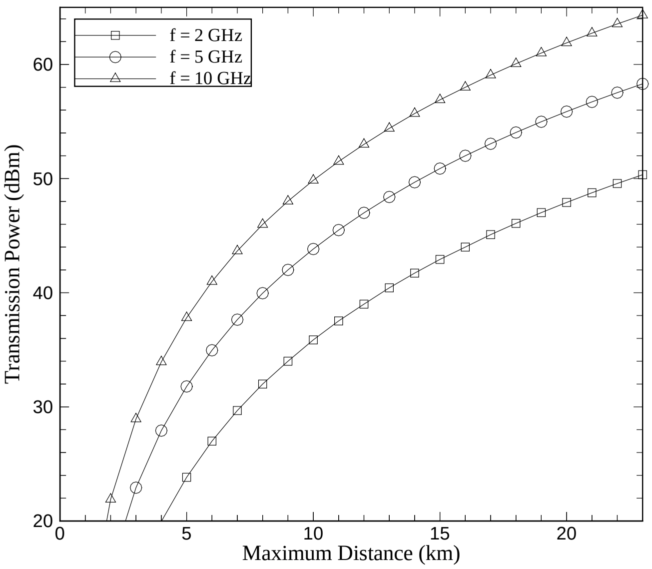

Fig. 2. Transmission power versus maximum distance when σ = 4, B = 20 MHz, coding rate = 3/4, SNR$_{r,\min}$ = 24.4 dB, F = 7, G_t = 15, G_r = 18, L = 5 dB.

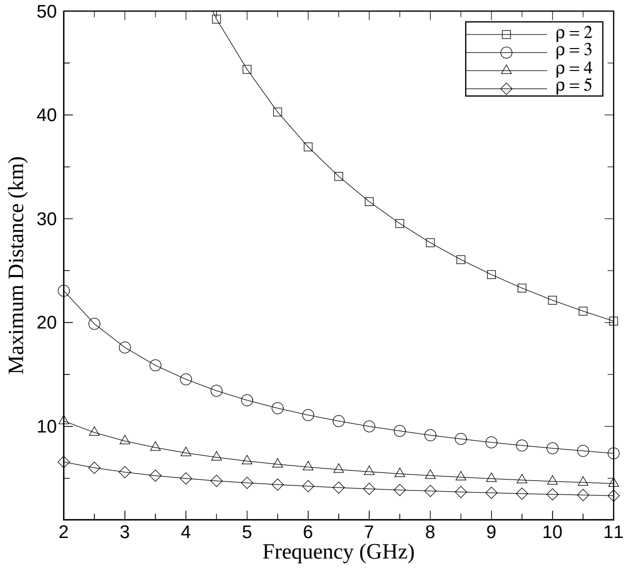

Fig. 3. Maximum transmission distance versus frequency when B = 20 MHz, coding rate = 3/4, SNR$_{r,\min}$ = 24.4 dB, F = 7, G_t = 15, G_r = 18, P_t = 15 W, L = 5 dB.

increasing with the maximum transmission distance. Meanwhile, a lower frequency, 2 GHz in this example, will get lower power consumption than that of higher frequencies. This implies that the power consumption can be further minimized if the MSS adjusts the transmission power according to the assigned channel to its current geographical location.

Fig. 3 compares the maximum transmission distance with different frequencies under different ρ when applying the fixed transmission power and antenna gain. We can see that higher frequencies will lead to shorter transmission distances and vice versa. We also note that the maximum transmission distance will be shorter when in urban environment (higher ρ). This implies that the scale of the macrocell is affected by different areas and can be adjust by system operators according to the environment. Fig. 4 shows the comparison of the maximum transmission distance with the measured SNR$_{r,\min}$ of the BS. When vary the SNR$_{r,\min}$ of the receiver, the achievable maximum transmission distance will proportionally decrease with increasing the required SNR$_{r,\min}$. The maximum transmission distance can also be achieved by adopting a higher sensitive receiver of the BS.

