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Quantize-and-Forward Relaying with M-ary Phase Shift Keying

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***Abstract*—Using cooperative transmission, two or more single-antenna users can share their antennas to achieve spatial diversity in a slow fading channel. One relaying protocol that achieves diversity, amplify-and-forward (AF), is striking in its simplicity, but prior analysis has been concerned with an idealized version of AF. In practice, the signal received by the relay must be quantized and stored in finite memory before retransmission. This paper examines a quantize-and-forward (QF) relaying approach that is amenable to implementation on resource-constrained relays. We describe QF relaying with M-ary phase shift keying (PSK) and derive the maximum likelihood-based soft-decision metric for this scheme. When each M-PSK channel symbol is quantized with q bits at the relay, simulation results show that quantizing with $q = 1 + \log_2 M$ bits (i.e., only one extra bit per symbol) provides comparable performance in Rayleigh fading to the idealized (unquantized) AF protocol as well as to an adaptive decode-and-forward protocol at frame error rates of practical interest. Furthermore, this performance is achieved *without* requiring channel decoding or channel state information at the relay (i.e., using only non-coherent detection at the relay). The proposed QF scheme allows the use of resource-limited relays (with low processing power and low memory) to achieve cooperative diversity.**

I. Introduction

Cooperative communication is a class of techniques which allow single-antenna users to obtain similar benefits as in conventional multiple-input, multiple-output (MIMO) systems, such as diversity against slow fading. In cooperative systems, spatial diversity can be achieved when single-antenna stations in a multi-user scenario "share" their antennas to create a virtual MIMO system [1].

The basic building block in cooperative systems is the relay channel, whereby a source transmits a message to a destination with the assistance of a relay. Certain strategies for utilizing the relay channel have been shown to achieve diversity while others do not [2]. For example, a fixed decode-and-forward (DF) relaying protocol—in which the relay always decodes, re-encodes and transmits the message—does not achieve diversity. However, an adaptive version of DF—in which either source-relay channel state information (CSI) or the result of a cyclic redundancy check (CRC) is used to decide whether to relay—does achieve diversity in the high signal-to-noise ratio (SNR) region.

Interestingly, diversity can also be achieved when the relay simply amplifies and forwards its received signal in a non-adaptive fashion [2]–[4]. Amplify-and-forward (AF) does not require the relay to decode the source's transmission, which is a major advantage over decode-and-forward. The relay in this method receives a noisy version of the signal transmitted by the source. As the name implies, the relay then amplifies and retransmits this noisy version. Provided the necessary CSI is available at the destination, it can optimally combine the signals received from the source and relay to obtain diversity. The signal amplified by the relay, though noisy, provides what may be viewed as "soft" information to the destination, as opposed to the hard decisions of fixed DF relaying. Other related work on AF relaying has found expressions for the symbol error probability [5] and has treated AF with non-coherent detection at the destination [6], [7].

However, pure amplify-and-forward relaying poses practical challenges. Previous analyses of AF have assumed an idealized version of the protocol, but in practice the signal received by the relay must be quantized and stored in finite memory before it is retransmitted. A more practical implementation may be referred to as quantize-and-forward (QF) relaying, where the received signal is quantized by the relay to a finite number of bits per sample. In this paper, we propose and analyze a QF relaying protocol for use with M-ary phase shift keying (PSK). We determine the optimum receiver for this scheme and wish to know how coarsely the relay's received signal can be quantized before the diversity gain achieved by pure AF is lost.

Previous work related to relay quantization for wireless channels has obtained information-theoretic results based on Wyner-Ziv source coding assuming the relay knows the channel gains of all links [8] or receives limited error-free feedback from the destination [9] (see also references therein). In one practical design, quantization is followed by joint Slepian-Wolf compression and error coding at the relay, assuming fixed channel gains known at all three nodes [10]. In another design, the relay first soft-decision decodes the source's channel-coded transmission, using CSI of the source-relay link, then quantizes and forwards the resulting soft reliability information [11].

Our proposed QF scheme for PSK signals differs from previous schemes in that the relay requires no feedback from the destination and no CSI. The relay performs a simple scalar quantization with no additional source and/or channel encoding or decoding. The purpose of the quantization at the relay is to model finite-precision storage and to limit the memory required in store-and-forward relays which cannot simultaneously receive and transmit (i.e., half-duplex relays). Rather than achieve higher rates, the performance objective here is to decrease the outage probability over fading channels at a given rate and achieve cooperative spatial diversity.

