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RESEARCH ARTICLE

Random Guessing for Beam Alignment: A Low Complexity Strategy for Reducing Blockage in mmWave Communications

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ABSTRACT High frequency (millimeter wave and higher) systems are being used for curb-to-home services and indoor networks with fixed transmitter and receivers. However, the environment between them can shift due to moving flora and fauna causing sudden blockages. To mitigate outages due to blocking, we investigate the use of a two-beam system rather than a conventional single line-of-sight (LOS) beam. A two-beam system requires a design that can adjust both the transmit phase and delay on one of the beams to ensure a strong signal when both beams are not blocked, and the ability to adapt the transmission rate when the receiver power drops due to intermittent blockages on either beam. We propose a low-complexity co-phasing strategy in which the transmitter guesses the phase and delay offset between the two beams until the receiver indicates a satisfactory channel has been established. Exact co-phasing of the beams is not required and the average number of guesses needed to find an appropriate delay and phase is relatively small. Once the link has been established, the transmitted signal power is split between the two beams to achieve maximum throughput for a fixed total power budget limit. The resulting scheme is not only computationally efficient, but is also robust to channel estimation errors that typically plague transmit adaptation strategies. Numerical results demonstrate the effectiveness of the approach, showing that a capacity within 0.1 dB of perfect co-phasing can be achieved with fewer than 100 guesses. In 90 % of the cases, 25 guesses were required on average to achieve a power that is within 0.1 dB of the optimum.

INDEX TERMS Beamforming, communications technology, feedback, mmWave, system design, multipath, estimation.

I. INTRODUCTION

As spectrum becomes more scarce, higher frequency systems are being adopted to fill the need for faster and more reliable communications. Unlicensed bands, such as 60 GHz, have opened up for wireless local area networks and other applications [1]. Even higher frequencies in the Terahertz regime [2] will be exploited to ensure connectivity and reliability.

Higher frequencies may come with a relatively large absolute bandwidth (e.g., 8 GHz for the 60 GHz band referenced above), yet may suffer from propagation issues. The reach of a millimeter wave (mmWave) signal is short and a lack of diffraction (relative to lower frequency signals) makes it prone to intermittent blockages from leaves or animals [3], [4]. The reach of the signal can be extended through the use of antenna arrays and focusing beams [5], [6]. However, as the beam becomes more narrow, the probability of blockage increases. This occurs when the width of the beam is less than or equal to the width of the obstacle in its way. Blockages could last for milliseconds or minutes depending on the size and speed of the blocking object [7].

In [8], the authors discuss "myths" associated with 60 GHz transmission and the ability to use reflections from the environment to boost the received signal power. In [9], it is noted

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that a secondary beam can be co-phased with a primary beam to increase the power of the received signal. To mitigate the effect of blockages, there have been proposals of intelligent reflective surfaces (IRS) to steer the beams in a particular direction [10]. In particular, IRS have been applied to adaptively change the orientation and direction of the beam [9]. Schemes like this can require complex channel estimation, feedback and updates.

In this paper we examine a high-speed link (tens of Gbps) between a fixed transmitter and receiver pair. The transmitter is equipped with antenna arrays that can radiate signals in arbitrary directions from independently-fed narrow-beam antennas, either in the form of multiple high-gain antennas or an array with multiple input manifolds. Without loss of generality, we focus on the simple case of a single-element receiver with omnidirectional or sectored radiation pattern capable of receiving both LOS and non-LOS signals from the transmitter. We propose a low-complexity scheme that uses two beams: a primary LOS beam and a secondary non-LOS beam established by a passive reflector. Such schemes have been proposed as in [11]–[16]; however, to the best of our knowledge, none of these schemes involve a method where two beams are approximately co-phased via a low-rate feedback system that guesses the delay and phase at the transmitter. For example, [11] does not change the delay of the second beam at the transmitter, but uses a RAKE detector to mitigate the multipath. Intelligent reflective surfaces [16] can delay the signal to mitigate multipath, but they require more complex and power-consuming techniques, e.g channel estimation. Our method does not require full channel estimation at the receiver.

The transmitter determines an acceptable phase/delay value by guessing the phase/delay offset between the beams until a satisfactory signal strength is observed at the receiver. The feedback link is assumed to operate in a frequency division duplex (FDD) fashion with a robust, low-rate modulation and detection (e.g. Frequency Shift Keying). The advantage of our method is that it reduces the loss in received power and capacity due to the second beam which creates multipath if phase/delay alignment is not applied. By guessing the relative time differences between the two beams as well as the phase difference, we can ensure that the received signal has a channel with minimal multipath. This leads to higher received power and thus higher capacity.

Our method does not require intelligent reflective surfaces such as in [17] but does require some number of passive reflectors in the environment to ensure a secondary beam. When neither beam is blocked, the received signal is stronger than for the case of only one transmitted beam. If one beam is blocked, the transmit signal power can be adapted to increase or decrease the transmission rate based on the observed received power. Because the probability that both beams are blocked is much smaller than the probability that a single-beam is blocked, the likelihood of complete data blockage is reduced.

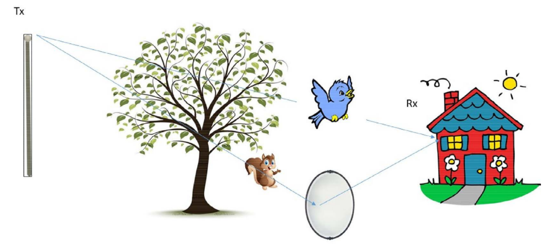


FIGURE 1. Example scenario of a transmitter with a primary LOS path and a secondary non-LOS path due to a passive reflector. Both paths can be subject to temporary blockages due to flora or fauna.

