4-2008

Autonomous Coordinator Selection in Beamformed 60GHz Wireless Networks

Xiangping Qin
xqin@siu.edu

Pengfei Xia
Samsung Electronics

Chiu Ngo
Samsung Electronics

Harkirat Singh
Samsung Electronics

Huai-Rong Shao
Samsung Electronics

See next page for additional authors

Published in Qin, X., Xia, P., Ngo, C., Shao, H.R., Niu, H., Kwong, C.Y., Fan, G., & Kim, S.S. (2008). Autonomous coordinator selection in beamformed 60GHz wireless networks. IEEE Wireless Communications and Networking Conference, 2008. WCNC 2008. doi: 10.1109/WCNC.2008.323

Authors
Xiangping Qin, Pengfei Xia, Chiu Ngo, Harkirat Singh, Huai-Rong Shao, Huaning Niu, ChangYeul Kwon, Guoping Fan, and SeongSoo Kim

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2008 proceedings.

Autonomous Coordinator Selection in Beamformed 60GHz Wireless Networks

Xiangping Qin*, Pengfei Xia*, Chiu Ngo*, Harkirat Singh*, Huai-Rong Shao*, Huaning Niu*
ChangYeul Kwon†, Guoping Fan†, SeongSoo Kim†
Samsung Electronics
*75 W Plumeria Drive, San Jose, CA 95134, USA
†416 Maetan-3Dong, Suwon, Kyungki-Do, Korea 443-742.

***Abstract*— In 60GHz wireless networks, autonomous coordinator selection is required to find a device to coordinate the transmissions among devices. In order to minimize the power consumption for the coordinator, we utilize the direction information extracted from beamformed transmissions in finding the coordinator automatically. The problem is formulated as a K-center problem, which is a NP-hard problem in general. Analysis is carried out to find optimal solutions in certain tractable topologies. Numerical algorithms and simulation results are further presented for random two dimensional topologies.**

I. Introduction

In 2001, the Federal Communication Commission(FCC) allocates a seven gigahertz wide spectrum in the 60GHz band, the millimeter wave band between 57GHz and 64 GHz, for wireless communications. The 60 GHz millimeter wave band allows unlicensed operation, providing a huge, consecutive bandwidth with less stringent transmit power mask. For these attractive features, 60 GHz wireless technology has been deemed to be a promising candidate for achieving giga bit per second (Gbps) wireless data and video transmissions. As technology advances, 60GHz wireless personal area network is emerging, which may include devices such as computers, TV, DVD player, projector, game console, and others.

One particular application is to use 60GHz wireless technology to transmit high definition video via wireless media in a home/office environment. With most network traffic in such cases being streaming audio and video, a coordinator is required to coordinate wireless communications among various devices. Conventionally, in wireless local area networks such as IEEE 802.11, the access point (AP) is designated as a coordinator. However, in 60GHz wireless networks, typically there is no special device appointed as the access point or coordinator, and any device in the network can serve as one. For example, in IEEE 802.15.3 [1], piconet coordinator (PNC) is selected based on the highest capability score. These capabilities include security capability, type of power source, number of associated devices. Handoff schemes are also provided in [1] to cope with the situation when the original coordinator turns off or some more capable device joins the network.

The above approaches however may not work well in a 60GHz network, where many devices would have similar capabilities and qualification to be the coordinator. On the other hand, what is essential for 60GHz wireless networks is that power consumption has become a determining factor as more and more devices are operating on batteries. As a result, minimizing the transmit power becomes one of the most important criteria in selecting the coordinator, which will be pursued in this paper. Minimizing the transmit power also has the additional advantage of minimizing interference to other devices.

In [2], a scheme to select the coordinator based on the geographical coverage criterion is proposed. An extension of [2] is provided in [4]. The idea is to ask the device to send out probing request messages in finding out number of neighbors each device has. Then the device which has the largest number of neighbors will be appointed as the coordinator. How to fix the transmit power level in advance is unfortunately not addressed. Moreover, since every device needs to probe all other devices to gain knowledge of the number of neighbors and list this information in the capability table, such a method requires considerable signaling overhead. For 60GHz transmissions, a high throughput on the order of Gbps is typically achieved through directional transmissions via directional antenna or antenna array beamforming. However, control messages such as probing still need be broadcasted to all devices via omnidirectional transmission or multiple directional transmissions, thus incurring a large overhead.

