

Evaluation of Beamforming Algorithm Effectiveness for the Smart Wireless LAN System

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Abstract

The Smart Wireless LAN (SWL) system integrates the Space-Division-Multiple-Access (SDMA) technique with the IEEE 802.11 wireless LAN standard to enable multiple users to transmit on a wireless LAN at the same time in the same frequency band. Four beamforming algorithms are studied which the SWL system can use to minimize the interference that each user experiences from the other users. Computer simulations of the Signal-to-Interference (SIR) performance of the four beamforming algorithms are presented, and their SIR results are compared with results from previous experiments. Simulation results for the complete SWL physical layer are presented and analyzed.

I. Introduction

The SWL system [1] utilizes SDMA to achieve throughput multiplication by exploiting the rich spatial diversity existing among spatially separated users. Spatial diversity is demonstrated by the amplitude and phase pattern of the data received by an antenna array. Each user has a unique pattern, also called a *spatial signature* (SS). Once the SS are acquired, different co-channel signals can be separated by beamforming based on their unique SS. Therefore, we can increase the number of "virtual" time slots by allowing multiple users to transmit in the same frequency band and time slots without significantly interfering with each other.

Measurement of channel propagation characteristics by a smart antenna system in typical scenarios was shown in [2]. We studied selected beamforming algorithms in those scenarios because the successful application of SDMA systems depends not only on the knowledge of the propagation channel but also on the beamforming algorithm used. Hence, in this paper we concentrate on the performance of beamforming algorithms for downlink transmission.

Computer simulation results will be presented for the stationary user case in scenarios which are similar to that of the experiments. The performance of the beamforming algorithms in the scenarios will be compared with the results found from our experiments. Simulation results for the complete SWL physical layer will also be discussed.

II. Description of Smart Antenna System

At a base station, an M -element uniform linear antenna array receives signals from different spatial users.

The received signals contain both direct path and multipath signals which are most likely from various directions-of-arrival (DOAs). We denote the array response vector to a transmitted signal $s_1(t)$ from a DOA θ by $\mathbf{a}(\theta) = [1, a_1(\theta), \dots, a_{M-1}(\theta)]^T$, where $a_i(\theta)$ is a complex number denoting the amplitude gain and phase shift of the signal at the $(i+1)^{th}$ antenna relative to that at the first antenna.

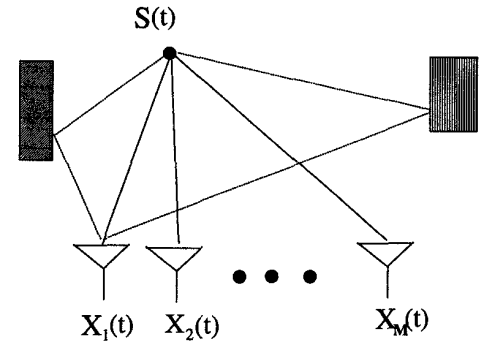


Figure 1: Uniform Linear Antenna Array with 2 Multipath

For a uniform linear antenna array with separation D in free space, as in Figure 1, the array response vector due to the signals received along the line-of-sight (LOS) path is $\mathbf{a}(\theta) = [1, e^{j2\pi f \sin \theta D/c}, \dots, e^{j2\pi f \sin \theta (M-1)D/c}]^T$, where f , c , and ^{T} denote the carrier frequency, speed of light, and transpose operator, respectively. In a typical wireless scenario, the antenna array is comprised of azimuthally broad coverage, even omni-directional elements. It not only receives a signal $s_1(t)$ propagated along the direct path but also many multipath echos from other DOAs. Hence, the total signal vector received by the antenna array is:

$$\mathbf{x}(t) = \underbrace{\alpha_1 \mathbf{a}(\theta_1) s_1(t)}_{\text{direct path}} + \underbrace{\sum_{l=2}^{N_m} \alpha_l \mathbf{a}(\theta_l) s_1(t)}_{\text{multipath}} = \mathbf{a}_1 s_1(t), \quad (1)$$

where $N_m - 1$ is the total number of multipath signals, the complex α_l describes the phase and amplitude difference between the l^{th} multipath signal and the direct path, and $\mathbf{a}_1 = \sum_{l=1}^{N_m} \alpha_l \mathbf{a}(\theta_l)$ is the SS associated with source 1.

