An Energy-Efficient Antenna Muting Scheme for 60GHz Wireless Networks

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***Abstract*—One of the challenges for implementing 60GHz based wireless networks is the large amount of power consumption due to the large number of antenna elements. Decreasing the beamwidth of each link, each link obtains higher spatial reuse gain, however, the energy consumption is increasing dramatically due to the increased number of antenna elements. In order to tradeoff the energy consumption and the spatial reuse gain obtained by directional antenna array, the antenna beamwidth has to be optimized. In this paper, the beamwidth optimization problem is formulated as an energy consumption minimization problem subject to a required data rate. Due to the randomness of topology, a probabilistic model is used to analyze the problem and to derive optimized beamwidth. Moreover, based on the analysis results, we propose an antenna muting scheme based on the distance of links to adjust the beamwidth of each link. According to our simulation results, the proposed scheme can save energy consumption up to 80% with an 8×8 antenna array.**

I. INTRODUCTION

As traffic demand increases rapidly, millimeter (mmWave) wireless communications become a promising technology for high data rate communication. However, since mmWave communication suffers from high attenuation, mmWave devices in wireless personal area networks (PANs) need to employ highly-directional antenna array. The usage of PAs in 60GHz antenna array systems is illustrated in Figure 1. It is shown that each antenna element equips a PA and a low noise amplifier (LNA) for transmitter and receiver, respectively. The power consumption is proportional to the number of the total antenna elements. Typically, the more the antenna elements used, the narrower the beamwidth can be obtained. Therefore, implementing as many elements as possible is expected to increase spatial reuse gain of the whole network [1], where the spatial reuse gain is defined in [2]. Meanwhile, the power consumption also increases, because the circuit implemented in each antenna element needs certain amount of power to work, especially power amplifier (PA), consuming most of the energy in circuit. The power consumption level needs to be controlled in order to apply 60GHz wireless networks in mobile terminals.

Although there are some researches related to beamwidth optimization [3], [4], but no work considered both the power consumption and throughput performance at the same time. Motivated by the idea of the antenna muting scheme in LTE [5], we consider both the power consumption and throughput performance using antenna muting scheme. In this paper, we formulate an optimization problem that minimizes the power consumption of the whole network. But generally the problem is hard to analyze, because the interference among nodes is related to a node topology and beamwidth of each node. Therefore a probabilistic analysis needs to be conducted for analyzing the optimization problem. Based on the analysis results, we propose an antenna muting scheme that controls the beamwidth by adjusting the number of active antenna elements, based on the link distance.

The rest of this paper is organized as follows. System model is described in Section II, which includes an antenna model II-A, a power consumption model II-B, and a link model II-C. In section III, the optimization problem is represented Section IV gives the proposed scheme. Section V shows the numerical results of the proposed antenna muting scheme. Finally, Section VI concludes the paper.

II. SYSTEM MODEL

We consider a general 60GHz wireless network which have a central controller. It is mentioned in practical 60 GHz protocols, e.g. 802.11ad or 802.15.3c. Assume that there are M-pair active devices (DEVs) are uniformly distributed in an $a \times a$ space, and one of them is chosen to be a piconet coordinator (PNC). The PNC controls the peer-to-peer communications and sends the beacon signal periodically. All DEVs respond to the beacon, and the PNC gathers global information including the location of DEVs. For simplicity, we assume a transmitter and a receiver use the same beamwidth, if they are in the same link.