In this paper, we propose autonomous coordinator selection algorithms which can minimize the transmit power of the coordinator, while reducing the overhead for message exchanging among devices. This is achieved by utilizing location information of the devices, such as the direction and distance information. Approaches based on distance information have been proposed in [3], where a least distance square(LDS) PNC selection heuristic is proposed to reduce the transmit power. In this paper, besides the distance information, we further utilize the direction information, which is readily available as a byproduct of antenna array beamforming. We model the problem as a K-center problem, which is NP-hard in general. Analysis is first provided for some tractable topologies, while heuristics reasoning and numerical simulations are then provided for the extension to random two dimensional topologies.

The paper is organized as follows. In section II,we formulate the problem of minimizing the transmit power of the coordinator as a min-max problem. Analysis is provided for some

1525-3511/08/$25.00 ©2008 IEEE

simple topologies in section III. Low complexity heuristics and simulation results are presented for random two dimensional topologies in section IV.

II. System Model

We consider n devices that are randomly located in a three dimensional space. Assume all these devices are coordinator capable, and they have a common target to elect a coordinator that can minimize the transmit power to reach other devices. The received power for device i can be given as

$$P_i = P_t \frac{1}{d^c},$$

where d is the distance between device i and the transmitter. Depending on the operation environment, the constant c typically chooses a value between $2 \leq c \leq 4$, and is normally known as the path loss factor. Here, without loss of generality, we do not take shadowing and fading effects into account. Once appointed, the coordinator needs to set the transmit power P_t such that the received power at all other devices are greater than a certain threshold, *i.e.*, $P_i \geq P_0, \forall i = 1, ..., n-1$ where P_0 is the threshold to guarantee received Signal to Noise Ratio(SNR).

Let d_{ij} be the distance between device i and device j. If device j is chosen as the coordinator, then the transmit power for the coordinator has to satisfy

$$P_t \geq P_0 d_j^c,$$

where $d_j = \max_{i \neq j} d_{ij}$.

To minimize the transmit power, we need to choose a device j such that d_j is minimized. Therefore, the coordinator selection problem can be formulated as the following min-max problem:

$$\arg \min_{j=1..n} \max_{i \neq j} d_{ij}. \tag{1}$$

The problem is also known as the K-center problem, which is NP-hard in general [5]. In this paper, we will focus on finding an efficient method to solve (1) for a small number of nodes, which is the typical case for 60GHz wireless personal area networks.

We first describe in the following a straight forward solution to (1) and evaluate the associated complexity. Particularly, to find out the location information of other devices, a probing message is first sent out from a certain device with power P_t. Upon reception of the probing message, receivers will send a probing response to tell the transmitter its received power P_r. For example, the RSSI (Received Signal Strength Indicator) can be fed back. Therefore, distance d_{ij} can be computed. Here we assume that c is known. Later on, simulations are given to show the effect of distance measurement errors.

Using this procedure, in order to solve (1), each device needs to send out n messages, one probing request message and $n-1$ probing response messages. Then the value of $d_j = \max_{i \neq j} d_{ij}$ needs to be exchanged among all n devices to find the overall minimum. Considerable signaling overhead is thus introduced by using this procedure.

One important reason for the large overhead above is that the only location information available for each device is the distance information. A peculiar characteristics of 60GHz wireless is that the signal is usually transmitted directionally in order to support high throughput communications on the order of Gbps. This can be achieved either through a directional antenna or by using a properly-weighted steerable antenna array, possibly at both the transmitter and receiver sides. Beamforming thus makes it possible for the transceiver to take advantage of the directional transmission in extracting the direction information that each device resides relative to other devices.

Basically, we can divide the space into multiple conceptually non-overlapping regions, with each region designated by a certain direction or by a certain beamforming vector. An illustration of the 2-dimensional space partition can be seen in Fig. 2. Each device is able to transmit in all of the directions, one at a time. In the 2-dimensional case, each partition can be parameterized by a single azimuth angle θ. In the 3-dimensional case, each partition need be parameterized by at least two parameters, the azimuth angle and the elevation angle. For illustration purpose, we will mainly focus on 2-dimensional cases.