Let $\mathbf{a}_1^i = \sum_{l=1}^{N_m} \alpha_l^i \mathbf{a}^i(\theta_l)$ be the SS of user 1 at the i^{th} time instance. In a typical wireless LAN scenario, the DOAs

of both the direct path signal and multipath components do not vary rapidly for a slight movement of the user, *i.e.*, $\theta_i^j \approx \theta_i^j$ or $\mathbf{a}(\theta_i^j) \approx \mathbf{a}(\theta_i^j)$ for $|i - j|$ smaller than certain time threshold. Usually, however, the phase and amplitude difference α_l (especially the phase) change more rapidly, which causes the SS to vary significantly even when the mobile user only moves slightly. This is due to the small wavelength employed for mobile communications, *e.g.*, 12.5 cm at 2.4 GHz. A small change in path length, *e.g.*, 6.25 cm, may lead to a large change (180°) in phase.

If there are d sources sharing the same frequency band and time slot, and $\mathbf{n}(\cdot)$ is background noise and other uncorrelated interference, then the antenna array receives:

$$\mathbf{x}(t) = \sum_{k=1}^d \mathbf{a}_k s_k(t) + \mathbf{n}(t). \quad (2)$$

III. The Smart Wireless LAN Physical Layer

A simplified block diagram of the physical layer for the updated SWL system is shown in Figure 2. This structure was created to be 802.11 compatible while allowing for the use of SDMA and was simulated by MATLAB. Data is randomly generated for four users, with three users serving as interference sources. The data comprises the MAC Protocol Data Unit (MPDU) field of the Physical Layer Convergence Protocol (PLCP) frame structure, which is specified in the 802.11 standard and shown in Figure 3.

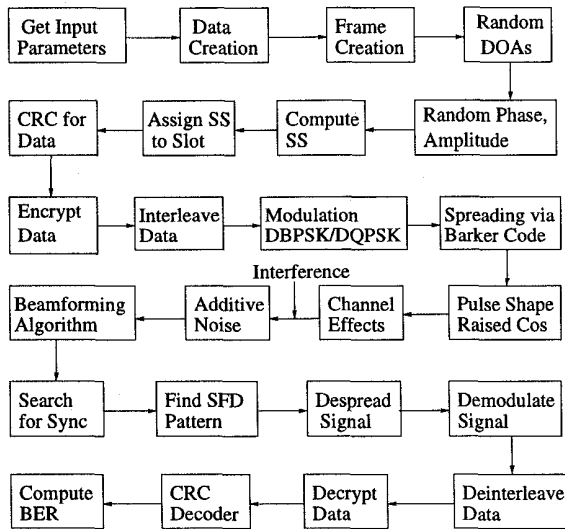


Figure 2: The SWL Physical Layer Block Diagram

The data is modulated with DBPSK or DQPSK to achieve the 1 and 2 Mbits/s data rates in 802.11. Encryption is an optional feature which uses the wired equivalent privacy (WEP) algorithm from 802.11. As in 802.11, each user uses the same code to spread their data, an 11-chip Barker code. Additive noise is scaled to achieve the specified SNR (signal-to-noise ratio) between the signal and the

Gaussian (mainly thermal) noise. The other operations are described later or conducted in a standard manner.

Certain features of 802.11 aid the implementation of an SDMA system. Timing considerations, critical for SDMA systems, are aided by 802.11 specifications such as the regularly broadcast frame by the base station which synchronizes the clocks of all terminals in its local area. Other features in 802.11 that aid SDMA systems are power control, the frame structure with contention and contention free periods, and terminal identification fields in each header.