A. Antenna Model

In this paper, we model an antenna array based on [6], [7]. Assume that each antenna element is modeled as an isotropic antenna. Its radiation pattern, $S_e(\phi, \theta)$, gives the normalized power pattern, and can be represented in spherical coordination form, i.e.,

$$S_e(\phi, \theta) = \cos(\theta) \tag{1}$$

where ϕ and θ denote the azimuthal angle and the horizontal angle, respectively. The elements are arranged along to x-axis and y-axis, as shown in Figure 2 [8]. Then two linear array factors, i.e., $S_{N,x}$ and $S_{N,y}$ respectively, is given by

$$\begin{aligned} S_{N,x}(\phi,\theta) S_{N,y}(\phi,\theta) = \\ \sum_{n=0}^{N-1} e^{jk_0 n d_x \sin\theta\cos\phi} \sum_{m=0}^{N-1} e^{jk_0 m d_y \sin\theta\cos\phi}, \end{aligned} \tag{2}$$

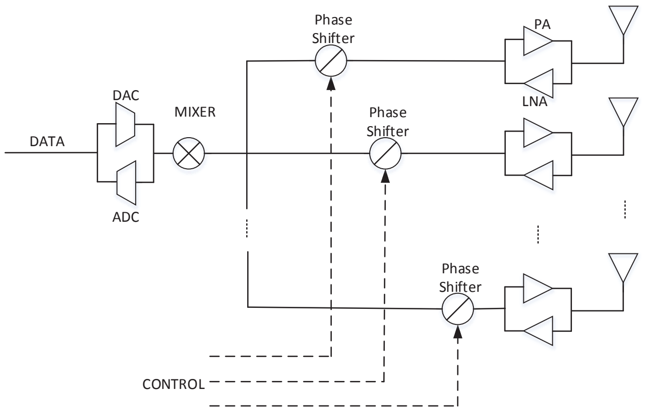
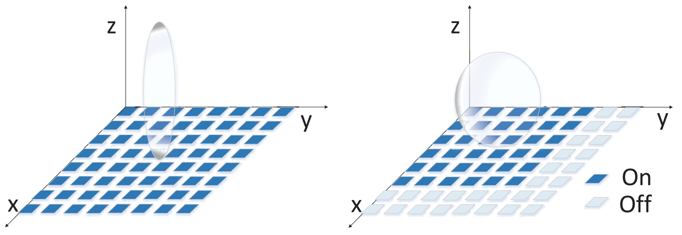


Fig. 1: Illustration of circuit equipped for mmWave transceiver.



(a) (b)

Fig. 2: Illustration of Antenna muting scheme showing its directivity and radiation variation.

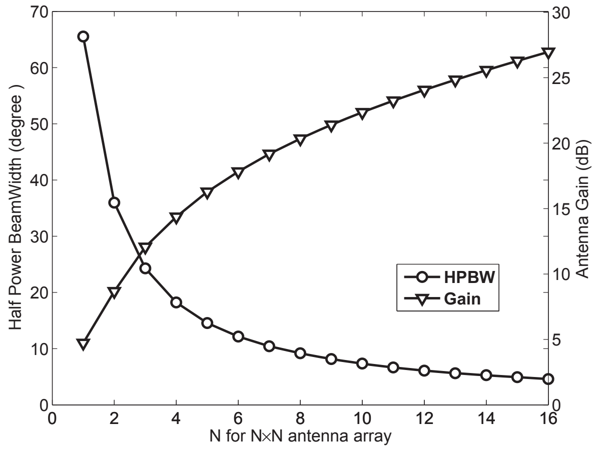


Fig. 3: Antenna gain and Half power beamwidth vs. N for $N \times N$ planar antenna array.

where $k_0 = 2\pi/\lambda_0$, λ_0 is the carrier wavelength, d_x and d_y denote the inter-element space for antenna array distributed along to x and y direction respectively. We assume that antenna elements are equally spaced. Therefore the total radiation pattern of $N \times N$ planar phased array antenna is represented as the product of the element pattern and two linear array factors, i.e.,

$$S_N(\phi,\theta) = S_e(\phi,\theta) S_{N,x}(\phi,\theta) S_{N,y}(\phi,\theta). \tag{3}$$

Then the antenna array gain is given by

$$G(N) = \frac{4\pi}{\int_0^{2\pi}\int_0^{\pi} S_N(\phi,\theta)\sin\theta \mathrm{d}\theta \mathrm{d}\phi}. \tag{4}$$

