Multibeam Antennas for Indoor Wireless Communications

Kuo-Hui Li, *Member, IEEE*, Mary Ann Ingram, *Member, IEEE*, and Ekkehart Otto Rausch

***Abstract*—A multibeam beamformer in combination with a decision feedback equalizer is considered for the base station in a single-cell 100-Mb/s TDMA/TDD QPSK indoor wireless network at 24 GHz. The outage rate in terms of required SNR/bit/antenna is estimated using a statistical, clustered propagation model and for beam selection diversity and two-beam combining.**

***Index Terms*—Adaptive array, decision feedback equalizer, indoor wireless communications, multibeam antenna.**

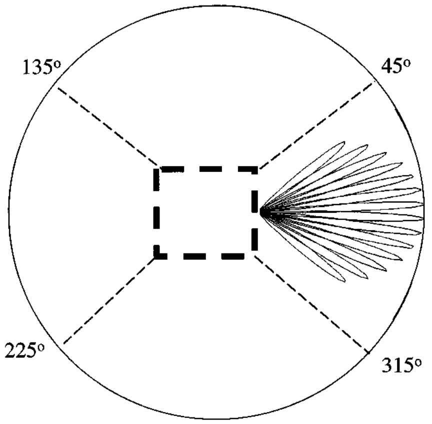

Fig. 1. The arrangement of four linear arrays. The lobes shown are the mainlobes of the beams from one linear array. These mainlobes cover the range $\pm 45^\circ$ relative to broadside.

I. Introduction

FREQUENCIES in the 20–60-GHz range are being considered for their wider allocated bandwidths and compact-sized devices [1], [2]. However, path loss and absorption due to typical building materials are higher at these frequencies than at cellular and PCS frequencies [1]. To compensate for this loss and reduce multipath spread, multibeam antennas have been considered [3], [4].

Driessen [5] showed that, with proper placement and pointing of a 15° beamwidth horn antenna at one end of the link and with a 45° or 70° beamwidth antenna at the other end of the link, 622 Mb/s BPSK and 1.244 Gb/s QPSK links without equalization could be established at 19 GHz with error-free performance for many indoor locations.

Gans *et al.* [6] concluded from a link budget analysis based on a ray-tracing model that beamforming arrays with at least 50 elements at both ends of the link are required to achieve the long range and high bit rate of Driessen's [5]. They also considered the required number of taps in a decision feedback equalizer (DFE) versus the beamwidth, assuming an omnidirectional antenna at the user transmitter and a continuously steerable directional antenna at the base station (BS) receiver [6].

In this paper, we consider the same general architecture as the second Gans model described above, but for a shorter range (50 ft) and a lower bit rate of 100 Mb/s. We assume a certain configuration of four linear beamformers (only discrete beam-pointing choices) and a statistical (azimuth-only) propagation model that emphasizes clustering of paths in angle and delay [7]. This model has the significant delay spread in a narrow angular region that was mentioned in a caveat in [6]. In addition, we consider the use of tapering to reduce crossover loss and the use of two beams simultaneously (jointly equalized) for angle diversity. So, while our system requires no manual pointing of antennas, it does have the complexity of an equalizer. We assume TDMA/TDD QPSK, a very slowly varying channel (based on pedestrian movement), no interference, and beam selection on the uplink based simply on power. In cellular or unlicensed band applications consistent with high levels of interference, more robust beam-selection criteria are required to combat the "beam-falsing" problem [8]. Our link budget analysis is reported elsewhere [9]; in this paper, we consider only SNR improvements offered by various changes in BS receiver design. In particular, we determine the tradeoffs between the amount of tapering, the number of angle diversity beams (one or two), the total number of beams, and the number of forward taps in the DFE.

II. Beamformer Description

We consider an arrangement of four linear arrays, as shown in Fig. 1, where each linear array is represented by a dashed line and serves a 90° sector, similar to that in [4]. The beam *mainlobes* are shown in polar format for the array on the right. For our simulations, we use the Kaiser window [10] as the tapering function.[1] Let the mth Kaiser window coefficient be denoted a_m, and let the element spacing be d; then the complex response of the ith beam to a signal arriving at an angle θ can be expressed as

$$B_i(\theta) = \sum_{m=0}^{N-1} a_m^* e^{j \frac{2\pi}{\lambda} d (\sin(\theta) - \sin(\xi_i)) m} \cdot \sqrt{\cos(\theta)} \qquad (1)$$

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[1] Other windows (e.g., the Taylor window or the Dolph–Chebyshev window [11]) could have been used.

