Traffic Modeling and Analysis of Wireless and Mobile Cellular Systems Using Smart Antennas

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ABSTRACT

As an efficient capacity enhancement technique, smart antenna has been introduced into wireless and mobile cellular systems. Since the traffic models for a wireless and mobile cellular system using smart antennas closely relate to users' space locations and the parameters of smart antennas, the conventional traffic models for a wireless and mobile cellular system using omnidirectional antennas are not suitable for the systems using smart antennas. In this paper, we propose and analyze two novel traffic models for two wireless and mobile cellular systems using smart antennas, which are switched-beam and adaptive beamforming systems, respectively. The handoff rates of a wireless and mobile cellular system using smart antennas are obtained and verified by simulations. Based on the obtained handoff rates, the performances of omnidirectional antenna systems, switched-beam systems, and adaptive beamforming systems are compared in terms of the blocking probabilities of originating calls and handoff calls.

Keywords: Traffic model, cellular system, smart antenna, handoff rate, blocking probability

1 Introduction

As an efficient capacity enhancement technique, smart antenna has been introduced to increase the capacity of a wireless and mobile cellular system [1]. Using smart antennas, base station (BS) transmits the signal to the desired mobile user (MU) with maximum gain, and minimizes the transmitted power to other MUs. It not only saves the transmission power, but also reduces the co-channel interference (CCI). Besides, it also drastically overcomes the delay spread and multipath fading. Therefore, it is a promising technique in future wireless and mobile cellular systems.

In general, there are two types of smart antennas, namely switched-beam antenna and adaptive beamforming antenna. Accordingly, there are switched-beam system and adaptive beamforming system (shown in Figure 1). In a switched-beam system, a cell is divided into a number of minisectors and each minisector is served by a narrow beam. A physical channel, such as a frequency, a time slot, a code or combination of them, can be reused in different minisectors if the CCI is tolerable. In an adaptive beamforming system, the BS can form multiple independent narrow beams to serve the MUs. In other words, two or more MUs which are not close to each other geometricly can be served by different beams. Therefore, the same physical channel can be assigned to two or more MUs in the same cell if the CCI among them is tolerable.

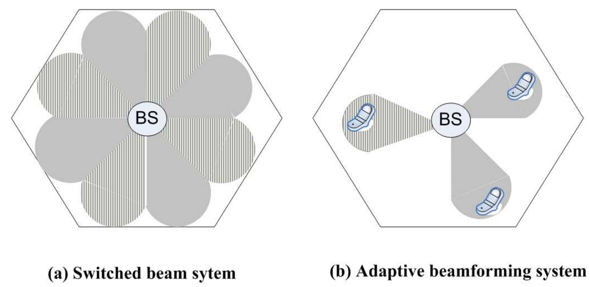

Figure 1: Types of wireless and mobile cellular system using smart antennas

Generally, there are two types of handoffs in a wireless and mobile cellular system, i.e., inter-cell handoff and intra-cell handoff. When an active MU moves from its current cell to an adjacent cell, an inter-cell handoff occurs. When an active MU's received signal quality deteriorates due to multipath fading problem etc., which makes current channel cannot support the ongoing communication, the MU needs to switch to another channel and an intra-cell handoff happens. An intra-cell handoff also occurs in a sectorized cell when an active MU moves across the boundary of two adjacent sectors in a cell.

A switched-beam system is similar to a sectorized system. In an adaptive beamfoming system, as described above, the same physical channel can be assigned to two or more MUs in a cell, simultaneously, if the CCI is tolerable. However, in a wireless and mobile cellular system using smart antennas, the deterioration of received signal will be caused not only by fading and noise, but also by a high CCI. As the angle separation between two MUs which use the same physical channels decreases or increases due to the mobility of MUs, the CCI increases or decreases. When the CCI is higher than predefined threshold, an intra-cell handoff happens. Either of the two MUs needs to hand current channel over to another. As the intra-cell handoff has different scenarios in wireless and mobile cellular systems using smart antennas, the traffic models of a system using conventional omnidirectional antennas cannot be adapted to analyze the cellular systems using smart antennas. Hence, new traffic models need to be established for a wireless and mobile cellular system using smart antennas. In our knowledgements, no work has been done on the traffic model in the wireless and mobile cellular systems using smart antennas. In this paper, we propose and analyze two novel traffic models for switched-beam and adaptive beamforming systems, respectively. Based on our proposed traffic models, we also analyze and compare the performance of the omnidirectional antenna, switched-beam, and adaptive beamforming systems in terms of the blocking probabilities of originating calls, intra-cell handoff calls, and inter-cell handoff calls.