A contribution of this paper is the maximum likelihood-based soft-decision metric derived for QF relaying with M-ary PSK in Gaussian noise. This metric is used by the destination for optimal combining of the source and relay transmissions and soft-decision decoding of the message encoded by the source. Though the relay does not require CSI, the destination requires CSI of all three links to compute this metric, and we propose a strategy to obtain this CSI. Through simulations of the system in slow Rayleigh fading channels, we demonstrate that when each M-PSK symbol received by the relay is quantized with $q = 1+\log_2 M$ bits (i.e., only one extra bit per symbol), second-order diversity is achieved and performance is comparable to both unquantized AF and adaptive DF at frame error rates of practical interest. Because QF has neither the memory requirements of AF nor the processing (channel decoding) requirements of DF at the relay, it is amenable to implementation on resource-constrained devices such as those used in low-cost wireless sensor networks.

Section II describes the channel model as well as the system models for AF and QF relaying. The QF soft-decision metric is derived in Section III. Section IV presents simulation results, and Section V summarizes the conclusions.

II. System Model

The basic premise in this paper is that a source and one relay cooperate in time-division manner to transmit a message to a destination. A message (or, more precisely, a frame of information bits) is transmitted in two time slots. In the first slot, the source encodes the message with a binary channel encoder and transmits the coded bits with M-ary PSK signals. In the second slot, the relay forwards a version of what it receives to the destination while the source is silent. Assuming the destination has CSI of the three links, it optimally combines the signals received from the source and relay and calculates a soft-decision metric (in the form of a log-likelihood ratio of each coded bit) that is fed to the channel decoder. While channel coding is not inherently required in AF or QF relaying as it is in DF, we include it in the analysis of AF and QF because it is likely to be used in practice to improve spectral efficiency, allows exploitation of the soft information availed by the decision metrics derived below, and permits a fair comparison between AF, QF, and DF.

The channel propagation model includes path loss with distance and Rayleigh fading that is constant during each frame and mutually independent among the three links in the system (see Fig. 1). The channel also adds white Gaussian noise with two-sided power spectral density $N_0/2$. The sampled output of the demodulator of a receiver is thus modeled as

$$y_i = \alpha_i s_i + z_i$$

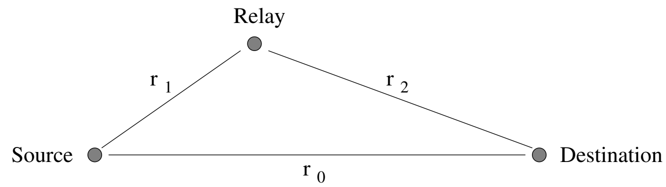


Fig. 1. Sample topology of source, relay and destination

where s_i is the transmitted PSK symbol on link i, α_i is the overall channel attenuation, including the effects of distance and fading, z_i is the noise contribution, all terms are complex representing in-phase and quadrature components, and the subscript $i \in \{0, 1, 2\}$ denotes the source-destination, source-relay, and relay-destination links, respectively. Under the stated channel assumptions, the channel factor, α_i, is zero-mean, circularly symmetric (c.s.) complex Gaussian with variance $1/r_i^n$, where r_i is the link distance and n is the path loss exponent. The noise term, z_i, is zero-mean, c.s. complex Gaussian with variance $\sigma^2 = N_0/E_s$, where E_s is the average received signal energy. The source's transmitted symbol, s_0 $(= s_1)$, is a unit-energy M-PSK signal ($s_0 \in \left\{e^{j2\pi m/M}\right\}, m = 0, 1, \ldots, M-1$).

A. Amplify-and-Forward

In fixed amplify-and-forward relaying, the received signals of the source-destination, source-relay, and relay-destination links, respectively, are

$$\begin{aligned} y_0 &= \alpha_0 s + z_0 && (1) \\ y_1 &= \alpha_1 s + z_1 && (2) \\ y_2 &= \alpha_2 \beta y_1 + z_2 \\ &= \alpha_1 \alpha_2 \beta s + \alpha_2 \beta z_1 + z_2 && (3) \end{aligned}$$

where β is the amplification factor. We set $\beta = \sqrt{1/\left(|\alpha_1|^2 + \sigma^2\right)}$ to meet a constant power constraint. Note that normalization of the amplified signal energy requires measurement by the relay of the received signal energy.