The paper is organized as follows. Section III discusses the system set-up and key assumptions. Section IV presents a "guessing scheme" for determining secondary beam co-phasing that does not require complex channel estimation at the receiver or transmission of complex information from the receiver to the transmitter. Section V presents results showing the effectiveness of the guessing scheme through a variety of metrics, while Section VI includes a discussion and summary of these results.

II. SYSTEM MODEL AND CAPACITY

We assume a fixed transmitter and receiver. As in [18], we assume a two-beam system capable of co-phasing. After an initial beam discovery phase, such as may be found in [18], [19], the transmit array has established two directional beams: the primary and the secondary, each fed by signals $x_1(t)$ and $x_2(t)$, respectively. With this set-up, the transmitter can send two signals in parallel across the two beams, which effectively act as parallel channels. The mechanism for doing this is beyond the scope of the paper. However one option could be multiple RF chains connected to a single phased-array. We assume that the transmitter knows the relative path gain on each of the channels based on feedback from the receiver. The scenario is illustrated in Fig. 1 where the primary and secondary beam can be blocked due to movement of objects.

Without loss of generality, we normalize the primary path gain to unity and the secondary path gain to $\alpha \in [0, 1]$. Under these assumptions, the receiver response is given by

$$y_r(t) = x_1(t) + \sqrt{\alpha} e^{j\phi} x_2(t - \tau) + n(t) \quad (1)$$

where ϕ represents the relative phase of the secondary beam at the receiver, τ is the difference in time between the arrival of the two beams and $n(t)$ is additive white Gaussian noise with variance σ^2. The phase difference $\phi = 2\pi f_c \tau + \psi$ has two components. The phase component $2\pi f_c \tau$ is due to the delay τ and the carrier frequency f_c of the signal, while the phase ψ represents additional phase differences arising from environmental factors, such as scattering.

Consider the case where the two beams naïvely transmit the same signal $x(t)$ with no co-phasing and a fraction $\beta \in [0, 1]$ of the total transmit power allocated to the secondary beam. Without co-phasing, the signals arriving along the two beams exhibit temporal dispersion, i.e. a two-tap channel. In contrast, with an estimate of the delay and phase offset, the transmitter can send an appropriately delayed and phase-rotated version of the primary signal on the secondary beam, i.e.,

$$x_1(t) = \sqrt{1-\beta}x(t-\hat{\tau}), \quad \text{and} \quad x_2(t) = \sqrt{\beta}e^{-j\hat{\phi}}x(t) \quad (2)$$

where $\hat{\tau}$ and $\hat{\phi}$ are the estimated delay and phase of the channel. This leads to a received signal of the form

$$y_r(t) = \sqrt{1-\beta}x(t) + \sqrt{\alpha\beta}e^{j\phi_e}x(t-\tau_e) \quad (3)$$

where $\tau_e = \tau - \hat{\tau}$, and $\phi_e = \phi - \hat{\phi}$. In a perfectly co-phased system, $\tau_e = 0$ and $\phi_e = 0$, and the received power is

$$P_r = 1 - \beta + \alpha\beta + 2\sqrt{\alpha\beta(1-\beta)} \quad (4)$$

This increase in power was also noted in [13]. In general, the frequency response of the system is

$$H(f) = \sqrt{1-\beta} + \sqrt{\beta\alpha}e^{-j(2\pi f\tau_e+\phi_e)} \quad (5)$$

The capacity of the channel is found by dividing the available bandwidth, B into narrow subbands centered at frequencies $f_k = kB/K$, yielding the channel transfer function $H_k = H(f_k)$. The normalized capacity of the dispersive channel (normalized by the available bandwidth B) is:

$$C = \frac{1}{K}\sum_{k=0}^{K-1}\log_2\left(1+\frac{|H_k|^2}{\sigma^2}\right) \text{ bits/sec/Hz} \quad (6)$$

In the rest of the paper when we refer to capacity, C, we mean the capacity normalized by the bandwidth in units of bits/sec/Hz. As $\tau_e \to 0$ and $\phi_e \to 0$, the components $|H_k|^2$ converge to a constant value, leading to

$$C = \log_2\left(1+\frac{1-\beta+\alpha\beta+2\sqrt{(1-\beta)\beta\alpha}}{\sigma^2}\right) \quad (7)$$

Our goal is to design a simple system that mitigates multipath, thus increasing the received power and capacity (7) when both beams are active. This system involves a scheme that accommodates occasional blockage, mitigated by the presence of the signal from the primary or secondary beam. We also show that guessing the delay and phase at the transmitter can ensure a two-beam channel that is very close to the capacity (7) without an extraordinary number of guesses.

III. BEAMS AND BLOCKAGE

In the following analysis we assume that we have a way to co-phase the two beams as will be discussed later in Section 4. This section focuses on ways to model and use the two beams in a system prone to intermittent blockage. While the use of two beams in mitigating blockage has been investigated before (e.g., [18]), we put forth two strategies for blockage mitigation: beam switching and simultaneous transmission on both beams. While the former alternates between allocating full power to one beam or another, the latter keeps each beam's power fixed at an optimally determined level. Given perfect co-phasing and depending on the probability of blockage, both beam-switching and fixed-power on both beams can be effective tools in the presence of random blockage.

