ALTERNATING TIME-OFFSET DOWNLINK SDMA FOR LEGACY IEEE 802.11A/G MOBILE STATIONS

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Abstract

We address the problem of downlink throughput improvement for IEEE 802.11a/g systems by using a modified access point (AP) equipped with multiple antennas. The main restriction is that standard terminals should not be modified in any way. An alternating time-offset space division multiple access (SDMA) solution is proposed to overcome restrictions imposed by the legacy terminals requirement. In this paper we concentrate on channel estimation over acknowledgement (ACK) bursts and effect of imperfections such as non-ideal channel reciprocity and delayed channel estimates. Simulations based on channel models approved by the IEEE 802.11 Standard Group demonstrate that a near doubling of downlink capacity can be achieved in a conference room environment in the case of low levels of channel reciprocity errors at the AP.

1. INTRODUCTION

Space division multiple access (SDMA) is a widely recognized smart antenna technology [1]. This technique allows a number of spatially separated users to share the same time-frequency channel. An important SDMA feature is that it is applicable to APs equipped with multiple antennas and single-antenna terminals. Different aspects of the SDMA technique have been addressed in the literature, including channel condition effects, signal processing aspects and MAC-level issues. Time division duplex (TDD) systems are especially suitable for SDMA application since the uplink (UL) channel information can be used during downlink (DL) data transmission [2]. In spite of many readily available general PHY and MAC-level SDMA algorithms, their application to specific systems (e.g., WLAN) is not straightforward. The problem is that specific features of a particular system, e.g., a data slot structure or specific UL/DL protocol, may significantly complicate SDMA implementation. For example, specific pilot assignment for different users and sub-carriers in an OFDM/SDMA system [3] is not compatible with the current OFDM/WLAN standards such as IEEE 802.11a/g and HIPERLAN/2.

A possibility of introducing an SDMA mode to a WLAN system based on the IEEE 802.11a/g standards [5], subject to the constraint that the AP may be modified but the standard terminals cannot be changed (legacy terminals), is investigated in [6], [7]. In these papers we have proposed an alternating time-offset AP transmission scheme for two-user DL SDMA in a conference room environment.

Part of this work has been done in the context of the IST 6FP OBAN project.

In this paper we focus on signal processing aspects of this problem such as channel estimation over ACK bursts to support DL SDMA transmissions, and the effect of imperfections such as non-ideal channel reciprocity and delayed channel estimates. MAC-layer issues are addressed in [7] and briefly summarized in Section 4. The efficiency of the proposed solution is evaluated in a conference room environment assuming a channel reservation for the SDMA mode. Simulations are based on the standard IEEE 802.11 channel model [8], [9], which includes all the main propagation effects such as delay spread, path loss, shadowing, spatial correlation, Doppler, fluorescent light effects, etc.

The problem formulation is given in Section 2. The alternating time-offset DL SDMA solution is presented in Section 3 including the uplink ACK reception algorithm and channel estimation procedure. The system and simulation assumptions and results are presented in Section 4. Conclusions are stated in Section 5.

2. PROBLEM FORMULATION

The narrowband transmitted and received signals (e.g., for each separate sub-carrier of an OFDM system) for the basic DL SDMA operation of a group of M users can be expressed as follows [1],[2]:

$$\mathbf{A} = \mathbf{W}\mathbf{S}, \tag{1}$$

$$\mathbf{b}_m = \mathbf{h}_m^T \mathbf{A} + \mathbf{c}_m, m = 1, \dots, M, \tag{2}$$

where $\mathbf{S}$ is the $(M \times T)$ matrix of the transmitted signals $(T^{-1}\mathrm{E}\{\mathbf{S}\mathbf{S}^*\} = P\mathbf{I}_M)$, T is the number of symbols, P is the signal power, $\mathbf{I}_M$ is the $(M \times M)$ unit matrix, $\mathbf{W}$ is the $(N \times M)$ weight matrix, $\mathbf{A}$ is the $(N \times T)$ matrix of the combined transmitted signal, $\mathbf{b}_m$ is the $(1 \times T)$ vector of the signals received by the mth terminal, $\mathbf{h}_m$ is an $N \times 1$ vector representing the propagation channel from the N AP antennas to the single antenna at the mth terminal, and $\mathbf{c}_m$ is a $(1 \times T)$ AWGN noise vector at the mth terminal with variance σ^2.