This paper is organized as follows: In the next section, we describe and analyze two novel traffic models for wireless and mobile cellular systems using smart antennas. In Section 3, we analyze the performance of omnidirectional antenna, switched-beam, and adaptive beamforming systems in terms of blocking probabilities based on the traffic models in Section 2. Section 4 gives the numerical results and performance comparison of different wireless and cellular cellular systems. Finally, we conclude the paper in Section 5.

2 Traffic Models

We assume that the service area of a wireless and mobile cellular system is covered by many identical circular cells with radius R. MUs are uniformly distributed in each cell with a density ρ. MU moves with a random moving speed V which has a probability density function (pdf) $f_V(v)$. MU randomly moves in any directions with an equal probability in $[0, 2\pi)$. We assume that the channels are ideal which means the quality of received signal is stable in our proposed models. Since the system is assumed to have homogeneous cells, our analysis can focus on a single cell which is called the marked cell [2] [3].

2.1 Omnidirectional antenna system

Since the channel is assumed ideal, we do not consider the intra-cell handoff calls in a ominidirectioanl antenna system. There are only originating calls and inter-cell handoff calls in the cell. The two-dimensional fluid flow model assumes that the MUs are uniformly distributed in a cell and each MS is equally likely to move in any direction and the distribution of the moving speed of the MUs is arbitrary. Due to its simplicity and generality, we adapt fluid flow model in our analytical model. According to biased sampling theory in boundaries, the number of cell outgoing MUs with moving speed between v and $v + dv$ per unit time [4] [5] is given by

$$N_O = \frac{\rho L v f_V(v) dv}{\pi}, \quad (1)$$

where L is the perimeter of the cell. Therefore, the number of total cell outgoing MUs per unit time is given by

$$\begin{aligned} N_T &= \int_0^\infty \frac{\rho L v}{\pi} f_V(v) dv \\ &= \frac{\rho L}{\pi} E[V]. \quad (2) \end{aligned}$$

where $E[V]$ is the mean moving speed of the MUs.

We assume that the area of a cell is A. Therefore, the total number of MUs in a cell is $A\rho$. The cell outgoing rate μ of a MU is given by

$$\begin{aligned} \mu &= \frac{N_T}{\rho A} \\ &= \frac{E[V]L}{\pi A}, \quad (3) \end{aligned}$$

Equation (3) is noted that the cell outgoing rate is unrelated to the distribution of the moving speed of MU and the shape of the cell. It only depends on the MU's mean moving speed, the perimeter of a cell and the area of a cell. Since, in our analytical model, the cell is circular with radius R, the cell outgoing rate μ_{om_inter} of an omnidirectional antenna system is given by

$$\mu_{om\_inter} = \frac{2E[V]}{\pi R}. \quad (4)$$

Since the system is assumed to have homogeneous cells, the number of total cell outgoing MUs from a cell equals the number of total cell incoming MUs to the cell. In other words, the cell outgoing rate equals the cell incoming rate. Therefore, the inter-cell handoff rate λ_{om_inter} in an omnidirectional antenna system is given by

$$\lambda_{om\_inter} = E[C] \cdot \frac{2E[V]}{\pi R}, \quad (5)$$

where $E[C]$ is the mean number of active MUs in a cell.

2.2 Switched-beam system

In a switched-beam system, the cell can be divided into a number of identical minisectors. We assume that the beamwidth in a switched-beam system is θ_b and each minisector is served by a beam. When a MU moves across the boundary of two adjacent minisectors in a cell, an intra-cell handoff occurs.

