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1-Bit Transceiver Cluster for Relay Transmission

Chen Cao, Hongxing Li, Zixia Hu and Huacheng Zeng

***Abstract*—Ultra-low-cost communication devices can enable massive deployment of disposable wireless relays. In this paper, we investigate the feasibility of using a 1-bit relay cluster to help a power-constrained transmitter. While the 1-bit transceiver enjoys the benefits of low cost and power consumption, it suffers from extreme information loss and failure of existing DSP techniques. To tackle these challenges, we propose a new receiver architecture design and nonlinear signal estimators. The results corroborate the effectiveness of our solution for the 1-bit relay transmission.**

***Index Terms*—1-bit ADC, relay cluster, high-order modulation, nonlinear estimator.**

I. Introduction

UBiquitous communications (UbiComm) that provide reliable connections for anything at anywhere will take center stage of future wireless networks such as Internet of Things (IoT). In such networks, traditional wireless communication transceivers may impede their massive deployment due to their high cost and power consumption. As a result, ultra-low-cost transceivers have become an intriguing alternative to realize future IoT. In particular, small wireless sensors with a hard cost/power constraint will benefit from the ultra-low-cost relays. Furthermore, the ultra-low-cost transceiver will enable massive deployment of disposable wireless relays. Note that these disposable relays can be arbitrarily scattered at the places needed to provide a reliable connection, and the failure of multiple these relays will not interrupt the connection.

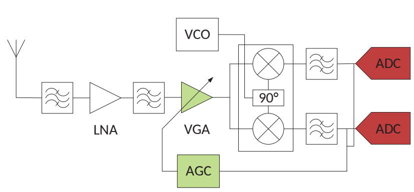

Fig. 1. Direct-conversion receiver architecture

While most existing works consider reducing the power consumption through upper-layer protocols such as routing and scheduling, in this paper we propose a fundamentally new transceiver architecture to eliminate the upper-layer protocols and significantly reduce the cost. Fig. 1 shows the architecture of conventional direct-conversion receivers, where a fundamental component is the analog to digital converter (ADC), converting the received signal into digital format with a typical precision of 8-12 bits. For example, a complete direct-conversion receiver RF front end in [1] consists of a frequency synthesizer, a quadrature demodulator (including a Variable Gain Amplifier (VGA) and an Automatic Gain Control (AGC)) and a 10-Bit ADC. The typical power dissipation in [1] for each IC is 40mW, 340mW and 565mW, respectively, which indicates the majority of the power is consumed in ADCs [2]. Therefore, it has been proposed to use comparators (1-bit ADCs) to replace the high resolution ADCs [3]–[8], and the power consumption can be reduced by up to one order of magnitude. Meanwhile, since only two different phases are recognized after the comparator, the VGA and AGC become unnecessary, which further reduces the cost and the power dissipation. Finally, the 1-bit comparator also reduces the performance requirement of power amplifiers for further efficiency improvement. The drawback of using the 1-bit transceiver is obvious: the extreme quantization will cause information loss and failure of traditional DSP techniques. Thus, the key of 1-bit transceiver design is to develop a feasible baseband to handle the 1-bit quantization. In the literature, use of the 1-bit ADCs has only been recently studied in MIMO systems [3]–[9].

In this paper, we explore the feasibility of deploying a 1-bit relay cluster for a distant transmission. Our envisioned system model is shown in Fig. 2, where there are one source node, one destination node and multiple 1-bit relays, all equipped with single-antenna. It must be emphasized that the 1-bit relays transmit simultaneously at the same frequency band, which completely eliminates the traditional multiple access requirement and thus greatly simplifies the transmission protocol (especially for a large number of relays). However, to make it work, the challenges are multi-fold: Unlike the 1-bit MIMO systems in [6]–[10], in our case the destination node cannot separate the superimposed signal with single-antenna.

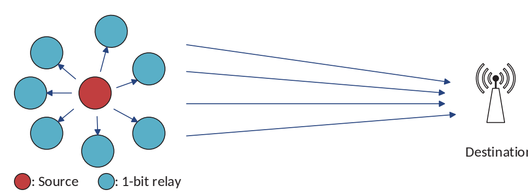

Fig. 2. 1-bit relays cluster transmission.

Meanwhile, the 1-bit ADCs also impede high-order amplitude modulation schemes because the amplitude information will be totally lost at the destination. Furthermore, the equivalent channel between the source and the destination is nonlinear so that traditional estimation techniques are not applicable any more. In this letter, our contributions are summarized as follows: 1) this is the first work to study the 1-bit relay cluster for the distant transmission. 2) A simple DC-offset method is used to support the M-QAM modulation. 3) A

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C.Cao, H.Li and H.Zeng are with the with the Department of Electrical and Computer Engineering, University of Louisville, KY 40292, USA (e-mail: c0cao004@louisville.edu.com).