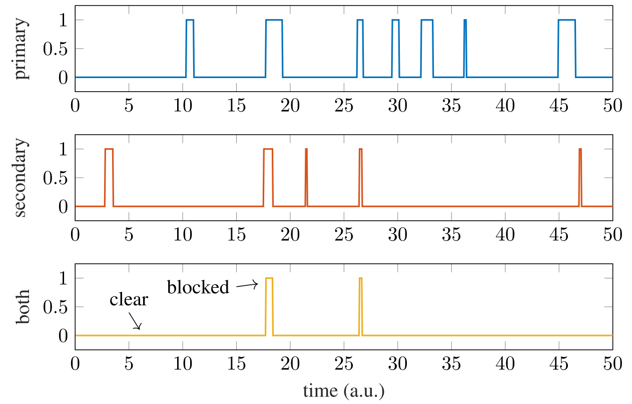


FIGURE 2. A realization of the beam blocking process with normalized parameters $T_{bl} = 1$ and $\lambda = 1/10$. A level of 1 indicates a beam being blocked; a level of 0, no blockage.

As in [3], one can model blockage due to moving objects as a Poisson process with an average arrival rate λ and an exponential blockage duration time with an average T_{bl}, where we assume $\lambda T_{bl} < 1$. In this case, the probability of blockage is [20]

$$P_{bl} = \frac{\lambda T_{bl}}{1+\lambda T_{bl}} \quad (8)$$

We assume the blockages on the primary and secondary beams are independent. A realization of beam blockage is shown in Fig. 2. The extra beam may mitigate the effect of random blockage; however, when a beam is blocked the received signal strength will decrease. Because the signal strength has decreased, the same transmission rate cannot be maintained with the same transmit power. Hence, the transmit power or transmission rate must change.

The following subsections describe various ways of controlling the power and rate of the two-beam system.

A. PRIMARY BEAM ONLY

We consider first a baseline case when transmission occurs only on the primary beam, i.e. no side beam is established and $\beta = 0$. The transmit power is P_t and outage occurs when a beam is blocked. The probability of outage is $P_{out} = P_{bl}$. Without loss of generality we assume the normalized received power when transmitting is $P_r = P_t$, assuming a link attenuation of 1 and no blockage.

The transmission can be on all the time, in which case power is wasted when the beam is blocked. Alternatively, transmission can be turned off when the beam is blocked and re-established once the beam is free again. In the latter case, the transmit power is

$$P_t = \begin{cases} P_r & \text{not blocked; probability } 1-P_{bl} \\ 0 & \text{blocked, probability } P_{bl} \end{cases} \quad (9)$$

TABLE 1. Cases and probabilities of blockage in a two-beam system.

Case	Description	Probability or Blockage
1	primary beam not blocked, secondary beam blocked	$P_1 = P_{\mathrm{bl}}(1-P_{\mathrm{bl}})$
2	primary beam blocked, secondary beam not blocked	$P_2 = P_{\mathrm{bl}}(1-P_{\mathrm{bl}})$
3	neither beam blocked	$P_3 = (1-P_{\mathrm{bl}})^2$
4	both beams blocked	$P_4 = P_{\mathrm{bl}}^2$

The capacity in this case is given by

$$C = (1 - P_{\mathrm{bl}}) \log_2 \left(1 + \frac{P_{\mathrm{t}}}{\sigma^2}\right) \tag{10}$$

B. BEAM SWITCHING

In a two-beam system, beam-switching refers to adaptive transmission using only unblocked beams. Four cases of beam blockage are shown in Table 1.

Here we consider two possible design approaches: either 1) the transmit power is adjusted to keep the received power fixed or 2) the transmit power is fixed with varying received power. With the first approach, transmission occurs at a constant information rate. With the second approach, the information rate can be adjusted through coding and modulation based on the received SNR.

When both beams are excited, a fraction $\sqrt{\beta}$ of the transmit signal is given to the secondary beam while the remaining fraction $\sqrt{1-\beta}$ is given to the primary beam. Note that the relative power on the two beams is β and $1-\beta$. Assuming the primary and secondary beams are co-phased and time-aligned, the signals will combine constructively, yielding the received power

$$P_{\mathrm{r}} = P_{\mathrm{t}}(\sqrt{1-\beta} + \sqrt{\alpha\beta})^2 \tag{11}$$

The received power is maximized when $\beta = \beta_{\mathrm{opt}} = \frac{\alpha}{1+\alpha}$, where α is the relative strength of the second beam. With this choice of β, the received power is

$$P_{\mathrm{r}} = P_{\mathrm{t}}(1+\alpha) \tag{12}$$

when neither beam is blocked (case 3). To maintain a fixed received power P_{r}^0 during blockage states 1, 2 and 3 in Tab. 1, the state-specific total transmit power $P_{\mathrm{t}i}$ and power allocation ratio β_i should be altered to

$$P_{\mathrm{t}} = \begin{cases} P_{\mathrm{t}1} = P_{\mathrm{r}}^0 & \text{case 1} \\ P_{\mathrm{t}2} = P_{\mathrm{r}}^0/\alpha & \text{case 2} \\ P_{\mathrm{t}3} = P_{\mathrm{r}}^0/(1+\alpha) & \text{case 3} \\ P_{\mathrm{t}4} = 0 & \text{case 4} \end{cases} \tag{13}$$

and

$$\beta = \begin{cases} \beta_1 = 1 & \text{case 1} \\ \beta_2 = 0 & \text{case 2} \\ \beta_3 = \beta_{\mathrm{opt}} = \alpha/(1+\alpha) & \text{case 3} \\ \beta_4 = \text{not applicable} & \text{case 4} \end{cases} \tag{14}$$

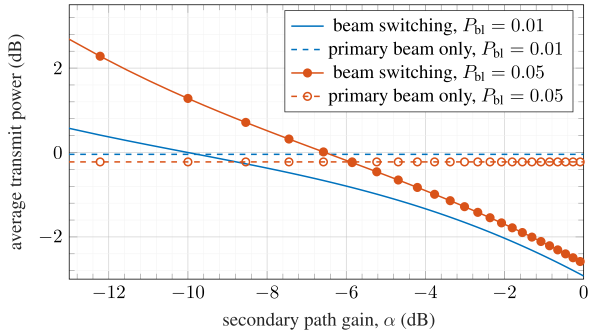


FIGURE 3. Average relative transmit power (16) required with beam switching for two different blockage probabilities $P_{\mathrm{bl}} = 0.01, 0.05$ and the corresponding power required for the baseline case (primary beam only).