As a by-product of antenna array beamforming, the probing device is able to estimate the direction θ where the probe response comes from, i.e., the direction where the probed device resides. The direction information becomes more and more accurate as we increase the number of partitions that the space is divided into. As we can see later, a near-optimal coordinator can be found with much smaller signaling overhead.

In the following, we will first analyze optimal solutions for some simple topologies, such as triangles. We then move on to analyze random topology in two dimensional space and three dimensional space respectively. Performance bounds are given in terms of maximal distance from the coordinator to the devices, which corresponding to the transmit power required for the coordinator. We propose some low-complexity algorithms in section 4 and present simulation results that corroborated our findings. Simulations are also conducted when only quantized information is available, to investigate the actual performance in realistic environments.

III. Analytical Results

Consider two dimensional topologies, to simplify the analysis, we assume only one round of probing request and response are allowed. The one round probing is done by randomly choosing one of the devices, device j, as the probing device. This device will send out a probing request to all other devices. Then from each device's response, device j measures the distance and direction information d_i and θ_i for all device i, $i \neq j$. In this section, we assume that the measurement of the θ_i is accurate. This assumption is later on relaxed in section IV. First we give the following lemma, which says the devices that are most critical for deciding the transmitting power of the coordinator are those on the edges.

Lemma 1: In a two dimensional space, consider a convex hull spanned by points $A_1, A_2, ..., A_k$, given any point in the convex hull A_j, the point that is farthest to A_j, $\arg\max_{i \neq j} d_{ij}$ for any A_i, must be one of $A_1, A_2, ..., A_k$.

Proof: Proof by contradiction. Assume that $m = \arg_i \max_{i \neq j} d_{ij}$ does not belong to $A_1, A_2, ..., A_k$, connect A_m and A_j and extend it to the edge of the convex hull. Assume the edge is A_1A_2, then the distance of A_j to A_1 or A_2 gives a longer distance than A_jA_m. ■

Given any set of random located n devices, first we choose a subset of these devices $A_1, A_2, ..., A_k$, so that they form a convex hull and all other devices reside in this convex hull.

To simplify the analysis, we first consider a continuous solution space, *i.e.* assume any location in the convex hull can be a possible location of a coordinator. The solution to this continuous space gives a lower bound on the actual problem. Now we start from the simplest two dimensional topologies, triangles. We denote $d(A_i, A_j)$ as the Euclidean distance of A_i and A_j.

Proposition 2: For an acute triangle A_1, A_2, A_3, the circumcenter A_m has the minimal distance of the maximal distance to any point on the triangle, *i.e.* $A_m = \arg\min_{A_i} \max_{A_j \neq A_i} d_{ij}$, for any point A_i and A_j on the triangle.

Proof: For any point A_p inside of the triangle area, the maximum distance of this point to any other points in the triangle area, will be $\max(d(A_p, A_1), d(A_p, A_2), d(A_p, A_3))$. Because A_m is the circumcenter, we have $d(A_m, A_1) = d(A_m, A_2) = d(A_m, A_3) = d_0$. For A_p, it is farther away from one of the edges, A_2A_3, than A_m. So we have $d(A_p, A_3) > d(A_m, A_3)$. So $\max(d(A_p, A_1), d(A_p, A_2), d(A_p, A_3)) > d_0$. ■

Corollary 3: For any convex hull, if there exists a circle that can pass through all the vertices, the circumcenter A_m has the minimal distance of the maximal distance to any point on the convex hull. $A_m = \arg\min_{A_i} \max_{A_j \neq A_i} d_{ij}$, for any point A_i and A_j on the convex hull.

proof: The same proof as the proof to 2 applies easily. ■

Proposition 4: For an obtuse triangle A_1, A_2, A_3, the middle point of the longest side, A_m s.t., $A_m = \arg\min_{A_i} \max_{A_j \neq A_i} d_{ij}$, for any point A_i and A_j on the triangle.

