FPGA Implementation of a Same-Frequency Cellular Repeater Using Adaptive Feedback Cancellation

Dennis R. Morgan*, Michael G. Zierdt*, Denis A. Gudovskiy†, John Z. Pastalan*, and Zhengxiang Ma‡
*Bell Laboratories, Alcatel-Lucent, Murray Hill NJ 07974-0636 USA, Email: {drrm,zeta,jpz}@bell-labs.com
†was with Alcatel-Lucent, now with Huawei Technologies, Moscow Russia, Email: Denis.Gudovskiy@huawei.com
‡was with Alcatel-Lucent, now with Huawei Technologies, Bridgewater, NJ 08807 USA, Email: zhengxiangma@huawei.com

***Abstract*—We have implemented a same-frequency cellular repeater that uses adaptive signal processing to cancel the feedback path, thereby allowing high gain while maintaining stability. Preliminary results are presented for a real-time laboratory demonstration using an FPGA development board, realizing cancellation of about 20 dB over a 10-MHz bandwidth.**

***Index Terms* — Adaptive feedback cancellation, cellular, FPGA, repeater**

I. Introduction

The cellular wireless industry has witnessed tremendous growth over the past two decades. The cell phone has become the most popular personal electronic device in history, with penetration rates reaching 70-80% in many regions of the world. Even in locations with well developed wireline telephony infrastructure, such as North America, people, especially the younger generation, have begun to "cut the wire" by making the cell phone their only voice communication device. However, the macro-cellular networks in North America today are still lacking in terms of coverage deep inside large commercial buildings. Also, both downlink and uplink signals are weakest at the edge of the coverage area due to shadowing and attenuation, so there is a growing need to boost signal strength in these fringe locations, particularly within suburban and rural residential homes.

Same-frequency repeaters can be used to enhance wireless coverage in problem areas without incurring any change in the supporting infrastructure [1]–[3] (assuming that the radiated uplink power is limited to that of an ordinary outdoor mobile phone, so as to limit interference to the network). A same-frequency repeater is a bi-directional wideband RF amplifier with two antennas: one, the "donor," is usually highly directional, pointing to the nearest base station, and the other, called "transmit," has a broad beam, providing coverage over a desired area. In some cases, a roof donor antenna may be required along with a strategically placed indoor transmit antenna. This kind of simple repeater requires careful installation so that feedback from the transmit antenna to the donor antenna does not cause the system to go into regenerative oscillation, which could seriously disrupt the macro-cellular network. Such instability will occur if the gain exceeds the feedback loss, so it is especially critical if high gain is desired. All of this entails the disadvantage of making the installation difficult and expensive. It would be much better if simple antennas could be used with spacing on the order of 1–3 m, so that the customer could easily install the system without requiring special knowledge or skill. For example, one could envisage the placement of the donor antenna on a window sill for communication with the base station, and the transmit antenna somewhere inside the same room. However, in order for this to work without requiring specially placed high-gain antennas, it is necessary to reduce the feedback by using other means.

In this paper, we develop an implementation of a same-frequency repeater that has been proposed for cellular applications [4], which features adaptive signal processing to cancel the feedback path. Feedback cancellation prevents harmful oscillations, thereby allowing high gain while maintaining stability. It is intended to provide useful gain without needing special receive/transmit antennas requiring directional gain, separation beyond a meter or so, or roof installation, thereby making this technology much easier to use and more accessible to a greater number of end users. This concept employs a low-level wideband pilot signal, whose power can be dynamically varied as necessary in real-time operation.

In Sections II we introduce the feedback cancellation concept. Then in Section III we present a real-time hardware design using an FPGA development board, and use this in a laboratory demonstration setup in Section IV to obtain some preliminary results.

II. Adaptive Feedback Cancellation

In practice, two repeaters are needed for any given site, one for downlink and one for uplink. Here we consider only frequency-division duplex (FDD), so that downlink and uplink transmissions are in different frequency bands and mutual interference can be neglected. Therefore, same-frequency repeater operation can be independently considered from either the downlink or uplink perspective. For specificity, we will illustrate and discuss the downlink part in this paper.