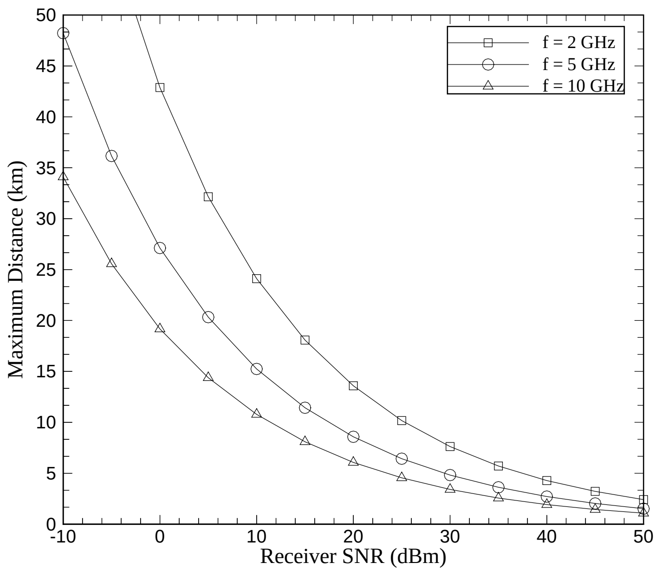

Fig. 4. Maximum distance versus receiver SNR when σ = 4, B = 20 MHz, coding rate = 3/4, F = 7, G_t = 15, G_r = 18, P_t = 15 W, L = 5 dB.

B. Channel Provisioning

Now we want to solve how to determine the scale of a macrocell and allocate channels in the macrocell accordingly, which can reflect the actual size of each section in the macrocell. Assume k independent discrete spectrum sections are available in a marcocell and are represented as $S_1, S_2, \ldots, S_k$. The total available bandwidth of these spectra will be $S = S_1 + S_2 + \ldots + S_k = \sum_{i=1}^{k} S_i$. If each channel has bandwidth B, the available number of channels in each spectrum section is given by

$$n_i = \left\lfloor \frac{S_i}{B} \right\rfloor, \; i \in \{1, 2, \ldots, k\}. \tag{13}$$

Thus, we have a total number of available channels $N = \sum_{i=1}^{k} n_i$ for usage.

Assume the BS has the omnidirectional antenna and a number of MSSs M are randomly distributed in a macrocell. Before assigning channels to the macrocell, we have to determine how to allocate an efficient number of channels for utilization according to the fraction of related measure of area so that each area has enough number of channels for use. Assume the macrocell is divided into h concentric circles and the width of each section created by these concentric circles is w as shown in Fig. 5. Thus the area size of the i-th concentric

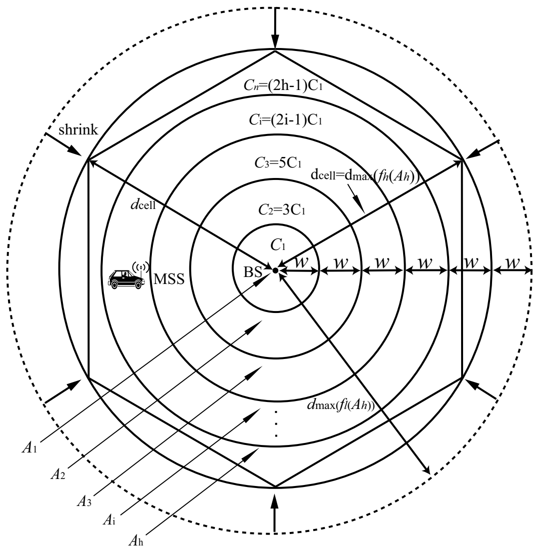

Fig. 5. An illustration of channel arrangement within the macrocell in a three-dimensional way. The channel allocation is from highest frequency to lowest frequency and is started from the inner side of the marcocell (the left side of the figure).