Proof: Assume the longest side is A_1A_2. Because $d(A_m, A_1) > d(A_m, A_3)$. $\max d(A_m, A) = d(A_m, A_1)$ for all A on the triangle. For any A_p other than A_m, we have $\max(d(A_p, A_1), d(A_p, A_2)) > d(A_m, A_1)$. ■

For any triangle, we have given the optimal solution for the continuous solution space. For arbitrary two dimensional topology, we give the upper and lower bounds on the minimal maximum distance in the following proposition.

Proposition 5: For any convex hull in two dimensional space, assume the maximum distance between any two points is d_1, then there exists a point A_m, so that for any point A in the convex hull, we have $\frac{1}{2}d_1 \leq \max d(A, A_m) \leq \frac{\sqrt{2}}{2}d_1$.

proof: There exists a square covers all the points in the convex hull, and the length of the side of the square is equal to d_1. Let the center of this square be A_m, then any point A inside this square satisfies, $\max d(A, A_m) \leq \frac{\sqrt{2}}{2}d_1$. The maximum distance to the two points which has distance d_1 is no less than $\frac{1}{2}d_1$. The desired result follows. ■

Proposition 6: For any convex hull in three dimensional space, assume the maximum distance between any two points is d_1, then there exists a point A_m, so that for any point A in the convex hull, we have $\frac{1}{2}d_1 \leq \max d(A, A_m) \leq \frac{\sqrt{3}}{2}d_1$.

proof: Same argument as in the proof for Proposition 5 applies. ■

So far, we have considered a continuous space where all the points within the convex hull can be the coordinator. However, when the locations of the devices are a finite set of points within the convex hull, the optimal location found from the continuous space might not be feasible. Assume A_m is the optimal location from the continuous space, and the finite set of possible locations are given as A_i, $i = 1..n$, we choose one point A_l that is closest to A_m, where $1 \leq l \leq n$. The distance of this point to any other points can be bounded by $\frac{\sqrt{2}}{2}d_1 + \Delta d$, where $\Delta d = d(A_m, A_l)$ for any two dimensional space. The distance can be bounded by $\frac{\sqrt{3}}{2}d_1 + \Delta d$ for any three dimensional space.

IV. Numerical Results

In this section, we introduce some heuristics and provide simulation results. First we propose algorithms for the case when the exact direction information θ_i for $i = 1..n$ is available. Then we relax this assumption, and give algorithms when only approximate direction information is available. Simulation results are given and comparisons are made to optimal solutions.

Then we consider the case where the distance measurement only gives an approximate values of the actual distance. The performance is evaluated and compared with the case when the distance measurement is accurate.

At the start of the network, one of the coordinator capable devices sends out a probing message to all other devices. After receives the responses from these devices, this device calculates (d_i, θ_i) for all $i = 1..n-1$. Then the following Algorithm 1 is run to find the device which is most suitable to be the coordinator. The basic idea is to find a rectangle which covers all the points, then choose a device that is closest to the center of the rectangle.

Algorithm 1 Estimate Algorithm with angle information

FindTheCoordinator (d_i, θ_i)
$(x_i, y_i) = (d_i \cos(\theta i), d_i \sin(\theta i))$ for all $i = 1..n-1$.
$x_{max} = \max_i(x_i)$, $x_{min} = \min_i(x_i)$, $y_{max} = \max_i(y_i)$ and $y_{min} = \min_i(y_i)$.
$(x_m, y_m) = (\frac{x_{max}+x_{min}}{2}, \frac{y_{max}+y_{min}}{2})$.
Find the coordinator (x_c, y_c) that is closest to (x_m, y_m).

Figure 1 shows simulation results of Algorithm 1. 100 random topologies with 10 random location points in a radius of 10 are simulated. The maximal distance from the selected

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2008 proceedings.

