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A Robust 60GHz Wireless Network with Parallel Relaying

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Abstract— **The challenge at millimeter-wave frequencies is that the propagation characteristics approximates to that of light. In a non line-of-sight scenario, when even the mobile station (MS) is near the base station, the attenuation may be tens of dBs due to shadowing and obstructions. Increasing the number of base stations reduces such effects but at the expense of cost and complexity. An attractive method to mitigate such shadowing effects is to use dedicated active or passive relay stations. Proposed here is a network infrastructure in the form of a 3D pyramid. It consists of a single access point with four (but not restricted to) active relays operating in parallel in a medium sized room of 400m^2. Simulation is performed in a sophisticated 3D ray tracing tool. Human shadowing densities of 1 person/400m^2 up to 1 person/1m^2 are set to test the robustness of such a system. Results show that comparing to a normal system with just a single access point either mounted on the ceiling or at the same level as a MS; the pyramid relaying system provides superior coverage and capacity.**

Keywords- Millimeter-wave, 60GHz, relay, pyramid, WPAN, WLAN, diversity

I. INTRODUCTION

Millimeter-wave (mmWave) radio has the potential for data transmissions in the order of hundreds of Mbps. To date, most literature focuses on highly directive point-to-point links for mmWave communications in order to combat the high attenuation property inherent at high frequencies, especially at 60GHz. Such links poses difficulties for WPAN/WLAN. For instance, the user's mobility becomes severely limited. The effective coverage distance for high data rate is reported to be within the boundaries of WPAN (20m) [1]. Due to this inherent property, the impact of object and human body shadowing becomes difficult to be ignored. It is reported in [2] that body attenuation can be as high as 18dB or more.

In this paper, *Section II* describes our proposed system to combat severe shadowing problems at 60GHz. This section also defines the basic assumptions used for the various system models. *Section III* describes our simulation objectives, strategies and methods. In *Section IV*, results produced by the models are discussed. Finally *Section V* gives the conclusion of this work.

II. SYSTEM MODEL

The performance of mmWave systems cannot be justified merely by having good BER performance. New ways has to be developed to overcome the effect of shadowing. The proposed system here employs a blanket coverage strategy to combat high attenuations from human and object shadowing with the assistance of active or passive relays. **Figure 1.** depicts such a configuration in which the relay points (RP) form the base of a pyramid structure and the access point (AP), the apex.
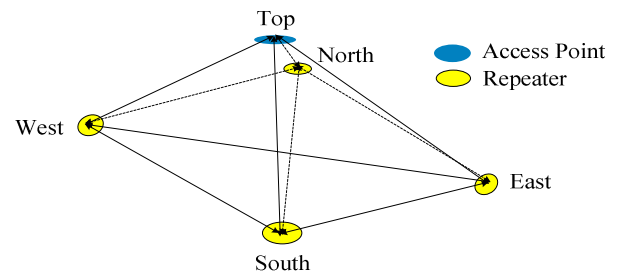

Figure 1. The pyramid network concept

Such an infrastructure giving coverage in all directions grants the user maximum freedom of movement, especially for body worn and WPAN devices. In addition, with the assistance of relays, the RF front end and power requirements of the MS will be simplified since most complexities are built into the AP and the RPs. For odd room sizes such as long corridors, only two RPs will also benefit from a pyramid network. Additional RPs may also be added to further increase coverage. At a wavelength of only 5mm, it is possible that super antenna arrays be formed at an area no larger than the palm of our hands. This can be extremely attractive and cost effective especially if passive devices which require no power supplies are used for the RPs. On the contrary, using reflectors can be large, unsightly and even tedious to set up. With suitable antenna configurations, the shadowing problem at 60GHz may be mitigated. Notice that only one AP is required for a pyramid relay structure. Within the pyramid, handovers are not necessary. However, for environments much larger than 20m, multiple pyramids may be established and the MS may move from one pyramid to another via appropriate handover algorithms.

Proposed here is a parallel relaying technique whereby each RP communicates directly with the AP. There are two methods by which links between RPs and AP can be established. The first method employs radio over fiber [3] (RoF) for wired relaying and the second, uses directional antennas with narrow beams for wireless relaying. There are pros and cons to each method. The first being the extra costs on cable installation and RF-optical front ends. However it provides the most reliable links with minimal cable losses and path delays and with maximum control since the AP may act as the central control node in this way. The second method has more flexibility in the placement of the RPs as long as they maintain LoS with the AP at all times. In addition, relay channels with high K-factors can also be established when they are mounted up high such that human and object shadowing do not occur between them. The first method utilizing RoF is considered here.