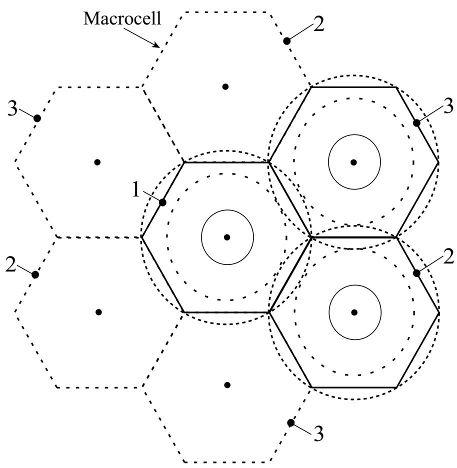

Fig. 6. An illustration of single macrocell coverage. The demonstration of a super macrocell arrangement. The number of each macrocell is denoted as a different identification of C_h, which is reserved to avoid interference and co-channel effect with each other.

circle $D_i = (iw)^2\pi$ and the area size of the i-th section denoted as A_i is given by

$$\begin{aligned} A_i &= D_i - D_{i-1} \\ &= (iw)^2\pi - [(i-1)w]^2\pi \\ &= (iw)^2\pi - \sum_{j=1}^{i-1} A_j \\ &= (2i-1)\pi w^2. \end{aligned} \tag{14}$$

For example, the area size of $A_2 = (2\times 2-1)\pi w^2 = 3\pi w^2$ and $A_3 = 5\pi w^2$. From (14), we can observe that the ratio of the i-th section's area size to the first section's area size is $A_i = (2i-1)A_1$.

Suppose MSSs are randomly and normally distributed in the macrocell, the channel allocation can follow the ratio of A_i to A_1 accordingly. Consequently, the the number of channels in each A_i denoted as C_i will be $(2i-1)C_1$. According to the characteristic of transmission distance increasing proportionally with a decreasing frequency, we allocate available channels in accordance with the highest to the lowest frequency channels from the inner to the outer side of the macrocell. Then we have $C_1, C_2, \ldots, C_h$ and $C_2 = 3C_1$, $C_3 = 5C_1$ and so forth as shown in Fig. 5. However, MSSs in the outer side of the macrocell will lead to the co-channel effect on these MSSs in the outer side of neighboring macrocell if we allocate same frequencies in the A_h. To tackle this problem, we reserve three times C_h channels for allocation in different neighboring macrocells so that neighboring A_h will have different frequencies for transmission as shown in Fig. 6. Deducting the contention channel ($C_0 = 1$) from N, the allocated channels satisfy

$$C_1 + C_2 + \ldots + C_{h-1} + 3C_h \le N-1 \tag{15}$$

To solve equation (15) for h, we have

$$\begin{aligned} &\sum_{i=1}^{h} C_i + 2C_h = \Big\{\sum_{i=1}^{h}(2i-1) + 2(2h-1)\Big\}C_1 \le N-1 \\ \Rightarrow&\Big\{\frac{[1+(2h-1)]h}{2} + 2(2h-1)\Big\}C_1 \le N-1 \\ \Rightarrow&(h^2+4h-2)C_1 \le N-1 \\ \Rightarrow&h \le \sqrt{\frac{N-1}{C_1}+6} - 2, \end{aligned} \tag{16}$$

and the upper bound of h is equal to

$$h = \left\lfloor \sqrt{\frac{N-1}{C_1}+6} - 2 \right\rfloor. \tag{17}$$

Now we have another problem to solve, that is, how long the radius of a macrocell d_{cell} will be. According to equation (12) and the environment's parameters, we can determine the maximum transmissible distance $d_{\max}$ as the d_{cell} easily. However, considering the mobility of MSSs, the MSS may easily move out the radio service range and lead to out-of-service effect if we allocate channels from high to low frequencies and start from the inner side of the macrocell. To overcome this problem, we use the maximum transmissible distance of the highest frequency of the A_h denoted as $f_h(A_h)$ as the macrocell's radius. The $f_h(A_h)$ can be obtained by