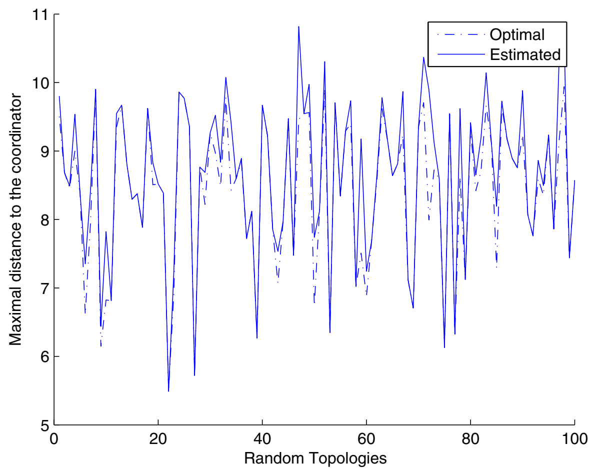

Fig. 1. Estimate Algorithm v.s. Optimal Algorithm

coordinator to all other devices is plotted. The coordinator selected by Algorithm 1 has an average maximal distance 8.65 meters, while the optimal solution has an average maximal distance 8.42. We can see that on average Algorithm 1 produces a coordinator that is only slightly worse than the optimal algorithm. However, by using the estimate algorithm, only one round of probing is required, which greatly reduced the messaging overhead.

Now we consider the case where the exact angle information θ_i is not available. Only approximate direction information is known. We assume there are eight sectors as shown in Fig. 2. The receiver knows which sector the transmitter is located. We modify the estimate algorithm to Algorithm 2, so that points at each sector are mapped to the closest axes as shown in Fig. 2, where all points in section 1 is mapped to the x axis, so on and so far. Then the estimate optimal point is found using Algorithm 1.

Algorithm 2 Estimate algorithm with sector information

Mapping all the points (x_i, y_i) for $i = 1..n$ to the closest axis (x_i^*, y_i^*).
Find the corresponding (d_i^*, θ_i^*)
(x_c, y_c) = FindTheCoordinator(d_i^*, θ_i^*).

From Figure 3, simulation results show that without the accurate direction information, the estimated distance to the coordinator is still close to the optimal, on average the distance is around 9.34, although we noticed that for some topology it can deviate somewhat from the optimal.

To further improve the performance, we consider an improved algorithm Algorithm 3. Fig. 4 shows another possible mapping when the direction information is not available. In this case, the points are mapped to the diagonal lines. Then apply Algorithm 1, find the best point (x_{c1}, y_{c1}) and maximum distance d_1. Using the original mapping in Fig. 2, apply Algorithm 1, find the best point (x_{c2}, y_{c2}) and the maximum