Zixia Hu is with Qualcomm Inc, San Jose, CA 95110, USA (e-mail: huzixia1984@gmail.com).

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black-box solution is provided to avoid the unscalable channel estimation process. 4) Two nonlinear estimators are designed with significant performance gains over the traditional linear estimator.

II. SYSTEM MODEL

Assume a power-restricted source with single-antenna needs to reach a distant destination. The signal strength at the destination is too low for detection. As shown in Fig. 2, a number of 1-bit communication nodes scattered around the source can help its transmission as intermediate relays. For low-cost reasons, these 1-bit relays are equipped with single-antenna and the full connection is realized in physical layer (PHY) without any complex protocol. The only responsibility of these relays is to receive-store-transmit in a specific time period. All the relays work independently without any message exchange among themselves or control from the destination. Therefore, the information of each the relay is not necessarily required by the destination, and the existence of a specific relay does not need to be acknowledged. This highly increases the flexibility of the entire network. Note that the source node will periodically broadcast a preset synchronization signal to realize both time and symbol synchronization among the relays.

The Pseudo Noise (PN) sequence is well suited for the 1-bit relay synchronization. Specifically, one PN sequence is transmitted only using I path (equivalent to BPSK). Since the PN sequence is binary, a 1-bit relay can detect the sequence directly and synchronize its own transmission.

A. Random-static DC-offset for the M-QAM modulation

Using the 1-bit relays, phase information of the source signal is preserved by the relay cluster, but amplitude levels are not distinguishable. To see that, let's see an example with three transmitted baseband signals: $signal_1 = 1$, $signal_2 = 2$ and $signal_3 = \exp(\pi/3j)$. There are 30 valid 1-bit relays. The channel realizations are sampled based on the complex Gaussian distribution, and the SNR at each relay is $20dB$. In Fig. 3, $signal_1$ and $signal_2$ have exactly the same histogram (the number of the relays with received signal 1 and -1), implying these two signals can not be distinguished by the relay cluster. On the contrary, the different histograms for $signal_1$ and $signal_3$ indicate that the phase difference is acknowledged by the cluster. Therefore, the M-Phase Shift Keying (M-PSK) is naturally supported by the 1-bit relay cluster. To further support amplitude modulations such as the M-Quadrature Amplitude Modulation (M-QAM), we propose a new receiver architecture with a random-static DC-offset (i.e., the value of this DC-offset is constant based on some probability density function). Specifically, DC-offsets are added at each the relay before the comparator. This can be simply realized by coupling the local oscillator (LO) with the RF signal before the mixer, as showed in Fig. 4. This artificial interference provides the needed diversity across the relays to distinguish amplitudes at the destination. Fig. 5 shows the histograms of the relays with the DC-offsets. Compared to Fig.3, $signal_1$ and $signal_2$ yield the different histograms that carry the amplitude information.

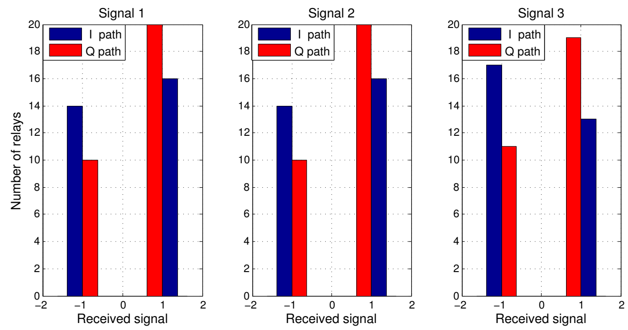

Fig. 3. Histogram of the relays on received signals: Rayleigh fading channel and SNR=20dB, number of relays =30

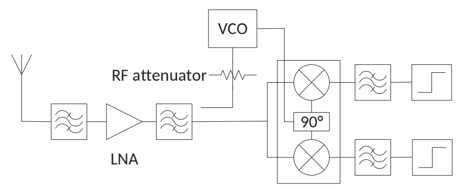

Fig. 4. Our relay Rx design with the LO coupling.