According to the Equation (3), the minisector outgoing rate μ_{sw} of a MU in a minisector is given by

$$\begin{aligned} \mu_{sw} &= \frac{E[V]L_{sw}}{\pi A_{sw}} \\ &= \frac{2E[V](2+\theta_b)}{\pi R \theta_b}, \quad (6) \end{aligned}$$

where the perimeter L_{sw} and area A_{sw} of a minisector are given by

$$L_{sw} = 2R + \theta_b R = (2 + \theta_b)R \quad (7)$$

and

$$A_{sw} = \pi R^2 \cdot \frac{\theta_b}{2\pi} = \frac{\theta_b R^2}{2}, \quad (8)$$

respectively.

Since the minisector outgoing MUs for each minisector consists of the outgoing MUs across the boundary between adjacent minisectors towards adajacent minisectors and outgoing MUs across the cell boundary to neighboring cell, we decompose the minisector outgoing rate as intra-cell outgoing rate and inter-cell outgoing rate. Since the length of the cell boundary for each minisector is $\theta_b R$ and the length of the boundary between adjacent minisecotrs within a cell is $2R$, the intra-cell minisector outgoing rate is given by

$$\begin{aligned}\mu_{sw\_intra} &= \mu_{sw} \cdot \frac{2R}{2R+\theta_b R} \\ &= \frac{4E[V]}{\pi R \theta_b}\end{aligned} \quad (9)$$

and the inter-cell minisector outgoing rate is given by

$$\begin{aligned}\mu_{sw\_inter} &= \mu_{sw} \cdot \frac{\theta_b R}{2R+\theta_b R} \\ &= \frac{2E[V]}{\pi R}.\end{aligned} \quad (10)$$

We can see that the inter-cell minisector outgoing rate in a switched-beam system is the same as that in an omnidirectional antenna system. We assume that the mean number of active MUs in each minisector is $E[C_s]$. Thus, the intra-cell handoff rate λ_{sw_intra} for each minisector is given by

$$\lambda_{sw\_intra} = E[C_s] \cdot \frac{4E[V]}{\pi R \theta_b}. \quad (11)$$

The inter-cell handoff rate λ_{sw_inter} for each minisector in the switched-beam system is given by

$$\lambda_{sw\_inter} = E[C_s] \cdot \frac{2E[V]}{\pi R}. \quad (12)$$

2.3 Adaptive beamforming system

In a wireless and mobile cellular system which uses adaptive beamforming technique, we assume that the beamwidth is θ_b. We further assume that θ_b is the minimum separation angle between two MUs if they use the same physical channel. The ongoing communication has to be terminated if the separation angle is less than θ_b. Therefore, an intra-cell handoff occurs when the separation angle between two MUs using the same physical channel is less than θ_b.

The traffic model for an adaptive beamforming system is different from the traffic model of a switched-beam system. In the switched-beam system, there is a fixed boundary between two adjacent minisectors and an intra-cell handoff occurs when an active MU moves across the boundary. However, there is no fixed boundary in an adaptive beamforming system. Therefore, we need to find when an intra-cell handoff happens.

We assume that two individual MUs, MU1 and MU2 shown in Figure 2, which hold the same physical channel but with different beam areas within the same cell. The intra-cell handoff happens when MU2 moves across the boundary which has separation angle θ_b to MU1 (thick line shown in Figure 2). The boundary which has separation angle θ_b to MU1 can be seen as the intra-cell handoff boundary. In the following analysis, we apply relative moving speed into the flow fluid model to obtain the outgoing rate of the MUs [6].