$$f_h(A_h) = f_{\text{high}} - \big((h-1)^2C_1 + 1\big)B, \tag{18}$$

where f_{high} is the highest frequency of the system and $((h-1)^2C_1+1)B$ is the summation of allocated channels' bandwidth from A_1 to A_{h-1}. Substituting (18) in (12), we can have the boundary of macrocell d_{cell} as

$$\begin{aligned} d_{\text{cell}} = d_0 \times 10\exp\Bigg\{\Bigg[&P_t + G_t + G_r \\ &- 20\log\left[\frac{4\pi d_0\big(f_{\text{high}} - ((h-1)^2C_1+1)B\big)}{c}\right] \\ &- X_\sigma - C_f - C_h - L - \text{SNR}_{r,\min} - N_o\Bigg]/10\rho\Bigg\}. \end{aligned} \tag{19}$$

We note that the boundary of the macrocell is shrunk from $d_{\max}(f_l(A_h))$ to $d_{\max}(f_h(A_h))$ to avoid out-of-service effect in the section. If the macrocell is divided into h sections with equal width w, according to (17), the width of each section will be

$$w = \frac{d_{\text{cell}}}{h}. \tag{20}$$

Once the channel C_1 is determined, channels of each area will be determined accordingly. However, how to determine the size of C_1 is an open issue for discussion. From (17), we have $h \propto 1/C_1$, that is, the h will be smaller if the C_1 is set larger. This will lead to bigger sections in the macrocell and, unfortunately, get unprecise frequency allocation. This drawback would not save the power consumption efficiently further and is discussed below.

Assume a MSS i wants to communicate, it should send a RNG-REQ message to the BS with a specified P_t in the contention channel C_0. The BS receives this request message and corresponding measured $\text{SNR}_{r,\min}$ and then estimates the distance $d_{\max,i}$ according to (12). The MSS i can be determined in the j-th section by the following equation:

$$j = \left\lceil \frac{d_{\max,i}}{w} \right\rceil. \tag{21}$$

Please note that the maximum transmission distances of frequencies in A_1 may exceed the boundary of A_1 if it use the specified P_t. This is because that we estimate the distance between the BS and the MSS by using lowest frequency and the specified P_t and then allocate the corresponding channel to the MSS for communication. If the MSS use a higher frequency with the specified P_t, the transmissible distance will exceed the distance of the location of the MSS to the BS. This implies that the transmission power can be minimized further. From (10) and (11), we can have the minimum transmission power of a MSS i

$$\begin{aligned} P_t &= \text{SNR}_{r,\min} + N_o + \text{PL}(d) + L \\ &= \text{SNR}_{r,\min} + N_o - G_t - G_r + 20\log\left(\frac{4\pi d_0 f_a}{c}\right) \\ &\quad + 10\rho\log\left(\frac{d_{\max,i}}{d_0}\right) + X_\sigma + C_f + C_h + L, \end{aligned} \tag{22}$$

where f_a is the assigned frequency by the BS. Besides, if we allocate channels according to this rule, a few lower frequency channels may not be allocated. We reserve these channels for prospective dynamic allocations when traffic load is heavy.

Let R_i^{cb} represent the transmission request from MSS i on channel c with request bandwidth b and the total request set $\mathcal{R} = \{R_{i1}^{cb}, R_{i2}^{cb}, \ldots, R_{im}^{cb}\}$. Assume the channel set $\mathcal{C} = \{c_1, c_2, \ldots, c_n | \ 1 \le n \le N\}$ and its precedent occupied bandwidth of c_n is denoted as b_n where $0 \le b_n \le B$. The detailed SDAC algorithm is shown in Fig. 7. The time complexity of the SDAC is $O(n)$ where $n = (2j-1)C_1$ is the number of channels in A_j. This implies that the SDAC is easy to be implemented and can select a channel for MSS rapidly.

