The Effectiveness of Preselection Diversity for Indoor Wireless Systems

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ABSTRACT: This paper presents the experimental results of an investigation into the effectiveness of preselection diversity in an indoor 900 MHz TDMA system. We show that a simple auxiliary antenna, used in conjunction with the standard $\lambda/4$ whip on a cellular handset, delivers nearly a 10 dB improvement in signal level in fades that occur 1% of the time, compared to one antenna. Our studies also show that a reasonably designed auxiliary antenna can perform within 2 dB of the primary antenna and, with polarization diversity, deliver a signal that is sufficiently decorrelated from the primary antenna ($r < 0.2$).

1. Introduction

We have been investigating techniques to improve the quality and performance of IS-136 compatible TDMA systems in an indoor personal base station environment. As presented at ICUPC '96[1] and elsewhere[2][3], modulation formats are being considered that deliver 16 kb/s end user data rates instead of the 8 kb/s delivered by the DQPSK signalling currently used in IS-136. These higher data rates result in reduced link margin due to denser signal constellations. To recover some of the link margin, particularly in the slow fading environment present in the indoor environment, preselection antenna diversity is proposed for the portable terminal. Other diversity techniques could deliver better performance, but preselection diversity was attractive for its simplicity, avoiding multiple independent receivers in the power- and space-constrained handset.

There are two significant concerns in the design of any antenna diversity system that could reduce its effectiveness. First, a second antenna might be a relatively inefficient antenna, ameliorating the benefit of diversity. Second, since the handset length is less than $\lambda/2$, the uncorrelated fading needed for effective diversity might not exist. For the experiments described in this paper, we wanted to address these questions and quantify what improvement was actually possible in an experimental system. Polarization diversity was selected as the best candidate, as others have found in similar types of systems[4][5].

2. System Architecture

IS-136 uses a 6 slot TDMA protocol with 40 ms frames. The base station transmits continuously, interleaving transmissions to each portable station in a fixed pattern. With standard "full-rate" speech coders, each portable station is assigned two 6.7 ms time slots, evenly separated within the 40 ms frame. Portable stations listen during their assigned time slots and transmit during a corresponding offset time slot on a different frequency.

In some selection diversity schemes, there is little savings in receiver complexity because it is necessary to measure the signals on all antennas continuously to pick the best antenna[6]. Preselection diversity takes advantage of the fact that the base station is continuously transmitting a signal. Although two of three time slots transmit no information to a portable, their presence is usable by a portable for antenna signal measurements. Signal quality measurements, dispersion of the constellation, distance metrics in the channel decoder, or error rates could be monitored during the antenna measurement periods[7][8]. However, for our experiments, we chose to make simple signal power measurements. The higher quality information that would be available from more involved measurements could improve the operation of the preselection diversity, particularly with interference impairments. Figure 1 illustrates the IS-136 frame structure, and diagrams how preselection diversity is applied to the signal.

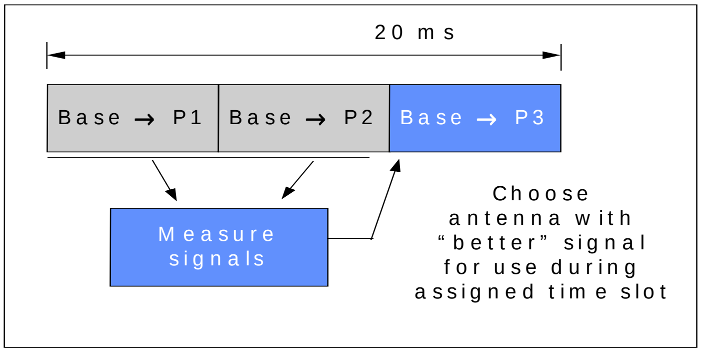

Figure 1- Preselection switching in a TDMA frame

In a product implementation, the portable receiver would switch between two or more antennas directly at RF, avoiding the need for separate RF stages, IF stages, filters, A/D converters, etc. So that we could reuse existing experimental hardware, we chose to switch between receive signals at IF. While this technique involves more hardware than a commercial product would use, its performance is equivalent.

