MIMO Technology for Advanced Wireless Local Area Networks

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ABSTRACT
This paper first gives a brief introduction to Multiple Input Multiple Output (MIMO) wireless communication systems. Various architectures of MIMO systems and corresponding features are discussed, including those proposed for the IEEE 802.11n standard. The impact on chip area and required data processing rates is then presented.

Categories and Subject Descriptors
C.2.1. [**COMPUTER-COMMUNICATION NETWORKS**]: Network Architecture and Design – *wireless communications.*

General Terms
Algorithms, Performance, Design, Standardization.

Keywords
MIMO, 802.11n, Wireless, Networking.

1. INTRODUCTION
Traditional wireless communication systems use a single antenna for transmission and a single antenna for reception. Such systems are known as single input single output (SISO) systems (Fig.1). In recent years, significant progress has been made in developing systems that use multiple antennas at the transmitter and the receiver to achieve better performance[3]. Such systems are known as multiple input multiple output (MIMO) systems (Fig.2).

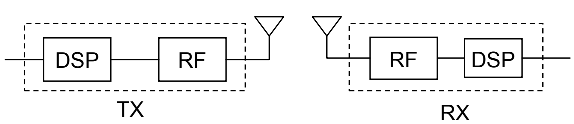

Figure 1. SISO wireless system

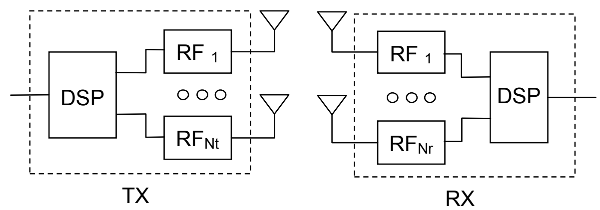

Figure 2. MIMO wireless system

There are two types of benefits of using multiple antennas: link budget / spatial diversity improvement and throughput improvement from spatial multiplexing. Both are intrinsic to wireless channels, where rich spatial variations or spatial dimensionality exist [3].

Spatial diversity refers to the fact that the probability of having all antennas at bad locations is significantly lower as the number of antennas increases. Link budget improvement refers to the fact that the signals from the various antennas can be combined to form a signal stronger than any of the individual signals. For receive spatial diversity, signals received on multiple antennas are weighted and combined, e.g. maximal ratio combining (MRC)[3]. There are two types of transmit spatial diversity, open-loop and closed-loop. Open-loop transmit diversity involves transmitting signals from multiple antennas in some deterministic pattern, that does not depend on the channel. Open-loop techniques include cyclic delay diversity (CDD) and space-time block codes (STBC)[3]. Closed-loop transmit diversity techniques, in contrast, require channel information to guide transmissions. An example is transmit beamforming (TxBF), where proper magnitude and phase weights computed from the channel estimation are re-applied across antennas to aim the signal in a given desired direction[3]. MIMO systems with spatial diversity achieve better performance, i.e. longer range for a given data rate, or higher data rate than SISO systems at a given same location.

A second way to exploit rich spatial dimensionality is via spatial multiplexing, i.e. transmitting and receiving multiple data streams from multiple antennas at the same time, and in the same frequency spectrum. The latter is possible because the signals received at different antennas are unique combinations of the transmitted data streams. Advanced digital signal processing algorithms can be used to recover the original data streams [3]. Spatial multiplexing can be implemented in either open-loop or closed-loop. In open-loop spatial multiplexing, different streams are simply transmitted from different antennas. In closed-loop spatial multiplexing, every stream is transmitted from all of the antennas using weights computed from the channel estimation. MIMO systems with spatial multiplexing achieve higher peak data rates and increases spectrum efficiency.

In recent years, there has been a rapid growth in the deployment of wireless local area networks (WLAN). IEEE 802.11a and 802.11g depict the standards for WLAN implementations in the 5 GHz and 2.4 GHz bands respectively, with raw data rates up to 54 Mbps. Standards-plus techniques have achieved data rates up to 108 Mbps [4]. As the WLAN industry matures, the demand for higher performance has spurred the adoption of link budget and spatial diversity improvement techniques into 802.11a/g products. Spatial diversity such as CDD, TxBF, and MRC can be implemented without modifications to the air format of the packets, and are completely compatible with the existing standards [1].

New WLAN applications, such as wireless HDTV video streaming, demand higher data rates beyond those supported by 802.11a/g. A high throughput task group within 802.11, TGn, was formed in 2003 to develop a new standard with targeted throughput of more than 100 Mbps at the MAC SAP, and spectral efficiency of greater than 3bps/Hz [5]. To achieve these targets, spatial multiplexing was included in all of the proposals submitted to TGn [6][7]. Completion of the 802.11n standard is projected for the year 2006.

2. MIMO SCALABILITY

One of the benefits of MIMO technology is its ability to scale data transmission speed with the number of antennas and radio and signal processing hardware. When coupled with the increasing integration levels governed by Moore's law, it provides a communications roadmap to the future.

