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A smart antenna receiver array using a single RF channel and digital beamforming

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Abstract—**A new type of smart antenna array receiver with adaptive digital beamforming is proposed. The proposed system offers a drastic reduction in hardware requirements for the smart antenna system through the use of a new Spatial MultIplexing of Local Elements (SMILE) scheme. In this scheme a single element of the array is sequentially connected to signal processing circuitry in order to sample the modulated carrier signal. The sampling rate is higher than the signal bandwidth so the information of the original signal can be fully restored in the post stages using low pass filters. The reconstructed baseband data is then used for adaptive digital beamforming. This system offers an *N* times reduction in RF hardware for an *N* element array. A four element prototype is built and discussed, including a new type of array feed network.**

I. Introduction

Adaptive digital beamforming (DBF) arrays have revolutionized the capabilities of antenna arrays. Early DBF projects were motivated by military interests, where no-compromise designs were possible at great expense [1][2]. However, with growing interest in low cost Wireless Local Area Networks (WLAN), the DBF approach is investigated for use in simple high volume applications. The DBF system provides several advantages over analog beamforming techniques. First, analog systems often use expensive microwave phase shifters and attenuators for each element. Second, the signal processing capability, such as adaptive beamforming of analog systems, is usually limited [3]. For a high throughput system, hybrid analog-digital beamforming techniques have been used to successfully demonstrate adaptive beamforming, adaptive nulling, and improved signal to interferer ratio [4][5]. In these works, in order to keep the signal amplitude and phase information from each antenna element, N RF channels including LNAs, mixers and other circuits have to be used for an N-element antenna array. This dramatically increases the system cost and power consumption and is one of the major hurdles for implementation of smart antenna systems in wireless terminals.

In this work we propose a new receiving smart antenna array utilizing a novel Spatial MultIplexing of Local Elements (SMILE) technique in conjuction with DBF. The novel SMILE technique greatly reduces the need for RF hardware. The proposed system achieves the functionality of a fully populated smart antenna system with a fraction of the hardware requirements by spatially sampling and then multiplexing the received antenna element. According to Nyquist sampling theory, if the sampling speed is higher than the signal bandwidth, the signal amplitude and phase

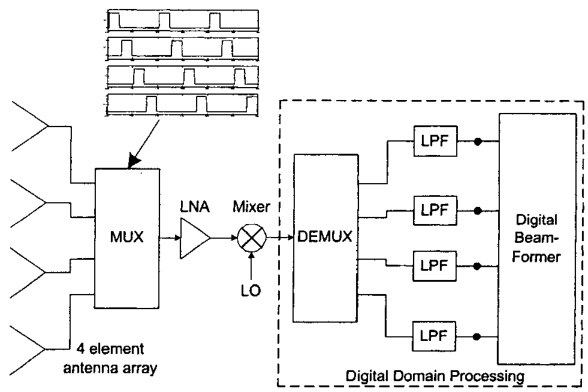

Fig. 1. SMILE system block diagram.

from each antenna element can be restored without loss of fidelity. Compared to an N element traditional smart antenna array the proposed system offers an N fold reduction in RF hardware requirements. It thus also reduces the power dissipation. However, sampling in microwave systems is challenging since switching among different antenna elements will introduce a change in impedance matching characteristics. Therefore, the feed network for real-time multiplexing has to be carefully designed.

In this paper, the system block diagram is first described. An antenna array integrated with a PIN diode multiplexing feed network is illustrated as a key building block of the system. Then measured data is given to validate the performance of the feed network and multiplexing function. After that, the complete system is tested and digital signal processing is carried out in software to restore the signal information from each element channel. Finally, DBF algoritms are applied and the results are given to demonstrate the adaptive beam scan capability of the system.

II. System Principles

The objective of the SMILE scheme is to reduce the repetitive use of RF hardware for each element channel. For the same purpose, one approach is presented by loading reactive components to each antenna element to control the individual signal phase before combining [6]. The drawback of this approach is that the signal phase and magnitude information is lost after combining, therefore advanced vector

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signal processing is not available. In this work, a dynamic spatial sampling scheme keeps the signal phase and magnitude information intact after the combining. Therefore, any existing array signal processing algorithms can be directly applied to the signal after restoration.