3. Experimental System

We have built a general purpose VME-based signal processing platform using TI TMS320C40 DSP boards. The DSPs were programmed to provide all the important functions of a wireless modem. The same hardware was used for studying the performance of handset antenna diversity for an indoor wireless environment.

The IS-136 experimental hardware consists of three major components:

- an RF unit to convert between baseband/IF signals and 900 MHz RF signals
- custom designed interface hardware
- the DSPs and associated analog/digital conversion hardware

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To this, a commercially available cellular handset was added, modified to include a second antenna. Figure 2 illustrates the hardware used for these experiments.

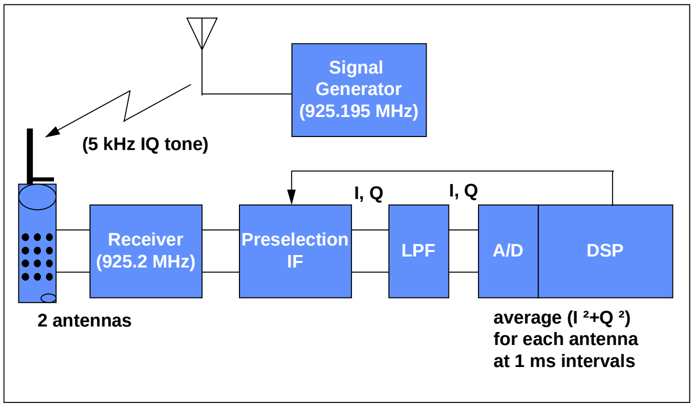

Figure 2 - Block diagram of measurement hardware

Two of the DSPs mentioned above ran C language programs to (a) provide real-time measurement and data collection and (b) download data to a UNIX file for subsequent processing. Most of the data analysis (e.g., the preselection algorithm and statistical analysis) was performed off-line on a Sun workstation.

3.1 Modified handset

For our experiments, we needed to create as realistic a platform as possible to attach the diversity antennas to. A commercially available cellular handset of recent, compact design was selected. The Ericsson AH-320 analog cellular handset was ideal - this handset includes an antenna connector right at the base of the antenna where the mobile mounting kit was to attach. An external connection to the handset's antenna was provided through the mobile antenna connector. This connector also provided a convenient place to physically mount the second antenna, keeping the base feed points of the two antennas close together. By so mounting these antennas, a dual diversity antenna system operates in an RF environment quite similar to what one would expect in a commercial product - above a realistic counterpoise (the handset case and battery) and appropriately separated from the user's head. Figure 3 shows the two antennas mounted on the handset, with their connecting cables to the RF unit.

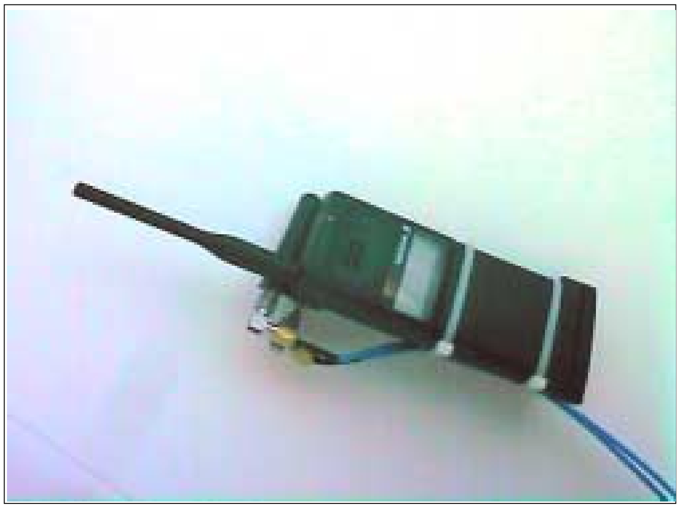

Figure 3 - Commercially available handset, modified with second antenna

In reviewing options for the auxiliary antenna, patch antennas, inverted-F's, and helical antennas were considered. Because of the small size of current handsets (the AH-320 is 2 inches by 5 inches by 1 inch), patch antennas were ruled out, since they would be wider than the handset. We decided to try the stub antenna that is customarily sold with a cellular handset. Figure 4 shows the stub antenna as it was sold and after trimming away the elastic material in which it is potted. Other potential antenna configurations might be considered[9][10], but were beyond the present scope of this study.