The conventional diagonally loaded zero-forcing ("MMSE"-type) solution for the weight matrix is as follows:

$$\mathbf{W} = \frac{1}{\sqrt{\mathrm{tr}(\mathbf{V}^*\mathbf{V})}}\mathbf{V}, \tag{3}$$

$$\mathbf{V} = \mathbf{H}^*(\mathbf{H}\mathbf{H}^* + \alpha\mathbf{I}_M)^{-1}, \tag{4}$$

where $\mathbf{H}$ is the $(M \times N)$ channel matrix of rows $\mathbf{h}_1^T \dots \mathbf{h}_M^T$ and α is the regularization coefficient, which is normally selected as $\alpha = \sigma^2/P$. Normalization in (3) is required to keep the total transmit power constant.

The basic SDMA solution (3)-(4) is actually the simplest one and can be modified in many ways [4]. Following the main objective of this paper, we consider the possibility of applying this basic solution taking into account the restrictions imposed by the IEEE 802.11 a/g specifications.

Direct application of the conventional simultaneous DL SDMA transmission scheme to an AP is difficult because of the IEEE 802.11a/g requirements for ACKs. A simultaneous DL SDMA transmission will result in each terminal responding, after a short interframe space (SIFS) interval of 16 μs, with an ACK burst. In this case, the ACK bursts almost completely overlap in time and mutually interfere upon arrival at the AP. It is important to note that the ACKs are not completely synchronous since each maintains a SIFS period of 16 μs only to within some finite accuracy. Each ACK slot consists of synchronization, pilot, and data segments [5]. Apart from confirming the successful reception of the MAC packet data units (MPDUs) (as in conventional operation), the pilot segments of the ACKs are needed to derive fresh estimates of the propagation channels in preparation for the next SDMA transmission. The overlap of the pilot segments severely impedes channel estimation. The overlap of the synchronization segments also severely degrades synchronization itself. Note that, according to the IEEE 802.11a/g specifications, all ACKs contain the same pilot and synchronization symbols. This precludes the use of any form of joint channel estimation in the case of simultaneous DL SDMA transmission.

In this paper we consider a two-user case, apply a time-shifted DL SDMA transmission, and concentrate on channel estimation over ACK bursts and the effect of imperfections such as non-ideal channel reciprocity and delayed channel estimates.

3. ALTERNATING TIME-OFFSET DL SDMA

3.1 Time-offset transmission

The particular case of two SDMA users in a group can be addressed by means of time-shifted SDMA transmission [6]. The solution is to impose a time-offset between the SDMA-transmitted MPDUs, causing a similar time offset in the ACK responses of the two terminals, as depicted in Fig. 1. This reduces the interference between the ACKs, in particular during the critical synchronization and pilot intervals of ACK1. In principle, the maximum allowed value of this offset is 16 μs because simultaneous transmission and reception are not allowed at the AP or terminal. As will be seen below, it is important that the ACK2 symbols interfering with ACK1 are known *a priori* (i.e., correspond to the synchronization and pilot symbols). This implies that the minimum allowed offset is restricted as well

$$\bar{T}_{\text{ACK}} - \bar{T}_{\text{sync}} - \bar{T}_{\text{pilot}} < \bar{T}_{\text{offset}} < \text{SIFS}, \tag{5}$$

where $\bar{T}_{\text{ACK}} = [24, 28, 32]\mu s$, $\bar{T}_{\text{sync}} = \bar{T}_{\text{pilot}} = 8\,\mu s$ are the durations of the ACKs, synchronization, and pilot intervals respectively. In our simulations in Section 4, we assume $\bar{T}_{\text{ACK}} = 24\mu s$, which corresponds to 16-QAM data signalling, and select $\bar{T}_{\text{offset}} = 12\mu s$.

3.2 ACK Recovery

The two partially overlapping ACK bursts shown in Fig. 1 may be recovered via the procedure summarized below. Further details are given in [6], [7].

- *S*tep 1. Sample the received signal synchronously for ACK1.
- *S*tep 2. Estimate an oversampled replica of ACK2 using interpolated signal at the synchronization and pilot intervals using the estimated channel for the time-shifted user.
- *S*tep 3. Perform fine synchronization for oversampled ACK 2 and subtract it from the input signal to get the cleaned up signal for ACK1 recovery.
- *S*tep 4. Recover ACK1 by means of a conventional beamforming receiver over the cleaned input signal; if there is an error, then the whole SDMA packet is lost.
- *S*tep 5. Oversample the input signal and the whole recovered ACK1 using the estimated channel for the non-shifted user.
- *S*tep 6. Subtract the oversampled ACK1 from the oversampled input signal according to Step 3.
- *S*tep 7. Recover ACK2 by means of a conventional beamforming receiver over the cleaned up input signal.

