On the Performance of Scheduling over Space-Time Architectures

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Abstract

In this paper, a unified comparison of space-time architectures paired with scheduling algorithms is presented. We define a new performance metric, which encapsulates both the spectral and energy efficiency of the scheme and consider various types of space-time architectures, including space-time block coding and BLAST. We consider a scenario in which K active data users, each of which is equipped with multiple antenna elements, report their channel state information (CSI) to a multi-antenna element base station (BS). Using a scoring function at the BS, time resources are allocated to the users in order to facilitate multiuser diversity which enhances the overall throughput of the system.

I. Introducation

Space-time architectures have been developed to improve the reliability and throughput of wireless systems using multiple antenna element technology. While both block and trellis-type space-time codes improve the energy efficiency of the scheme by exploiting the spatial and temporal diversity, the Bell Labs Layered Space-Time Architecture (BLAST) significantly improves the spectral efficiency of the scheme while suffering from a poor energy efficiency. A vast body of research has been published on the performance and structure of these techniques separately. In this paper, we aim to compare these architectures in a unified manner such that both the spectral and energy efficiencies are addressed. To that end, we define a new performance metric of averaged “good throughput”, termed “goodput”. This metric can be defined as the inherent spectral efficiency of the scheme times the correct frame rate. Using this metric, we also assess the impact of scheduling algorithms, executed in the access-control (MAC) layer of a wireless network, on the performance of space-time architectures, employed at the physical (PHY) layer of the system.

One important application to space-time architectures may be high-data-rate downstream wireless Internet access to nomadic users [1]. The nature of such data traffic is asymmetric, requiring a much higher downlink rate from the base station (BS) than that generated in the uplink channel by the user terminal. In addition to traffic asymmetry, data services differ from voice services in their tolerance to delay. We consider in this paper a scenario where a single BS provides data services to K users, each of which is equipped with multiple antenna elements. Since the data rate that can be supported to each user is proportional to its received SNR, it may be beneficial to use CSI and the unequal latency property of the service to serve multiple users with disparate SNRs. This may improve the overall throughput of the system as compared with the case of equally served users regardless of their channel conditions. The BS applies one of the space-time architectures (e.g., STBC, STTC or BLAST) paired with a scheduling protocol that routes the transmission of packets to users based on their reported CSI in the uplink channel.

Two extreme scheduling algorithms are considered. The first one, denoted “greedy”, routes each transmission to the user with the best instantaneous channel conditions. The second, denoted “round robin” (RR), routes the transmission of packets equally across users. Results indicate that the “greedy” scheduler gives rise to a multiuser diversity mechanism, where the link with the best instantaneous SNR is selected (out of K independent links) on a per frame basis. The round robin scheduler is equivalent to the single user case since all users are equally served in an orthogonal TDM-like manner. The multiuser diversity, introduced by the “greedy” scheduler, enhances the average SNR during scheduled bursts and thus improves the performance of the space-time architecture. We study the interactions between multiuser diversity and spatial diversity by calculating the statistics of the effective SNR at the space-time combiner output with and without K-fold multiuser diversity.

The remainder of the paper is organized as follows. In section II we propose the "goodput" metric which encapsulates both the spectral efficiency (measured in [bps/Hz]) and the energy efficiency (measured in SNR required to achieve acceptable error rate performance). Section III describes the space-time architectures under consideration. Section IV presents performance results for these schemes paired with the "greedy" or round-robin scheduling algorithms. Finally, section V concludes the paper.

II. "Goodput" as a Performance Metric

We compare various combinations of scheduling algorithms and space-time architectures using a single metric of averaged "good throughput", termed "goodput", defined by

$$\overline{\rho} = \eta \frac{K}{L} \sum_{k=1}^{K} N_k (1 - FER(k, SNR)), \qquad (1)$$

where η is the theoretical spectral efficiency of the scheme, K denotes the number of users, L is the total number of data frames to all users, N_k is the number of actual transmitted frames to the kth user (need not be constant in "greedy" mode) and $FER(k, SNR)$ is the FER of the kth user for a given signal-to-noise ratio. Since both η and FER are embedded in the computation of $\overline{\rho}$, the "goodput" metric encapsulates both the spectral and energy efficiency of the scheme.