B. Quantize-and-Forward

In quantize-and-forward transmission, instead of sending an amplified version of y_1, the relay detects the phase of y_1, performs uniform quantization with q bits, and transmits a PSK signal with the quantized phase and same power as the source's transmission. To reduce the processing burden at the relay, we assume that the phase of y_1 is detected *non-coherently*, that is, the detected phase includes the effect of channel rotation and the relay's phase offset.

The received signals of the source-destination and source-relay links are the same as (1) and (2), respectively, while that of the relay-destination link is given by

$$y_2 = \alpha_2 e^{j\widehat{\angle y_1}} + z_2 \quad (4)$$

where $\widehat{\angle y_1} \in \{\phi_0, \phi_1, \ldots, \phi_{2^q-1}\}$ denotes the quantized phase of the source-relay signal, y_1. With uniform quantization,

$\hat{\angle y_1} = \phi_k = 2\pi k/2^q$ if $\angle y_1$ is within

$$\frac{\pi}{2^q}(2k-1) < \angle y_1 \le \frac{\pi}{2^q}(2k+1), \quad k = 0, 1, \ldots, 2^q - 1. \tag{5}$$

The lower and upper limits of (5) are denoted below by ϕ_k^l and ϕ_k^u, respectively. As we shall see in Section IV, there is little to be gained by pursuing a possibly optimized, non-uniform quantization scheme.

III. Soft-Decision Metrics

In this section, we derive the maximum likelihood decision metric for QF relaying with M-PSK signals when the additive noise is white Gaussian. This metric, given in the form of the binary log-likelihood ratio (LLR) of each coded bit, is used by the destination for soft-decision decoding of the received signal. We assume that the complex channel attenuations $\{\alpha_i\}$ are available at the destination as side information.

After observing the channel outputs of a transmitted M-PSK signal corresponding to a length-$\log_2 M$ sequence of coded bits, $\mathbf{c}$, the LLR of the jth coded bit, c_j, is defined as

$$L_j(\mathbf{y}, \boldsymbol{\alpha}) \triangleq \log \frac{\Pr[c_j = 1 \,|\, \mathbf{y}, \boldsymbol{\alpha}]}{\Pr[c_j = 0 \,|\, \mathbf{y}, \boldsymbol{\alpha}]} \tag{6}$$

where $\mathbf{y} = \begin{bmatrix} y_0 & y_2 \end{bmatrix}$ and $\boldsymbol{\alpha} = \begin{bmatrix} \alpha_0 & \alpha_1 & \alpha_2 \end{bmatrix}$ are the observed channel outputs and known CSI at the destination, respectively. In terms of the transmitted signal s that corresponds to $\mathbf{c}$, (6) can be expressed as

$$L_j(\mathbf{y}, \boldsymbol{\alpha}) = \log \frac{\sum_{s:c_j=1} p(s|\mathbf{y}, \boldsymbol{\alpha})}{\sum_{s:c_j=0} p(s|\mathbf{y}, \boldsymbol{\alpha})} \tag{7}$$

where $p(s|\cdot)$ is the conditional probability of signal s, and the summations are over all signals such that $c_j = 1$ and 0, respectively. Using Bayes' rule and assuming all coded sequences are equiprobable, (7) can be written in terms of the conditional probability density function of the channel outputs:

$$L_j(\mathbf{y}, \boldsymbol{\alpha}) = \log \frac{\sum_{s:c_j=1} f(\mathbf{y}|s, \boldsymbol{\alpha})}{\sum_{s:c_j=0} f(\mathbf{y}|s, \boldsymbol{\alpha})}. \tag{8}$$

The soft-decision metric is then obtained by substituting the likelihood function in (8).

A. Amplify-and-Forward

First, we review the likelihood function for amplify-and-forward. Because the AF channel outputs, y_0 and y_2, conditioned on s are independent, the AF likelihood function is simply the product of the marginal densities:

$$f_{\mathrm{AF}}(\mathbf{y}|s, \boldsymbol{\alpha}) = f(y_0|s, \alpha_0)\, f(y_2|s, \alpha_1, \alpha_2). \tag{9}$$

From (1), the source-destination channel output y_0 is complex Gaussian with mean $\alpha_0 s$ and variance σ^2. From (3), the relay-destination channel output y_2 is complex Gaussian with mean $\alpha_1\alpha_2\beta s$ and variance $\sigma^2\left(|\alpha_2|^2\beta^2 + 1\right)$. Substituting the Gaussian densities into (9), the AF likelihood function is proportional to

$$f_{\mathrm{AF}}(\mathbf{y}|s, \boldsymbol{\alpha}) \propto \exp\left[-\frac{|y_0 - \alpha_0 s|^2}{\sigma^2} - \frac{|y_2 - \alpha_1\alpha_2\beta s|^2}{\sigma^2\left(|\alpha_2|^2\beta^2 + 1\right)}\right].$$