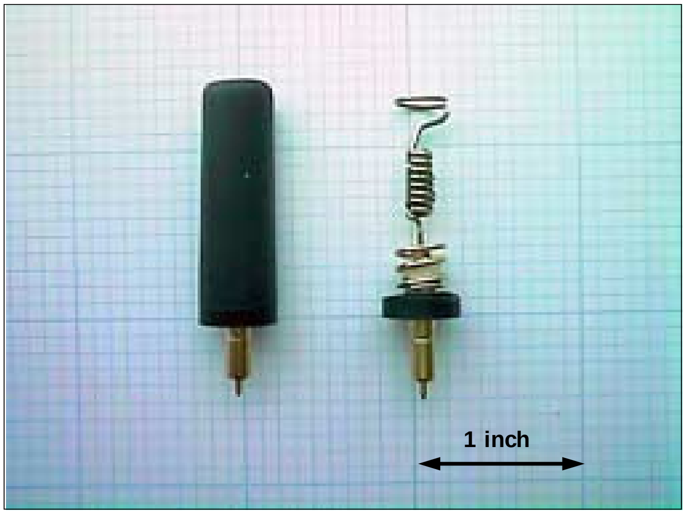

Figure 4 - Stub antenna used as second antenna

4. The Experiment

System performance improvement derived from preselection diversity depends on a number of factors including antenna gain, antenna position, correlation of the fading between antennas, etc. For instance, degradation of the signal level at the auxiliary antenna can have a significant effect on preselection diversity improvement. Antenna to head separation could affect antenna efficiency. To test these effects, we experimented with several antenna mounting positions and examined the effect on preselection diversity gain.

At any particular position in a room, signals may add constructively or destructively at either or both antennas being tested. To average over space and time, antenna power measurements were made every 1 ms, alternating between the two antennas for a 2 minute interval. During this interval, the handset was held in a typical position near the head while pacing around the room at a moderate speed (1 - 2 mph). An attempt was made to cover as much of the room as possible, spending equal amounts of time in each position. Direction of travel was changed as much as possible to account for head shadowing effects on each antenna.

5. Results

Most of our experiments were conducted with a transmitter-receiver separation of about 20 to 40 feet. For these experiments, which we considered to be a worst case, given the short path length (i.e., providing the least opportunity to generate uncorrelated fading), we saw excellent antenna decorrelation and significant preselection diversity gain. Typical antenna correlation coefficients were between 0.05 and 0.2 with an improvement in signal level of 5 to 9 dB. (Note: we define diversity improvement for the 1% fade events. Without diversity, these fades would be 20 dB below the mean signal level. A 9 dB improvement would reduce the fade depth to 11 dB.) To test a truly worst case scenario, we measured the results with the receiver in the same room as the transmitter, only a 12 foot antenna separation. Even in this case, we saw antenna correlation coefficients of 0.5 to 0.6 with diversity improvement of 6 dB. Obviously, in the same room, there would be enough fade margin that diversity would not be needed. However, this particular experiment showed that very little antenna decorrelation is needed to ameliorate the effect of deep fades.