Under these conditions, the total average transmit power is

$$\begin{aligned} P_{\mathrm{t}} &= \sum_{i=1}^{4} P_i P_{\mathrm{t}i} \\ &= P_{\mathrm{r}}^0 \left(P_{\mathrm{bl}}(1-P_{\mathrm{bl}}) \left(1 + \frac{1}{\alpha}\right) \right. \\ &\quad \left. + (1-P_{\mathrm{bl}})^2 \frac{1}{1+\alpha} \right) \end{aligned} \tag{15}$$

The average relative transmit power in (15) needed to achieve a constant receiver power is shown in Fig. 3. Note that as $\alpha \to 1$, the required transmit power decreases. For small blockage probability ($P_{\mathrm{bl}} \to 0$), the transmit power $P_{\mathrm{t}} \approx P_{\mathrm{r}}^0/(1+\alpha)$ which shows the advantage of co-phasing and time-coordinating the two beams. When the gain of the secondary beam α is too low, e.g., −9 dB, for $P_{\mathrm{bl}} = 0.01$, the beam switching scheme is not efficient and requires more power than the single beam scheme. This is due to the large amount of power needed to bring the secondary beam to the same level as the primary beam.

Because we have a constant received power P_{r}^0, the capacity for this version of beam switching is

$$C = (1 - P_{\mathrm{bl}}^2) \log_2 \left(1 + \frac{P_{\mathrm{r}}^0}{\sigma^2}\right) \tag{16}$$

If the power cannot be adjusted at the transmitter when switching beams, we assume a fixed power at the transmitter P_{t}, and the allocation parameter β prescribed in (14). This strategy yields the received powers

$$P_{\mathrm{r}} = \begin{cases} P_{\mathrm{r}1} = P_{\mathrm{t}} & \text{case 1} \\ P_{\mathrm{r}2} = \alpha P_{\mathrm{t}} & \text{case 2} \\ P_{\mathrm{r}3} = (1+\alpha) P_{\mathrm{t}} & \text{case 3} \\ P_{\mathrm{r}4} = 0 & \text{case 4} \end{cases} \tag{17}$$

The capacity is now given by

$$\begin{aligned} C &= \sum_{i=1}^{4} P_i \log_2 \left(1 + \frac{P_{\mathrm{r}i}}{\sigma^2}\right) \\ &= P_{\mathrm{bl}}(1-P_{\mathrm{bl}}) \left(\log_2 \left(1 + \frac{P_{\mathrm{t}}}{\sigma^2}\right) + \log_2 \left(1 + \frac{\alpha P_{\mathrm{t}}}{\sigma^2}\right) \right) \\ &\quad + (1-P_{\mathrm{bl}})^2 \log_2 \left(1 + \frac{(1+\alpha) P_{\mathrm{t}}}{\sigma^2}\right) \end{aligned} \tag{18}$$

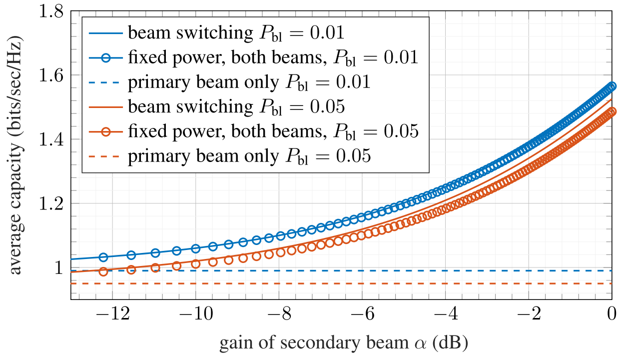


FIGURE 4. **Average capacity for fixed power beam switching (18) and constant transmit power without beam switching (20) versus the path gain of the secondary beam, α, when the $P_t/\sigma^2 = 1$. Horizontal dashed lines correspond to the average capacity of a one-beam system (7).**

The average capacity (18) versus the path gain of the secondary beam, α, is shown in Fig. 4. As the secondary path gain increases, so does the capacity of the switched beam system. This is due to the increase in power when both beams are on.