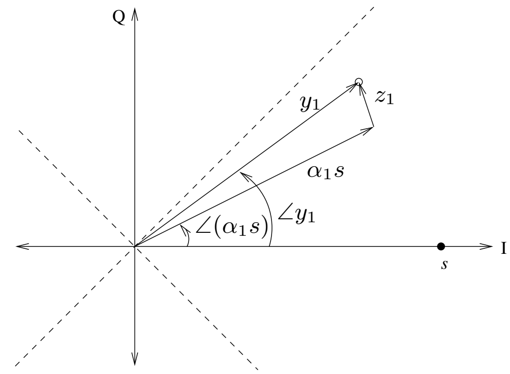


Fig. 2. Vector illustration of a received signal at the relay and quantization boundaries for $q = 2$

B. Quantize-and-Forward

As in AF, y_0 and y_2 are independent, conditioned on s, and (9) applies to the QF likelihood function, as well. Clearly, the density of the source-destination channel output, y_0, is also the same.

The density of the QF relay-destination channel output, y_2, on the other hand, is slightly more involved. From (4), and conditioned on the quantized phase at the relay $\hat{\angle y_1}$, y_2 is complex Gaussian with mean $\alpha_2 e^{j\hat{\angle y_1}}$ and variance σ^2. To remove the conditioning on the quantized phase, we need the probability distribution of $\hat{\angle y_1}$, conditioned on α_1 and s. To assist with deriving this distribution, we refer to an example depicted in Fig. 2. In this illustration, the transmitted signal (s), attenuated signal ($\alpha_1 s$), noise (z_1), and y_1 are represented as vectors in the I-Q plane. Furthermore, quantization boundaries are illustrated for the case of $q = 2$ (i.e., four-phase quantization).

Determining the probability distribution of $\hat{\angle y_1}$ amounts to calculating the probability that y_1 lies in each quantization quadrant in Fig. 2. The problem is similar to the calculation of the probability of error of a conventional M-PSK receiver in additive white Gaussian noise (AWGN), except that the received signal is rotated relative to the "decision" boundaries (or quantization boundaries, in this case) and its magnitude is scaled. One approach is to integrate the density of the phase of y_1 over each quantization region.

The density of the phase of a PSK signal received in AWGN is [12, (5.2-55)]

$$f_\Theta(\theta) = \frac{1}{2\pi} e^{-\gamma_s \sin^2\theta} \int_0^\infty v e^{-\left(v - \sqrt{2\gamma_s}\cos\theta\right)^2/2}\, dv \tag{10}$$

where γ_s is the SNR of the received signal and the transmitted phase is zero. For easier numerical evaluation where efficient computation (or table look-up) of the complementary error function, $\mathrm{erfc}(\cdot)$, is available, (10) can be expressed using [13, (3.462.5)] as

$$f_\Theta(\theta) = \frac{1}{2\pi}\left[e^{-\gamma_s} + \sqrt{\pi\gamma_s}\cos\theta\, e^{-\gamma_s \sin^2\theta}\,\mathrm{erfc}\left(-\sqrt{\gamma_s}\cos\theta\right)\right]. \tag{11}$$

Adapting (11) to our problem, we only need to shift the center of the density to $\angle(\alpha_1 s)$, i.e.,

$$f_{\angle y_1}(\theta) = f_\Theta[\theta - \angle(\alpha_1 s)] \tag{12}$$

and note that, for this shifted density, $\gamma_s = |\alpha_1 s|^2/\sigma^2$. With (12), the probability that $\angle y_1$ is quantized to ϕ_k can be evaluated numerically by integrating (12) over the quantization region of ϕ_k:

$$\Pr\left[\hat{\angle y_1} = \phi_k | s, \alpha_1\right] = \int_{\phi_k^l}^{\phi_k^u} f_{\angle y_1}(\theta)\, d\theta. \tag{13}$$