III. Space-time Architectures

The following four specific space-time architectures are considered for the physical layer, assuming that both the base station and the terminal are equipped with 4 antenna elements:

1. Space-Time Block Code (STBC) (rate 3/4, H_4) with M-ary PSK (Figure 1, [2])
2. STBC (same as in 1) as inner code concatenated with a rate 1/2, constraint length 7 outer convolutional code (Figure 2, [3])
3. Uncoded V-BLAST with MMSE nulling, successive interference cancellation (SIC) unit and ordering of layers (Figure 3, [4, 5])
4. Coded PIC BLAST with iterative cancellation decoding (Figure 4, [6])

We note that the transmitted power and frame length are held constant for all cases.

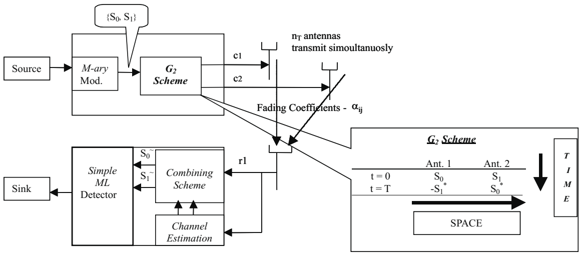

Figure 1: STBC block diagram

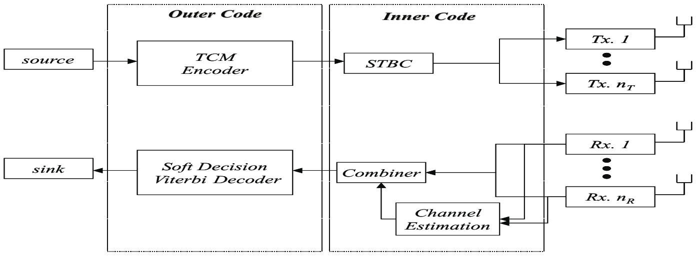

Figure 2: Concatenated STBC with Outer Convolutional Code

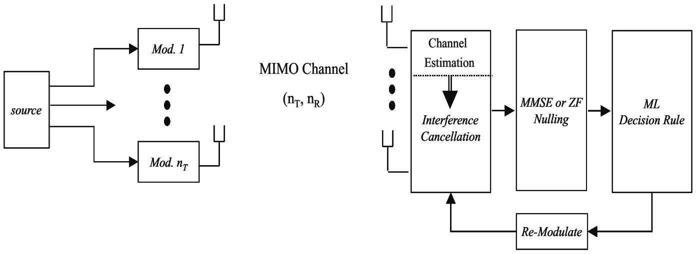

Figure 3: V-BLAST Architecture

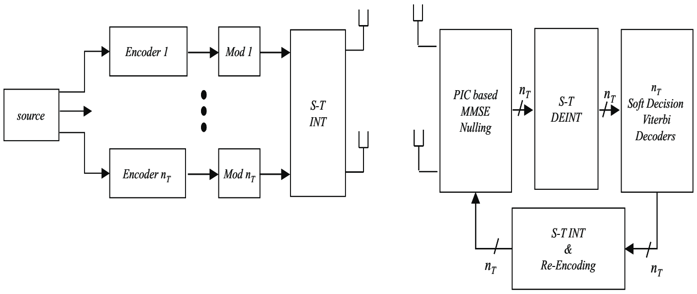

Figure 4: Iterative PIC decoding BLAST architecture

IV. PERFORMANCE RESULTS

Figure 5 presents simulated results for various combinations of space-time architectures and scheduling algorithms. The effectiveness of the metric $\overline{\rho}$ is demonstrated by addressing both the energy and spectral efficiency of the scheme. We observe that each scheme has a different operating point, where the "goodput" $\overline{\rho}$ converges to the theoretical throughput η. For example, V-BLAST with QPSK modulation requires an SNR of 20 dB to guarantee 8 [bps/Hz], coded BLAST requires SNR of 11 dB to provide 4 [bps/Hz], uncoded STBC with QPSK modulation requires SNR of 6 dB to provide 1.5 [bps/Hz] and coded STBC can operate reliably at SNR of 0 dB with spectral efficiency of 0.75 [bps/Hz]. This provides insight into the benefits (and drawbacks) of the various space-time architectures. It is further observed that the "greedy" scheduling algorithm enhances throughput significantly due to multiuser diversity. A detailed treatment of the impact of multiuser diversity on space-time architectures is provided in the next section and in [7]. As reference curves, we also include the 1% outage capacity of the MIMO channel [8] computed with and without multiuser diversity. These curves serve as an upper bound on the throughput of practical space-time architectures. It is observed that the coded PIC BLAST scheme operates within 5 dB from channel capacity.

