AN ADAPTIVE ANTENNA INTEGRATED WITH AUTOMATIC GAIN CONTROL FOR RECEIVER FRONT END

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Abstract

In this paper a new type of adaptive antenna is presented, which is intended for use in mobile receivers. A nonlinear, adaptive, analog feedback controller has been developed to control the phase relationship between the two receiving elements. Both the controller and a complete RF prototype are described in this paper.

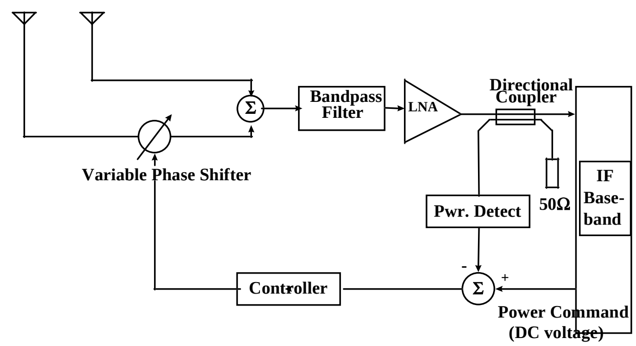

Figure 1: Proposed System

Introduction

Fading, due to multipath propagation, has resulted in the incorporation of diversity in many modern wireless systems. This concept has a wide variety of realizations. However, they are all similar in that multiple copies of the signal are received whose fading characteristics are independent of one another [1]. Examples of spatial diversity, in which widely spaced antennas are used, abound in the literature [2]. Our proposed system falls into this category.

In modern spatial diversity systems, it is common to perform a down conversion on each antenna signal before processing. The signals are digitized, then the computational power of a DSP chip is brought to bear on the problem of intelligent combining. This approach to building spatial diversity systems can be expensive; each new diversity branch requires its own LNA, mixer, and A/D.

Figure 1 shows the system that we envision, based on the prototype we have developed.

Such a system would be noteworthy for several reasons. First, the antenna diversity does not come at the price of additional expensive RF parts. This is in contrast to the multiple antenna systems that do the combining in baseband processing, which requires that each antenna have its own LNA and mixer. Second, the adaptive antenna would be completely modular; essentially a stand-alone "smart" antenna. The command level voltage could either be derived from the IF/baseband block or be a simple, fixed reference. Third, the command level essentially sets the level of the automatic gain control at the receiving antenna, which relaxes the linearity requirement of the LNA. Finally, the nonlinear, analog controller is a novel design and for this application, we believe, more cost efficient than traditional microprocessor-driven approaches.

The Controller

The design of the feedback controller is complicated by the fact that the sign of the loop transmission is uncertain. This problem owes its existence to the nonlinear, time-varying transfer

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function between a phase change and the resultant change in detected power. This is best shown mathematically; consider the sum of two equal-frequency sinusoids that differ only in phase. If we examine the magnitude squared,

$$\left| Ae^{j\omega t}e^{j\theta} + Ae^{j\omega t}e^{j\phi} \right|^2 = 2A^2(1+\cos(\phi-\theta)) \quad (1)$$

we can see the exact nature of the non-linearity. Denoting the phase difference as α and differentiating, we can linearize this function and look at its behavior for small fluctuations in phase about a set operating point:

$$\frac{d}{d\alpha}\left[2A^2(1+\cos\alpha)\right] = -2A^2\sin\alpha \quad (2)$$

If the operating point is beyond our control, as it is in this case, the incremental relationship between a phase change and a change in received power cannot even be ascertained to within a minus sign. In a mobile environment, the problem is exacerbated by the random time-varying nature of this relationship: the phase difference between the two received signals (before they are processed) is what determines the operating point, and this changes as the receiver moves.

The basic behavior of the controller is based on an algorithm that was introduced and analyzed by Trybus and Hamza [3, 4]. It was intended for use in extremum controllers, whose purpose was to operate an industrial process at an extreme value of the process output; it has since been applied to antenna arrays by Denidni and Delisle [5]. In the present system the error, or the difference between the desired input power and the received input power, is the variable to be minimized. The controller moves its output in a given direction for a fixed amount of time, continuously monitoring the error. If the magnitude of the error is increasing, the controller changes direction for the next time step. Otherwise, it keeps moving in the same direction. The system will, in the steady state, fluctuate about the desired value. A simplified diagram of the basic controller is shown in figure 2.

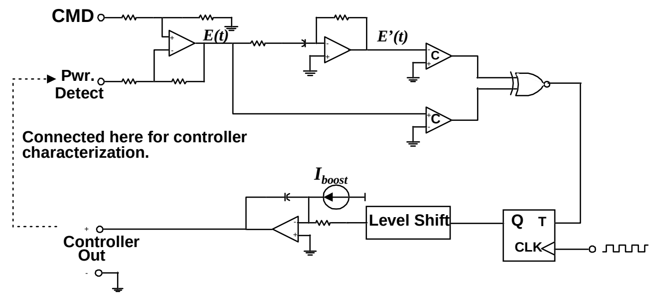

Figure 2: Simplified schematic of basic controller.