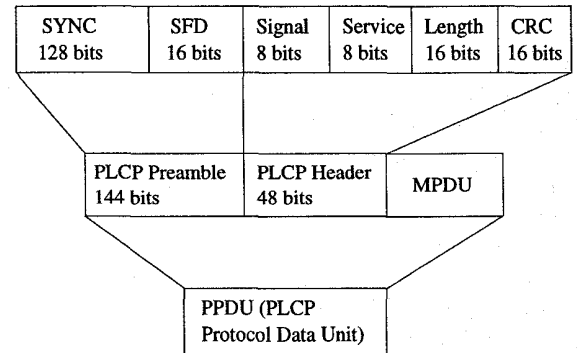


Figure 3: The Physical Layer Convergence Protocol Frame

Despite these advantages for SDMA, adapting SDMA for the IEEE 802.11 system requires special care due to certain unique properties of 802.11. For example, spread spectrum techniques similar to CDMA are used in 802.11, with the unfortunate requirement that each terminal use the same spreading code. Consequently, a straightforward application of SDMA to 802.11, allowing for multiple terminals to transmit at once, would result in a loss of the 10 dB of spreading gain. SWL achieves the spreading gain while allowing for multiple simultaneous transmissions by the insertion of a 3-chip delay between each of the resulting signal vectors, as shown in Figure 4. Each row represents the spreading code used by a terminal and the actual starting point of the Barker code is shown by a solid vertical line. Because of the ideal property of the Barker code (minimal correlation between shifted versions of the code), this allows the downlink coding gain from spreading to be achieved despite all the users using the same code. In a similar manner, the uplink coding gain is achieved by adjusting the timing of the start of each user's uplink transmission, taking into account the propagation delay found earlier. Due to the beamforming effectiveness shown later, each user should receive one significant and distinct signal to synchronize to and can easily despread its signal.

When multiple users wish to uplink to the base station at the same time, the base station can separate the signals because it already knows the SS of the individual users. Using that knowledge, the base station performs pseudoinverse SS beamforming to find the matrix that will be multiplied with the received waveform to obtain the data vectors containing the signals of the multiple

terminals. In effect, the weighting routine steers the beam in the direction associated with the array response vector of the desired source and places nulls in the other source directions to minimize their interference. A maximum likelihood method, pseudoinverse DOA, dominant DOA, and conjugate SS beamforming methods have also been studied via simulation. A new method based on the filter bank concept [3] is also being studied which should achieve superior performance than the pseudoinverse SS method at a cost of additional computational complexity.

+1	-1	+1	+1	-1	+1	+1	+1	-1	-1	-1
-1	-1	-1	+1	-1	+1	+1	-1	+1	+1	+1
+1	+1	+1	-1	-1	-1	+1	-1	+1	+1	-1
+1	+1	-1	+1	+1	+1	-1	-1	-1	+1	-1

Figure 4: Implementation of the 3-Chip Offset

A First SIR Fit technique similar to the First Fit SDMA/TDMA technique in [4] is used for dynamic slot assignment of users based on their SS. Beginning from the first time slot, the base station tries to assign a new user to the first time slot that is below its capacity N , currently four in SWL. If adding the SS of user i to the time slot results in $SIR_i < SIR_{min}$, the base station keeps trying open time slots until the test is passed, possibly placing the user in a time slot with no other users. Note that this technique differs from the First Fit technique in [4] by comparing SIR, not SINR (signal-to-interference-plus-noise ratio), because we use the previously obtained SS for the test. This method also doesn't attempt to try to assign more than N users to a particular time slot. This is in order to reduce the computational complexity of the technique, in preparation for our upcoming experiment.