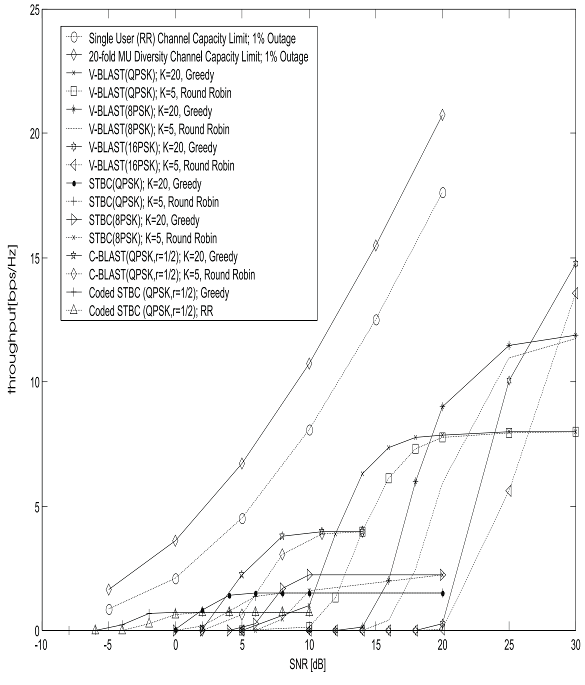

Figure 5: "Goodput" of scheduling over space-time architectures (4Tx-4Rx)

Zooming into the good energy efficiency-low spectral efficiency regions of this two dimensional space, Figure 6 demonstrates the "goodput" of STBC with and without outer error correction code paired with "greedy" ($K = 20$) or round robin scheduling algorithm.

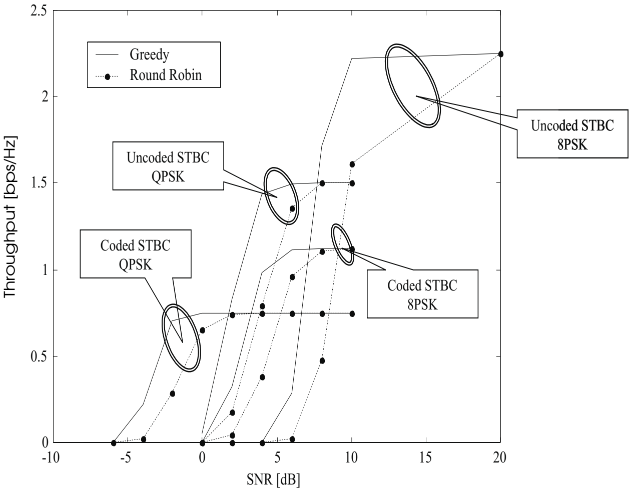

Figure 6: "Goodput" of scheduling over space-time block codes (4Tx-4Rx)

Again, the "greedy" scheduler increases throughput quite significantly due to enhancement of SNR. Note that coded STBC with 8PSK is inferior to uncoded STBC with QPSK. This is due to the rate loss associated with the use of convolutional code. As was shown in [9], trellis codes may be a better choice for an outer error correction code of STBC as they facilitate coding gain without sacrificing spectral efficiency.

One disadvantage of the "goodput" metric is that not all points on the curve are valid operating points (i.e., acceptable FER values). To address that, Figure 7 presents a "sample" of the throughput curves at a fixed FER of 1% for the four disparate space-time architectures operating with round robin scheduling algorithm. Also here, we include the 1% outage capacity of the MIMO channel as a reference curve.

Results show that V-BLAST architecture paired with QPSK, 8PSK and 16PSK achieves $8, 12$ and 16 [bps/Hz] at SNRs of $20, 30$ and 35 dB, respectively. Space-time block code (H_4 orthogonal design) paired with QPSK and 8PSK requires SNRs of 6 and 11 dB, to achieve 1.5 and 2.25 [bps/Hz], respectively. Upon completion of the fourth iteration, the iterative coded BLAST with QPSK achieves 4 [bps/Hz] at SNR of 11 dB. If one would like to achieve extremely good energy efficiency, STBC concatenated to a rate $1/2$ convolutional code yields spectral efficiency of 0.75 [bps/Hz] at a low SNR of 2 dB.