Let the velocity of MU1 be $\overrightarrow{\mathbf{V_1}}(V_1, \Phi_1)$, where V_1 (random number) is the moving speed and Φ_1 (random number) is the moving direction, respectively. Similarly, let the velocity of MU2 be $\overrightarrow{\mathbf{V_2}}(V_2, \Phi_2)$, where V_2 (random number) is the moving speed and Φ_2 (random number) is the moving direction, respectively. MU1 and MU2 follow the same distribution of moving speed and the same distribution of moving direction. Let $f_{V_i}(v)$ be the pdf of the moving speed V_i of MUi and $f_{\Phi_i}(\phi)$ be the pdf of the moving direction Φ_i of MUi $((i = 1, 2))$. The moving speed $\overrightarrow{\mathbf{V_r}}$ of MU2 relative to MU1 is given by

$$\overrightarrow{\mathbf{V_r}} = \overrightarrow{\mathbf{V_2}} - \overrightarrow{\mathbf{V_1}}. \quad (13)$$

The magnitude of $\overrightarrow{\mathbf{V_r}}$ is given by

$$V_r = \sqrt{V_1^2 + V_2^2 - 2V_1V_2\cos(\Phi_1 - \Phi_2)}. \quad (14)$$

Therefore, the mean value of V_r is given by

$$\begin{aligned}E[V_r] &= \int_{V_{min}}^{V_{max}}\int_{V_{min}}^{V_{max}}\int_0^{2\pi}\int_0^{2\pi} v_r f_{V_1,V_2,\Phi_1,\Phi_2}(v_1,v_2,\phi_1,\phi_2) \\ &\quad d\phi_1 d\phi_2 dv_1 dv_2,\end{aligned} \quad (15)$$

where $f_{V_1,V_2,\Phi_1,\Phi_2}(v_1,v_2,\phi_1,\phi_2)$ is the joint pdf of the random variables V_1, V_2, Φ_1, and Φ_2, V_{min} and V_{max} are minimum and maximum moving speeds of MUs, respectively. Since moving speed and moving direction are independent, Equation (15) can be rewritten as,

$$\begin{aligned}E[V_r] &= \frac{1}{\pi^2}\int_{V_{min}}^{V_{max}}\int_{V_{min}}^{V_{max}} (v_1+v_2)F_e(\frac{2\sqrt{v_1v_2}}{v_1+v_2}) \\ &\quad \cdot f_{V_1}(v_1)f_{V_2}(v_2)dv_1dv_2,\end{aligned} \quad (16)$$

where

$$F_e(x) = \int_0^1 \sqrt{\frac{1-x^2t^2}{1-t^2}}dt \quad (17)$$

is a complete elliptic integral of second kind. If given the distribution of the moving speed of MUs, $E[V_r]$ can be calculated in numerical ways.

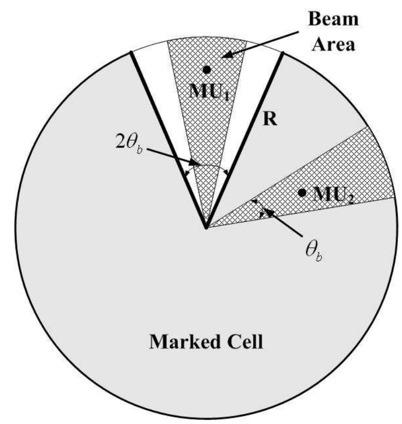

Figure 2: Calculation of intra-cell outgoing rate in the adaptive beamforming system

The area of handoff region is

$$A_{ad} = \pi R^2 \frac{2\pi - 2\theta_b}{2\pi} = (\pi - \theta_b) R^2. \quad (18)$$

According to Equation (3), the intra-cell beam outgoing rate μ_{ad_intra} in an adaptive beamforming system is given by

$$\mu_{ad\_intra} = \frac{2E[V_r]}{\pi R(\pi - \theta_b)}. \quad (19)$$

The average rate of intra-cell handoff calls in the cell is dependent on the number of active MUs who reuse the same physical channels in the cell. It must be handled according to the different state of the cell (the number of active MUs, the number of allocated channels etc.). Therefore, the average arrival rate λ_{ad_intra} of intra-cell handoff calls in a cell is given by

$$\lambda_{ad\_intra} = E[C_a] \cdot \frac{2E[V_r]}{\pi R(\pi - \theta_b)}, \quad (20)$$

where $E[C_a]$ is the average number of active MUs who reuse the same physical channels.

If the average number of active MUs in a cell is $E[C]$, the inter-cell handoff rate λ_{ad_inter} is given by Equation (5).