SIGNAL-AWARE DYNAMIC CHANNEL ALLOCATION

BEGIN
  if receive a R_i^{cb} with measured $\text{SNR}_{r,\min}$ from MSS i **then**
    estimate the $d_{\max,i}$ and refer to its correspondent A_j;
    Repeat until find a channel for allocation
      check all channels c_n in A_j from high to low frequency;
        if $b_n + b_i \le B$ **then**
          allocate c_n for MSS i;
          $b_n \leftarrow b_n + b_i$;
        endif
      if cannot find an available channel **then**
        random select a channel for allocation;
      endif
    END Repeat;
  endif
END

Fig. 7. The algorithm of SDCA in the BS.

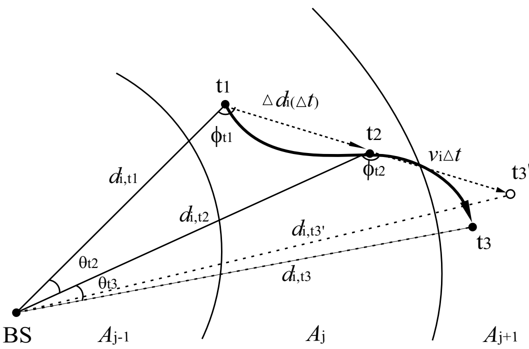

Fig. 8. An illustration of mobility.

C. The Mobility

In the following, we will discuss the mobility of the MSS in detail. To prevent the out-of-service effect of MSSs due to mobility, we investigate a location prediction scheme to add to the SDCA for channel migration. The IEEE 802.16 Standard [20] recommends that the BS has to broadcast a REP-REQ message to all MSSs for channel measurements within 10 seconds to check whether the MSS is still in the service set. Therefore, the BS can get the SNR value by the replied REP-RSP message from each MSS to estimate the distance periodically.

Thus, shown in Fig. 8, the movement distance between time t_1 and t_2 of MSS i denoted as $\Delta d_i(\Delta t)$ can be calculated by using cosine theorem as

$$\Delta d_i(\Delta t) = \sqrt{d_{i,t_1}^2 + d_{i,t_2}^2 - 2d_{i,t_1}^2 d_{i,t_2}^2 \cos\theta_{t_2}}, \tag{23}$$

where the θ_{t_2} can be estimated by using smart antenna systems [26], [34] that employ antenna arrays coupled with adaptive signal-processing techniques at the BS. From (23), the average velocity v_i of the MSS i is given by $v_i = \Delta d_i(\Delta t)/\Delta t = \Delta d_i(\Delta t)/(t_2 - t_1)$.

To predict the maximum distance between the MSS i and the BS in time t_3 denoted as t_3', where $t_3' = t_2 + \Delta t$, we have to obtain the ϕ_{t_1}. According to cosine theorem, the ϕ_{t_1} is obtained by

$$\phi_{t_1} = \cos^{-1}\left(\frac{d_{i,t_1}^2 + (\Delta d_i(\Delta t))^2 - d_{i,t_2}^2}{2d_{i,t_1}\Delta d_i(\Delta t)}\right). \tag{24}$$

TABLE I

SYSTEM PARAMETERS IN SIMULATIONS

Parameters	Value
Frame length	20 ms
MPDU	1885 byte
Bandwidth (B)	5 MHz
F_s/B	7/6
$F_s = 7/6 \cdot 20$	5.833 MHz
(T_g/T_b)	1/4
$T_b = 256/F_s$	43.89 μs
OFDM symbol time,	
$T_{sym} = T_g + T_b$	54.86 μs
Modulation/code rate	64-QAM 3/4
$Carriers N_{FFT}$	256
Bit rate	16 Mb/s
SNR$_{r,\min}$	24.4 dB
Tx antenna gain (G_t)	16 dB
Rx antenna gain (G_r)	18 dB
Receiver noise figure (F)	7 dB

We simply suppose that each MSS moves forward directly. Then the moving distance can be estimated as $\Delta d'(t_3 - t_2) = \Delta d(\Delta t) = v_i \Delta t$. Therefore, the estimated distance at time t_3' will be

$$d_{i,t_3'} = \sqrt{d_{i,t_1}^2 + \left(\Delta d_i(\Delta t) + v_i \Delta t\right)^2} - \sqrt{2 d_{i,t_1}\left(\Delta d_i(\Delta t) + v_i \Delta t\right)\cos\phi_{t_1}}. \quad (25)$$