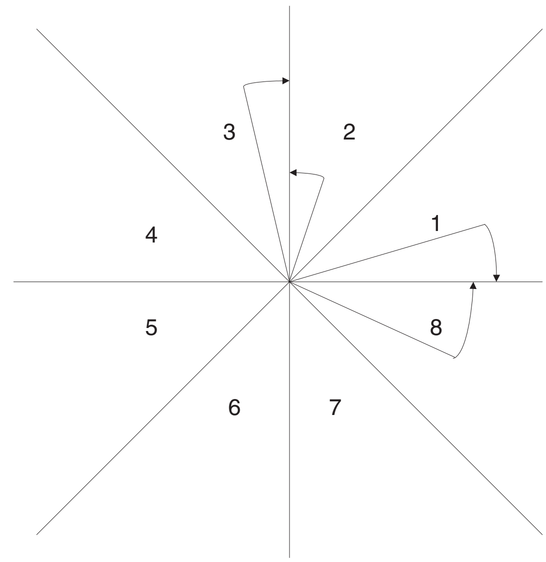

Fig. 2. Eight sectors of received signals

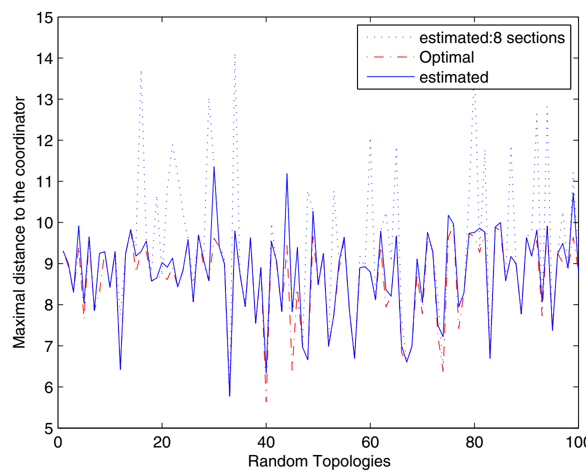

Fig. 3. Estimate Algorithm for 8 sections v.s. Optimal Algorithm

Algorithm 3 Improved estimate algorithm

Mapping all the points (x_i, y_i) for $i = 1..n$ to the closest axis (x_i^*, y_i^*).
Find the corresponding (d_i^*, θ_i^*)
(x_{c1}, y_{c1}) = FindTheCoordinator(d_i^*, θ_i^*).
$d_1 = \max_{i=1..n-1} d((x_{c1}, y_{c1}), (x_i, y_i))$
Mapping all the points (x_i, y_i) for $i = 1..n$ to the closest diagonal lines (x_i', y_i').
Find the corresponding (d_i', θ_i')
$(x_{c2}, y_{c2}) = \text{FindTheCoordinator}(d_i', \theta_i')$
$d_2 = \max_{i=1..n-1} d((x_{c2}, y_{c2}), (x_i, y_i))$
if $d_1 > d_2$ **then**
  choose $(x_c, y_c) = (x_{c1}, y_{c1})$
else
  $(x_c, y_c) = (x_{c2}, y_{c2})$
end if

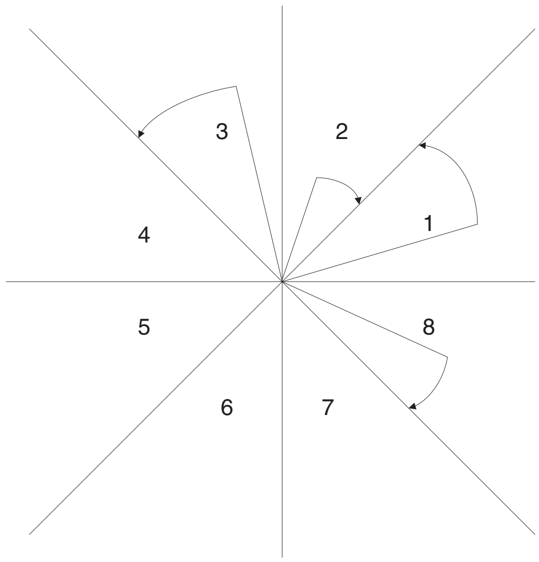

Fig. 4. Eight sectors of received signals

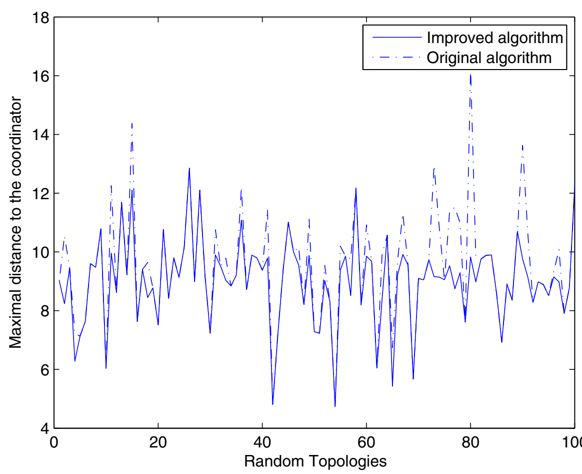

Fig. 5. Improved Estimate Algorithm v.s. Estimate Algorithm for 8 sections

distance d_2. Compare d_1 and d_2, find the better choice between (x_{c1}, y_{c1}) and (x_{c2}, y_{c2}) as the coordinator selection. The simulation results are shown in Fig. 5. It can be seen that the average performance improved. The average maximal distance is around 8.99. For a certain portion of the random topologies, the deviation is greatly reduced by the improved algorithm.