A block diagram of the system is shown in Fig. 1. By using the SMILE technique, N channels of signal from N antenna elements are multiplexed to form one single-channel RF output. The sampling/switching network utilizes four PIN diode switches, one per channel, in this four element prototype. The PIN diodes are switched sequentially as depicted in Fig. 1 and are represented by the MUX in the block diagram. The switch-driving waveform is shown above the MUX in the diagram.

The switching rate is determined by the Nyquist sampling theory. The modified switching rate is $f_s = B * N$, where B is the bandwidth of the baseband signal and N is the number of antenna elements being switched. On the other hand, the signal bandwidth received by this system is also limited by the switching speed of the device. One should note that each element only receives $1/N$ of the power of the entire array. However, assuming the PIN diode switch does not introduce any in-band noise, the received noise is also reduced by $1/N$. Thus the signal to noise ratio of the active array is unaffected by the sampling of the envelope at the antenna array.

After the multiplexing is done in the feed network, the single-channel RF output is amplified by an LNA then mixed down to an IF where an ADC takes the lower frequency data to the digital domain. Digital demultiplexing is thus performed to separate the signal from different element channels. Signal reconstruction is done by passing each channel through a digital lowpass filter. Finally standard array processing like digital beamforming are applied.

III. Antenna Array and Feed Network

A four element array is used in the current system design. The antenna element in this array is the quasi-Yagi antenna proposed in [7]. This antenna element is well suited for array applications, with wide bandwidth, 90 degree flat pattern, and mutual coupling below -20 dB. A photograph of the array is shown in Fig. 2. The circuit is fabricated on RT/Duroid 6010.2 substrate, $\epsilon_r = 10.2$, thickness 50 mil, and is uniplanar in design. In the photo the PIN diodes are located just beneath the radial bias stubs of each element. A DC bias return is located near the SMA connector.

The SMILE technique used in this design necessitates a new type of array feed network. Since array phasing is important, a parallel feed network is integrated with the antenna array. However, as each element is switched on and off the loading of the antenna to the feed network changes from 50Ω to an open circuit. A schematic of the feed network used is shown in Fig. 3. In the figure, the switch reference plane is the location at which the loading change occurs. The T-like junctions shown are not traditional T-Junctions. In this case, all three transmission lines have a characteristic impedance of 50Ω. The network is designed to be always matched to 50Ω at its input when exactly one antenna element is active. In order to achieve this goal, the length of the feed lines is tuned in order to bring the open circuit impedance presented by the switch to the edge of the transmission line junction. Thus the open circuit does not load the feed network. By carefully selecting the length of feed lines, it is also possible to minimize the mutual coupling between the array elements since only one element is on each time.

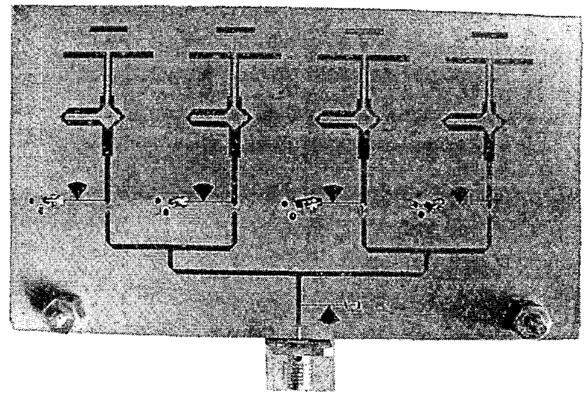

Fig. 2. Photograph of the 4 element antenna array with PIN diode switches.

To test the performance of the feed network, a connectorized circuit is assembled with PIN diode switches. Each channel is connected to an Agilent 8510C network analyzer. Measured S-parameters of each channel are shown in Fig. 4. Each individual channel has a bandwidth of more than 200 MHz for a VSWR less than 2:1. Insertion loss of each channel is approximately 1.7 dB, including 0.4 dB from two SMA connectors and 0.6 dB from the PIN diode. The insertion phase of each channel was verified to be equal. The PIN diodes used in this design are Agilent Technologies beam-lead diodes, HPND-4005, and have an off-state (zero DC bias) isolation of 15 dB at 5.8 GHz. Additional isolation is obtainable with reverse bias at the expense of complicating the switch driver circuit. Simula-

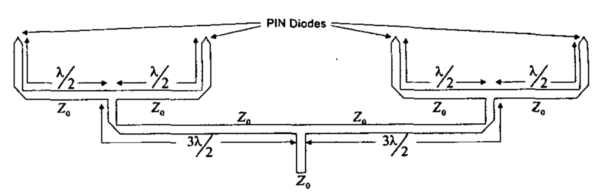

Fig. 3. Schematic of the "always matched" feed network.