With the probability distribution of the quantized phase (13), we are in a position to evaluate the density of the QF relay-destination channel output, y_2, as

$$\begin{aligned} & f(y_2|s,\alpha_1,\alpha_2) \\ &= E_{\hat{\angle y_1}}\left[f\left(y_2|\alpha_2, \hat{\angle y_1}\right)|s,\alpha_1\right] \\ &= \sum_{k=0}^{2^q-1} \Pr\left[\hat{\angle y_1} = \phi_k|s,\alpha_1\right] f(y_2|\alpha_2,\phi_k) \end{aligned} \tag{14}$$

where $f(y_2|\alpha_2,\phi_k)$ is the Gaussian density

$$f(y_2|\alpha_2,\phi_k) = \frac{1}{\pi\sigma^2}\exp\left(-\frac{1}{\sigma^2}|y_2 - \alpha_2 e^{j\phi_k}|^2\right).$$

Finally, the QF likelihood function is obtained by combining (14) with the Gaussian density of the source-destination channel output, y_0, giving

$$f_{\mathrm{QF}}(\mathbf{y}|s,\boldsymbol{\alpha}) = \frac{1}{\pi\sigma^2}e^{-|y_0-\alpha_0 s|^2/\sigma^2} f(y_2|s,\alpha_1,\alpha_2).$$

Evaluation of the QF likelihood function is more complex than that of AF due to the need to evaluate (13) for each of the M signals in the PSK constellation and each of the 2^q quantization regions. However, by exploiting rotational symmetry, (13) need only be evaluated for one signal, reducing the complexity by a factor of M. Additional savings in complexity may be possible by only calculating the probabilities of quantization to the nearest quantization point and its two neighbors, approximating the other probabilities as zero. More importantly, in slow fading channels, these calculations need only be done once per block of symbols over which the fading is approximately constant.

C. On Channel Estimation at the Destination

Both the AF and QF decision metrics derived above depend on CSI of all three links. In practice, this information must be estimated. While estimation of the source-destination and relay-destination channel factors, α_0 and α_2, at the destination can be straightforward, obtaining an estimate of the source-relay channel factor, α_1, requires additional mechanisms. To accommodate resource-limited relays, one would want to retain the feature that the relay not be required to estimate the channel state. One strategy based on a pilot-assisted approach is to embed pilots in the source's transmission which are relayed with higher fidelity to the destination. In addition, the relay generates and embeds its own pilots into its transmission. The destination, then, receives two sets of pilots, one originated by the source and relayed with finer quantization, and the other originated by the relay. The destination could use the former to estimate the concatenated source-relay-destination channel factor, $\alpha_1\alpha_2$, and the latter to estimate α_2, from both of which α_1 could be derived. The transmission of pilots and the finer quantization of the source's pilots at the relay could be considered the overhead cost of this channel estimation approach. However, in slow fading channels for which cooperative diversity is mainly intended, this overhead is anticipated to not be significant. While the accuracy of such channel estimation is beyond the scope of this paper, it would be worthwhile to address its impact as part of further work.

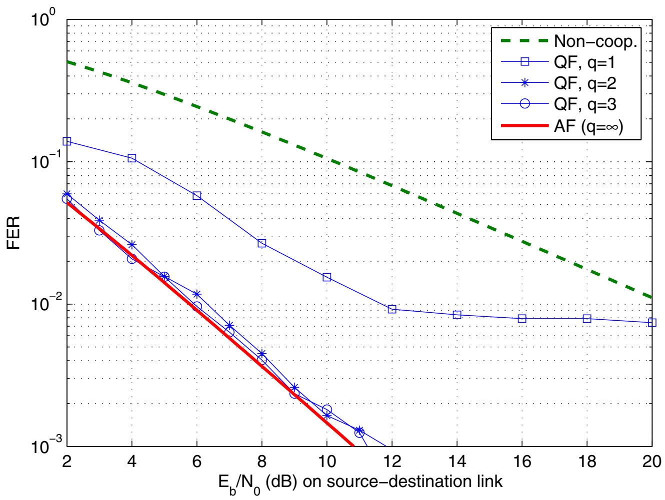
An alternative is to have the relay estimate the phase of the source-relay link and quantize the corrected phase. In this case, the destination would not need to estimate the source-relay link's phase, with (12) becoming $f_{\angle y_1}(\theta) = f_\Theta(\theta)$, but the destination would still need an estimate of the source-relay SNR for γ_s in (11).