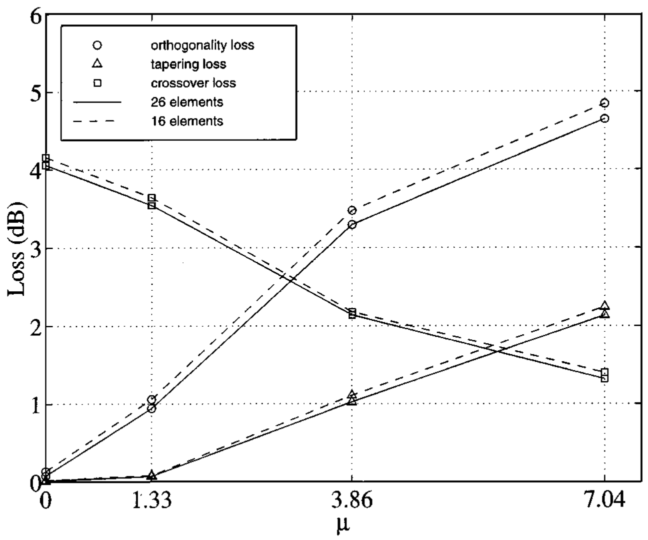

Fig. 2. The worst-case crossover loss, tapering loss, and minimum orthogonality loss for different values of the Kaiser window parameter, μ.

where ξ_i is the pointing angle of the ith beam, N is the number of antenna elements in each linear array, and λ is the wavelength. The values of the Kaiser window, μ, that we consider are 0, 1.33, 3.86, and 7.04, yielding broadside 3-dB beamwidths of 5.5°, 5.6°, 7.4°, and 9.6°, respectively, for $N = 16$ and $d = 0.585\lambda$.

We considered the 8-beam, 16-beam, 24-beam, 40-beam, 56-beam, and 88-beam cases, which use 2, 4, 6, 12, 16, and 26 elements spaced $d = 0.585\lambda$ apart in an array, respectively. We assumed zero backlobes and we terminated 2 beams per array for the 40-beam and 56-beam cases, and 4 beams per array for the 88-beam cases because they are outside the scanning range ±45°.

The beamformer can be implemented electronically using a Butler matrix, or using a Rotman lens [11]. Ideal orthogonal beamformers suffer a 3.92-dB crossover loss, which can be mitigated by tapering, while keeping the same beam spacing. The tapered beams, however, are no longer orthogonal, resulting in a so-called orthogonality loss [11]. Tapering also reduces the gain of the mainlobe, which is quantified by tapering loss [11]. Scanning loss, incurred by beamformers that use linear arrays, is approximately equal to $20\log_{10}\sqrt{\cos(\theta)}$ in decibels (dB), where θ is the angle from broadside, when there is no mismatch and the pointing direction is not near endfire.

The worst-case crossover loss, tapering loss,[2] and minimum orthogonality loss, as a function of the Kaiser window parameter, μ, for $N = 16$ and $N = 26$, are shown in Fig. 2. We observe that as μ increases the orthogonality loss and tapering loss increase, but the crossover loss decreases. The losses for different numbers of beams are very similar.

III. SIMULATION RESULTS

A raised cosine filter with 25% roll-off factor is used for an overall filter response that is shared equally by the transmitter and receiver. The most powerful beams are fed into a joint $T/2$-spaced DFE, where T (=20 ns) is the transmit symbol period. The DFE has an infinite number of taps in the feedback part and finite number of taps in the feedforward (FF) part. To analyze the DFE performance with beam selection diversity and optimum baseband two-beam combining,[3] we use an approach that is essentially the same as in Despins *et al.* [12]. Instead of computing an averaged channel impulse response to get an average BER used by Despins *et al.*, we calculate the BER for each trial of the propagation model, and then use the ensemble of BERs to calculate outage probabilities.

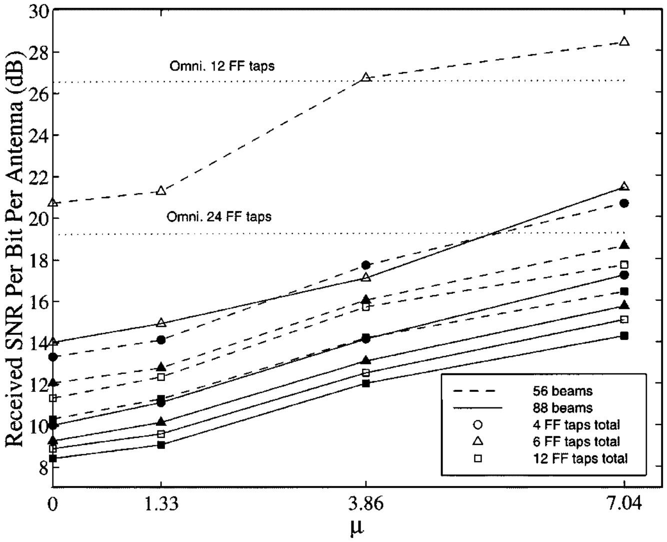

Fig. 3. The required SNR (dB) per bit per antenna using optimum baseband two-beam combining (closed symbols) and using beam selection diversity (open symbols) as a function of μ for 56-beam and 88-beam systems, and 4, 6, and 12 FF taps. The outage probability is 10^{-2} with a BER threshold of 10^{-5}.