Both methods however, may be prone to heavy interference between the relays themselves during uplink and downlink sessions. This could be mitigated by segregating the uplink and downlink frequencies with FDD and timing intervals with TDD, for example. Note that for TDD, the overall capacity of the system will be reduced due to the delayed transmissions via relayed links. Actual details on radio resource allocation are beyond the scope of this paper. Additionally, mmWave dielectric lens antenna could also be used to further limit interference from the highly directive beams of other RPs. The lens antenna operates by providing a circular uniform symmetrical power pattern throughout its coverage [4] as shown in **Figure 2.** Further more, it is also cheap and easy to fabricate.
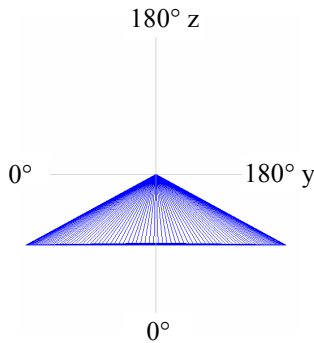

Figure 2. Uniform dielectric lens antenna pattern with 76° in elevation

The proposed pyramid system here may be classified as an infrastructure network with fixed parallel relay terminals [5] as depicted in **Figure 3.**
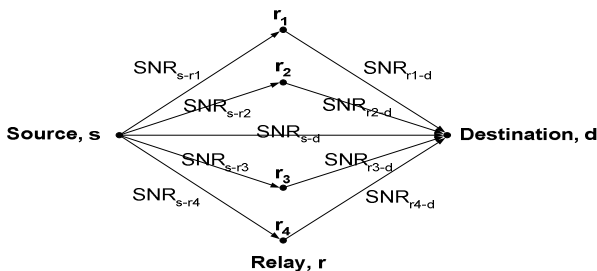

Figure 3. The pyramid parallel relay model

The pyramid system's capacity with the RPs operating in the amplify-and-forward (AF) mode may then be defined as:

$$C = \frac{1}{2}\log_2\left\{1 + SNR_{s-d} + \sum_{n=1}^{4}\left(\frac{SNR_{s-r_n}SNR_{r_n-d}}{1 + SNR_{s-r_n}SNR_{r_n-d}}\right)\right\} \quad (1)$$

,where s, d and r denotes the source, destination and relay stations respectively. SNR is the signal to noise ratio. The quantity ½ accounts for the additional time required for transmitted signals to reach the destination via relayed routes, assuming TDD mode for a single user. This quantity can also be modified for multiple users, but it is beyond the focus of this paper.

A. Basic simulation assumptions

The diffraction phenomenon at 60GHz is negligible and not taken into account. The ceiling, floor and the walls are assumed to be smooth such that the effect of diffused indoor scatterings is not taken into account. Only up to second order reflections are considered since received power from higher order reflections are too small to be considered. The targeted environment is free from inanimate objects so that free space with path loss exponent of 2 is assumed. Human body shadowing attenuation is set to be 18 dB as reported in [2]. The attenuation level is assumed to be constant throughout the simulated human body.

Oxygen absorption at 60GHz in an indoor environment is negligible [6]. The distances between each RP and the AP are equal so that the link qualities of all RPs with the AP can be assumed to be consistent in all directions. RoF is assumed to establish links between the RPs and the AP and that the optical media is assumed to be lossless with negligible delays. The AP employs selection combining technique to select the relay with the strongest signal strength. Analysis in this paper is based on a single user with human models as shadowing objects. The transmit powers of the AP and RPs are set at 20dBm. The user bandwidth is assumed to be 1GHz. Thus the noise floor is -84dBm, taking the noise reference to be -174dBm/Hz.

III. SIMULATION OBJECTIVES AND STRATEGY

A combination of deterministic and statistical methods is used to simulate the performance of the pyramid network under human shadowing conditions. The result here is focused on the uplink and free space is assumed. Millimeter-wave dielectric lens and 120° directional antenna patterns are used for the AP and the RPs in the pyramidal configuration. For the conventional single AP case, a vertically polarized dipole antenna pattern is considered. The MS is also assumed to have the same dipole pattern in all test scenarios.