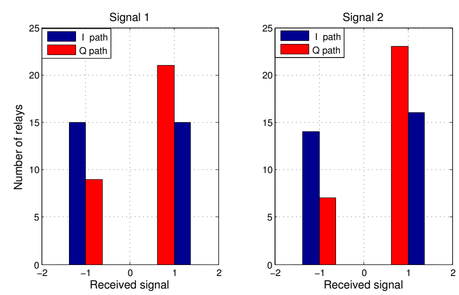

Fig. 5. Histogram of the relays on received signal with the DC-offsets: Rayleigh fading channel and SNR=20dB, number of relays =30

Another advantage of our random-static DC-offset solution is that it evolves naturally from the direct-conversion receiver architecture. Specifically, it is well known that a direct-conversion Rx suffers from the LO leakage: the LO may be conducted or radiated through an unintended path to the mixer's input port. As a by-product, the LO signal effectively mixes with itself, producing a DC component at the mixer output.

In particular, due to manufacturing process and environment, the amount of LO leakage varies across the relays, which naturally results in a random-static DC-offset at baseband.

B. Black-box solution for the 1-bit relays cluster system

For the single-input-single-output (SISO) system shown in Fig. 2, we assume flat uncorrelated Rayleigh slow fading channels. We denote the number of the relays in a cluster as n, the source symbol as $x_{1\times 1}$, the channel matrices as $\mathbf{h}_{1,n\times 1}$ (from the source to the relays) and $\mathbf{h}_{2,1\times n}$ (from the relays to the destination), the DC-offset as $\mathbf{d}_{1\times n}$ (constant) and the circularly symmetric complex Gaussian noise as $\mathbf{w}_{1,1\times n}$, $w_{2,1\times 1}$. The received symbol $y_{1\times 1}$ at the destination node is

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given by:

$$y = \mathbf{h}_2 f_q \left(\mathbf{h}_1 x + \mathbf{d} + \mathbf{w}_1 \right) + w_2, \tag{1}$$

where $f_q(\cdot)$ is the 1-bit quantization function. For massive relay deployment, n can be very large. Apparently, it is impractical to estimate $\mathbf{h}_1$ and $\mathbf{h}_2$. Estimating $\mathbf{h}_1$ and $\mathbf{h}_2$ will cost unscalable overhead and power. Therefore, to solve this problem, instead of using the traditional system model in (1), the destination node will treat the equivalent channel $y = \hat{f}^{-1}(x)$ between the source and the destination as a black box shown in Fig. 6, and try to find out the relationship between x and y through training data. With the black-box assumption, decoding in the destination node is independent of the number of the relays. In other words, increasing the number of the relays doesn't increase the system complexity, and failure of multiple the relays has little impact on decoding process[1].

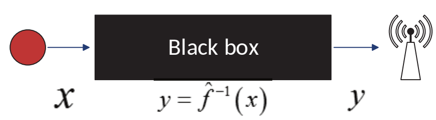


Fig. 6. Black box view of the system.

III. Estimator design for 1-bit relays decoding

At the destination, the key is to estimate x based on y using the function $\hat{x} = \hat{f}(y)$, where parameters of $\hat{f}$ are determined by minimizing the mean square error (MSE) of the pilot samples $\left(\left(\bar{x}_1, \bar{y}_1 \right), \left(\bar{x}_2, \bar{y}_2 \right), \cdots, \left(\bar{x}_n, \bar{y}_n \right) \right)$ as

$$\min_{\hat{f}} \sum_i \left| \hat{\bar{x}}_i - \bar{x}_i \right|^2. \tag{2}$$

In this letter, we exclude the maximum a posterior (MAP) estimator because of it's impractical complexity. Instead, we consider the following three estimators.

A. Linear estimator (LE)

The traditional estimator is linear based:

$$\hat{x} = ay + b. \tag{3}$$

Plug (3) in (2). The optimization problem is quadratic and we can obtain the optimal solution as

$$a = \left(\sum_i \left| \tilde{\bar{y}}_i \right|^2 \right)^{-1} \sum_i \tilde{\bar{y}}_i^{\,*} \tilde{\bar{x}}_i, b = \frac{1}{n} \sum_i \bar{x}_i - \frac{a}{n} \sum_i \bar{y}_i, \tag{4}$$

where $\tilde{\bar{y}}_i = \bar{y}_i - \frac{1}{n} \sum_i \bar{y}_i$ and $\tilde{\bar{x}}_i = \bar{x}_i - \frac{1}{n} \sum_i \bar{x}_i$.

[1]The destination node will periodically re-estimate the black-box system, the failure of multiple relays only exhibits as a fluctuation of the equivalent channel.