Substituting (24) in (25) we have

$$d_{i,t_3'} = \left(d_{i,t}^2 + 2 v_i \Delta t \sqrt{d_{i,t_1}^2 + d_{i,t_2}^2 - 2 d_{i,t_1} d_{i,t_2} \cos\theta_{t_2}} - \frac{v_i \Delta t \left(2 d_{i,t_1}^2 - 2 d_{i,t_2}^2 d_{i,t_2}^2 \cos\theta_{t_2}\right)}{d_{i,t_1}^2 + d_{i,t_2}^2 - 2 d_{i,t_1} d_{i,t_2} \cos\theta_{t_2}} + (v_i \Delta t)^2\right)^{1/2}. \quad (26)$$

Once the predicted distance $d_{i,t_3'} \geq wj$, i.e., the MSS might exceed the boundary of A_j, the BS will notice the MSS i to migrate to a new channel in A_{j+1} with the message (P_t', c_n'). Therefore, by using the prediction to prevent the out-of-service effect, the performance of the BWA system can be maintained well. Besides, the overhead of prediction will not be heavy since we only use the routine procedure of channel measurement, which is specified in the IEEE 802.16 standard, to get the information for estimation.

V. SIMULATION MODEL AND RESULTS

A. Simulation Model

In this section, in order to evaluate the performance of SDCA, we design a detailed simulation model as described in the following. We adopt the IEEE 802.16 MAC protocol as the data link layer protocol and the 64-QAM modulation model with 3/4 coding rate. Each channel's bandwidth is considered as 5 MHz and is operating in TDD mode. Each OFDM symbol time is evaluated a cyclic prefix of 1/4 of the useful time T_b and is chosen to deal with delay spread values for NLOS operation in suburban areas. We assume the initial transmission power of the BS is 300 mW. The maximum transmission power is limited to 450 mW. Other simulations parameters can be found in Table I.

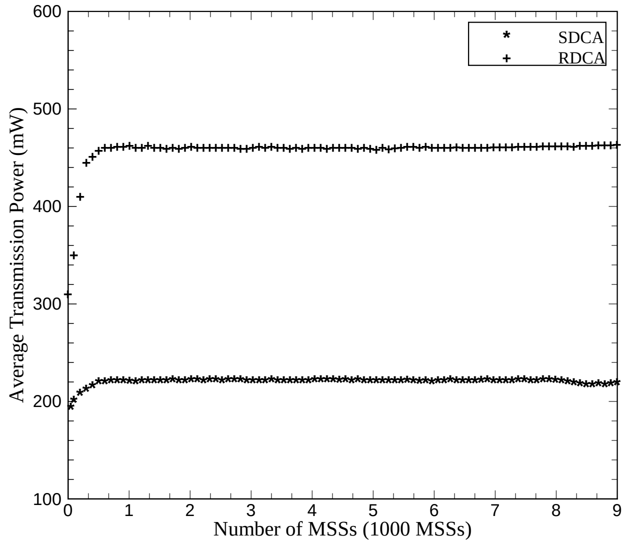

Fig. 9. The average transmission power versus the number of MSSs (M) when σ = 4, B = 5 MHz, coding rate = 3/4, SNR$_{r,\min}$ = 24.4 dB, F = 7, G_t = 16, G_r = 18, L = 5 dB.

There are 1800 channels are ranged in the spectrum from 2 to 11 GHz. The size of macrocell is fixed and has a 6 km radius, which is calculated from $P_t = 300$ mW, $B = 5$ MHz, $C_1 = 1$, and $f_h(A_h) = 3.39$ GHz. The width of each section is 150 m. All MSSs are randomly distributed in the macrocell through all simulations. The frame arrival rate of each MSS is a constant value and is set 2 frames/second. If a MSS is allowed to entry the system, the BS also has 2 frames/second data frames for the MSS. That is, each allowed MSS will occupy total 3 Mb/s bandwidth including the uplink and downlink bandwidth. Each MAC frame, MAC protocol data units (MPDUs), consists of a 6-byte MAC header, a 32-bit cyclic redundancy check (CRC), and a fixed 1875-byte length of MAC service data unit (MSDU) and equals to 20 ms. The MAC frame consists of four initial maintenance opportunities (UIUC=2) slots, 10 request contention opps (UIUC=1) slots. The transmit to receive (T_x/R_x) transition gap (TTG) and the R_x/T_x transition gap (RTG) are both 5.14 μs.