The assumption that the SS is known is reasonable since each user is required to transmit a frame to the base station during the contention period in order to join the network. Since only one user is allowed to transmit at a time during that period as specified in 802.11, we can easily find that user's SS. Experimental studies in [1, 5] showed that the SS remains fairly constant over time for a stationary terminal.

When the downlink transmission containing the multiple user's frames is received by a user, it is able to distinguish its signal from the signals directed to the other users by using the PLPC preamble and taking advantage of the beamforming effectiveness. The PLPC preamble, shown in Figure 3, contains the SYNC and SFD fields. The SYNC field consists of an alternating 0-1 pattern, and the user searches through this data to synchronize its despread timing with the receive signal. This is necessary because the exact timing for the start of the Barker code is unknown by the terminal, so the terminal searches a sliding 10-bit (110-chip) window to find the maximum despread signal, which gives the synchronization timing. This search works

because the beamforming routine reduces the interference signals below the desired signal. Also, because the Barker code is uncorrelated with any unsynchronized part of itself, the terminal will find a low signal until the chips are aligned correctly and the timing is synchronized (where our simulation then finds a significantly higher peak). After synchronization is achieved, the terminal then searches for the known SFD pattern, which indicates that the PLCP Header and MPDU (the data) will immediately follow.

IV. Experimental Results

The SIR is critical because in many cases it is the limiting factor that determines the capacity of a system [6]. To measure the SIR of various systems, we simulated a situation with two moving users. We then calculated the SIR of the two users using the pseudoinverse SS, conjugate symmetric SS, pseudoinverse DOA, and dominant DOA beamforming methods in three distinct but typical cases.

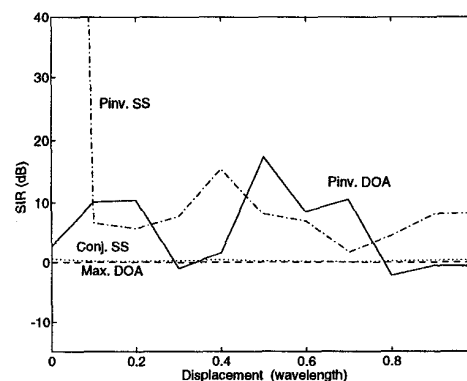


Figure 5: SIR Results for LOS User for Small Displacement

From our experimental results in [7], we found that when the users were close in the radial direction, only the pseudoinverse SS technique performed well for a stationary user, as shown in Figure 5. When the users had adequate radial separation, all algorithms performed well. When one user was blocked from the base station while the other user had LOS, all the algorithms performed well for the LOS user, while only the pseudoinverse SS algorithm performed well for the blocked user (when that user was stationary). In fact, the pseudoinverse SS method achieved the best SIR performance among all techniques for the stationary case. The rest of the experimental results are in [7].

V. Computer Simulation Results

The simulations studying the SIR performance of the beamforming algorithms for the SWL system made the significant assumption that all users were stationary. The

Algorithm	4 Spread	4 Close	2 Spread	2 Close
Pseudo SS	309.65 dB	279.525 dB	312.635 dB	296.11 dB
Conj Sym SS	11.97 dB	-6.42 dB	6.215 dB	-0.285 dB
Pseudo DOA	309.63 dB	277.24 dB	312.635 dB	296.11 dB
Dom DOA	11.97 dB	-10.12 dB	6.215 dB	-0.285 dB

Table 1: SIR Results for the Ideal Case Direct-Path Only

Algorithm	4 Spread	4 Close	2 Spread	2 Close
Pseudo SS	15.34 dB	-0.22 dB	27.385 dB	11.575 dB
Conj Sym SS	-0.27 dB	-5.91 dB	4.28 dB	-0.1 dB
Pseudo DOA	15.215 dB	-0.49 dB	27.385 dB	11.575 dB
Dom DOA	-0.27 dB	-8.9 dB	4.28 dB	-0.1 dB

Table 2: SIR Results with Noise with Direct-Path Only

stability of SS for stationary users was studied in [1, 5], where two different experiments showed that the SS remained virtually the same over at least an eight hour period. The standard scenario envisioned by the authors for a wireless LAN user is for the terminal to remain stationary while in use. If a user moves or if its SS changes for any reason, the base station will request that the user send a message during the contention period to update its SS.