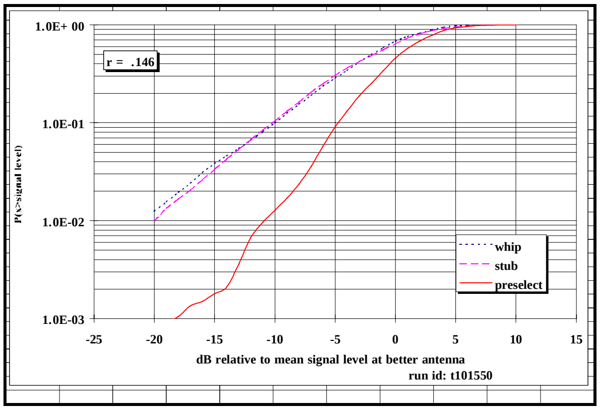

Figure 5 - Typical distribution of signal level, with and without diversity

Figure 5 shows the results from one representative run. As described above, signal power levels were measured for each antenna in 1 ms intervals. The mean for each antenna was calculated over the entire 2 minute experiment and the greater of the two mean signal levels was chosen as a reference level. The abscissa indicates the signal level on each antenna and for the preselected signal level in dB relative to this reference level. The ordinate indicates the probability that the abscissa exceeds the signal level. Thus, this chart indicates the likelihood that a fade of a given amount may occur. With 60,000 power samples from each antenna, low probability events, e.g., fades greater than 30 dB below the reference level, only happened a few times during each experimental run. Thus, the preselection signal curve gets rather "grainy" for corresponding low probability events.

Looking further into the question of antenna correlation, we tried a few experiments where both the antennas were mounted vertically. Obviously for this case, we could not count on independent fading of the two signal's polarization. Further, since the two antennas were mounted less than one inch apart and less than 2 inches apart at their midpoints, we would expect little signal decorrelation due to antenna separation. Even in this case, we observed antenna correlation of ~0.5 with 7 dB diversity improvement. Fading profiles show that, even for signals with relatively highly correlated fading, the deep fade events occur sufficiently far apart to allow simple preselection diversity to offer an improvement. The deepest fades, likely to cause the most damage, are fortunately short term, distinct events that rarely occur on both antennas at the same time. (Note: In the simplest case, for a 30 dB fade to occur, there would need to be two signals arriving at the antenna with signal levels matched to less than 0.01 dB and a 180±3 degree phase difference. The slightest disturbance in the environment alters this condition, so it must be a short term event. Further, for preselection diversity to offer **no** advantage, the second antenna must be simultaneously in a similar deep fade with its impinging signals equivalently matched and phased. It is quite unlikely that both antennas would simultaneously be in such rare circumstances, even if most of the time their fading was somewhat correlated.)

Our experiments also addressed the question of efficiency of the second antenna. As described above, the second antenna used throughout the testing was the standard stub antenna that is provided with a cellular handset. Relative antenna performance between the whip and the stub was varied. Generally, the whip delivered a mean signal level (averaged over each 2 minute experiment) that was perhaps about 1 or 2 dB better than the stub antenna. Usually, the stub was *not* operating at any appreciable disadvantage to the full size whip. Further, our experimental results have shown that a one dB reduction in the auxillary antenna gain translates into a fraction of one dB reduction in preselection diversity gain.

Finally, placement of the second antenna was considered. To best simulate the operation of a commercial product, we would have liked to put the second antenna inside the handset case. This was, however, impractical to try for these tests. Instead, we fabricated brackets to mount the stub antenna at various positions outside, but close to, the handset. Except for one position, where the stub antenna was almost touching the user's ear, we found that the stub antenna performance and the concomitant diversity gain were relatively immune to head-antenna separation. Most of the tests were performed with the stub antenna about the same distance from the head as the whip antenna, but extending slightly to the side of the handset. For all the experiments, we attempted to position the antennas so their base feedpoints were as close as possible.

6. Explaining the results

There is one question that needs to be answered if we are to have confidence in the repeatability of these experiments: Why does indoor preselection diversity work with cross polarized antennas that are so close together? To answer this question, consider: When the signal leaves the transmitter (which was vertically polarized for most of our experiments) it is predominantly polarized with the same orientation as the transmit antenna. In a typical indoor environment, the signal travels only a few feet before it encounters some metallic object - a piece of pipe, conduit, electrical wire, equipment, furniture, etc. - where it is reflected or scattered, perhaps generating cross polarization components. A few feet more, and another source of reflection/scattering is encountered. After having traveled a short distance, it is difficult to determine whether the original signal was horizontally or vertically polarized. Further, an object that leads to generating a predominantly horizontally polarized signal is distinct from (and likely widely separated from) an object that generates a predominantly vertical signal, guaranteeing a fair degree of polarization decorrelation of the two resulting signals. Thus, the large set of essentially independent signal generators with random physical orientations that one encounters in a typical indoor office environment insures that there will be a benefit to diversity even when only polarization of the receiving antennas is used to generate independently fading signals.