B. Simulation Results

To compare with SDCA, a random dynamic channel allocation (RDCA) scheme is used for comparison. Fig. 9 shows the average transmission power of MSSs by varying the number of MSSs M in SDCA and RDCA, respectively. From Fig. 9, we can see that the SDCA only consumes 47.83% transmission power than the RDCA. This is because that the RDCA adopts random fashion to allocate channel for MSSs and may choose a higher frequency for the MSS. This misarrangement may compel the MSS to use a higher power to communicate with the BS and leads to waste the battery power. On the contrary, SDCA allocates appropriate channels for MSSs according to their geographical locations in the macrocell and calculates a minimum transmission power to inform the MSS so that the overall battery consumption will be minimized. This outcome also indicates that the battery consumption can be minimized

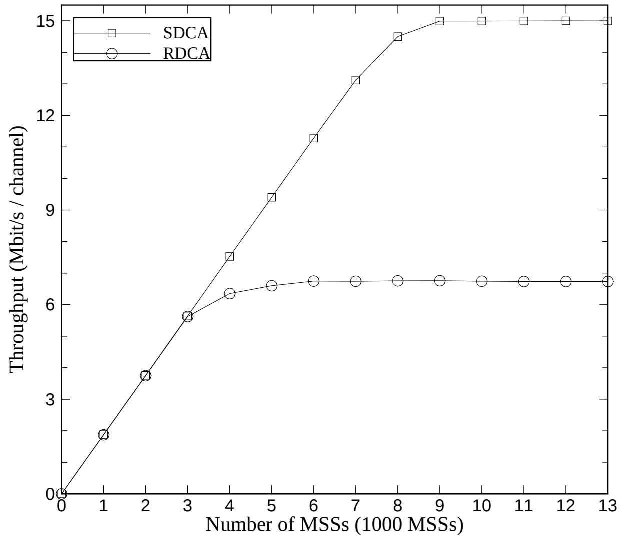

Fig. 10. The comparison of channel throughput dervied by SDCA and RDCA when number of MSSs nodes.

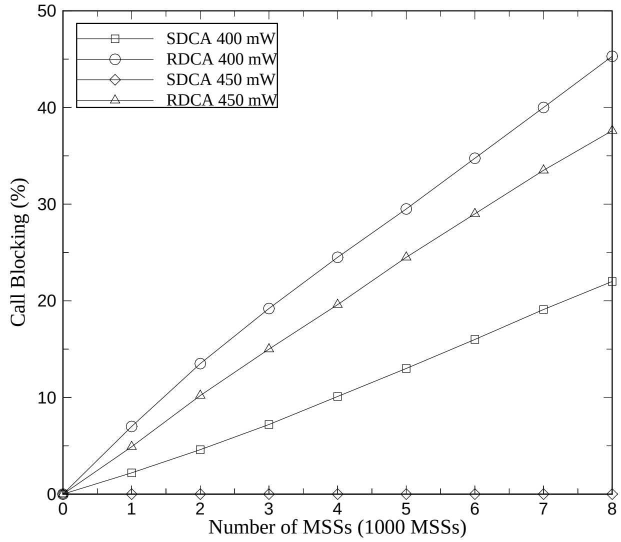

Fig. 11. The Call blocking ratio versus different number of MSSs under the maximum transmission power.

further if we can get the information of the distance and frequency of the MSS when designing the B3G or 4G systems.