IV. Simulation Results

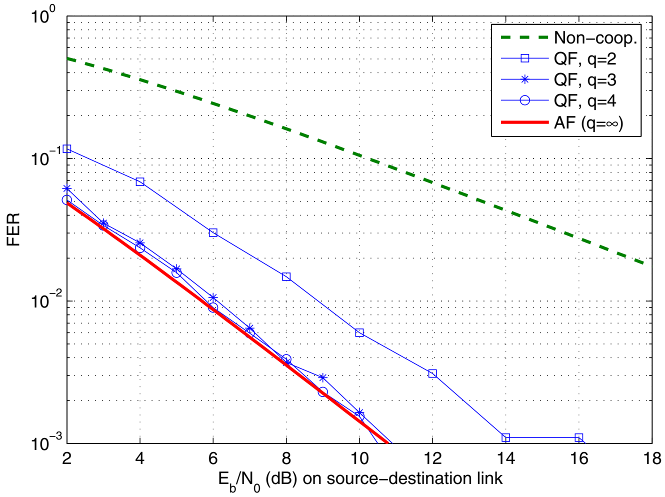
Performance of the quantize-and-forward cooperative transmission scheme with soft-decision decoding at the destination was evaluated by simulation as follows. The source encodes a 1024 bit frame with a rate-1/3 binary parallel concatenated convolutional code using generator polynomial $(1, 13/15)_8$. Encoded bits are punctured to rate 2/3 and mapped to PSK symbols with Gray encoding. The channel is as described in Section II (i.e., flat Rayleigh fading plus AWGN) with path loss exponent $n = 4$. The destination feeds the soft-decisions (log-likelihood ratios) of the received coded bits into an iterative decoder that uses soft-input/soft-output MAP decoding. Results are presented in terms of the frame error rate (FER) after eight iterations of decoding. For non-ergodic channels, this performance measure can be interpreted as the outage probability.

Fig. 3(a) plots the FER as a function of the SNR per bit (E_b/N_0) on the source-destination link when the relay is located midway between the source and destination and when binary PSK (BPSK) modulation is used. Results for three different quantization levels are shown, $q = 1, 2$, and 3 bits per BPSK symbol. For comparison, results for unquantized amplify-and-forward and non-cooperative (no relay) transmission are also shown using analytical results which have been shown to compare favorably with simulation results [4].[1] We observe that hard-decision quantization at the relay ($q = \log_2 M = 1$) results in a 6 dB penalty relative to unquantized AF at a FER of 10^{-2}, and encounters a transient error floor just below 10^{-2} FER. However, with only one additional bit of quantization per channel symbol at the relay ($q = 2$), the penalty at 10^{-2} FER is reduced to under 1 dB, and the performance with $q = 3$ bits of quantization is almost indistinguishable from the unquantized case. The significance of these results is that diversity performance comparable to

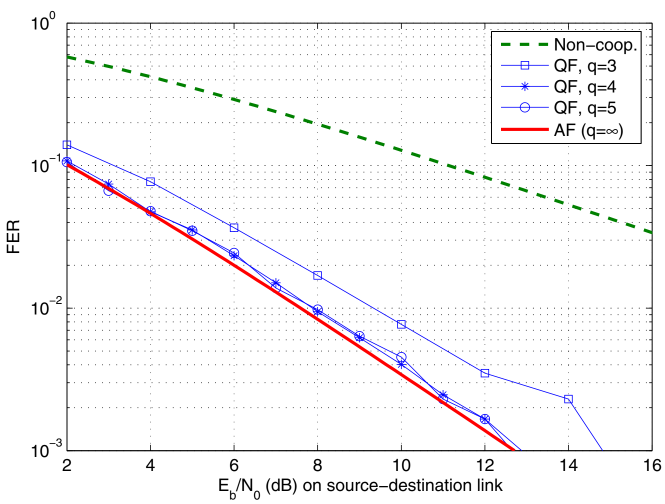
[1]For comparison at equal information rates, the non-cooperative transmission utilizes the unpunctured rate-1/3 code.