B. Support vector machine (SVM)

Linear parametric models can be re-cast into an equivalent 'dual representation' in which the estimations are also based on linear combinations of a kernel function evaluated at the training data points. For models based on a fixed nonlinear feature space mapping $\phi(y)$, the kernel function is given by $\kappa(y, y') = \phi(y)^* \phi(y')$. For example, the Gaussian kernel is given by $\kappa(y, y') = \exp\left(-(y - y')^2 / 2\sigma^2 \right)$. By utilizing the nonlinear feature mapping, the black-box system can be modeled as $\hat{x} = \hat{f}(y) = w\phi(y)$, where w is the undetermined coefficient. The Representer theorem [11] shows that we can adopt $w = \mathbf{a}^H \phi(\bar{\mathbf{y}}) = \sum_i a_i \phi(\bar{y}_i)$, where a_i is the model parameter. Therefore, our nonlinear estimator based on the training samples is given by

$$\hat{x} = \mathbf{a}^H \phi(\bar{\mathbf{y}}) \phi(y). \tag{5}$$

Plug (5) into (2), we can solve the quadratic optimization problem with a analytical solution as

$$\mathbf{a} = \left(\phi(\bar{\mathbf{y}}) \phi(\bar{\mathbf{y}})^H \right)^{-1} \bar{\mathbf{x}}. \tag{6}$$

Thus, our nonlinear estimator is given by

$$\begin{aligned} \hat{x} &= \bar{\mathbf{x}}^H \left(\phi(\bar{\mathbf{y}}) \phi(\bar{\mathbf{y}})^H \right)^{-1} \phi(\bar{\mathbf{y}}) \phi(y) \\ &= \bar{\mathbf{x}}^H K^{-1}(\bar{\mathbf{y}}, \bar{\mathbf{y}}) K(\bar{\mathbf{y}}, y), \end{aligned} \tag{7}$$

where $K(\mathbf{y}, \mathbf{y}') = \begin{pmatrix} \kappa(y_1, y_1{'}) & \cdots & \kappa(y_1, y_n{'}) \\ \vdots & \ddots & \vdots \\ \kappa(y_n, y_1{'}) & \cdots & \kappa(y_n, y_n{'}) \end{pmatrix}$.

C. Neural network (NN)

In the SVM, every single estimation requires re-computing of all samples because of $K(\bar{\mathbf{y}}, y)$. To make the model more compact, we can use other nonlinear models such as the neural network. We adopt a 2-layer neural network given as

$$\hat{x} = \mathbf{a}_2^H f_a \left(\mathbf{a}_1^H y + \mathbf{b}_1 \right) + b_2, \tag{8}$$

where $f_a(\cdot)$ is the nonlinear activation function (e.g., the sigmoid function $f_a(y) = (1 + \exp(-y))^{-1}$); $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{b}_1$ and b_2 are the model parameters; and the dimension of these parameters can be arbitrarily chosen by investigating the estimation performance. Plug (8) into (2), we have

$$\min_{\mathbf{a}_1, \mathbf{a}_2, \mathbf{b}_1, b_2} \sum_i \left| \mathbf{a}_2^H f_a \left(\mathbf{a}_1^H \bar{y}_i + \mathbf{b}_1 \right) + b_2 - \bar{x}_i \right|^2. \tag{9}$$

Eq.(9) is not a convex optimization problem and there is no analytical solution. We can use the Newton algorithm to find a local optimal point and the parameters are updated by:

$$\left[\mathbf{a}_1^{(\beta+1)}; \mathbf{a}_2^{(\beta+1)}; \mathbf{b}_1^{(\beta+1)}; b_2^{(\beta+1)} \right] = \left[\mathbf{a}_1^{(\beta)}; \mathbf{a}_2^{(\beta)}; \mathbf{b}_1^{(\beta)}; b_2^{(\beta)} \right] - \Delta$$

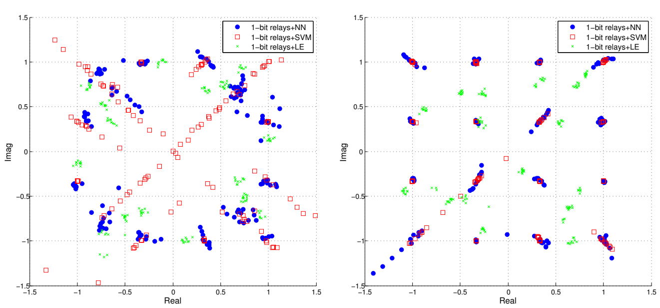
where $\Delta = \mathbf{H}^{-1} \mathbf{J} \mathbf{e}$, $\mathbf{e} = \left(\hat{\bar{x}}_1 - \bar{x}_1, \hat{\bar{x}}_2 - \bar{x}_2, \cdots, \hat{\bar{x}}_n - \bar{x}_n \right)^T$, $\mathbf{H}$ and $\mathbf{J}$ respectively are the Hessian and the Jacobian matrix of $\mathbf{e}$. To reduce the complexity of calculating the Hessian matrix, we adopt the Levenberg-Marquardt algorithm that approximates the Hessian matrix using the Jacobian matrix as