The second thing needed for *preselection* diversity to work is a relatively stationary channel for the time frames of interest. For our experiments, power measurements on the two reference signals, as well as the desired signal, were made over an 18 ms window. By observing a typical fading profile, as shown in Figure 6, it can be seen that over such a short interval there is very little change in the signal power at either antenna, except for the brief periods of a deep fade. If one antenna *is* in a deep fade, with its signal level rapidly changing, given a reasonable amount of decorrelation between antennas, the *other* antenna is quite likely not to be in a fade, having a signal level that is relatively constant within a frame.

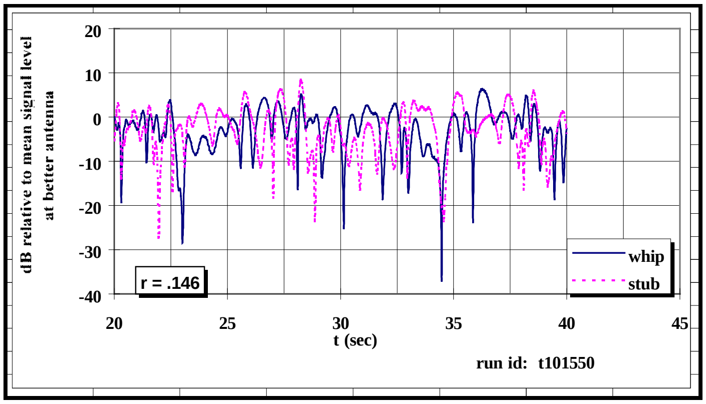

Figure 6 - Fading Profile for Individual Antennas

7. Comparison with the theory

Theory predicts that, for selection diversity with signals from two uncorrelated antennas, we should observe a 10 dB improvement in signal level in fades that occur 1% of the time. Figure 7 is derived from Jakes[11], equation 5.2-4 and figure 5.2-2, with the axes adjusted to match the figures elsewhere in this paper. It can be seen that our typical results are very close (within 1 dB) of the theoretical results for two branch diversity.

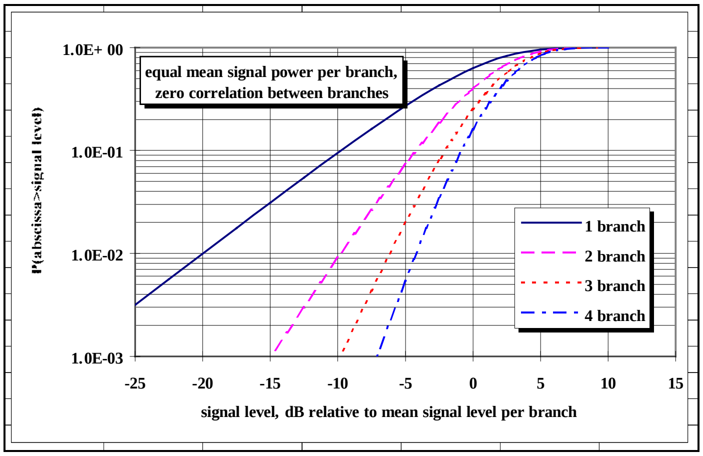

Figure 7 - Theoretical performance of M-branch selection diversity

Of course, Figure 7 is for an ideal case, where the correlation between antennas is zero. With correlation between the antennas, there is degradation in the performance of selection diversity - the probability that the second antenna is in a fade is now conditionally dependent on what the signal level is at the first antenna. Figure 8 shows the theoretical degradation in diversity improvement (at the 1% point) as a function of ρ^2, the envelope correlation. For correlation coefficients less than 0.2, less than .5 dB degradation in selection diversity improvement can be expected.