The data rate of a SISO system is determined by:

$$R = E_S * B_W$$

Where R is the data rate (bits/second or bps), E_S is the spectral efficiency (bits/second/Hertz or bps/Hz), and B_W is the communications bandwidth (Hz). For instance, for 802.11a, the peak data rate is obtained by:

$B_W = 20$MHz
$E_S = 2.7$ bps/Hz
yielding R = 54Mbps

SISO systems obtain greater performance by using greater bandwidth. For instance, Atheros' Turbo® mode allows for:

$B_W = 40$MHz
$E_S = 2.7$ Bps/Hz
yielding R = 108Mbps

Using MIMO, an additional variable is introduced – the number of independent data streams, N_S, that are communicated simultaneously in the same bandwidth, in different spatial paths. The spectral efficiency is now measured per-stream as E_{SS}. The data rate of a MIMO system becomes:

$$R = E_{SS} * B_W * N_S$$

For the current 802.11n proposal, there are 10, 20, and 40MHz modes allowed, yielding peak rates with the following parameters [6]:

$B_W = 10, 20,$ or 40MHz
$E_{SS} = 3.6$ bps/Hz ($B_W = 10$ or 20)
$E_{SS} = 3.75$ bps/Hz ($B_W = 40$)
$N_S = 2, 3, 4$
yielding R=144Mbps (20MHz, Ns = 2)
yielding R=300Mbps (40MHz, Ns = 2)
yielding R=600Mbps (40MHz, Ns = 4)

Thus peak data rates ranging from 144Mbps to 600Mbps can be obtained by modifying the bandwidth and number of spatial streams.

3. MIMO HARDWARE REQUIREMENTS

In order to maintain multiple independent data streams, multiple RF and baseband chains are required. There must be at least as many chains on each side as the number of spatial streams. I.e.:

$$N_S = \min(N_R, N_T)$$

In practice, to obtain better radio link robustness, N_R and/or N_T are typically chosen to be larger than N_S for greater spatial diversity and link budget margin. I.e. for a robust $N_S = 2$ system, N_R could be 3. Or for increased link margin, diversity, and performance with a single stream systems, $N_R = N_T = 2$ could be used.

Figures 3 and 4 show block diagrams of the MIMO transmitter and receiver, indicating the parallelism and required data rate scaling. The scaling factors indicate the growth in complexity of each of the blocks as a function of the design variables. This complexity in turn scales the power consumption and area of each block. The complexity scaling is due to both sample rates as well as required sample precision.

As a reference point, an 802.11g single-chip transceiver fabricated in 0.18µm CMOS reported in ISSCC 2005 [2] occupies $41mm^2$ of total area, with 72% in digital logic. In transmit mode, the system-on-a-chip consumes 498mW of power, 226mW from the digital components. In receive mode, it consumes 513mW total, 330mW from the digital components.

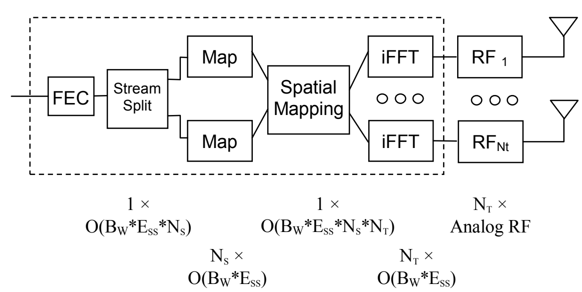

Figure 3. Block diagram of MIMO transmitter showing required parallelism and data rates

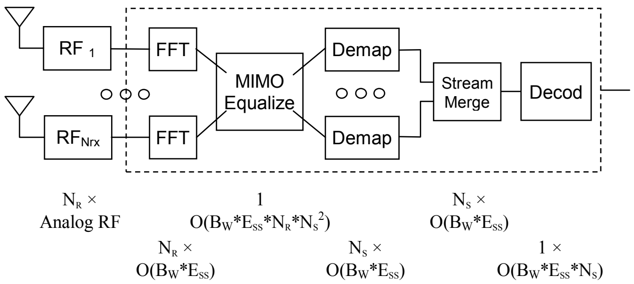

Figure 4. Block diagram of MIMO receiver showing required parallelism and data rates

4. CHALLENGES IN MIMO DESIGN

MIMO systems deliver greater performance, but with additional cost and power consumption. Competitive pressures of consumer markets impact tolerable cost (area), while thermal and battery life constraints limit tolerable power consumption in wireless portable devices. Additionally, mixed signal issues including coupling and cross-talk become critical in integrated high performance wireless systems which co-locate the digital circuitry with the analog RF electronics. Lastly, the quest for ultra-low cost solutions leads to additional systems-level integration of CPUs and other peripherals.

5. SUMMARY

This paper discussed various architectures of MIMO systems and corresponding features, including that proposed for IEEE 802.11n standards committee. The scaling in area and required data rates for a MIMO system were presented.

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