Now consider the case where the distance can only be measured at the quantized value of every two meters, *i.e.* 2, 4, ..., 10 meters. In other words, we tolerate 2 meters deviation for measurement on a disk with 10 meters radius. As shown in Fig. 6, the distance measurement approximation degrades the performance slightly. On average, the distance approximate algorithm gives the maximal distance 8.68, slightly greater than the average distance 8.65 meters with accurate distance measurement. In Fig. 7, we further simulate the effect of distance approximation on the performance of the estimated

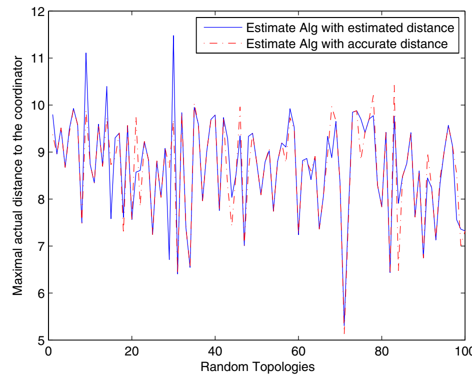

Fig. 6. Estimate algorithm with estimated distance

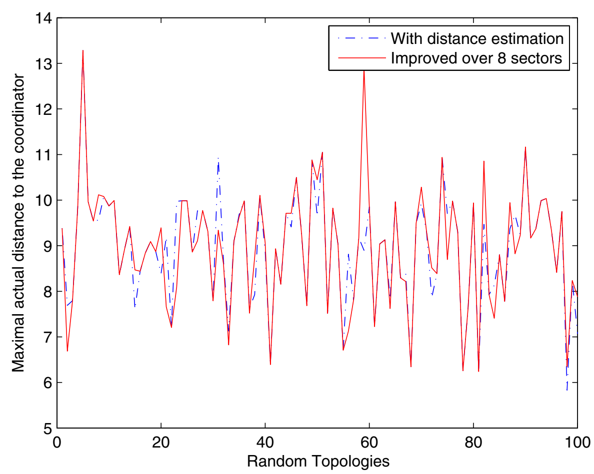

Fig. 7. Estimate Algorithm for 8 sections with estimated distance

algorithm for an 8 sector model. Interestingly, the distance estimation did not degrade the performance, but enhanced it slightly with average 8.97 meters compared to 8.99. It is observed that the distance estimation deviation has less impact on the performance than the deviation of the direction estimation. The reason is that as shown in Algorithm 1, the distance approximation does not affect the choice of the maximum and minimum most likely. Hence the choice of the coordinator is still reasonably good.

V. Conclusions and Future Work

In this paper, we study the problem of choosing a coordinator among a number of devices in wireless 60GHz networks. The device which requires the least transmit power is considered the best choice. We take advantage of the directional information that is available due to beamforming in the physical layer, and design algorithms to find the best coordinator with minimal overhead. Analysis is given for simple topologies and performance bounds are provided for any two dimensional and three dimensional topologies. For random topologies, simple algorithms are presented while the performance is shown via simulation results. The algorithm given in this paper is designed for the snapshot of the network. Dynamics of the change of the topology will be a topic for the future work. Besides, we are also interested in further investigating the impact of the field measurement on the algorithm design, and the performance deviation with more or less information exchange.

REFERENCES

[1] IEEE 802.15.3 Working Group. Part 15.3: Wireless medium access control (MAC) and physical layer (PHY) specifications for high rate wireless personal area networks (WPAN). IEEE Draft Standard, Draft P802.15.3/D17, Feb. 2003.

[2] Shig Sugaya, Kaz Takamura, Masa Akahane , Sony Corporation "IEEE802.15.3: A proposal to add geographical coverage based criteria to Coordinator selection as well as to clarify the usage of 'Des-mode' and Coordinator handover. " July 03, 2001

[3] Yuefeng Zhou, David I. Laurenson, Stephen McLaughlin, "A Novel Piconet Coordinator Selection Method for IEEE802.15.3-Based WPAN", International Workshop on Wireless Ad Hoc Networks, IWWAN 2005.

[4] HeonJu Jeong; Mooho Cho; SungHee Kim; DaeSik Kim; JungTae Lee; "PNC candidate inquiry method for PNC handover on WPAN Personal", Indoor and Mobile Radio Communications, 2004. PIMRC 2004. 15th IEEE International Symposium on Volume 3, 5-8 Sept. 2004 Page(s):1752 - 1756 Vol.3

[5] S. Khuller and Y. J. Sussmann, "The capacitated K-Center problem", Proc. of the 4 th Annual European Symposium on Algorithms, LNCS 1136, pages 152–166, (1996).