The SIR results, averaged among the users, are shown in Table 1 for the direct-path only case with 2- and 4-users in the ideal situation where the SS is known exactly by the base station. It is evident from the results that all algorithms performed adequately when the DOAs are spread (greater than 10 degree separation), with the pseudoinverse methods clearly superior. However, the closely spaced case (less than 2 degree separation) had poor results for all but the pseudoinverse methods. The reason behind the poor performance is that the conjugate symmetric SS and dominant DOA beamforming techniques cannot separate two users when their angle separation is too small. The closely spaced case mirrors the results from Case 1 in [7] (where the terminals were placed within 1 degree of each other, as in the simulation) of the experimental results, and the case where the DOAs are spread mirrors the results of Case 2 in [7]. The major discrepancy in the results is that the SIR results are better in the computer simulation, especially for the pseudoinverse DOA case. Also note that the direct-path only scenario results in the pseudoinverse methods having basically the same results because, in the absence of noise and with perfect knowledge of the SS, they are identical in the 2-user case and very similar in the 4-user case. This is also true between the conjugate symmetric SS and dominant DOA techniques.

The authors investigated why the first simulation had much better performance than the experimental results. To check whether the assumption of exact knowledge of the SS was too ideal, a new computer simulation was created that assumed that all signals and the previously obtained SS were corrupted by independent Gaussian noise.

Algorithm	4 Spread	4 Close	2 Spread	2 Close
Pseudo SS	18.39 dB	14.503 dB	29.575 dB	27.49 dB
Conj Sym SS	-4.847 dB	-8.895 dB	7.165 dB	-0.625 dB
Pseudo DOA	3.573 dB	-0.648 dB	18.985 dB	17.285 dB
Dom DOA	-9.63 dB	-10.353 dB	11.93 dB	-0.575 dB

Table 3: SIR Results with Noise with Multipath Included

The noise level was set such that the desired SNR level would be experienced by each terminal and the previously obtained SS would be corrupted by the same level of noise. The SIR results for this more realistic simulation with a 10 dB SNR level is shown in Table 2 for the direct-path only case. Clearly, each beamforming algorithm's performance suffered from the additive noise, especially the pseudoinverse DOA technique. The simple direct-path only scenario is shown because it allowed for comparison with the experimental results. The SIR results obtained for both the closely spaced and spread cases are consistent with the experimental results when the terminals were stationary.

The SIR results for the scenario where all users have multipath and direct-path signals with a 10 dB SNR level are in Table 3. The conjugate symmetric SS and dominant DOA techniques suffered the most from the addition of multipath and the pseudoinverse SS technique still performed the best, as expected from our experimental results.

In all cases, the pseudoinverse SS technique performed the best, as in our experiments. The pseudoinverse DOA technique performed better than the dominant DOA and conjugate symmetric SS techniques, also as in our experimental results for the stationary case. The performance of the computer models was directly affected by the noise level in the system, and the lower performance levels from the simulations as compared to the experiments seems to be due to the conservative 10 dB SNR assumption.