The simulation objective is to give an idea of the pyramid system's general performance as compared to conventional single AP systems. Though a deterministic model is used, a generic empty 20x20x4m medium sized square room is selected. With an empty room, free space can thus be assumed. Specific room types are beyond the coverage of this paper.

For the pyramid relay system, it is desirable that a uniform coverage is provided regardless of shadowing, and yet limiting

interference between relays to the minimum at the same time. One strategy is to use dielectric lens antennas as depicted in **Figure 2.** Another is to utilize antennas such as the 120° directional antenna. Since these antennas are inverted to provide coverage towards the ground, strong and highly directed rays between relays (in the wireless relaying case) as well as strong undesired ceiling reflections are mitigated, especially for the lenses. Besides the room size, the height of the antennas is also a crucial part of the entire coverage design.
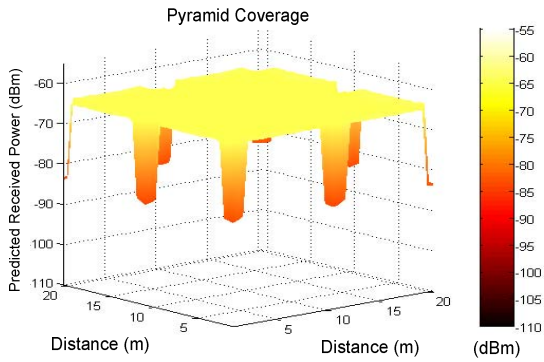

Figure 4.   Coverage estimation of the pyramid relaying system with uniform power dielectric lens antennas

The individual coverage estimations of each RP as well as the AP itself are combined to generate an overall received power pattern as shown in the figure. The power dips in **Figure 4.** are 'dead zones' which occur at the lens's coverage boundary. Within the dead zones, received power is very weak. The effective lens's coverage is approximately up to 12m in diameter. As shown in the diagram, for a 400m^2 room, these lenses are placed such that the dead zones are less than 0.25m^2. It is not expected that a MS is fixed at these positions all the time. One other objective is also to get the maximum coverage with the minimum number of relay stations.

A.   Shadow simulation methods

To model human shadowing in specific environments, geometrical values of rays and objects are needed. These are extracted from a highly accurate and sophisticated 3D ray tracing tool [7]. Human figures are then modeled as rectangular boxes so that orientations of 90° or 180° can be considered. These are then placed randomly across the entire room's available space as demonstrated in **Figure 5.** To compute the interception of rays with the human figures, a widely available 3D ray-box interception algorithm is applied. Direct and reflected rays are attenuated by 18dB when they pass through a shadowing figure.

The number of human figures to be placed is according to a shadow density parameter specified in the simulator. The shadowing is uniformly distributed across the entire room and is independent and identical (i.i.d.) so that each shadowing situation is uncorrelated with the AP and the RPs, and that identical shadow positions can be reproduced for all systems. For each shadow density, the results are iterated for at least a thousand times and then averaged. The process is repeated for various other MS positions in order to access the performance of different coverage strategies.
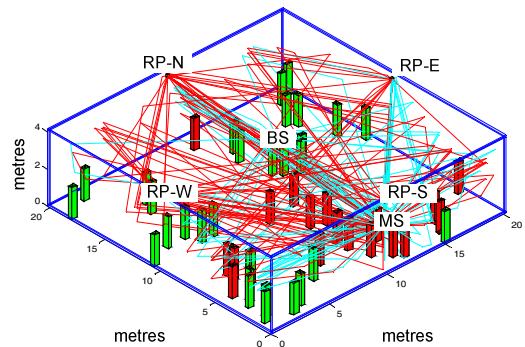

Figure 5.   3D ray tracing output for the pyramid relay system with human body shadowing

For instance, in **Figure 5.** the red (dark in monochrome) lines and boxes indicate that the ray paths are intercepted and thus attenuated. To get a better representation of the presence of people in a room, the human figures are randomly assumed to be either standing (1.78m) or sitting (1.2m). The human figures have widths of 0.3 x 0.5m.

IV.   RESULTS AND DISCUSSIONS

Please refer to **Table 1** for the legend of subsequent figures. Three strategic MS positions are considered to test the extremes of the system coverage:

MS1 – Close to one of the relays.

MS2 – At one corner, furthest from the AP

and the relays.

MS3 – Very close to the AP but not directly

below.