Figure 1 shows a discrete-time baseband model of the downlink part of the proposed repeater [4]. The weak base station signal $s(n)$, also known as the "donor" signal, comes in at the left and is picked up by the donor antenna along with

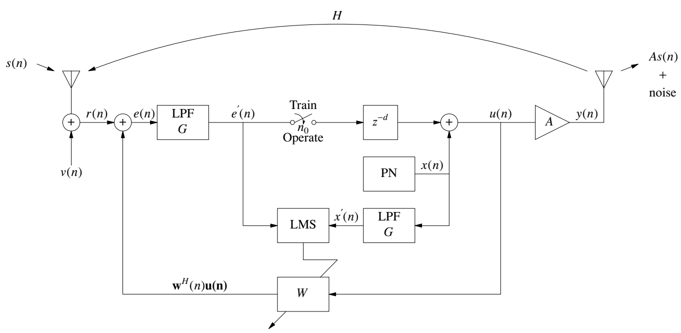

Fig. 1. Discrete-time baseband model of proposed repeater, using adaptive feedback cancellation.

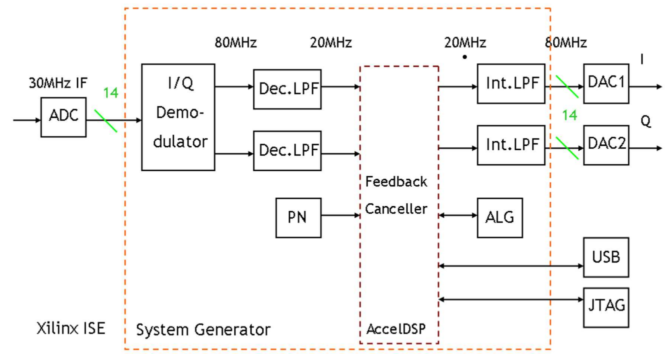

Fig. 2. Overall FPGA Scheme.

some uncorrelated receiver noise $v(n)$. The receiver front end, anti-aliasing filter, reconstruction filter, and repeater transmit power amplifier (PA) are all assumed to be wider than the operating band, which is determined by the digital lowpass filter (LPF) G placed at the input. During operation, the output of the LPF is delayed by d samples and passed to the PA, which has gain A and retransmits the desired signal along with some amplified noise. If nothing else were done, the maximum stable PA gain would be limited to the loss of the propagation path H from the transmit antenna to the donor antenna. This would consequently limit the effectiveness of the repeater since the maximum achievable gain determines the useful range [4]

The scheme of Fig. 1 involves electronic cancellation of the feedback path H using an adaptive filter W, where the adaptive filter input is taken from the input to the PA so that the adaptation step size does not depend on the PA gain A. Initially, the repeater is placed in the Train mode (switch open in Fig. 1), whereby the donor signal is only used to adapt the feedback cancellation filter W, and is not passed through to the PA. A QPSK pseudo-noise (PN) pilot signal $x(n)$ is applied to the PA input and also serves as the reference signal for the adaptive filter.

An adaptive algorithm known as the least-mean-square (LMS) algorithm [5] is used here to adjust the tap weights of the transversal filter W so as to minimize the power of the filtered error signal $e'(n)$. Actually, because of the LPF in the error path, we must use the so-called "filtered-x" LMS (FXLMS) version of the algorithm, which is well known in active noise control [6], whereby the PN reference signal is also filtered by an identical LPF. Thus, the FXLMS algorithm in effect uses the LMS algorithm with the filtered error signal $e'(n)$ and filtered PN reference signal $x'(n)$, which then results in the weight update equation

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \mu \mathbf{x}'(n) e'^{*}(n) \tag{1}$$

where μ is the adaptive step size, $\mathbf{x}'(n) \stackrel{\text{def}}{=} [\ x'(n) \quad x'(n-1) \quad \cdots \quad x'(n-L+1)\ ]^T$, and superscript * denotes complex conjugate. Further details can be found in [4]