Using the channel model developed by Spencer *et al.* consistent with the parameters of the Crabtree Building [7], 11 000 independent channel impulse responses were generated. The carrier frequency is 24 GHz, the path loss exponent is 3.5 [2], the range is 15.24 m (=50 ft), and an omnidirectional antenna (antenna gain = 0 dB) is used at the transmitter. The ray angles of arrival (AOAs) are Laplacian with standard deviation, 21.5° [7]. With omnidirectional antennas at both ends, this model yields an average rms delay spread of 34 ns. We express the performance of the multibeam antenna in terms of required received SNR per bit per antenna in decibels for an outage probability of 10^{-2} with a BER threshold of 10^{-5}. This SNR is plotted versus μ and the number of FF taps with two different numbers of beams. Co-channel interference and orthogonality loss are not included in the simulations.

The required SNR for 4, 6, and 12 FF taps using beam selection diversity and optimum baseband two-beam combining for the 56-beam and 88-beam cases with different μ's are shown in Fig. 3. The closed symbols and open symbols are for two-beam combining and selection diversity, respectively. We observe that the required SNR decreases as the number of beams increases; this effect is most pronounced for the beam selection/6 FF taps case. The beam selection/4 FF taps case is not on the graph because it could not achieve the outage rate for any SNR. Tapering

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[2] For simplicity, omnidirectional antenna elements are assumed in the calculation of the tapering loss.

[3] A two-beam combiner has two forward filters and a common feedback filter.

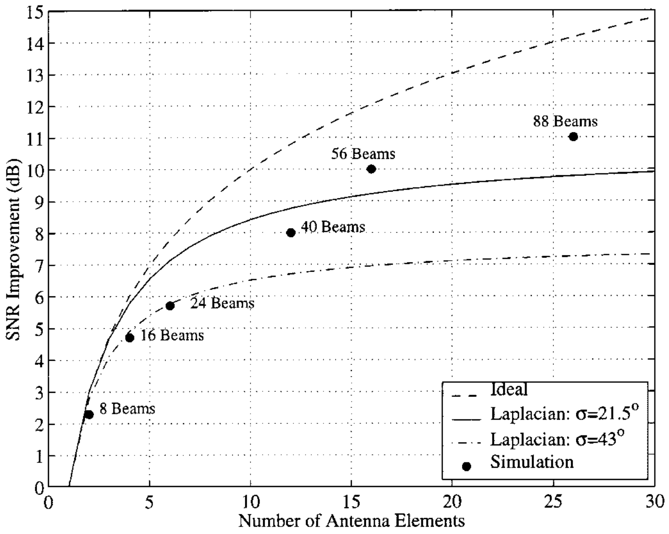

Fig. 4. The SNR improvements of the proposed system relative to the omnidirectional system when the number of FF taps is sufficient at an outage probability of 10^{-2} with a BER threshold of 10^{-5}. The dashed line is for the case of ideal antenna gains. The solid and dashed-dot lines are for the SNR improvements of multibeam antennas with Laplacian distributed AOAs and standard deviations of 21.5° and 43°, respectively.

degrades performance. Apparently, the increased delay spreads from the broader mainlobes and the losses from tapering outweigh the improvement in crossover loss. The required SNR also decreases as the number of taps increases. We observe numerous trade-offs, for example, in the 56-beam case, two-beam combining with 6 taps yields similar performance to a single beam with 12 taps.

Increasing the number of FF taps beyond the number of temporal degrees of freedom of the channel will not further reduce the required SNR [13]. We find that 24 FF taps are sufficient for an omnidirectional antenna to achieve its minumum SNR of 19.2 dB. For the nontapered $(\mu = 0)$ 56-beam and 88-beam cases, the number of taps that minimize the SNR requirement are 22 and 12, respectively, regardless of the choice of selection diversity or two-beam combining. Furthermore, two-beam combining does not offer a SNR improvement relative to selection diversity when the sufficient total number of taps is used.

Although increasing the number of antenna elements in an array increases the pattern gain, the maximum SNR improvement from the array is limited for limited angular spreads [14]. We compute the overall improvement by the array as the minimum SNR required by an omnidirectional base unit with 24 taps minus the minimum SNR required with 22 taps for 56 beams and 12 taps for 88 beams (using two-beam combining). These improvements, along with those for 8, 16, 24, and 40 beams, are shown in Fig. 4. Also shown are the improvements assuming ideal antenna gain (uncorrelated fading) and for Laplacian distributed AOAs with standard deviations of 21.5° and 43°. We observe that SNR improvement increases with the number of beams, but with diminishing returns. We also find that SNR improvements for 40 beams and smaller are between the two curves for the Laplacian distributions. Though the 21.5° Laplacian distribution is used for each cluster in our simulations, we average 3 clusters per channel impulse response. Therefore, the actual angular spread is larger than that of a single cluster.

IV. CONCLUSION

We considered the relative performance of a number of different BS beamformer/DFE configurations for 100-Mb/s QPSK using a clustered statistical indoor propagation model. We observed a significant SNR improvement for the beamformer case relative to the single omnidirectional antenna case when enough DFE FF taps are provided to fully exploit the in-band diversity in all cases. We determined that tapering was not beneficial in this TDMA interference-free environment. While performance improves as the total number of beams increases, beyond 56 beams, the improvements are small, therefore, cost is likely to heavily influence the choice of the total number of beams.

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