The half power beamwidth (HPBW) of antenna array, $\theta_{3\text{dB}}(N)$, is given by the solution of following equation, representing that the normalized power pattern of the total array equals 0.5,

$$20\log(|S_e(\phi,\theta)||S_{N,x}(\phi,\theta)||S_{N,y}(\phi,\theta)|/N^2) = 0.5. \tag{5}$$

The antenna gain and the HPBW as the function of N are represented in Figure 3 numerically. Therefore the antenna gain of a transmitter and a receiver can be decided, and denoted as $G(N)$ because the transmitter and the receiver in the same link use the same number of antenna elements, and $\theta_{3\text{dB}}(N)$ is for the HPBW. Since inter-element spaces, d_x and d_y, affect the shape of array pattern, we fixed the inter-element spaces to $\lambda/4$ in order to avoid generating grating lobes. Therefore, we suggest a way to mute antenna as shown in Figure 2, i.e., turning off the outermost antenna elements.

B. Power Consumption Model

The total power consumption can be considered as the sum of power consumption at each circuit blocks, consisting of analog to digital converter (ADC), digital to analog converter (DAC), frequency synthesizer, mixer, LNA, and PA [9]. In [10], a transmitter and a receiver are designed for 60GHz, both in a 65nm CMOS technology. Each receiver antenna element consists of a LNA, a phase shifter, and a part of a combiner. Each transmitter antenna element consists of a PA and a phase shifter.

Assume that both a transmitter and a receiver equip N^2 antenna elements, the total power consumption can be calculated as

$$\begin{aligned} P_{total}(N) =& P_{ADC} + N^2\left(P_{PA} + P_{ps,T} + P_{mix}\right) + \\ & N^2\left(P_{LNA} + P_{ps,R} + P_{mix}\right) + P_{DAC} + P_T \end{aligned} \tag{6}$$

where P_{ADC}, P_{PA}, $P_{ps,T}$, P_{mix}, P_{LNA}, $P_{ps,R}$, and P_{DAC} denote the power consumption of a ADC, PA, phase shifter of transmitter, mixer, LNA, phase shifter of receiver, and DAC, respectively, and P_T denotes the output power of the transmitter. According to operating characteristic of the PA [11]–[13], P_{PA} can be approximated to a constant value.

C. Link Model

Assume that there are M active links in a network, and denote a set of the links $L = \{l_i | i \in 0, 1 \cdots M\}$. The distance from a transmitter of l_j to a receiver of l_i is $d_{j,i}$. Then its received power can be obtained by using the Friis transmission equation, i.e.,

$$P_R(j,i) = k_1 G_0 P_T G_T(N_j) G_R(N_i) d_{j,i}^{-\alpha}, \tag{7}$$

where k_1 is a coefficient proportional to $(\lambda/4\pi)^2$, G_T and G_R are antenna gain of transmitter and receiver respectively, α is an attenuation coefficient, and G_0 denotes the cross correlation coefficient that diminishes interference signal from other links to allowing concurrent transmissions [2]. G_0 is set to 1 if $j = i$, else a small value, e.g. 0.01.

III. PROBLEM FORMULATION

A. Spatial Reuse Gain Analysis

Spatial reuse gain, defined in [2], is proportional to the average number of concurrent transmissions. It can be calculated by obtaining the size of independent set of contention graph which is consisting of the active flows. Denote $CG = (V, E)$ as a contention graph [14], where V is a set of vertices representing each active link and E is a set of edges between vertices representing whether each link is in the ER of others. Only the nodes included in a same independent set of contention graph are able to transmit concurrently. It is an *NP-hard* problem to obtain the size of independent set for general graph, because the links are distributed in the space randomly. Therefore a probabilistic model is suitable to analyze the spatial multiplexing gain for generalized topology.