It can be seen in figure 2 how a "step" is mechanized. The voltage input to the op-amp integrator can assume one of two values (one positive, the other of the same magnitude but negative), which is then integrated to produce a ramp for the duration of the clock cycle. The designer has two parameters that can be varied: the clock rate and the slope of the ramp during a clock cycle. Together they determine the amplitude of the fluctuation about the desired value. The tracking speed, or the ability of the controller to track a rapidly varying output, is most closely related to the chosen rate of change during a step. A fast controller will have a very high slope during each step, and a fast clock to keep the output tightly focused about the desired value.

Of course, the allowable clock speed is limited by a number of things, most notably the bandwidth of the differentiator. This speed limit forces a tradeoff between tracking speed and steady-state error, a tradeoff that can be beaten to a certain extent if the controller adaptively adjusts its own step size. This is the purpose of the I_{boost} current source in figure 2, whose direction depends on the direction of the step being taken. The magnitude of I_{boost} is determined by a separate circuit that monitors the output of the controller; it then produces a current that is proportional to the time average of the first derivative. There is also a transient detect circuit that gives the controller the ability to "shift gears," or make a sudden change in step size in response to a perceived fast transient. The addition of adaptive behavior led to a tenfold increase in the loop tracking speed, with no corresponding increase in DC steady-state error.

The oscillatory behavior of the controller about the desired value is of some concern in an

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actual RF system, and should be addressed. Use of this controller will add a rapid, small amplitude modulation to the RF envelope before it reaches the baseband electronics. Although this fluctuation will, effectively, amount to a small amount of interference, we do not expect this to adversely affect system performance except in the case of an extremely low SNR.

RF Prototype

Figure 3 shows the RF experimental setup. It employs a 360° phase shifter, which is a cascade of two 180° phase shifters. Each was built using quadrature hybrid couplers, with varactors as variable reactance reflective terminations [6]. The power detector is a cascade of a peak detector circuit (built around an RF zero-bias detector diode) and a DC-1MHz gain-of-ten amplifier. The clock rate in this system is 0.7 MHz.

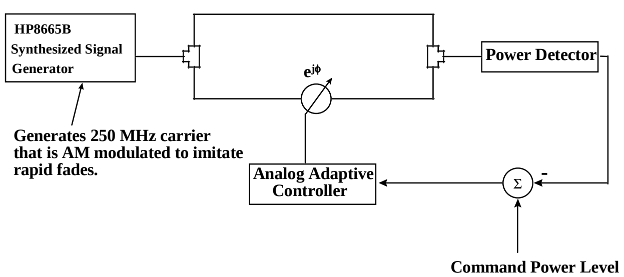

Figure 3: RF experiment.

This test setup represents the worst-case fading scenario (from a control standpoint), in that the separate antenna elements undergo highly correlated fading. By adjusting the command power level, which was a manually variable DC voltage source, we could evaluate the controller's behavior.

From the standpoint of automatic gain control, the command level can fall into one of three categories: greater than the available power, too low to be obtained (loss in the phase shifter renders complete cancellation impossible), and somewhere in between these two extremes. In the first and second case the controller should do its best, which is to adjust the received power to the appropriate extreme. In the third case, the variation of the power envelope with time should be relatively flat. This is the behavior that we observed in the prototype.

Results and Discussion

The results of our testing are summarized in table 1. It has been shown that for a propagating carrier wave the fading envelope is bandlimited to twice the maximum Doppler shift [7]. For a car traveling at 60 MPH receiving a 2 GHz carrier, the bandwidth is 360 Hz. This bandwidth scales linearly with vehicle speed, and varies as the inverse of the carrier wavelength.

Depth of Fade (dB) → Type of modulation ↓	6 dB	7 dB	8 dB	9 dB	10 dB
Sinusoidal (Tracking Bandwidth) KHz	6.5	3.8	3.1	2.6	2.4
Triangular (KHz)	6.7	4.5	3.3	2.4	2.3
Square Wave (Recovery time	25	28	30	31	32

Table 1

These data clearly show that our prototype is able to deal with rapid fading; to achieve a fading bandwidth of 2.4 KHz, the aforementioned car would have to travel at 400 MPH.

The interpretation of the data for sinusoidal modulation is relatively straightforward: it provides a clear indication of the controller's ability to compensate for bandlimited fading. For some linear feedback controllers the tracking speed, or the ability to follow a ramp input, is also of interest, and therefore figures for triangular wave modulation are included. Last, because of the nonlinear nature of this controller, the relationship between sinusoidal

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frequency response and step response has been blurred; we expect that the recovery time data will be useful in certain applications.

Conclusion

The success of this prototype demonstrates the feasibility of such an implementation, particularly in narrow-band transmission schemes such as the IS-54/-136 TDMA protocol. We expect that a minor modification would be necessary in the case of spread-spectrum protocols, where the bandwidth of the signal greatly exceeds the coherence bandwidth of the channel. A broadband measurement of received signal power may not be appropriate in this case; rather, a baseband estimate of the received SNR might better serve as a power feedback signal. Finally, we believe that this analog, adaptive controller will find applicability to a general class of feedback control problems.

Acknowledgments

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