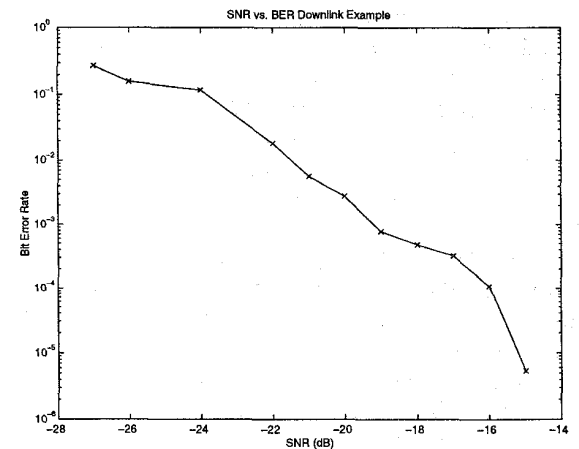


Figure 6: SNR vs. BER with Perfect SS Knowledge

A simulation was constructed to study the complete

SWL physical layer. The simulations used a 2000 bit data frame, with four users receiving frames at the same time. Each simulation ran for at least 10 frames, with the data, noise, DOAs, and SS randomized for all users each time, and the average bit error rate (BER) was computed. A typical downlink example is shown in Figure 6, where the base station used pseudoinverse SS beamforming to minimize the interference to the other simultaneous users.

There are a few factors that should be noted when we interpret the results shown in Figure 6. First, the SNR does not include the interference in the system due to the other three users which are receiving frames simultaneously with our desired signal, so the actual SINR of the system is worse than the SNR listed. Second, the SS vectors were chosen randomly each simulation run so it was possible that two terminals were assigned highly correlated SS. It was shown in [4] that this random assignment of users has an inferior performance than the First Fit method similar to what SWL uses. Third, the SNR specified doesn't include the coding gain from the use of spreading, which adds about 10 dB to our overall system performance. It also doesn't include the antenna gain that we achieve by using an antenna array [8], which significantly increases the effective SNR of our system. Finally, more advanced beamforming techniques can achieve superior performance at a cost of additional computational complexity.

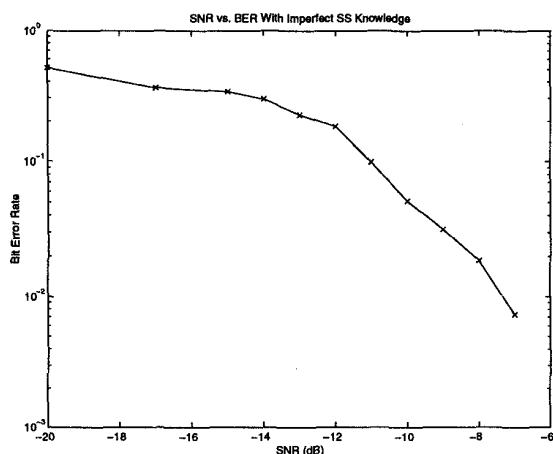


Figure 7: SNR vs. BER with Imperfect SS Knowledge

The results in Figure 6 are significantly better than the results in [1]. This is due to the improved timing and synchronization features with the addition of the SYNC and SFD fields in the header, use of DBPSK/DQPSK instead of BPSK/QPSK, and improved beamforming application.

The simulation also assumed perfect knowledge of the SS, where in a real system our beamforming routines would perform at a lower level due to noise corruption of the SS. With imperfect knowledge of the SS, the system performance decreases as in Figure 7, where each SS was corrupted with noise before computation of the beamforming

weight vectors. The results in Figure 7 were worse than expected, which was found to be due to the assumption that the SS vector was corrupted with the same noise level as the system noise. Studies are currently underway to find the appropriate levels of SS uncertainty for various scenarios, with comparisons with our experimental results.

VI. Conclusion

In order to successfully allow multiple users to transmit simultaneously in the same frequency band, as specified in the SWL system, beamforming must be used to minimize the interference that each user experiences from signals to or from other users. Four beamforming techniques were studied under typical scenarios, through both experimental measurements and computer simulations.

From our computer simulation results, we found that assuming that the base station had perfect knowledge of the SS was too strong of an assumption, resulting in better performance than found by the experiments, especially for the pseudoinverse DOA algorithm. When we allowed the known SS and all of the transmitted signals to be corrupted by noise, our results were consistent with the simulation results. The pseudoinverse SS method achieved the best SIR performance for all cases, as in our experimental results.

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