C. FIXED POWER TRANSMISSION ON BOTH BEAMS

If beam switching and power adjustment are not available, the transmitter sends the signal on both beams at all times. As before, the signal is divided between the two beams with the fraction $1 - \beta$ of the total power given to the primary beam and fraction β given to the secondary beam. For a fixed transmit power P_t, the received power in each blockage state is

$$P_r = \begin{cases} P_{r,1} = (1-\beta)P_t & \text{case 1} \\ P_{r,2} = \beta\alpha P_t & \text{case 2} \\ P_{r,3} = (\sqrt{1-\beta} + \sqrt{\alpha\beta})^2 P_t & \text{case 3} \\ P_{r,4} = 0 & \text{case 4} \end{cases} \tag{19}$$

When $\beta = \beta_{opt}$, the average capacity is calculated using (18) as

$$C = P_{bl}(1-P_{bl}) \times \left[\log_2\left(1 + \frac{1}{1+\alpha}\frac{P_t}{\sigma^2}\right) + \log_2\left(1 + \frac{\alpha^2}{1+\alpha}\frac{P_t}{\sigma^2}\right) \right] + (1-P_{bl})^2 \log_2\left(1 + (1+\alpha)\frac{P_t}{\sigma^2}\right) \tag{20}$$

The capacity (20) is plotted in Fig. 4. When the blocking probability P_{bl} is very small, i.e. 0.01, there is very little difference between the capacity for beam switching (16) and keeping the power the same on both beams regardless of blockage (18). In both cases, the dominant term is case 3, the case where the receiver sees both signals. Both have a capacity that depends on the stronger co-phased signal. As the blockage probability P_{bl} increases to 0.05, beam-switching shows a slight advantage over fixed-power transmission on both beams. This is due to the fact that there is a higher probability of one beam being blocked. The additional power found at the receiver with beam switching becomes apparent as well. When the probability of blockage is very low, the scheme benefits mostly from the combined strength of the two beams; as the probability of blockage increases, the scheme depends more on a reliable received power.

IV. GUESSING THE DELAY AND PHASE OF THE SECONDARY BEAM

All previous discussion of dual-beam systems assumes the ability to perfectly estimate and implement the appropriate beam phase and delay offsets such that $\tau_e = 0$ and $\phi_e = 0$ in (3). In this section, we propose a simple 1-bit feedback scheme for guessing appropriate transmitter delay and phase settings without the need for extensive channel estimation. As simulations will show in Sec. V, only a small number of guesses are required to determine settings yielding near-ideal performance.

The steps to set up the system are the following.

1) Establish the primary beam and secondary beam using methods as in say, [11], [21]
2) Measure the path gain, α, of the secondary beam and feed that back to the transmitter.
3) Transmit the same signal on both beams with a synchronizing signal, e.g. a single-carrier pseudo-random noise sequence. The receiver can estimate an approximate delay value that can be sent back to the transmitter.
4) Guess the delay and phase. To refine the delay and phase, the transmitter starts guessing the delay based on the initial value and transmitting the primary signal with a compensated delay and phase. When the receiver detects that the normalized received signal strength is within a prescribed threshold of the ideal co-phased path gain $1 + \alpha$, the procedure stops.

This process could occur periodically, e.g. once a day to accommodate any fixed shifts in the environment. Step 4 alters the transmitted delay until the receiver determines that the signal is within an acceptable threshold of the ideal co-phasing scenario. Two approaches may be taken in implementing this step. One method involves the transmitter sending a series of signals with different delay and phase guesses and the receiver sending back an index of the signal where the received power was above a specified threshold. Alternatively, the transmitter and receiver could engage in a "back and forth" procedure where the transmitter sends individual signals with unique delay and phase guesses and the receiver responds with 1-bit feedback indicating whether the most recent guess led to satisfactory normalized dual-beam path gain.

The complexity required to run the procedure above is very low. The transmitter must guess a delay within a specified range based on the approximate delay difference between the primary and secondary beam. The only computation required is estimating the power of the wideband received signal and feeding it back to the transmitter. This is in contrast to estimating the delay at the receiver and relaying that information back to the transmitter with possible channel estimation errors.

As shown in the following analysis, a small difference in the delay between the two beams can lead to frequency selectivity and a reduction in power. This implies a need for channel estimation that requires a fine sampling grid. For example, if one wanted to estimate solely the delay between the two paths at the receiver at a fractional spacing level using a low-complexity delay estimator as in [22], the complexity would be on the order of $(1+2N_f)N+(N_f/2+1)N\log_2(N)$, where N_f is the number of subsamples of the symbol period and N is the number of points in the discrete Fourier transform used in the process. To illustrate this fact further, if $N_f = 100$ and $N_f = 128$, the complexity for finding a delay within $(1/100)^{th}$ of a sample space would be on the order of $201 \times 128 + 51 \times 100 \times 7 \approx 6 \times 10^4$ which is much greater than 100 guesses at the transmitter. Note that in 90% of the simulated cases, fewer than 100 guesses are required to achieve delay and phase errors resulting in a received power within 0.1 dB of optimal co-phasing. In addition, the feedback is minimal. If it takes 100 guesses to achieve a reasonable power level, this is an acceptable number given that this adjustment could be on a once a day schedule rather than several times throughout the day. In addition, if the delay were applied at an IRS, channel estimation would consume power at the IRS. This is in contrast to the minimal power required to send candidate signals at the transmitter.

In addition, methods such as [11] and [13] that proactively change the phase of the transmitted signal, do not adjust the delay of the second beam. Not adjusting the delay requires either equalization at the receiver as in [11] or adjusting the phase on each subcarrier in an OFDM-based modulation for a wideband system as in [13]. By adjusting the delay at the transmitter through guesses, we increase the available SNR and reduce the complexity of adjusting the transmit phase on each subcarrier.

Though the feedback system of guesses may obtain a satisfactory solution, any finite resolution phased and delay adjustment mechanism is expected to lead to non-zero co-phasing errors. Given a delay error τ_e and phase error ϕ_e, and a transmit excitation that is uniform within the allocated bandwidth B, the received power is

$$P_r = ((1-\beta+\alpha\beta) + 2\sqrt{\alpha(1-\beta)\beta}\left(\frac{\sin(2\pi B\tau_e+\phi_e)-\sin(\phi_e)}{2\pi B\tau_e}\right)) \quad (21)$$

where $\phi_e = 2\pi f_c\tau_e + \psi_e$.