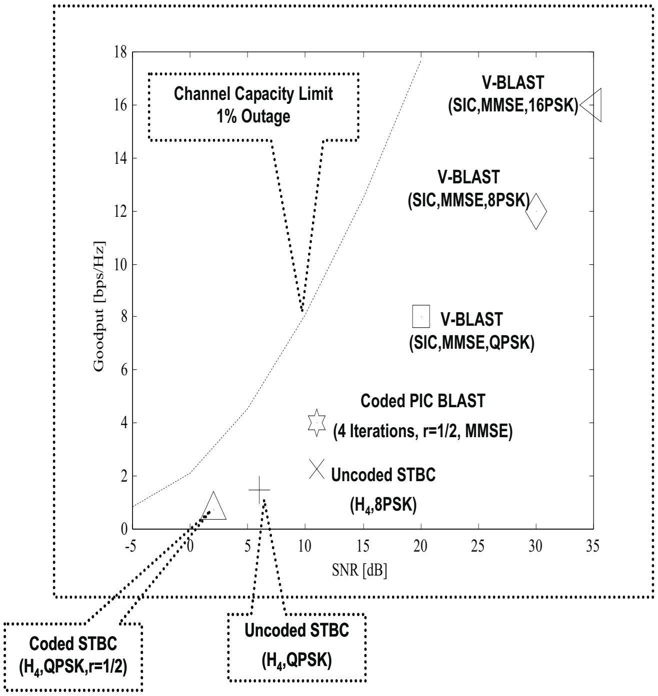

Figure 7: "Goodput" of round robin scheduling over space-time architectures for a fixed FER of 1% (4Tx-4Rx)

Next, FER results as a function of SNR for the four schemes with "greedy" or round robin scheduling algorithms are presented. Note that the information presented in this plot has been already embedded into Figure 5 (see Eq. (1)). Here, we focus on the energy efficiency of the scheme and observe that with the "greedy" scheduling, 1% FER is achieved at $SNR = -1, 4, 11$ and 21 dB for coded STBC, uncoded STBC, coded PIC BLAST and uncoded V-BLAST, respectively. Using the round robin scheduling algorithm, 1% FER is achieved at $SNR = 2, 8, 13$ and 23 dB for the four schemes, respectively. Thus, the "greedy" scheduling algorithm enhances the performance of the scheme by about 2.5 dB.

A surprising result is that the "greedy" scheduler, which introduces multiuser diversity, enhances the performance of STBC with 4Tx-4Rx antenna array configuration. Since the spatial diversity order of this scheme is 16, the MIMO Rayleigh fading channel has been approximately transformed to an equivalent single-input single-output AWGN channel. It is well known [10, 11] that by increasing the spatial diversity order of STBC further, performance in terms of reliability and capacity is bounded by AWGN results. Natural questions are therefore: 1) How does multiuser diversity enhance performance further ? 2) Is multiuser diversity mechanism equivalent to spatial diversity ? The answer to these questions is provided in [7].

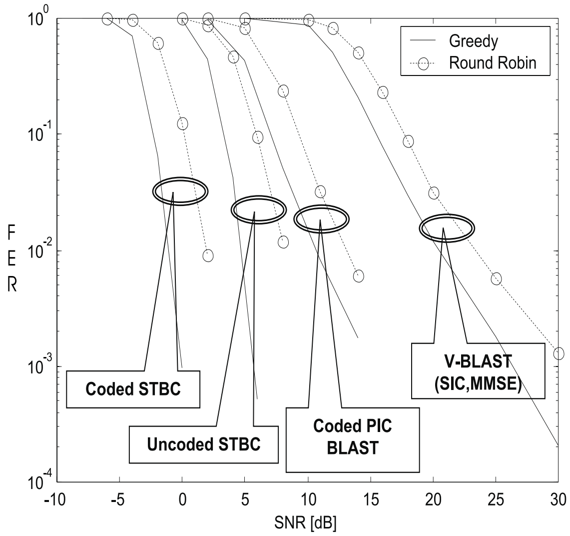

Figure 8: FER results for scheduling over space-time architectures (4Tx-4Rx;$K = 20$)

V. Conclusions

A unified approach to compare the performance of various space-time architectures paired with scheduling algorithms is presented. The "goodput" metric is proposed to address both the spectral and energy efficiency of the scheme. Two scheduling algorithms, known as the "greedy" and round robin approaches, applied different routing protocols for the transmission of packets to users in the service area. The "greedy" scheduling algorithm was shown to yield multiuser diversity, resulting in an enhanced averaged effective SNR.

Acknowledgments

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