3.3 Alternating channel estimation

Both channels $\hat{\mathbf{h}}_1$ and $\hat{\mathbf{h}}_2$ can be estimated via the cleaned up input signals $\mathbf{x}_1$ and $\mathbf{x}_2$ obtained at Steps 3 and 6 respectively. However, since the non-delayed ACK1 is cleaned up with more reliability than the delayed ACK2, the estimate of $\hat{\mathbf{h}}_1$ derived from $\mathbf{x}_1$ is also more reliable than the estimate of $\hat{\mathbf{h}}_2$ derived from $\mathbf{x}_2$. One of the reasons for this difference is that according to Step 6, $\mathbf{x}_2$ is based on the oversampled replicas of both the input signal and ACK1, but $\mathbf{x}_1$ involves only one oversampled replica of the synchronization and pilot segments of ACK2. Another reason is that while pilot symbols are transmitted on all 52 OFDM sub-carriers according to the 802.11 specifications (the rest of the 64 sub-carriers are not used for transmission), the synchronisation symbols are transmitted only on 12 (roughly equi-spaced) sub-carriers out of the total of 52 OFDM sub-carriers. This means that the synchronization segment of ACK2 interferes with only 12 sub-carriers of the pilot segment of ACK1. In contrast, the 52 sub-carriers of the data segment of ACK1 interfere with all 52 sub-carriers of the pilot segment of ACK2. This situation is illustrated in Fig. 2 for $\bar{T}_{\text{offset}} = 12\mu s$, which satisfies inequality (5). The poor quality of $\hat{\mathbf{h}}_2$ estimates can have a severe impact on the successful application of SDMA.

The above issue may be addressed by estimating only the channel associated with the reliably-recovered non-delayed ACK1. The identity of the user associated with the non-delayed MPDUs and ACKs should then be switched for successive SDMA transmissions. This is depicted in Fig. 3 for terminals A and B. Alternating of the users allows channel estimation for both users in two consecutive successful SDMA slots even if only one non-shifted pilot interval is used for estimation. Although this scheme reduces the update rate of the channel estimates, this is more than compensated for by the improved quality of the channel estimates.

The proposed channel estimation procedure is as follows:

Step 1. Apply the conventional channel estimation procedure over the pilot interval:

$$\hat{\mathbf{h}}_1(f) = \mathbf{x}_1(f)/s_{\text{P}}(f),\, f \in \mathcal{F}_{-\text{S}}, \tag{6}$$

where $s_{\text{P}}(f)$ is the pilot simbol at the fth sub-carrier and $\mathcal{F}_{-\text{S}}$ is the set of all working subcarriers $\mathcal{F} =$

$[6 \ldots 32\, 33 \ldots 58]$ except the ones used for synchronization $\mathcal{F}_{\mathrm{S}} = [8\, 12\, 16\, 20\, 24\, 28\, 36\, 40\, 44\, 48\, 52\, 56]$ [5].

Step 2. Estimate the channel at the synchronization sub-carriers using interpolation:

$$\hat{\mathbf{h}}_1(f) = \mathrm{INTERP}\left\{\hat{\mathbf{h}}_1(u), u \in \mathcal{F}_{-\mathrm{S}}\right\}, f \in \mathcal{F}_{\mathrm{S}}, \qquad (7)$$

where $\mathrm{INTERP}\{\cdot\}$ is the interpolation operator based, for example, on the spline technique.

Another version of Step 2 can be developed by estimating the channel at the synchronization sub-carriers over the synchronization interval, which is not affected by the ACK2 interference in the time-offset SDMA, as shown in Fig. 1.

4. SIMULATION RESULTS

We simulate a conference room environment, where all radios can hear each other and packet errors appear mainly because of non-ideal SDMA rather than interference at terminals due to hidden terminals. Our main assumptions are as follows:

System assumptions: 1). The channel can be reserved for two users for the whole SDMA session. 2). A non-SDMA initialization is applied at the beginning of the SDMA session, which consists of conventional (without beamforming) successive DL transmissions to the SDMA users followed by conventional UL channel estimation at the ACK reception stage. 3). The backoff interval defined in [5] does not increase after receiving an erroneous SDMA packet; instead, it leads to a non-SDMA initialization similar to the one at the beginning of the SDMA session.