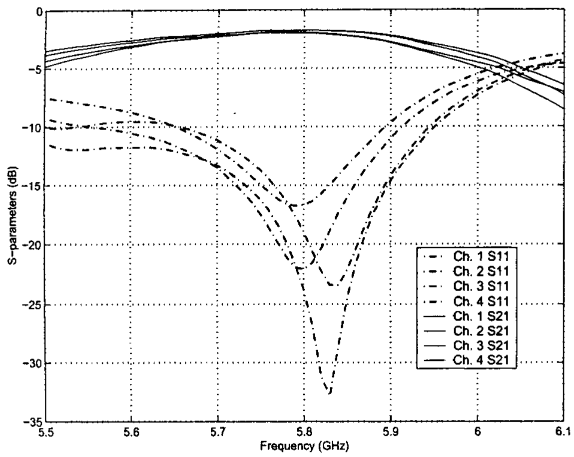

Fig. 4. S-parameters of the feed network, each channel activated sequentially.

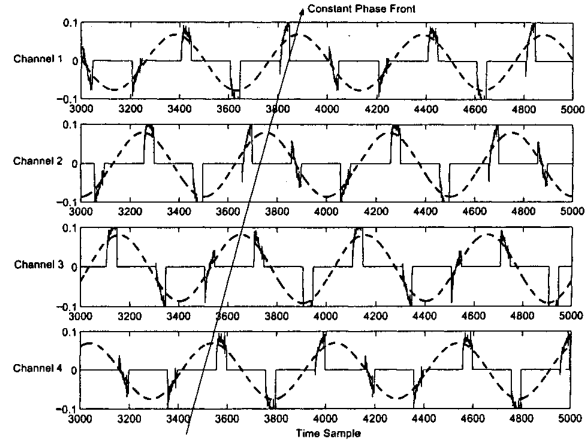

Fig. 5. Recovered multichannel baseband data. Shown with a line of constant phase and measured sampling pulses.

tions in Agilent ADS indicate minimal phase error (approx. $1° \sim 3°$) resulting from adjacent channel leakage at 15 dB below the on–state channel. It should be noted that special care must be taken when switching the PIN diodes rapidly with digital pulses due to the large amount of charge stored in the I region of the diode [8]. A residual tail, due to this stored charge, on the falling edge of the pulse will allow the switch to remain on outside of its time slot. The result of having two switches on at the same time is twofold. Primarily, data may become distorted due to two phases being received in a single time slot. Second, when two antenna elements are switched on simultaneously, the impedance matching discussed in section III is adversely affected. A simple solution to this problem is a shunt resistor in parallel with the PIN diodes' driver circuit to help drain the charge to ground.

IV. Data Recovery and Beamforming Results

A testbed is set up to demonstrate the system performance. For digital domain processing, a digital sampling oscilloscope is used in place of the A/D converter and the sampled data is transferred to a PC through a GPIB card for further signal processing in the MATLAB environment. Since the proposed system down converts each element's signal as it is switched, the IF signal at the output of the new array needs to pass through a demultiplexer in order to separate the signal information of different elements. The demultiplexer is currently implemented in software. Each channel of data is then low pass filtered with a cutoff of the original signal bandwidth to remove high frequency switching effects and restore the original signal waveform.

A 200 KHz offset RF signal with a carrier frequency of 5.8GHz is used as signal source in the transmitter. The sampling rate is 500 KSPS, or 1.5 times of the Nyquist sampling rate. After receiving the signal, each of the four channels of data that were recovered from signal processing are shown in Fig. 5 for the array rotated to $-25°$. In the figure the original time slices of the received signal are plotted along with the recovered sinusoid. A constant phase front is drawn in the figure to indicate phase progression through the four channels.

A trade-off becomes evident when using MATLAB to demultiplex the signal. In order for MATLAB to properly reconstruct the retrieved signal the phase discontinuity of the multiplexed IF signal must be considered. This is because as the array turns further away from boresite the phase difference between each element becomes more pronounced. When each element is switched on and off at large angles the resulting IF signal is highly discontinuous. In order to accurately capture these phase jumps the digital sampling oscilloscope bandwidth must be high enough. Otherwise phase errors will be introduced. The solution to this problem is to demultiplex the IF signal on board with the original clock signal. In this way, oscilloscope bandwidth requirements are reduced. This function is currently being implemented.