Referring to the figures, four system setup scenarios are considered. **System 1** (Δ) – 'Pyramid Lens': a pyramid system utilizing dielectric lens antennas for the AP and the four relays. **System 2** (o) – 'Pyramid Dir': a pyramid system utilizing 120° directional antennas for the AP and the four relays. **System 3** (∗) – 'AP Top Omni': A conventional single AP with a vertically polarized omni-directional dipole antenna mounted on the ceiling at the center of the room. **System 4** (ف) – 'AP Level Omni': The same single AP is placed at the same level as the MS at the center of the room. In all figures, the x-axes indicate decreasing human shadowing activities starting from 1person/1m^2 up to 1 person/400m^2.

In **Figure 6.** , due to the availability of alternative routes with relays from all four directions, System 1 & 2 give very low rms delay spreads in all shadowing situations. This also accounts for the high K-factors as depicted in **Figure 7.** Interestingly, an unusually high delay spread curve for System

3 when the MS is placed at MS3, shows that the channel condition becomes dispersive with very long delays. The negative and low K-factor values prove this case as well.

As depicted in **Figure 7.** , System 1 & 2 give rather consistent high K-factor performances in all human shadowing situations. The performance of System 4 with the MS being very close to it (MS3), gives the best performance. However, its average capacity performance drops to zero quickly in other MS positions as depicted in **Figure 9.** when shadowing is larger than 1person/100m^2. It is also interesting to note the performance of System 4 at MS2. Its K-factor increases exponentially from a human density of 1 person/18m^2 onwards. It occurs when the average SNR performance falls below zero as depicted in **Figure 8.** This is due to the fact that the MS being at the furthest distance results in much greater opportunities that multipaths are blocked as shadowing density increases. Overall, the slight increase in the rest of the K-factor curves indicates that more delayed paths being blocked.

Depicted in **Figure 8.** , we can clearly see that the average SNR performance of System 4 drops rather quickly when the MS is far away from it. In contrast, the SNR performance of System 3 is rather good; accept that in certain cases the channel becomes highly dispersive as shown in **Figure 6.** Note that the average SNR curves may be much steeper and may drop significantly when the room becomes cluttered with furniture and other objects. This is due to the overall path loss exponent being much higher than free space; typically between 4 and 5.

The average theoretical capacity of System 3 in this empty room scenario ranges from 0.0 to 2.3 bps/Hz. For System 1 with selection combining, the average theoretical capacity is between 0.8 to 4.8 bps/Hz. With System 2, the capacity ranges from 0.75 to 1.4 bps/Hz. Note that average here means the average of all shadowing instances, not the MS positions in the entire room. This is also the case for the other figures. Here the pyramid capacity is computed based on the selected branch of relays or the AP branch itself.

For power constrained systems, it is useful to note the number of bits a system can transmit for every Joule of energy used. This is depicted in **Figure 9.** 's y-axis on the right assuming a user is allocated with 1GHz of bandwidth when operating at 60GHz. The bits/Joule ratio can be computed with the following relation:

$$\frac{C\left[\dfrac{bits}{\sec ond * Hz}\right] x B\left[Hz\right]}{\left(P_{AP} + P_{relay}\right)\left[\dfrac{Joule}{\sec ond}\right]} = u\left[\dfrac{bits}{Joule}\right]$$

(2)

,where C is the capacity, B the bandwidth, P_{AP} and P_{relay} the AP and relay transmitted powers respectively, and u is the transmitted bits per unit energy. With this as a guide, suitable algorithms can thus be formulated to control powers at the AP and the relays so to obtain the maximum number of transmitted bits with the least amount of energy.

V. CONCLUSION

It can be concluded that when a single AP is situated about the same level as the MS, the overall performance is very sensitive to the transmitter-receiver distance when shadow activities increase. Mounting the AP up on the ceiling gives better chances of reception; however in certain cases the channel becomes very dispersive. With the assistance of relays strategically positioned in the form of a 3D pyramid structure, alternative paths from all directions are created. And with suitable antennas, the overall pyramid system performance remains consistently high even under severe shadowing.

VI. FUTURE WORK

Full cooperative diversity [8] methods of relaying may be considered for the pyramid relay system in the near future. In this way, the relays may be much more intelligent as they communicate (cooperate) with each other independently in an ad-hoc fashion, though excessive delays via too many relay links may be a problem. However, these delays may be mitigated with intelligent algorithms. Further more, any MS within the infrastructure may also serve as an additional relay point to create alternative routes. Finally, more MS positions will also be considered for better estimations.