The power in (21) is plotted in Figure 5. As the normalized delay error $B\tau_e$ increases, the power factor with the cosine term in (21) goes to zero. The delay error τ_e, clearly has a larger role in the variability of the received power.

Note that depending on the carrier frequency f_c and the bandwidth $f_2 - f_1$, the power will oscillate fairly quickly even as τ_e approaches zero. If we were to estimate the delay at the receiver and transmit it back to the transmitter, we would experience two problems. The first is that it would be difficult

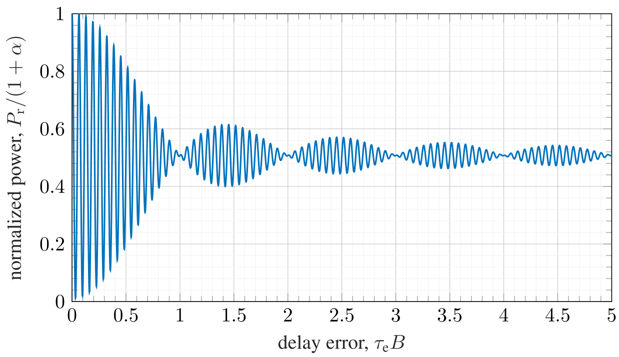


FIGURE 5. Received power (21) as a function of delay error, $\tau_e B$ where B is the available bandwidth. The received power is referenced to the case where a primary beam only would have received power 1. The carrier frequency is $f_c = 60$ GHz, the bandwidth, $B = 4$ GHz, the additional phase error due to reflection $\psi_e = 0$, $\alpha = 0.8$ and $\beta = \beta_{opt}$.

to estimate the delay accurately enough to ensure good co-phasing of the signal. In [23], for example, the difficulty of estimating a super-accurate time-delay in LTE networks is demonstrated. The problem will be much worse at mmWave frequencies due to the oscillation in the power that depends on the carrier frequency. As shown in Fig. 5, the delay has to be accurate within several fractions of the sampling time $T = 1/B$ to ensure maximal co-phasing benefits. This sampling grid largely depends on the ratio of the carrier frequency to the system bandwidth, f_c/B. The second problem is presented by any timing differences between the transmitter clock and the receiver clock. A timing delay estimate of ΔT seconds that is transmitted to the receiver may need calibration to ensure that the same timing delay is used at the transmitter. We eliminate these issues by guessing the delay (as well as any additional phase offset) at the transmitter, thus achieving arbitrarily close co-phasing of the two signals. In addition, when the receiver responds that the co-phasing is adequate, no calibration at the transmitter is required. As expected, requiring performance increasingly close to that of ideal co-phasing generally increases the number of guesses.

To reduce the number of guesses we can take a two-step approach. First we assume, based on feedback from the receiver, that we know the relative delay within $\pm T = 1/B$ seconds. We guess the relative delay τ and the additional offset ψ, where the total phase offset $\phi = 2\pi f_c\tau + \psi$, until we reach our first threshold, the minimum acceptable received power threshold $P_{th,1}$. Then we use a new, tighter threshold $P_{th,2}$, and shorten the delay guessing range for a second round. The first threshold should be chosen to ensure that the estimated delay is less than one sample away from truth. For example, in Fig. 5, when the delay guess results in a power that is within 75% of the maximum power, the delay error must be within half a sample period. This allows us to shorten the delay search area in the second round of guessing.

Because the values are guessed uniformly over a predefined delay interval until a specified received power is achieved, the guessing algorithm does not depend on prior guesses and avoids the risk of becoming trapped in a local optimum that does not satisfy the objective criterion. For example, if we were content with a receiver power that was greater than 60 % of the maximum achievable receiver power (above 0.6 on the vertical axis of Fig. 5), a guessed delay close to 1.5 $\tau_e B$ would yield an acceptable receiver power. As the threshold requirement becomes more stringent, say 99 % of the maximum value, only delays between zero and $0.25\tau_e B$ would be acceptable. We shorten the delay period for guessing based on this knowledge, as will be shown in the following section.

V. SIMULATION

In the simulations below, we tested 10,000 cases for each value of α with unknown delays, τ, uniformly distributed within a range of values and phase offset ψ uniformly distributed between 0 and 2π. In our simulations and our guessing we assumed that the unknown delay was uniformly distributed within a set of parameters. For the initial guessing period, we guessed within a range of delays ± 1 sample ($T = 1/B$) of the true delay. Using the two-step process described above, once we guessed a delay $\hat{\tau}$ and $\hat{\psi}$ that led to a power level within 1.25 dB of a perfectly co-phased system, we shortened the range for guessing the delay to $\pm 3/8$ samples. The phase offset $\hat{\psi}$ is still uniformly distributed within $[0, 2\pi]$ in the second round of guessing. As shown in Fig. 5, if the power is within 1.25 dB of the maximum value, we are within the $\pm 3/8T$ for the delay value. With no guessing, τ_e and ψ_e take on random values and one can see that the received power is relatively low. In the simulations the SNR of the primary beam was 10 dB. The power computation included the noise in the signal, while the average power shown in the plot is the true average power.