First, the probability of a event that transmitter of l_j is placed in the ER of l_i, denoted as $Q(i,j)$, is given by

$$\begin{aligned}Q(i,j) =&(1 - \frac{A_1(i,j) + A_2(i,j)}{S})\frac{\theta_j}{2\pi} + \\ &(1 - \frac{A_3(i,j) + A_4(i,j)}{S})(1 - \frac{\theta_j}{2\pi}),\end{aligned} \tag{8}$$

where $A_1(i,j)$, $A_2(i,j)$, $A_3(i,j)$ and $A_4(i,j)$ are modified area of exclusive regions given in [2], assuming that each link uses its own beamwidth. These area are given by

$$A_1(i,j) = \pi r_1^2(i,j)(1 - \frac{\theta_i}{2\pi}) \tag{9}$$

$$A_2(i,j) = \pi r_2^2(i,j)\frac{\theta_i}{2\pi} \tag{10}$$

$$A_3(i,j) = \pi r_3^2(i,j)(1 - \frac{\theta_i}{2\pi}) \tag{11}$$

$$A_4(i,j) = \pi r_4^2(i,j)\frac{\theta_i}{2\pi}, \tag{12}$$

where $r_1(i,j)$, $r_2(i,j)$, $r_3(i,j)$ and $r_4(i,j)$ are the ER radius between receiver of l_i and transmitter of l_j [2]. These are given by

$$r_1(i,j) = \left(\frac{k_1 G_0 G_{TM}(\theta_j) G_{RS}(\theta_i) P_T}{N_0 W}\right)^{1/\alpha} \tag{13}$$

$$r_2(i,j) = \left(\frac{k_1 G_0 G_{TM}(\theta_j) G_{RM}(\theta_i) P_T}{N_0 W}\right)^{1/\alpha} \tag{14}$$

$$r_3(i,j) = \left(\frac{k_1 G_0 G_{TS}(\theta_j) G_{RS}(\theta_i) P_T}{N_0 W}\right)^{1/\alpha} \tag{15}$$

$$r_4(i,j) = \left(\frac{k_1 G_0 G_{TS}(\theta_j) G_{RM}(\theta_i) P_T}{N_0 W}\right)^{1/\alpha} \tag{16}$$

Denote p_{ij} as the probability of the events that transmitter of either l_i or l_j is lied on the each other's ER, calculated as

$$p_{ij} = Q(i,j) + Q(j,i) - Q(i,j)Q(j,i). \tag{17}$$

We assume two events are independent of each other. Then p_{ij} is the probability of existing an edge between link i and link j in CG. Since it is hard to obtain the average of independent set size, we focus on the lower bound. Assume $\theta_i \geq \theta_{i+1}$ for $1 \leq i < M$, then it results in $p_{ij} > p_{ij'}$, if $j < j'$, where the size of vertices set $|V|$ equals to M. Therefore we can model a randomized contention graph using this relation, conservatively, by setting $p_{ij} = p_{ii}$, if $j > i$. The number of edges of a vertex i, D_i, are a binomial random variable, which has a probability

$$Pr\{D_i = k\} = \binom{M-i}{k} p_{ii}^k (1 - p_{ii}^{N-i-k}), \tag{18}$$

where p_{ii} is calculated as p_{ij} when $\theta_i = \theta_j$. The expectation of D_i is given by $E[D_i] = (M-i)p_{ii}$. Then, the lower bound of independent set size, denoted as $r(\Theta)$, can be determined as following condition,

$$M = \sum_{i=1}^{r(\Theta)} D_i + r(\Theta), \tag{19}$$

where $\Theta = \{\theta_i | i \leq M, i \in \mathbb{N}\}$. Since D_i is a random variable and $r(\Theta)$ is dependent on it, therefore $r(\Theta)$ is also a random variable. It is difficult to obtain a closed form of $r(\Theta)$. But a simple relation between the beamwidth of each link and the expected independent set size can be shown by following proposition.