Simulation assumptions: 2.4 / 5.2 GHz frequency range; 16-QAM, convolutional encoding with 3/4 code rate; 4320 information bit packets (35 OFDM symbols or 140 μs total slot duration); 10 ms SDMA session; 2λ separation between AP antennas, 4λ separation between terminals; "B" and "D"-channels defined in [8], [9] with 15 ns and 50 ns RMS delay spread respectively with fluorescent effects ("D"-channel); (3-9) m and (5-15) m distance range for the "B" and "D" cases respectively; 16 dBm transmit power; -92 dBm noise power; asynchronous ACK arrivals with (16±0.5) μs delay; $q = 20$ oversampling factor in Steps 2 and 5 in Section 3.2.

Simplification assumptions: ideal (linear) front-end filters at AP and terminals; zero frequency offset; no quantization effects; perfect receiver synchronization at AP and terminals.

Further details on system and simulation assumptions are given in [7].

Non-ideal channel reciprocity is simulated similarly to [3]. The RMS values of amplitude and phase errors for terminals are fixed at 0.7 dB and 5° respectively. The RMS values of amplitude and phase errors for the AP are variable as indicated in Fig. 4-6.

The following algorithms are simulated:

Benchmark 1: Conventional non-SDMA with single transmit antenna.

Benchmark 2: Non-SDMA with beamforming at AP.

Benchmark 3: SDMA with ideal ACK receiver.

Alternating time-offset SDMA with $T_{\mathrm{offset}} = 12\mu s$.

At this stage we do not consider any spatial scheduling, i.e. we randomly select two users and start an SDMA session at every simulation trial. The throughput is measured as the total number of bits successfully transmitted during a 10 ms SDMA session.

Fig. 4-5 show CDFs of the overall throughput for two and three-antenna APs in the "B"-channel 2.4 GHz environment and Fig. 6 gives the performance of a three-antenna AP in the "D"-channel 5.2 GHz case. Benchmark 2 demonstrates some performance improvement because of the increased signal-to-noise ratio (SNR) in the non-SDMA beamforming case. Benchmark 3 suggests that in the case of an ideal channel reciprocity, the throughput can be doubled in the considered environment for almost all randomly selected channels. The proposed SDMA solution demonstrates results close to Benchmark 3 for most of the trials. The CDF shift of the alternating time-offset solution (with respect to Benchmark 3) is due to the introduced time-offset. The non-ideal channel reciprocity causes some performance degradation, especially in the two-antenna 2.4 GHz "B"-channel case in Fig.5 as well as in the three-antenna 5.2 GHz "D"-channel case in Fig.6, depending on the AP channel calibration errors. These results can be useful for formulation of the AP radio frequency requirements.

5. CONCLUSIONS

The proposed alternating time-offset SDMA solution supports legacy terminals but requires some modifications to the transmission protocol at the AP. The main features of the IEEE 802.11a/g standards, such as channel conditions, transmission protocol, and data and ACK slot structures, have been taken into account. The downlink capacity in a conference room environment is almost doubled for low levels of channel reciprocity errors at the AP, as demonstrated by simulations based on the channel models approved by the IEEE 802.11 Standard Group.

Acknowledgement

The authors would like to thank L. Shumacher for providing the MATLAB software for channel generation. Also, thanks are expressed to D. Morgan, D. Avidor, J. Ling, K. K. Leung, D. M. Samardzija, and R. A. Valenzuela for participating in many fruitful discussions. Part of this work has been done with financial support from the IST 6FP OBAN project.

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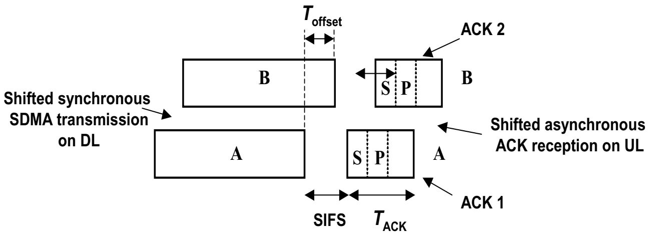

Figure 1: Time-offset SDMA slot for two users.