When the feedback path is sufficiently canceled, the repeater is placed in the Operate mode (switch closed in Fig. 1), and the desired donor signal is passed along to the PA. At this point, the pilot signal persists, perhaps at reduced level, so as to maintain tracking of path changes. (The PN pilot signal should at all times be at least 15 dB, and preferably 20 dB, below the desired signal level so as not to seriously interfere with normal operation.) If in the course of operation, the feedback path changes appreciably, as for instance when someone is moving in proximity to the antennas, the repeater should fall back to the Train mode for some brief period of time to reestablish sufficient feedback cancellation. A sensing mechanism and decision logic to do this are discussed in the next section.

III. Real-Time Hardware Design

We designed a real-time hardware system implemented on a Xilinx XtremeDSP Development Kit III with Virtex-4 XC4VSX35 FPGA chip, which includes specialized DSP48 slices. The overall scheme is illustrated in Fig. 2, which employs at its heart a feedback canceler core, designed using the Xilinx AccelDSP tool, along with ancillary blocks for input/output, demodulate/modulate, and control/interface logic designed using Xilinx System Generator and ISE. The LMS feedback canceler core is implemented using four complex weights. Overall, the combined feedback canceler and supporting functions use 64% of the logic slices and 29% of the DSP48 slices.

For research purposes, a convenient control algorithm was developed that operates on a PC connected to the FPGA board via a USB port. The PC control was limited to weight reset and selection of Train/Operate mode. A more efficient control algorithm for the feedback canceler was implemented on the FPGA itself, based on a simple finite-state machine that automatically retrains the canceler whenever overflow is detected.

IV. Laboratory Demonstration

A laboratory demonstration hardware setup is diagrammed in Fig. 3, showing the FPGA with 14-bit ADC and DAC on the left, analog RF components in the center, and antennas on the right. The operating frequency is 1800 MHz with a 30-MHz analog I/Q baseband interface. The physical deployment is arranged on workbenches in a 4.1-m $\times$ 9.8-m laboratory, with

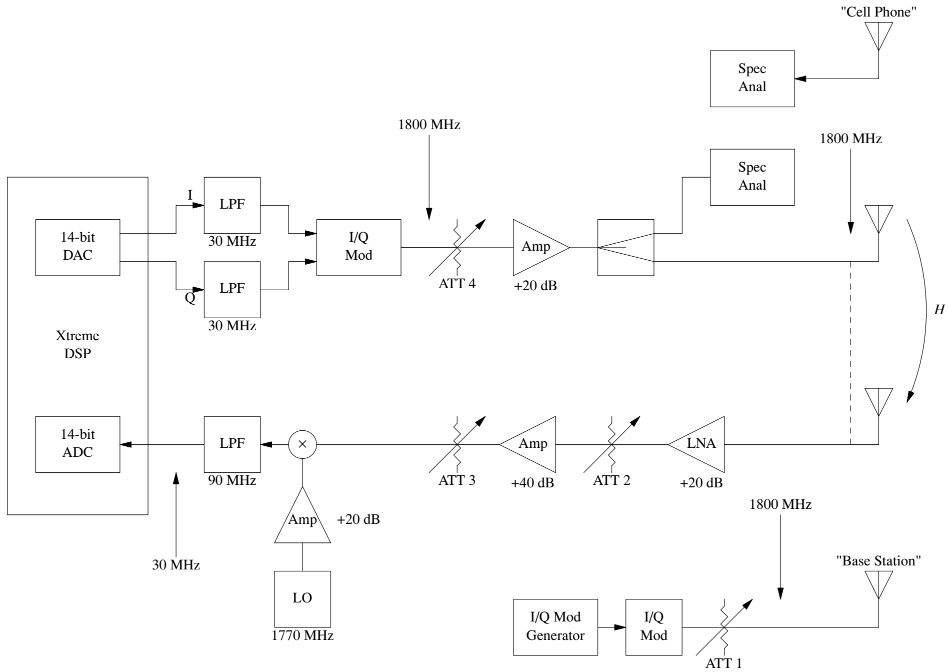

Fig. 3. Repeater demonstration hardware setup.

the usual assortment of cabinets, equipment racks, etc. The antenna on the lower right of Fig. 3 simulates a base station and transmits a CDMA signal over a 5-m path to the donor antenna, which is spaced 1-m upstream of the repeater transmit antenna. A fourth antenna on the upper right represents a cell phone receiver, and is placed 1-m downstream of the repeater transmit antenna.