Proposition 1: *If $\Theta_a = \{\theta_1, \theta_2, \cdots, \theta_M\}$ and $\Theta_b = \{\theta'_1, \theta'_2, \cdots, \theta'_M\}$ are sorted in ascending order, and satisfy $\theta_i \leq \theta'_i$ for $1 \leq i \leq M$, then the following inequality holds:*

$$\mathbb{E}[r(\Theta_a)] \geq \mathbb{E}[r(\Theta_b)]. \tag{20}$$

Proof: Let $\theta_i = \theta'_i$ for $1 < i \leq M$, and $\theta_1 + \alpha = \theta'_1$, where α is a arbitrarily small positive real number or zero. Then $\mathbb{E}[D_i]$ and $\mathbb{E}[D'_i]$, which denote the average number of edges of l_1 for θ_1 and θ'_1 respectively, satisfy

$$\mathbb{E}[D_1] = (M-1)p_{11} < (M-1)p'_{11} = \mathbb{E}[D'_1]. \tag{21}$$

Since D_1 is included by $\sum_{i=1}^{r(\Theta)} D_i$ for all $r(\Theta)$ and equation (19) holds, therefore, the increased D_1 brings a decrease of $r(\Theta)$. In other words, inequation (21) results $\mathbb{E}[r(\Theta_a)] \geq \mathbb{E}[r(\Theta_b)]$. Using the similar way, it can be extended to all of links. ■

Denote X_i as the number of slots that l_i is scheduled within N slots. X_i can be obtained from the size of independent set including l_i.

When the REX scheduling is applied, the average data rate of the l_i for N slots is given by

$$R_i = W\frac{X_i}{M}\log_2\left(\frac{P_R(i,i)}{N_0 W + \sum_{i\neq j, j\in r(\Theta)} P_R(j,i)} + 1\right), \tag{22}$$

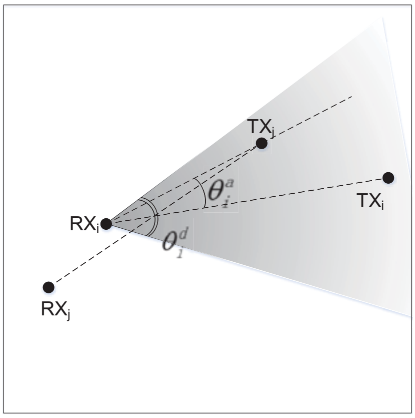


Fig. 4: Illustration of two links l_i and l_j, and two intersection angles θ_i^a and θ_i^d.

where W is a bandwidth, and N_0 is the noise power spectral density. This is lower bounded by the data rate when the links transmits in a TDMA fashion, given by

$$R_i' = \frac{W}{M}\log_2\left(\frac{P_R(i,i)}{N_0 W}+1\right). \tag{23}$$

B. Minimizing Energy Consumption

Focusing on global optimization of the energy consumption for entire network, we can set an optimization problem,

$$\begin{aligned} \underset{\Theta}{\text{minimize}} \quad & \sum_{i=1}^{M} P_{total,i}(\theta_{3dB}^{-1}(\theta_i))X_i \\ \text{subject to} \quad & R_i \geq R_{Th} \; i = 1,\cdots,m. \end{aligned} \tag{24}$$

where $P_{total,i}$ is the total power consumption of l_i, $\theta_{3dB}^{-1}(\cdot)$ is the inverse function of θ_{3dB}, and R_{Th} is the threshold data rate constraints for all of users.

We can find out that $P_{total,i}(\theta_{3dB}^{-1}(\theta_i))$ is a monotonically decreasing convex function of θ_i, through Figure 3. However, because the data rate R_i is dependent on topology, it is hard to analyze it. Therefore we simplify the constraint inequality, change R_i into R_i'. This simplification is allowable, because R_i is lower bounded by R_i' [2]. R_i' is a monotonically decreasing concave function of θ_i. Then the optimal solution $\theta_i^* \in \Theta^*$ can be founded by following equation,

$$R_i'(\theta_i^*) = R_{Th}. \tag{25}$$

From the equation (20) and the results of (25) , we can find out that Θ^* not only brings energy saving, but also brings reduction of spatial reuse gain. In other words, there is a tradeoff between energy saving and the spatial reuse gain.