3 System Models and Performance Analysis

In order to compare the performance of omnidirectional antenna, switched-beam, and adaptive beamforming systems, we assume that S physical channels are allocated to each cell. The average arrival rate of originating calls in a cell is equal to λ_O. The performance of omnidirectional antenna, switched-beam, and adaptive beamforming systems will be compared in terms of the blocking probabilities of originating calls, intra-cell handoff calls, and inter-cell handoff calls.

Since the assumption of exponential distribution is reasonable for call holding time and cell/minisector dwell time by some field data [7]. This assumption also makes the analysis more tractable. Therefore, we also adapt this in our analytical model.

3.1 Omnidirectional antenna system

In an omnidirectional antenna system, there are S channels available in each cell. There are originating calls and inter-cell handoff calls in an omnidirectional antenna system only. Due to ideal channel is assumed, we do not consider the intra-cell handoff calls in ominidirectional antenna system. The originating calls and inter-cell handoff calls are handled in the same way. When an originating call or an inter-cell handoff call is generated, the BS always assigns a free channel to the MU if there is any available channel in the cell. If there is no free channel in the cell, the call will be blocked. The average arrival rate of calls in each cell is $\lambda_O + \lambda_{om\_inter}$, where λ_{om_inter} is given in Equation (5). The rate that the MUs release their channels is equal to $\mu_{om\_inter} + \mu_c$, where μ_{om_inter} is given in Equation (4) and μ_c is the reciprocal of average call holding time. Therefore, a simple $M/M/m$ queuing system model can be applied to calculate the blocking probability of originating calls or inter-cell handoff calls in an omnidirectional antenna system. The blocking probability of originating calls or inter-cell handoff calls equals the probability that all the channels are busy when an originating call or an inter-cell handoff call is generated. Therefore, the blocking probability B_{om} of originating calls or inter-cell handoff calls is given by

$$B_{om} = \frac{\frac{a_{om}^S}{S!}}{\sum_{i=0}^{S} \frac{a_{om}^i}{i!}}, \quad (21)$$

where a_{om} is the offered traffic and given by

$$a_{om} = \frac{\lambda_O + \lambda_{om\_inter}}{\mu_{om\_inter} + \mu_c}. \quad (22)$$

3.2 Switched-beam system

Since the same physical channel can be reused in different minisectors in a switched-beam system, the number of available channels increases compared to the omnidirectional antenna system. We assume that each physical channel can be allocated to two different minisectors. Therefore, there are total $2S$ channels available in each cell. As the beamwidth is θ_b, the number of available channels in each minisector is $\lfloor 2S \times \frac{\theta_b}{2\pi} \rfloor$. Besides the orginating calls and inter-cell handoff calls, there are intra-cell handoff calls in a switched-beam system. These calls are handled in the same way. When an originating call, an inter-cell handoff call, or an intra-cell handoff call, is generated, the BS allocates a free channel to the MU if there is any free channel in the minisector where the call is generated. If no free channel is available, the call will be blocked. Since the average arrival rate of originating calls in each minisector λ_{sector_O} equals $\frac{\lambda_O}{N}$, where N is the number of minisectors, the average arrival rate of all the calls in each minisector is $\lambda_{sector\_O} + \lambda_{sw\_inter} + \lambda_{sw\_intra}$, where λ_{sw_inter} is given by Equation (12) and λ_{sw_intra} is given by Equation (11). The average rate that the MUs release their calls is $\mu_c + \mu_{sw\_inter} + \mu_{sw\_intra}$, where μ_{sw_inter} is given by Equation (10), μ_{sw_intra} is given by Equation (9) and μ_c is the reciprocal of average call holding time. Similar to the omnidirectional antenna system, a $M/M/m$ queuing model, where m equals $\lfloor 2S \times \frac{\theta_b}{2\pi} \rfloor$, is applied to calculate the blocking probability of originating, inter-cell handoff, or intra-cell handoff calls in each minisector of the switched-beam system. The blocking probability of originating, inter-cell handoff, or intra-cell handoff calls in the switched-beam system is equal to the probability that all the channels are busy when an originating call, an inter-cell handoff call or an intra-cell handoff call is generated. The blocking probability B_{sw} of originating calls, intra-cell handoff calls, or inter-cell handoff calls is given by