A two-carrier CDMA signal centered at 1800 MHz was generated and fed to the simulated base station antenna, and a spectrum analyzer was connected to the simulated cell phone antenna. The feedback canceler took about 1 ms to achieve about 20 dB of convergence with a –20 dB PN pilot signal (as compared to about 1200×64 samples / 20 Msamples/s $\equiv 3.8$ ms for the Matlab simulation of [4] which used a ray-trace propagation model of a different type of room). The steady-state results are displayed in Fig. 4. The lowest trace shows the spectrum with the repeater turned off, where we observe the two weak CDMA signals, one above and one below the 1800 MHz center frequency. Next, the repeater is turned on without feedback cancellation, and the gain is manually increased to just below the point of instability. We see from the middle trace that only about 10 dB of boost is obtained. Finally, we activate feedback cancellation and allow the system to automatically increase the gain further, using the built-in gain control algorithm. The resulting upper trace shows an additional 17 dB, making a total boost of 27 dB.

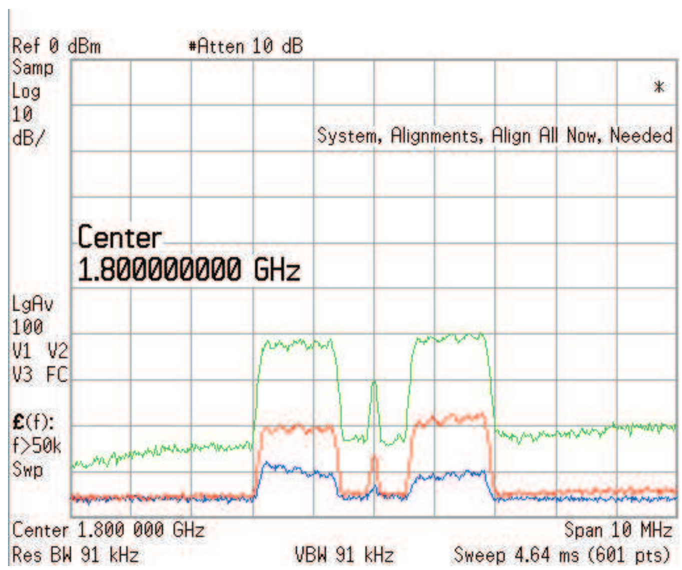

Fig. 4. Output specra at simulated cellphone repeater.

REFERENCES

[1] M. R. Bavafa and H. H. Xia, "Repeaters for CDMA systems," in *Proc. VTC*, 1998, pp. 1161–1165.

[2] Qualcomm Engineering Services Group, "Repeaters for indoor coverage in CDMA networks," Qualcomm White Paper. Available: http://www.repeaterone.com/pdf/80-31576-1_RevB.pdf

[3] A. H. Ali and J. G. Gardiner, "The performance of repeaters in UMTS networks," in *Proc. IEEE MELECON*, 2004, pp. 465–468.

[4] D. R. Morgan and Z. Ma, "A same-frequency cellular repeater using adaptive feedback cancellation," in *Proc. GlobeCom 2012*, to appear.

[5] S. Haykin, *Adaptive Filter Theory*. Englewood Cliffs, NJ: Prentice-Hall, 1991.

[6] S. M. Kuo and D. R. Morgan, *Active Noise Control Systems: Algorithms and DSP Implementations*. New York: Wiley, 1996.

[7] A. A. M. Saleh and R. A. Valenzuela, "A statistical model for indoor multipath propagation," *IEEE J. Sel. Areas Commun.*, vol. SAC-5, pp. 128–137, Feb. 1987.