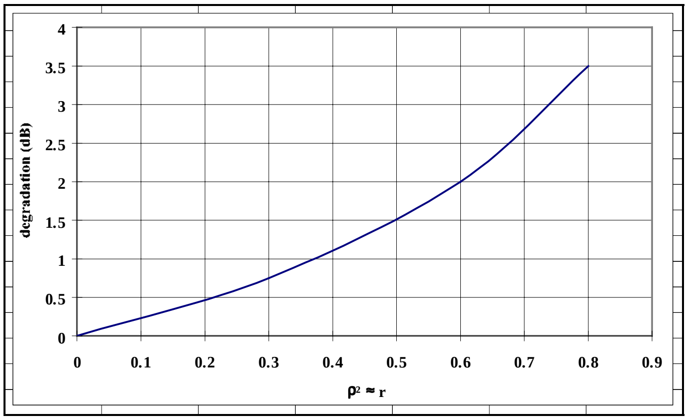

Figure 8 - Degradation due to antenna correlation, 2 branch selection diversity

8. Conclusion

We have shown that antenna preselection diversity can be an effective means of significantly enhancing the performance of an indoor wireless system. Under a set of worst case conditions using equipment that, as closely as practical, models a commercial system implementation, we have demonstrated that significant reductions in fade depths are achieved with easily implementable systems.

In typical operating conditions, we conclude that it is feasible to use a shortened auxiliary antenna that, on average, has less than a 2 dB disadvantage when compared to a full size $\lambda/4$ whip antenna. This, together with typical antenna correlation coefficients less than 0.2, leads to almost 10 dB improvement in signal level for fades that occur 1% of the time.

I'd like to acknowledge fruitful discussions with several colleagues, including Zoran Kostic and Nelson Sollenberger.

REFERENCES

[1] N.R. Sollenberger and S.J. Kasturia, "A 16 kb/s Voice Mode for Indoor IS-136 TDMA Systems," *Proceedings of the 1996 IEEE International Conference on Universal Personal Communications*.

[2] Z. Kostic and N. Abbasi. "Effects of Transmitter, Receiver, and Channel Impairments on the Performance of the Enhanced IS-136 System for Transmission of High-Quality Speech," *Proceedings of the 1997 IEEE Vehicular Technology Conference.*

[3] E. Geldblum and N. Seshadri, "High-rate Coded Modulation Schemes for 16 Kbps Speech in Wireless Systems," *Proceedings of the 1997 IEEE Vehicular Technology Conference*

[4] J-F. Lemieux, M.S. El-Tanany, and H.M. Hafez, "Experimental Evaluation of Space/Frequency/Polarization Diversity in the Indoor Wireless Channel," *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 3, pp. 569-74 August, 1991.

[5] D.C. Cox, H.W. Arnold, and P.T. Porter, "Universal digital portable communications: A systems perspective," *IEEE J. Select. Areas Commun*., vol. SAC-5, pp. 764-73, June, 1987.

[6] J.D. Parsons and J.G. Gardiner, *Mobile Communications Systems*, ch. 6, Wiley, 1989.

[7] P.B. Wong and D.C. Cox, "Low-complexity Diversity Combining Algorithms and Circuit Architectures for Co-channel Interference Cancellation and Frequency-Selective Fading Mitigation," *IEEE Transactions on Communications*, vol. 44, no. 9, pp. 1107-16, September, 1996.

[8] J.C-I. Chuang and N.R. Sollenberger, "Burst Coherent Demodulation with Combined Symbol Timing, Frequency Offset Estimation, and Diversity Selection," *IEEE Transactions on Communications*, vol. 39, no. 7, pp. 1157-64, July, 1991.

[9] K. Ogawa and T. Uwano, "A Diversity Antenna for Very Small 800-MHz Band Portable Telephones," *IEEE Transactions on Antennas and Propagation*, Vol. 42, no. 9, pp. 1342-5 September, 1994.

[10] D.H. Schaubert, F.G. Farrar, A. Sindoris, and S.T. Haynes, "Microstrip Antennas with Frequency Agility and Polarization Diversity," *IEEE Transactions on Antennas and Propagation*, Vol. AP-29, no.1, pp. 118-23 January, 1981.

[11] W.C. Jakes, ed., *Microwave Mobile Communications*, IEEE Press, 1994.

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