$$B_{sw} = \frac{\frac{a_{sw}^m}{m!}}{\sum_{i=0}^{m} \frac{a_{sw}^i}{i!}}, \tag{23}$$

where a_{sw} is the mean of the offered traffic in each minisector and given by

$$a_{sw} = \frac{\lambda_{sector\_O} + \lambda_{sw\_inter} + \lambda_{sw\_intra}}{\mu_c + \mu_{sw\_inter} + \mu_{sw\_intra}}. \tag{24}$$

3.3 Adaptive beamforming system

In order to compare the performance of an adaptive beamforming system with a switched-beam system, we assume that one physical channel can be allocated to at most two MUs simultaneously. Therefore, there are at most $2S$ channels available in each cell in the types of systems. Similar to the switched-beam system, there are three types of calls in an adaptive beamforming system, i.e., originating calls, intra-cell handoff calls, and inter-cell handoff calls. However, the strategy of channel assignment is different. When an originating call, an inter-cell handoff call, or an intra-cell handoff call is generated, the BS will assign a free physical channel to the MU. If there is no free physical channel in the cell, the BS reuses one of the busy physical channels if possible and assigns it to the MU. When an originating call, an inter-cell handoff, or an intra-cell handoff call, is generated, it will be blocked if there is no channel available in the cell. The adaptive beamforming system can be modeled as two-dimensional Markov chain [8]. The blocking probabilities of originating calls, the blocking probability of inter-cell handoff calls, and the blocking probability of intra-cell handoff calls are also obtained in [8].

4 Numerical Results and Discussions

4.1 Outgoing rates

In order to verify our analysis of the outgoing rates in the systems using switched-beam and adaptive beamforming antennas, we compare the outgoing rates obtained from analysis and simulation. In the simulation, the cell is circular with radius R. The moving speed of MUs has a distribution (uniform or trunked Gaussian) from V_{min} to V_{max}. The moving direction is uniformly distributed in 0 to 2π. The beamwidth θ_b of the smart antennas is $\pi/3$. The MUs are uniformly distributed in the cell.

Figure 3 plots the inter-cell outgoing rate and intra-cell outgoing rate in the switched-beam system. The moving speed has uniform distribution from $V_{min} = 10$ to $V_{max} = 20$. Figure 4 shows the intra-cell outgoing rate for the adaptive beamforming system. In Figure 4, when the distribution of the moving speed is a trunked Gaussian distribution with $V_{min} = 10$ and $V_{max} = 20$, the intra-cell outgoing rate is also plotted for reference purpose.

From Figures 3 and 4, we can see that the simulation results can verify our proposed analysis.