(a) BPSK



(b) QPSK



(c) 8-PSK

Fig. 3. FER vs. SNR with q-bit quantization, relay at midpoint

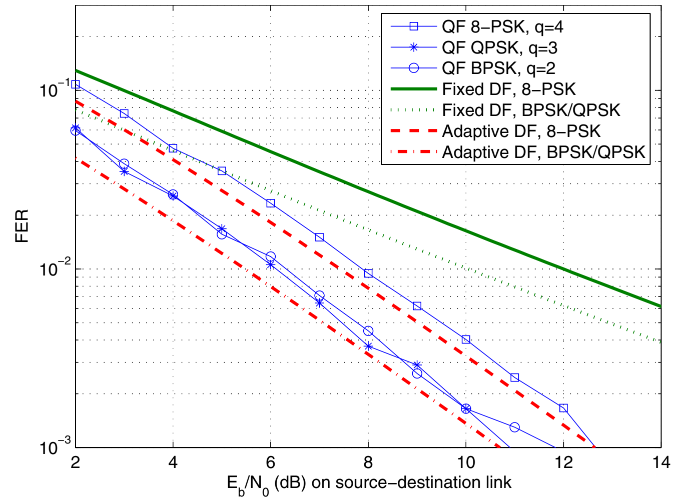


Fig. 4. FER vs. SNR, comparing QF using $q = 1 + \log_2 M$ with DF

that of unquantized amplify-and-forward can be achieved with simple relay processing (i.e., without channel decoding or channel state information) and limited memory (here, 2 bits per channel symbol).

Figs. 3(b) and 3(c) show comparable results for QPSK and 8-PSK modulation. The penalty of hard-decision quantization ($q = \log_2 M$) using these modulation schemes is about 3 dB and 2 dB, respectively, at 10^{-2} FER. The reason the penalty decreases with M is that larger constellations inherently provide the decoder with softer information on individual coded bits. With increasing M, each PSK symbol represents a larger number of coded bits, and, with Gray encoding, wrongly quantizing a symbol to one of its neighboring symbols in the constellation results in a smaller percentage of coded bits being wrongly detected at the relay and requiring correction by the destination's decoder. Nevertheless, with both QPSK and 8-PSK as with BPSK, one additional quantization bit ($q = 1 + \log_2 M$) yields performance that is very close to unquantized amplify-and-forward. Since performance close to the unquantized is already achieved with only one extra bit and *uniform* quantization, there is little to be gained by attempting to optimize performance with *non-uniform* quantization.

Fig. 4 compares QF relaying using $q = 1 + \log_2 M$ quantization bits with both fixed and adaptive decode-and-forward. The DF results are based on the analytical expressions in [4] which have been shown to compare favorably with simulation results. As expected, fixed DF does not achieve diversity while adaptive DF, where the relay uses a CRC after channel decoding to decide whether to forward, does achieve diversity. Relative to adaptive DF, the penalty of QF with one extra bit of quantization is less than 1 dB, with the benefit that channel decoding is not needed at the relay. However, QF requires source-relay CSI at the destination, while DF requires it at the relay.

The preceding results are for the case when the relay is located midway between the source and destination, that is, when the average SNRs of the source-relay and relay-

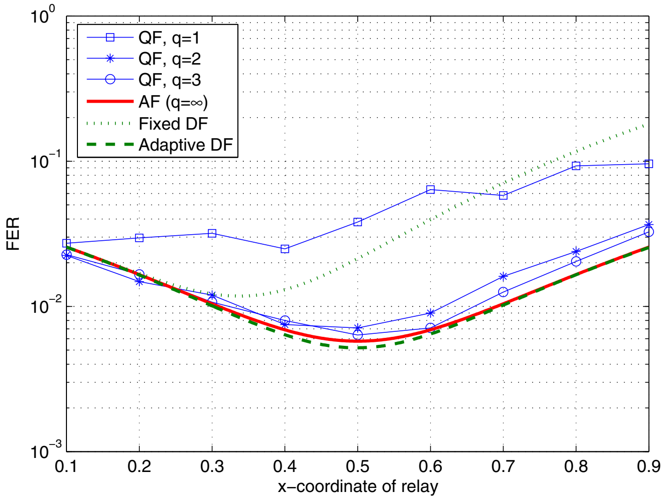


Fig. 5. FER vs. relay position on unit-distance source-destination line, BPSK, $E_b/N_0 = 7$ dB

destination links are equal. Next, we varied the position of the relay along the line between the source (at $x = 0$) and destination ($x = 1$). Fig. 5 illustrates the FER as a function of relay position (x) for the case of BPSK modulation and a fixed source-destination E_b/N_0. (Results for QPSK and 8-PSK follow the same trends.) While hard quantization at the relay results in significant loss, again, quantizing with one or more additional bits restores much of the gain achieved by unquantized amplify-and-forward. Hard quantize-and-forward relaying shares a similar profile with fixed decode-and-forward in that performance is comparable to the diversity-achieving protocols when the relay is close to the source (due to fewer detection/decoding errors) but deteriorates as the relay moves closer to the destination, with the optimum relay position being closer to the source. However, with softer quantize-and-forwarding, performance is close to that of both unquantized AF and adaptive DF across the range of positions, with the optimum relay position being at the midpoint.