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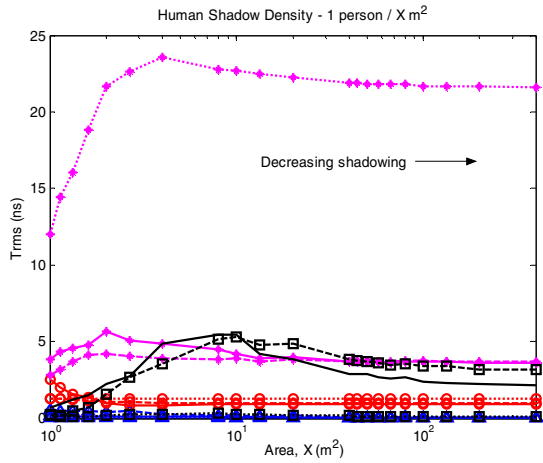
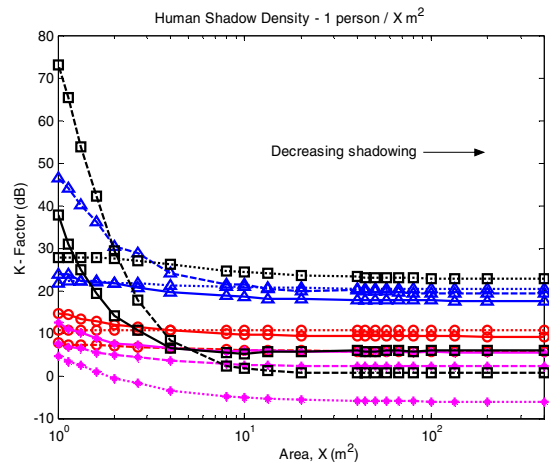Figure 6. RMS delay spread of various system configurations and MS positions

Figure 7. K-factor of various system configurations and MS positions
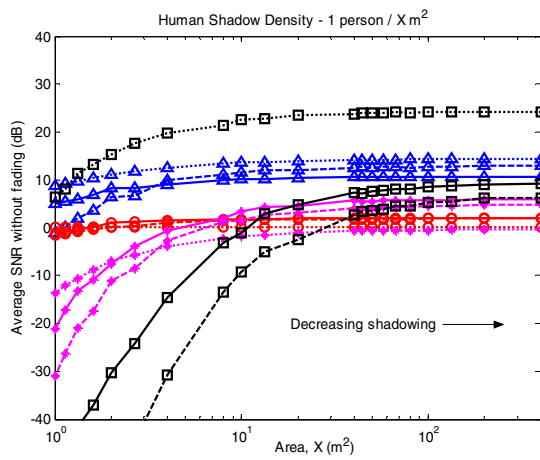

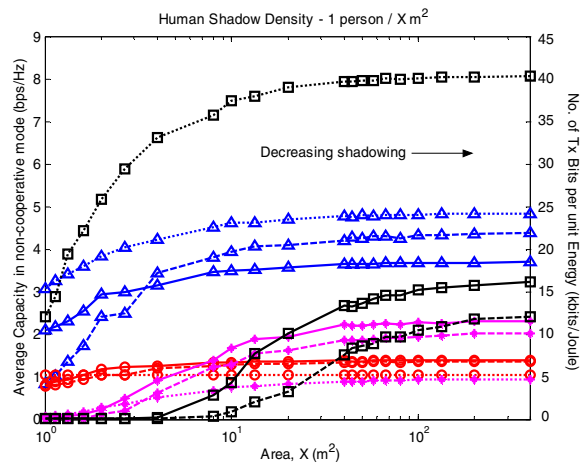Figure 8. Average SNR of various system configurations and MS positions

Figure 9. Average capacity and Bits per Joule analysis of various system configurations and MS positions

Pyramid Lens - MS1	AP Top Omni - MS1
Pyramid Lens - MS2	AP Top Omni - MS2
Pyramid Lens - MS3	AP Top Omni - MS3
Pyramid Dir - MS1	AP Level Omni - MS1
Pyramid Dir - MS2	AP Level Omni - MS2
Pyramid Dir - MS3	AP Level Omni - MS3

Table 1: Legend