IV. THE PROPOSED ANTENNA MUTING SCHEME

The main idea of the proposed antenna muting scheme is that each link selects its own beamwidth which minimizes the energy consumption while maintain its data rate above the required rate, in a real situation. When the number of antenna elements are given, there are possibilities for energy saving by turning off some of antenna elements. Once the topology is given, the spatial reuse gain analysis with the help of probabilistic model may be ended in sub-optimal, because it has focused on the lower bound. Therefore each link has to select a beamwidth to perform energy-efficiently, based on the given situation.

Firstly, to maximize spatial reuse opportunity, each node needs to avoid interferer as many as possible. Since the PNC is able to obtain the location information of the entire network. Then it can get the beamwidth set Θ vector that makes collisions among nodes as few as possible. We have shown that if the beamwidth of each node is as large as possible, subject to a required data rate, then the objective function in equation (24) can be minimized. Then, each node needs to use the largest beamwidth while it avoids collision. Denote the optimal beamwidth set as $\Theta^h = \{\theta_i^h | i \leq M, i \in \mathbb{N}\}$, where θ_i^h is determined by θ_i^a and θ_i^d. A beamwidth θ_i^a is given by

$$\theta_i^a = \min_j \angle \mathrm{Tx}_j \mathrm{Rx}_i \mathrm{Tx}_i, \tag{26}$$

where Tx_j, Rx_i and Tx_i denote the transmitter of l_j, the receiver of l_i, and transmitter of l_i, respectively, as shown in Figure 4. When $2\theta_i^a$ is implemented to l_i, the received interference signal at the receiver of l_i decreases, since its beamwidth makes it avoid unintended signals. However if θ_i^a is larger than a certain angle, then the antenna gain is not enough to meet the required receiver sensitivity. To prevent this phenomenon, another beamwidth set Θ^d can be derived using the required data rate R_{Th}. First, the receiver sensitivity, $P_{R,Th}$, is given by

$$P_{R,Th} = N_0 W\left(2^{\frac{M}{W}R_{Th}} - 1\right), \tag{27}$$

obtained from equation (23). Only when the received power obtained by the equation (7) is larger than $P_{R,th}$, it can satisfy that $R_i' \geq R_{Th}$.

A beamwidth set, Θ^d, satisfying the minimum gain of all DEVs that allows successful transmission condition is obtained as

$$\theta_i^d = \min\left(\theta_{\mathrm{3dB}}\left(G^{-1}\left(\sqrt{\frac{P_{R,th}}{k_1 P_T d_{j,i}^{-\alpha}}}\right)\right), \theta_{\max}\right), \tag{28}$$

where $G^{-1}(\cdot)$ is the inverse function of $G(N)$, and $\theta_{\max}$ is the maximum beamwidth that can be realized by current antenna array. At last, the proposed antenna muting scheme selects a realizable beamwidth, i.e.,

$$\theta_i^h = \max\left(\min\left(2\theta_i^a, \theta_i^d\right), \theta_{\min}\right), \tag{29}$$

where $\theta_{\min}$ denotes the smallest beamwidth that is realizable on the current antenna array size. Since the realizable beamwidth set is decided by the number of switched on antenna elements, the actual beamwidth is chosen to $\theta_{\mathrm{3dB}}(N^*)$ that satisfies

$$\theta_{\mathrm{3dB}}(N^*-1) < \theta_i^h \leq \theta_{\mathrm{3dB}}(N^*). \tag{30}$$