V. Conclusion

Motivated by the desire to bring the benefits of cooperative diversity to wireless sensor networks made up of nodes with low processing power and limited memory, this paper investigated a quantize-and-forward relaying protocol for PSK systems as an alternative to amplify-and-forward, which is known to offer diversity in fading channels. The main benefits of the quantize-and-forward relaying protocol proposed here are that the relay is not required to decode the channel-encoded transmission of the source, can utilize non-coherent detection (i.e., channel state information is not required at the relay), and requires little memory to store the received signal from the source before relaying it to the destination (on the order of a few bits per channel symbol). The bulk of the processing, rather, is shifted to the destination, which in sensor networks is typically a higher-functioning sink node. While some of the aforementioned benefits are shared by amplify-and-forward relaying, the main difference is the storage requirement, as pure, unquantized amplify-and-forward relaying is impractical. Quantize-and-forward relaying, therefore, is a practical approach to cooperatively achieving diversity in slow-fading wireless networks with resource-limited relays.

A maximum likelihood-based soft-decision metric was derived for the described quantize-and-forward protocol, and simulations were performed in conjunction with a turbo code in Rayleigh fading channels. Results demonstrated that quantizing with only $1 + \log_2 M$ bits per M-PSK symbol at the relay achieves comparable error rate performance to idealized amplify-and-forward as well as to adaptive decode-and-forward, meaning that only a moderate increase in memory beyond what is required for conventional hard-decision detection is needed at the relay, while at the same time forgoing the extra processing burden of fully decoding at the relay. However, as with AF, optimum combining of the signals at the destination requires CSI of the three links, and a possible approach to obtaining this CSI was discussed. Ongoing work is investigating practical relaying protocols that use orthogonal signals and non-coherent detection and that require no CSI at the destination.

References

[1] A. Nosratinia, T. E. Hunter, and A. Hedayat, “Cooperative communication in wireless networks,” *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

[2] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” *IEEE Trans. Inform. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[3] M. Yu and J. Li, “Is amplify-and-forward practically better than decode-and-forward or vice versa?” in *Proc. IEEE Int. Conf. Acoustics, Speech, and Signal Processing (ICASSP)*, vol. 3, March 2005, pp. 365–368.

[4] M. R. Souryal and B. R. Vojcic, “Performance of amplify-and-forward and decode-and-forward relaying in Rayleigh fading with turbo codes,” in *Proc. IEEE Int. Conf. Acoustics, Speech, and Signal Processing (ICASSP)*, vol. 4, May 2006, pp. 681–684.

[5] A. Ribeiro, X. Cai, and G. B. Giannakis, “Symbol error probabilities for general cooperative links,” *IEEE Trans. Wireless Commun.*, vol. 4, no. 3, pp. 1264–1273, May 2005.

[6] R. Annavajjala, P. C. Cosman, and L. B. Miltstein, “On the performance of optimum noncoherent amplify-and-forward reception for cooperative diversity,” in *Proc. MILCOM*, vol. 5, Oct. 2005.

[7] D. Chen and J. N. Laneman, “Cooperative diversity for wireless fading channels without channel state information,” in *Proc. Asilomar Conf. Signals, Syst. and Comp.*, vol. 2, Nov. 2004, pp. 1307–1312.

[8] A. Høst-Madsen and J. Zhang, “Capacity bounds and power allocation for wireless relay channels,” *IEEE Trans. Inform. Theory*, vol. 51, no. 6, pp. 2020–2040, Jun. 2005.

[9] M. Katz and S. Shamai (Shitz), “Relaying protocols for two colocated users,” *IEEE Trans. Inform. Theory*, vol. 52, no. 6, pp. 2329–2344, Jun. 2006.

[10] Z. Liu, V. Stanković, and Z. Xiong, “Wynzer-Ziv coding for the half-duplex relay channel,” in *Proc. IEEE Int. Conf. Acoustics, Speech, and Signal Processing (ICASSP)*, vol. 5, March 2005, pp. 1113–1116.

[11] R. Hu and J. Li, “Practical compress-forward in user cooperation: Wyner-Ziv cooperation,” in *Proc. ISIT*, Jul. 2006, pp. 489–493.

[12] J. G. Proakis, *Digital Communications*. 4th ed., New York: McGraw-Hill, 2001.

[13] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series and Products*. 6th ed., New York: Academic Press, 2000.