$$\mathbf{H} \approx \left(\mathbf{J}^H\mathbf{J} + \lambda \text{diag}\left(\mathbf{J}^H\mathbf{J}\right)\right) \tag{10}$$

where λ is the damping parameter which can be arbitrary chosen by investigating the estimation performance.

IV. Numerical Results

Our simulation has the following setup: the modulations are 16-QAM and 16-PSK respectively; the number of relays is 30; the number of pilot symbols is 128; the number of data symbols is 1280; Since all relays are scattered near the source nodes, we assume the SNR of these relays $E\left[|h_1|^2|x|^2/|w_1|^2\right]$ is 20dB. The DC-offset $\mathbf{d}$ is sampled from $\mathcal{N}(0,1)$. The kernel for the SVM is the Gaussian kernel; the number of hidden nodes for the NN is 10. We take 200 independent trials of the Rayleigh fading channel $\mathbf{h}_1$, $\mathbf{h}_2$ and the DC-offset $\mathbf{d}$. To make the results comparable, we assume that the transmit power of a single relay is identical to that of the source node. First of all, Fig. 7 compares the 16-QAM decoding constellations without and with the DC-offsets. In Fig. 7(a), without the DC-offset, the pairs $(1+j, 1/3+j1/3)$, $(-1+j, -1/3+j1/3)$, $(1-j, 1/3-j1/3)$ and $(-1-j, -1/3-j1/3)$ are not distinguishable by any the estimator. This problem is caused by the 1-bit relays rather than the estimator design. With our proposed DC-offset solution, the entire 16-QAM constellation can be recovered as showed in Fig. 7(b), which proves the effectiveness of the DC-offset solution for the M-QAM.



(a) without the DC-offsets (b) with the DC-offsets

Fig. 7. 16-QAM decoding constellation.

Next, we compare the performance of the direct-link transmission (w/o relays) and the 1-bit relay transmission with the three estimators. Since the direct-link channel is linear, the linear estimator is sufficient for decoding (i.e., the other two estimators cannot provider additional gains). After the symbol estimator, we use the hard detection to get the bit error rate (BER) directly. Fig. 8 shows the performance of the estimators based on SNR ($E\left[|h_2|^2/|w_2|^2\right]$).

From Fig. 8, we have the following results: (1) The performance of the 1-bit relay with the LE stays the same in all the conditions as expected. This is because that the equivalent channel itself is nonlinear and the LE is not able to handle this channel at all. The fluctuation appearing in the LE performance curve is caused by the finite set of test data. (2) Using the designed nonlinear estimators, 30 1-bit relays can approximately reduce the BER to a half, comparing to the direct-link without the relays. (2) In the low SNR region (SNR<4dB), the NN has a lower BER than the SVM. However, as the SNR increases, the performance of the SVM exceeds that of the NN.

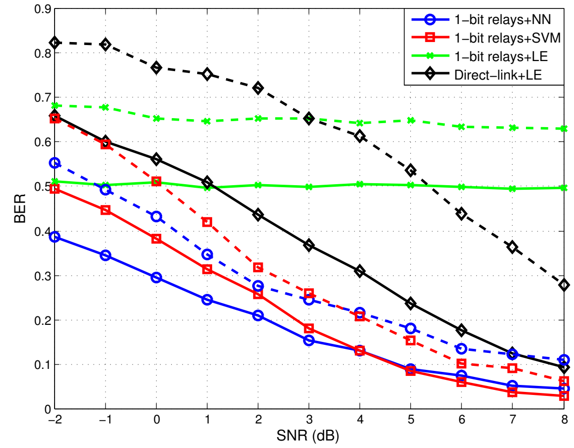


Fig. 8. Performance of the nonlinear estimators. (Solid line: 16-QAM, Dash line: 16-PSK)

V. Conclusion

In this paper, we demonstrated the feasibility to massively deploy a 1-bit relay cluster for a distant transmission. The simulation results verified that our solution is practical and effective for the 1-bit relay transmission.

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