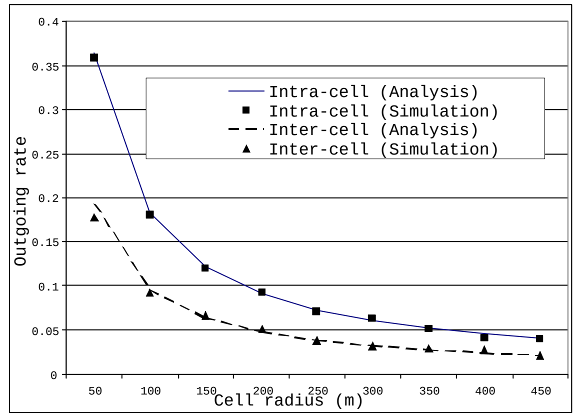

Figure 3: Intra-cell and inter-cell outgoing rate in the switched-beam system

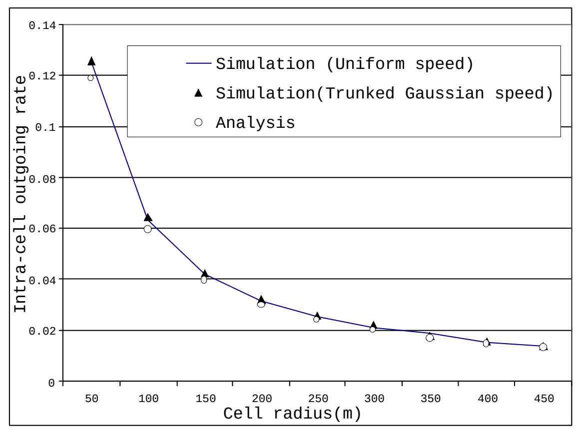

Figure 4: Intra-cell outgoing rate in the adaptive beamforming system

4.2 Performance comparison

We assume that $S = 9$ physical channels are allocated to each cell for three different systems described above. We further assume that the beamwidth θ_b of the smart antennas is equal to $\pi/3$. Therefore, there are 6 minisectos in each cell and 3 channels available in each minisector in the switched-beam system. There are 9 channels available in each cell in an omnidirectional antenna system, 18 channels available in an switched-beam system, and at most 18 channels available in an adaptive beamforming system.

Figure 5 shows the blocking probabilities of originating calls, inter-cell handoff calls, and intra-cell handoff calls in omnidirectional antenna system, switched-beam system, and adaptive beamforming system. Since the blocking probabilities of originating calls and inter-cell handoff calls are same in the omnidirectional antenna system, we only plot the blocking probability of originating calls in the omnidirectional antenna system. Similarly, we only plot the blocking probability of originating calls in the switched-beam system. As shown in Figure 5, the blocking probability of originating calls in the switched-beam system is lower than the blocking probability in omnidirectional antenna system due to the increased num-

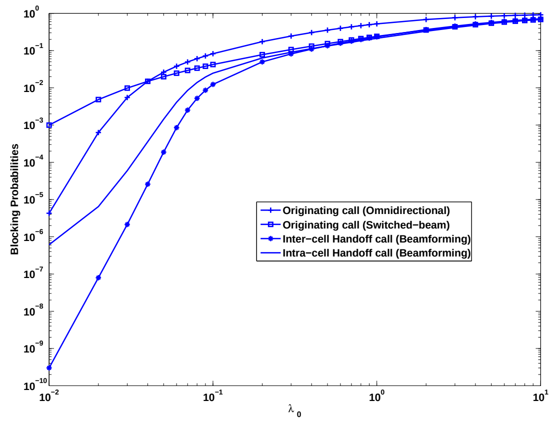

Figure 5: Blocking probabilities of different cellular systems

ber of the available channels. The blocking probability of originating calls further decreases in the adaptive beamforming system. We also find that the performance of intra-cell handoff calls in adaptive beamforming system is greatly improved compared to the switched-beam system due to the following reason. Since flexible strategy of channel assignment is applied to the adaptive beamforming system, the channel utilization is improved. For example, in a switched-beam system, if all the channels are occupied in one minisector, an originating call in this minisector will be blocked although there are free channels in other minisectors. However, the free channels can be allocated to the originating call in an adaptive beamforming system since all the channels are allocated within the cell. Figure 5 also shows that the blocking probability in the omnidirectional antenna system is less than that in the switched-beam system under low λ_O. In the switched-beam system, there are intra-cell handoff calls and inter-cell handoff calls. However, there is only inter-cell handoff calls in the omnidirectional antenna system. When the λ_O is low, the system performance mainly depends on the handoff calls. Therefore, the blocking probability in the omnidirectional antenna system is less than that in a switched-beam system because of less handoff calls (no intra-cell handoff calls).

5 Conclusions

In this paper, we proposed two novel traffic models for wireless and mobile cellular systems using smart antennas, i.e., the switched-beam systems and the adaptive beamforming systems. We analyzed the inter-cell outgoing rate and intra-cell outgoing rate both in the switched-beam and the adaptive beamforming systems. In addition to outgoing rate, we also obtained inter-cell handoff rate and intra-cell handoff rate in the switched-beam and the adaptive beamforming systems. The comparison of blocking probabilities showed the adaptive beamforming system achieves the best system performance among three different cellular systems. Compared to an omnidirectional antenna system, the switched-beam system also increases the system performance greatly.

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