Once each channel's data has been recovered it is used to form the antenna pattern through the use of digital beamforming. The DBF process allows the antenna's radiation pattern to be scanned over a wide range of angles without the use of the associated expensive RF hardware. Beamforming results for the new SMILE antenna array are shown in Fig. 6. The antenna pattern is scanned successfully from $-20°$ to $+20°$. However, the peak of the antenna pattern for $+20$ degree scan is slightly shifted. As mentioned above, it is due to the asymmetrical phase errors caused by the finite bandwidth of the sampling oscilloscope. This error becomes more serious when the switching occurs from one edge element to the other edge element, where the phase jump is the most steep. The antenna can be used for a scan range as far as $\pm 30°$. Beyond that, the edge effects and mutual coupling of the array degrade the antenna pattern.

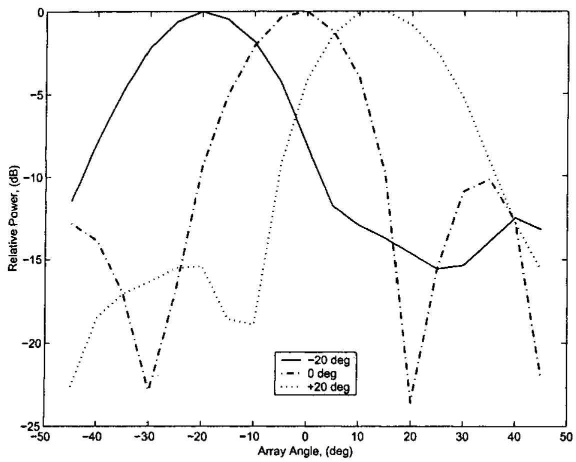

Fig. 6. Baseband digital beamforming radiation pattern.

V. Conclusions

A new type of smart antenna receiver array using a new SMILE scheme and single RF channel and digital beamforming capabilities has been proposed. This new type of system architecture boasts a significant reduction in RF hardware on board. The majority of hardware found on most smart antenna systems, both analog, RF, and digital, is eliminated through the sampling of the received signal's envelope at each antenna element. The multiplexed RF signal is then down converted and digitized to be processed at lower speeds. The maximum signal bandwidth the system can receive is limited by the sampling rate of the existing switch device.

A four element receiver array was prototyped to illustrate the newly proposed SMILE architecture. The prototype included a new kind of feed network that is always matched during the antenna switching sequence. The performance of the feed network and PIN diodes switches is validated through experiments. Finally, the sampled, down converted signal is used for digital beamforming in the MATLAB environment.

References

[1] H. Steyskal, "Digital Beam forming antennas: An introduction," *Microwave J.*, vol. 30, no. 1, pp. 107-124, Jan. 1987.

[2] H. Steyskal and J.F. Rose, "Digital Beamforming for radar systems," *Microwave J.*, vol. 32, no. 1, pp. 121-136, Jan. 1989.

[3] W. Stutzman, J. Reed, C. Dietrich, B. Kim, and D. Sweeney, "Recent results from smart antenna experiments - - base station and handheld terminals," *2000 IEEE RAWCON*, pp. 139-142, 2000.

[4] S. Jeon, Y. Wang, Y. Qian, and T. Itoh, "A novel planar array smart antenna system with hybrid analog-digital beamforming," *IEEE MTT-S Symp. Dig.*, vol. 1, pp. 121-124, May 2001.

[5] R. Miura, T. Tanaka, I. Chiba, A. Horie, and Y. Karasawa, "Beamforming experiment with a DBF multibeam antenna in a mobile satellite environment," *IEEE Trans. Microwave Theory and Tech.*, vol. 45, No. 4, pp. 707-714, April 1997.

[6] J. Cheng, Y. Kamiya, and T. Ohira, "Adaptive beamforming of ESPAR antenna using sequential perturbation," *IEEE MTT-S Symp. Dig.*, vol. 1, pp. 133-136, May 2001.

[7] Y. Qian, W. Dael, N. Kaneda, and T. Itoh, "A uniplanar Quasi-Yagi antenna with wide bandwidth and low mutual coupling characteristics," *IEEE Antennas and Prop. Soc. Symp., Orlando, FL* pp. 924-927, July 1999.

[8] W. Doherty, R. Joos, *The PIN diode circuit designers' handbook*, Microsemi Corp. Watertown, MA, 1998.