Fig. 10 shows the throughput in each channel by using SDCA and RDCA, respectively. We can see that both the throughput of the SDCA and RDCA increase with increasing the number of MSSs. The throughput of SDCA reaches 15 Mb/s per channel (approximate $15/16.9 \times 100\% = 89\%$ throughput deducting the physical and MAC header) when $M = 9000$. This is because that the SDCA uses a moderate transmission power (300 mW) and the frequency $f_h(A_h) = 3.39$ GHz to pre-plan the macrocell's scale. Therefore, each MSS in the macrocell will be equally distributed and then get the higher throughput. Nevertheless, the RDCA only reaches 6 Mb/s per channel throughput when $M = 4000$ since it does not allocate channels according to positions. This will lead to higher call blocking ratio due to the limitation of maximum transmission power and may allocate many MSSs in one channel.

In this simulation, we want to investigate the call blocking ratio under different number of MSSs and different maximum transmission power. If the required transmission power exceeds the maximum transmission power of the MSS in the assigned frequency, the MSS will not reach the BS and encounters the call blocking. From Fig. 11, we can see that SDCA gets lower call blocking ratio than RDCA since the SDCA estimate the distance and the frequency as well as considering the transmission power well.

Finally, we extend the mobility model to vehicular environment (from 1 to 10 m/s). The mobility model uses the random way point model [4] in the macrocell field. Here, each MSS starts its journey from a random location to a random destination with a randomly chosen speed (uniformly distributed between 0–10 m/s). Once the destination is reached, another random destination is targeted after a pause. We vary the pause time, which affects the relative speeds of the mobiles. In the mobility model, we investigate the out-of-service effect by increasing the mobility. We randomly place 1000, 3000, and 5000 numbers of MSSs into the macrocell to observe the out-of-service effect. We can see that the out-of-service ratio increases with increasing the velocity of the MSS. However, the SDCA can control the out-of-service ratio in an acceptable value about 6.5%. From this result, we can see that the SDCA can support mobility well.

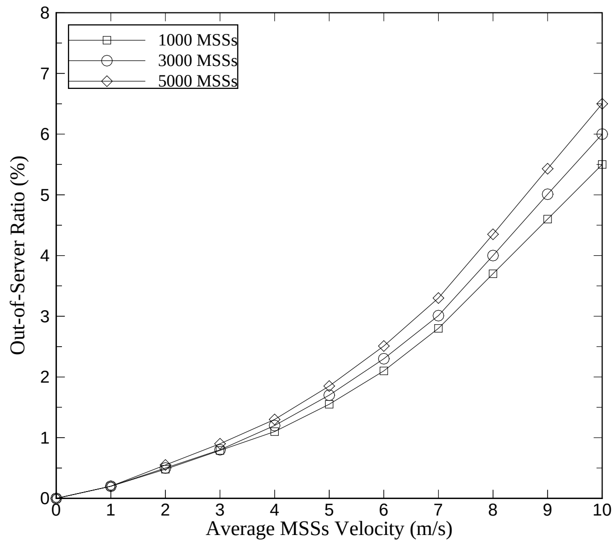

Fig. 12. The out-of-service ratio versus average velocity of the MSS when M = 1000, 3000, and 5000 by using SDCA.

VI. Conclusion

In this paper, we propose a signal-aware dynamic channel allocation (SDCA) to improve the channel utilization as well as to reduce the probability of out-of-service for the IEEE 802.16 networks. The relationship between the signal-to-noise ratio (SNR) by different modulation schemes and the maximum transmission distance is also introduced in this paper. According to received SNR value from the MSS, the BS can determine an adequate channel for allocation so that the channel is used more efficiently. Moreover, by adopting the SDCA, the power consumptions of the BS and MSSs are saved further since it allocates adequate channels for MSSs by considering the corresponding geographic locations. Simulation results show that the channel utilization can be improved by up to 89% over the original IEEE 802.16 standard specifications. Without a doubt, the SDCA is suitable for channel allocation in IEEE 802.16 networks. This result encourages us to apply this mechanism to increasing the capacity of the BWA system.

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