A Simple Beamforming Network for 802.11b/g WLAN Systems

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Abstract— An IEEE 802.11b/g WLAN beamformer is presented here. The system comprises of a beamforming network with controller modules integrated onto a PCB, and 4 equispaced monopole antenna array. A beamforming network is realised using cost effective power dividers, delay lines, and digital attenuators, as an alternative method to replace costly digital phase shifters. The main lobe can be steered in all directions on the H-plane. The measured radiation patterns showed that this transceiver system is fully configurable using software control and steering accuracy is better than ±5°, for both transmitting and receiving modes. Programs were written to detect the angle-of-arrival of signals, and facilitate automated beam steering.

Keywords-component; formatting; style; styling; insert (key words)

I. INTRODUCTION

Smart antenna technology has been researched for several decades [1-5]. It can used to increase desired coverage, lower power emission, improve link quality, and increase spectral efficiency. These enhancements are achieved by directing multiple radiation lobes toward desired transmitters or receivers and nulls towards interferers. Implementing such a system in real-time, through digital signal processing alone is complex and expensive. A simpler, cheaper and sufficiently effective alternative is to use beamforming. Beamforming performs spatial filtering by directing radiation lobes towards the wanted direction but with little or no control over its nulls. So the idea is to use a simpler system that ensures that the peak of the antenna radiation pattern is in a particular direction while accepting the presence of weaker lobes, not necessarily nulls, in the other directions. Such beamforming networks’ response times can be speeded up by switching between several pre-defined beam patterns.

The current IEEE 802.11n Multiple-Input Multiple-Output (MIMO) technology increases the channel capacity by making use of the rich multipath environment. However, in an outdoor environment with little multipath, beamforming technology retains its advantage for increasing targeted coverage and link quality by steering the main lobe in the desired direction.

Conventional RF beamforming networks use digital phase shifters and attenuator ICs. Ferroelectric materials have also been used to realize the phase shifters [6 - 7]. Such phase shifters for achieving full 360° phase shifts with minimal loss at the correct frequency are sometimes hard to come by. In contrast, this paper demonstrates an RF beamformer that is implemented using just quadrature splitters/combiners and variable attenuators. This design reduces the cost and complexity of the beamformer. The design allows each channel of the beamformer to be easily varied within all four quadrants.

II. BEAMFORMING TRANSCEIVERS

The beamforming operation is expressed mathematically as [2],

\[ y(t) = \sum_{i=0}^{N-1} w_i x_i(t) = w^H x(t) \]  

(1)

where \( y(t) \) is the output of the beamformer, \( x(t) = [x_0, x_1, \ldots, x_{N-1}]^T \), \( x_i(t) \) is the output of \( i \)-th element, and \( w = [w_0, w_1, \ldots, w_{N-1}]^T \) is the weighting vector, and the superscripts \( T \) and \( H \), respectively, denote the transpose and complex conjugate transpose of the vector or matrix. By varying \( w \), the radiation beam pattern can be controlled. The manipulation of phase and magnitude for a beamforming network can be achieved at the RF stage or IF(intermediate frequency) stage, and these processes can be analog or digital.

A. Digital Beamforming (DBF) Transceiver

Digital beamforming, is conceptually simple and precise, but computationally intensive and expensive. It usually employs costly DSPs, FPGAs or ASICs [8-10] for real-time processing. The computational load varies proportionally to the
number of elements in the array and sampling rate of the ADC/DAC. Such a system is difficult to implement for a large array, especially, at high data rates.

Digitizing the signals at the RF stage offers the advantages of DSP (digital signal processing), however, in order to maintain a constant phase relationship between all channels, a common LO (local oscillator) for the RF (radio frequency) subsystems, and a common clock for ADC/DACs are required. Also, the ADC/DACs would have to use several GHz sampling rates. Even if this can be overcome with sub-sampling techniques, the ADC/DACs would need to have several GHz input bandwidth which would make the system costly and more difficult to design. Hence, it is easier to digitize the signal at the IF or baseband stages for signal demodulation.

B. Analog Beamforming Transceiver[11-13]

The analogue beamforming transceiver can be implemented at the RF or IF stages. While, precise and consistent manipulation of phase and magnitude is more difficult to achieve using analog devices, they are still simpler to implement, as compared to a fully digital implementation. A phase-shifter is commonly employed for varying the phase and amplitude of the signals in each channel. It is relatively easier to implement analog phase shifting at the IF stage (lower frequency), however, the linearity and consistency requirement of mixers become more stringent.