The power was calculated in the frequency domain as:

$$P_{\mathrm{r}} = \frac{1}{K} \sum_{k=0}^{127} |H_k + n_k|^2 \tag{22}$$

where $K = 128$ and $H_k = H(kB/K)$, which allows for some smoothing of the noise in the received signal. The average relative power for the guessing scheme, as well as several comparable schemes, are shown in Fig. 6. Despite smoothing, the noise in the power metric at the receiver accounts for the difference in the guessed power (about 0.2 dB away from the optimum power) and the desired value (0.1 dB away from the optimum). In this simulation we set $\beta = \beta_{\mathrm{opt}}$ for different values of α. This is why the no-guessing average power has a non-linear behavior, dipping around $\alpha = 0.5$. This can be explained in the following way. As shown in (21), when the two beams are not co-phased, we lose power. When $\alpha = 0$, i.e there is no secondary beam, $\beta = 0$ and all the power is directed to the primary beam. When $\alpha = 1$, on average a bad guess will halve the available power which was twice as high as the power with no secondary beam. More explicitly, when α is between 0 and 1 and $\beta = \beta_{opt} = \frac{\alpha}{1+\alpha}$, the received

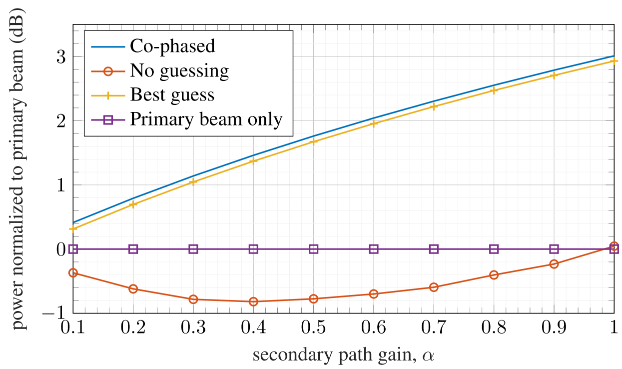


FIGURE 6. Average relative power (dB) of the received signal with guessing and no guessing versus the gain of the secondary beam. The two-step process has a first threshold of 1.25 dB down and a second of 0.1 dB down. The SNR of the primary beam is 10 dB. The average power metric at the receiver includes an averaged noisy measurement; hence the true received power plotted here is not exactly within 0.1 dB from the best guess.

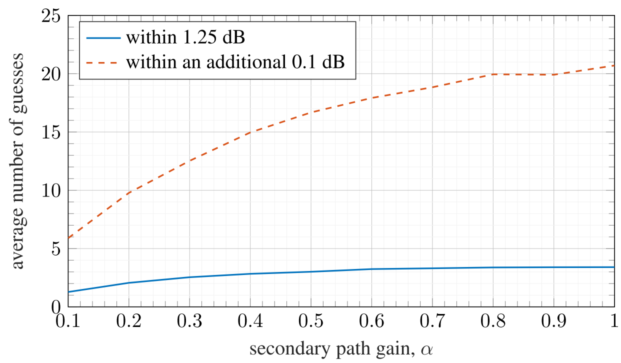


FIGURE 7. Average number of guesses to get to the first threshold within 1.25 dB and the second threshold, within an additional 0.1 dB.

power is

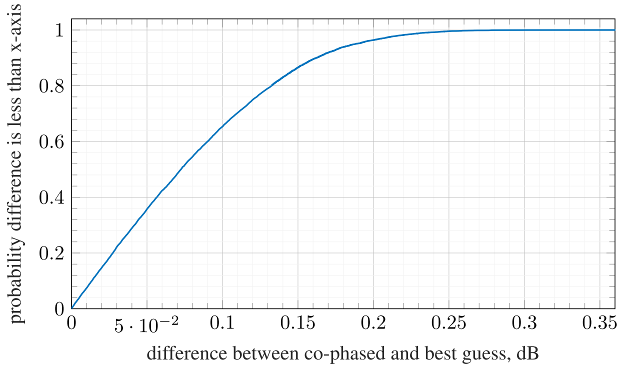
$$P_r = \frac{1 + \alpha^2 + 2\alpha B(\tau_e, \psi_e)}{1 + \alpha} \tag{23}$$

where $B(\tau_e, \psi_e)$ is the sinc-like component found in (21). Note that if the sinc-like function is close to zero, the received power is close to $\frac{1+\alpha^2}{1+\alpha}$ which is equal to 1 when $\alpha = 0$ or 1 and is less than 1 for values of α between 0 and 1.

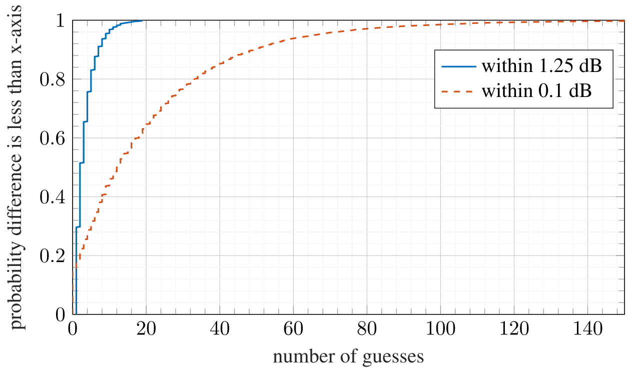
The average number of guesses we need to achieve the first threshold (1.25 dB down) and the second,(0.1 dB down) are also shown in Fig. 7.

Focusing in on the case of $\alpha = 0.8$, cumulative distribution functions are shown for the power of the best guess and the number of guesses it takes to achieve the best guess in Fig. 8. Due to the noise in the estimated power, the probability that the power is within threshold (0.1 dB) is quite small, around 1/10. That problem can be corrected by sending multiple copies of the signal with a particular delay and phase so that the receiver can average the signal before finding the power.