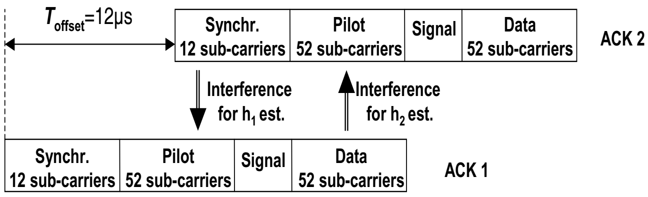

Figure 2: Interference to channel estimation over ACK bursts.

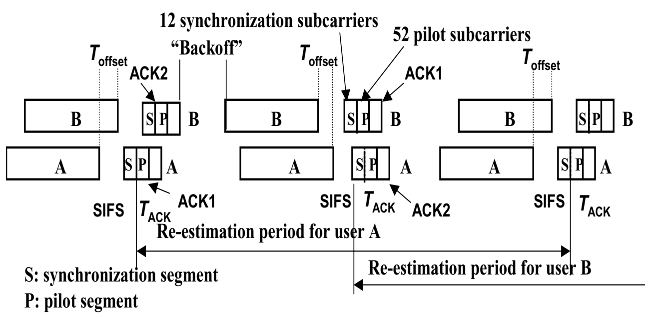

Figure 3: Alternating time-offsed SDMA.

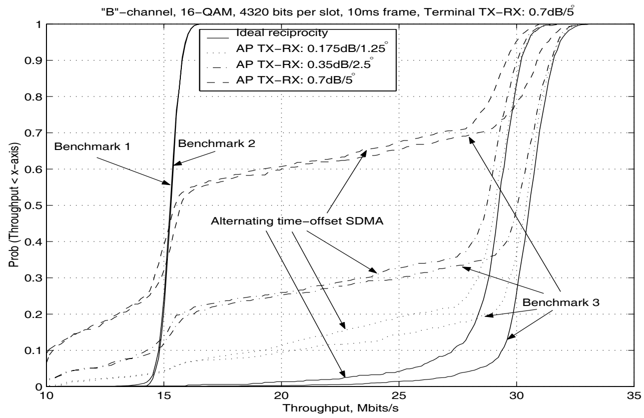

Figure 4: Throughput performance for two users and two-antenna AP in the "B"-channel 2.4 GHz environment.

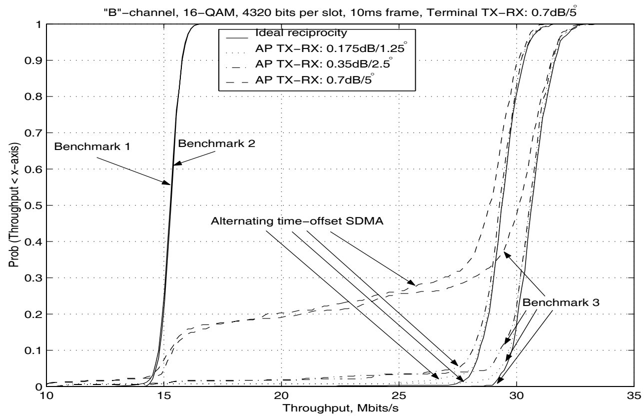

Figure 5: Throughput performance for two users and three-antenna AP in the "B"-channel 2.4 GHz environment.

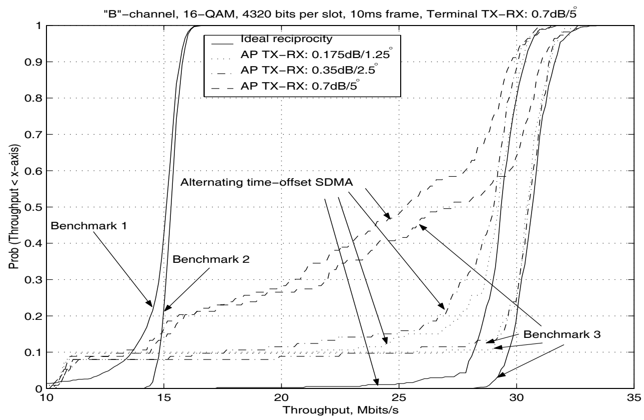

Figure 6: Throughput performance for two users and three-antenna AP in the "D"-channel 5.2 GHz environment.