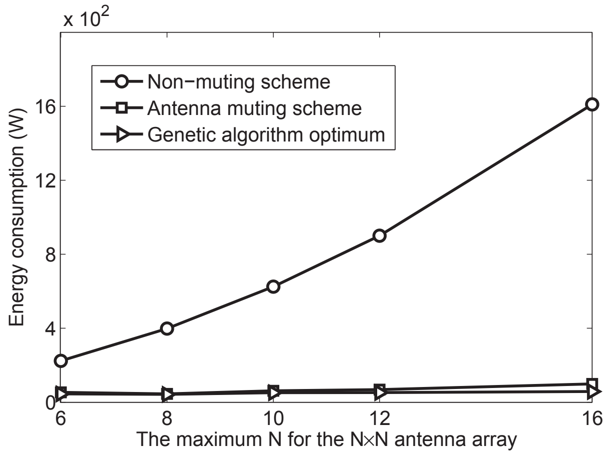


Fig. 5: Energy consumption vs. the maximum N for the $N \times N$ antenna array.

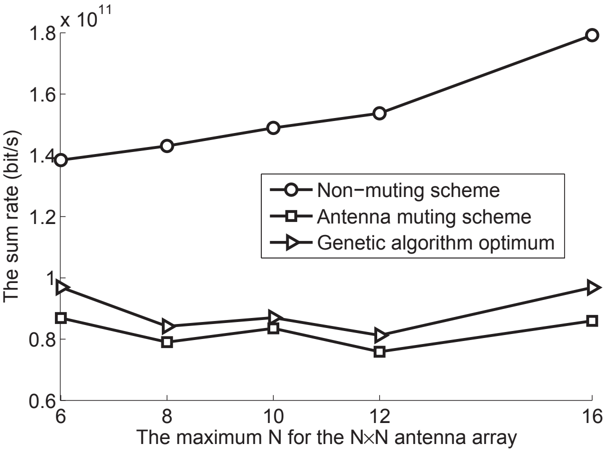


Fig. 6: The sum rate vs. the maximum N for the $N \times N$ antenna array.

V. NUMERICAL RESULTS

In this section numerical results are provided to evaluate the proposed antenna muting scheme. In our mmWave WPANs scenario, $a = 10m$, $M = 30$, $k_1 = -51$dB, $N_0 = -114$dBm/MHz, $W = 500$MHz, and $G_0 = 0.01$ [2]. For simplicity, the slot duration is set to 1.

The results are the sum of energy consumption and the sum rate of M users. The optimum is founded by the genetic algorithm. We can find out the optimum is very close to our results. As the results present in Figure 5, the antenna muting scheme can save huge amount of energy, especially for large antenna array, because there is much more room for energy saving in large antenna array. It states that even if a link can use large size antenna array, it may be unnecessary to use all of antenna elements when the distance between nodes in a link is small enough, because each link just need to make its own data rate larger than R_{Th}. At the same time, however, it decreases the sum rate, as shown in Figure 6. Because our scheme increases the beamwidth of each node, and expands the ER of each node at the same time. As a result, more collisions occur among nodes, which allows fewer links to transmit concurrently. Consequently, the sum rate decreases. It is consistent with the tradeoff relation that the increased beamwidth brings less spatial reuse opportunities.

VI. CONCLUSIONS

We have analyzed the relation between energy consumed by antenna array and the spatial reuse gain. The proposed antenna muting scheme gives optimized beamwidth set for active links based on its own link distance. Our analysis shows that it brings energy saving at the cost of spatial reuse gain. In addition, the numerical results show that our scheme can reduce the energy consumption up to 80% when 8×8 antenna array is implemented, while the data rate meets the required value and very close to the optimal performances obtained by genetic algorithm.

ACKNOWLEDGEMENT

This work was supported in part by the National Basic Research Program of China (973 Green: No. 2012CB316001), the Nature Science Foundation of China (No. 61021001, No.60925002), and Hitachi R&D Headquarter.

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