The role of the beam weighting β is important from a theoretical standpoint, but as shown in Fig. 9, having a fixed $\beta = 1/2$ regardless of the relative power α will change the optimal co-phased power. It will not affect the ability to guess

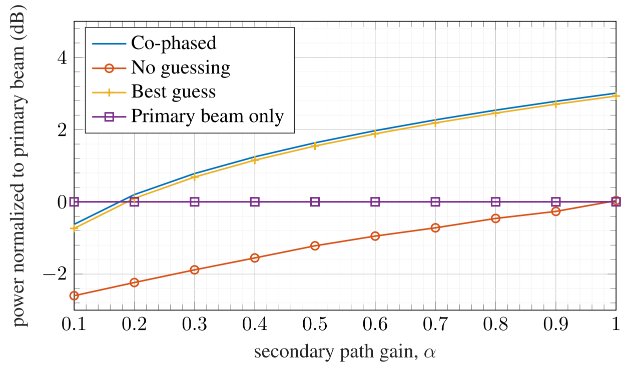


(a) Cumulative distribution function (cdf) of the difference in dB between a perfectly co-phased system and our slightly noisy best guess. This cdf reflects $\alpha = 0.8$, where the average is shown in Fig. 6.

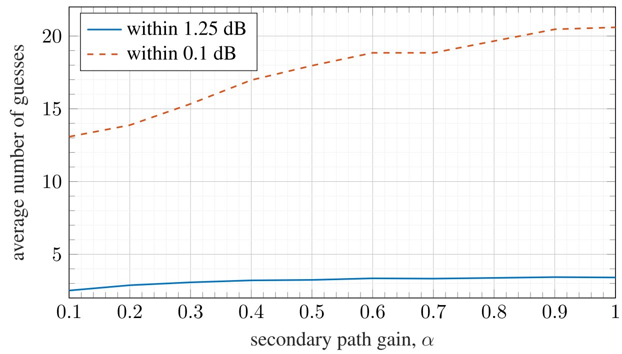


(b) Cumulative distribution function of guesses to get within 1.25 dB the first threshold and the second threshold, (within 0.1 dB) for $\alpha = 0.8$.

FIGURE 8. Cumulative distribution functions describing the performance of the guessing.



(a) This figure shows the average received power versus α with the same conditions as in Fig. 7 but with a fixed $\beta = 1/2$ rather than a β_{opt} for each α.



(b) This figure shows the average number of guesses versus α with the same conditions as in Fig. 6 but with a fixed $\beta = 1/2$ rather than a β_{opt} for each α.

FIGURE 9. Average received power and average number of guesses for a fixed $\beta = 1/2$ rather than a β_{opt} for each α.

a delay and phase that gets us relatively close to the co-phased maximum. Hence, our allocation of power to the primary and secondary beams does not require 100% precision nor knowledge of the gain of the secondary beam.

In general guessing can lead to an appropriate value of $\hat{\tau}$ and $\hat{\psi}$ because the acceptable range for these values is not prohibitively small. For example, suppose the percent of time the received power is within 0.1 dB of the maximum value is approximately 10% of the time. As guessing until there is success is a geometric distribution, it would take, on average, 10 times to guess an appropriate delay, assuming $\psi_T = 0$. Our system is more complicated due to the noise and the unknown additional phase error ψ_e. Still our results indicated that fewer than 100 guesses will suffice more than 90% of the time. This is not a prohibitively large number compared to the complexity of channel estimation and the promise that the guessed delay and phase will provide a performance close to optimal.

VI. DISCUSSION

To mitigate the effect of intermittent blocking from moving flora and fauna in the environment, we established a two-beam scheme for data transmission. The two beams are aligned in phase and delay so as to result in a frequency non-selective channel, thus boosting the power efficiency of the system. The beam alignment is achieved through a guessing strategy at the transmitter with "yes" or "no" acknowledgment from the receiver. This low-complexity scheme has an advantage over explicit channel estimation at the receiver in both accuracy and complexity of implementation. While explicit channel estimation requires an ultrafine grid to ensure adequate co-phasing, no such requirements are present with guessing. By guessing the delay and phase at the transmitter, we additionally avoid errors in channel delay estimation at the receiver and ensure a strong signal when neither beam is blocked.

The method described in this paper, designed for a single-user system, could be adapted to include multiple transmitters and receivers; the extra complexity involved in a multiple transmitter and receiver system would require more initial beam-finding, but assuming no interference, the guessing-feedback technique would follow the same principles and have similar results. Unlike intelligent reflective surfaces, our system requires only passive reflectors and static receivers and transmitters which come at no cost in additional power. It accommodates the changes in the environment using guessing, feedback and two-beam diversity.

The trade-off with the guessing system is the need for feedback from the receiver to the transmitter with the "yes" or "no" responses. However, this is a simple 1-bit feedback that requires very low rates. Alternatively, the transmitter can send a certain number of possible guesses, and let the receiver feed back the index of the best guess. This eliminates the need for constant low-rate feedback during the guessing phase. The set-up can be performed once a day to recalibrate the system, given the primary and secondary beams. The guessing scheme eliminates the need for transmitting pilot symbols and using an ultra-fine grid to estimate the delay and phase. Even if the system had the ability to estimate a very fine delay value to send back to the transmitter, noise in the estimate as well as the need to quantize the estimated delay could lead to further issues. By guessing delay and phase at the transmitter, we ensure adequate co-phasing of the primary and secondary beams without any worry of calibration, transmission or noise issues.

Our proposed system has two parts: guessing the delay and phase of the second beam and methods to use the two beams to mitigate the effect of blocking. Once the guessing phase is over, the system can be operated using either beam-switching or constant transmit power to mitigate the effect of intermittent blockage from random flora and fauna disturbing the beams.

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