III. VECTOR MODULATOR

Beamforming is achieved by applying vector modulation to the individual channel. The output signals of the vector modulator is expressed as,

\[ y(t) = \text{Re} \left[ \sum_{i=0}^{N-1} w_i x(t) \right] \]  

(2)

where \( x(t) = \text{Re}[e^{j\omega t} e^{j\phi}] \) is the input signal. The weights \( w_i = w_{re} + jw_{im} \) are divided into their individual real and imaginary components. Substituting \( w_i \) into (2) yields,

\[ y(t) = \text{Re} \left[ \sum_{i=0}^{N-1} w_i e^{j\omega t} e^{j(\phi_i + \phi_0)} \right] \]  

(3)

\[ y(t) = \sum_{i=0}^{N-1} [w_{re} \cos(\omega t + \phi_0) - w_{im} \sin(\omega t + \phi_0)] \]  

(4)

Equations (3) and (4) are fundamental to vector modulator implementation in the analog form. Fig. 1 shows the implementation of the vector modulator which consists of a phase shifter and digital attenuator. The attenuator controls the amplitude of the \( |w_i| \) coefficient and the phase shifter controls the phase \( \phi_i \) in equation (3).

Figure 1. Vector modulator using phase shifter and attenuator

A cost effective method to realize vector modulation using digital attenuators, delay lines, and power dividers is shown in Fig. 2. This offers an alternative to using a digital phase shifter IC, which can be costly and not always readily available at the required frequency and specifications. The amplitude of \( w_{re} \) and \( w_{im} \) are controlled by their respective digital attenuators, while their polarities are determined by switching between 0º/180º delay lines. Quadrature 0º/90º power divider/combiner are also employed. This implementation is bi-directional, and it can operate in both transmit and receive modes for a full duplex system.

The quadrature (90o) power divider/combiner and a digital attenuator are used for steering the phase and amplitude in quadrant I (0-90o), as depicted by the shadowed area in Fig. 3. Given that \( y = |\phi| e^{j\omega t} = \omega_{re} + j\omega_{im} \), both \( \omega_{re} \) and \( \omega_{im} \) vectors are controlled by the digital attenuators. The 0º/180º delay lines and switches enable the steering range to be extended from quadrant I to all the other quadrants (0–360º). A low noise amplifier, a power amplifier, and two switches are used to compensate for the losses incurred during the beamforming stages.
Figure 3. Four operating quadrants of the beamforming network.

IV. EXPERIMENT AND RESULTS.

A prototype with the PCB dimension 14cm × 15cm (Fig. 4) of the beamforming network was built and tested to verify its performance.

Figure 4. Prototype of beamforming network

Fig. 5 shows the block diagram of the experimental setup. It consists of an antenna array, beamforming network and a host PC. The antenna array consists of four equispaced monopole, spaced half a wavelength apart at 2.45 GHz. A WLAN NIC (network interface card) is installed on the host PC to communicate with the access points (APs). Control commands are sent from the PC to the digital attenuators and switches for the 0/180° delay lines, through the LPT (line print terminal) parallel port.

A monitoring-software, with SCAN and COMM modes, was written for direction-of-arrival (DOA) applications. In the SCAN mode, the host PC sends a sequence of control commands to the beamformer, to scan the wireless environment for the location of access points. In the COMM mode, control commands are sent to the beamformer, to direct the main lobe towards the desire access point. Figure 6 depicts the various parts of the control software GUI (graphics user interface). Part I displays the signal strength of the run-time wireless resources. Part II displays the control settings and results after scanning the wireless environment. While Part III shows the parameter inputs for the COMM and SCAN modes.

Figs. 7(a)-(d) show the measured transmit and receive radiation patterns using the beamforming network in an anechoic chamber. The measured radiation patterns have beamforming errors of less than ±5°.

Figure 5. Block diagram for the beamforming network

Figure 6. Host control software GUI
V. CONCLUSION

A cost effective beamforming network using digital attenuators at RF stage, power splitters and switches is presented. Beam steering into all four quadrants (I-IV) for every channel is made possible. Experimental results showed a full 360° steering capability. A reflector could also be used to make the radiation pattern more directional, when the beamformer is mounted on a wall.

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REFERENCES


