Nonlinear Amplifier Distortion in Cooperative Amplify-and-Forward OFDM Systems

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Outline

Introduction

- In cooperative communications, neighbor devices are used as relays that help the transmitter and the receiver to gain extra diversity
  - In this paper: the classical three-node network
- OFDM signal has high peak-to-average power ratio (PAPR)
  - Real power amplifiers (PAs) are nonlinear
  - Nonlinearity causes signal waveform distortion and adjacent channel interference
  - Expensive solutions: predistortion, output back-off
- The nonlinearity problem in cooperative communication systems has to be solved in a different way, because relays are cheap terminals
  - Almost no literature is available on this topic

Half-duplex amplify-and-forward OFDM relay link

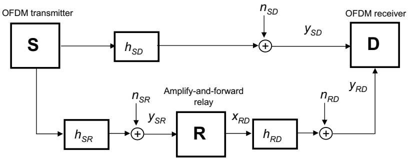

Fig. 1. System model of the cooperative communication system.

- The signal model:
$$\begin{aligned} Y_{SD}(k) &= H_{SD}(k)X(k) + N_{SD}(k) \\ Y_{SRD}(k) &= H_{SRD}(k)X(k) + N_{SRD}(k) \end{aligned}$$
  - where $N_{SRD}(k) = H_{RD}(k)N_{SR}(k) + N_{RD}(k)$ and $H_{SRD}(k) = H_{RD}(k)H_{SR}(k)$
- Conventional maximum ratio combiner (MRC):
$$Y_D(k) = \frac{H^*_{SD}(k)}{\sigma^2_{SD}} Y_{SD}(k) + \frac{H^*_{SRD}(k)}{\sigma^2_{SRD}(k)} Y_{SRD}(k)$$
  - noise power of the relay branch $\sigma^2_{SRD}(k) = |H_{RD}(k)|^2 \sigma^2_{SR} + \sigma^2_{RD}$

Nonlinear distortion (NLD)

- The critical component is the PA of the relay
- OFDM signal is approximately Gaussian
  - Thus, the PA output signal can be modelled as

$$y(t) = F[x(t)] = F_A[\rho(t)]e^{F_P[\rho(t)]}e^{j\phi(t)} = Kx(t) + d(t),$$

    where $x(t)$ and $d(t)$ are uncorrelated
- This allows us to consider two new options for the receiver processing
  - Modify the MRC to take into account the distortion noise
  - Extend the power amplifier nonlinearity cancellation (PANC) technique for cooperative communications

NLD-aware MRC

- Exploiting knowledge on the PA model
- The received signal at the relay branch when including the nonlinear distortion:

$$Y_{SRD}(k) = KH_{SRD}(k)X(k) + KH_{RD}(k)\left[N_{SR}(k) + K^{-1}D(k)\right] + N_{RD}(k)$$

- Improved maximum ratio combiner (MRC):

$$Y_D(k) = \frac{H^*_{SD}(k)}{\sigma^2_{SD}} Y_{SD}(k) + \frac{KH^*_{SRD}(k)}{\hat{\sigma}^2_{SRD}(k)} Y_{SRD}(k)$$

  - noise power of the relay branch $\hat{\sigma}^2_{SRD}(k) = |KH_{RD}(k)|^2 \hat{\sigma}^2_{SR} + \sigma^2_{RD}$ and $\hat{\sigma}^2_{SR} = \sigma^2_{SR} + K^{-2}\sigma^2_{NLD}$

PANC for cooperative communications

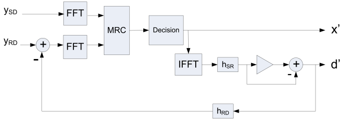

Fig. 2. PANC model for a cooperative system.

TABLE I
THE MODIFIED PANC ALGORITHM FOR COOPERATIVE SYSTEMS

For i = 1 to number of iterations. 1. Demap received symbol: $\hat{X}(k)$ 2. Transform to time domain: $\hat{x}(t)$ 3. Convolve with channel: $\hat{y}_{SR}(t) = h_{SR}(t) * \hat{x}(t)$ 4. Amplify using the amplifier model: $\hat{x}_{RD}(t) = F[\hat{y}_{SR}(t)]$ 5. Compute the distortion term: $\hat{d}[y_{SR}(t)] = \hat{x}_{RD}(t) - K y_{SR}(t)$ 6. Subtract the distortion term from y_{RD} 7. Transform to frequency domain and combine End

- Iterative receiver cancellation of the nonlinear distortion noise
  - Exploiting detected symbols and the PA model, an approximation of the distortion term is generated and subtracted from the input signal
  - After demodulating again, a better estimation of the transmitted symbols is obtained

NLD-aware MRC with PANC

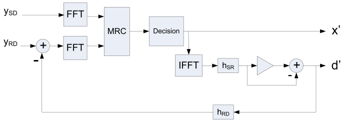

Fig. 2. PANC model for a cooperative system.

- The proposed MRC and PANC cannot be combined directly, because the NLD-aware MRC weights the received signals according to NLD while the PANC's objective is to remove the NLD
  - The NLD-aware MRC is optimal for the reception of the signal y_{RD} but not for $y_{RD} - h_{RD}(t) * d[y_{SR}(t)]$
- Two steps for combining these two techniques successfully:
  1. The reception of the signal using NLD-aware MRC
     - NLD has not been canceled yet
  2. The PANC process using regular MRC
     - PANC has removed the estimated distortion from the received signal

Simulation setup

- Uncoded bit-error rate (BER) simulations for 16-QAM
  - Independent Rayleigh fading multipath channels with a Doppler spread $f_c \approx 10$ Hz:
    - delay profile: 1, 2, 3, 4 subsymbols
    - power profile (dB): 0, -1, -3, -9
    - terminal velocity: 5 km/h
    - carrier frequency: 2.4 GHz
    - bandwidth: 6.0 MHz
  - 512 subcarriers, CP length 16 subsymbols
- A solid-state power amplifier implemented by the Rapp model
  - The AM/AM and AM/PM conversion functions

$$F_A[\rho] = \frac{v\rho}{[1 + (v\rho/V_{sat})^{2r}]^{1/(2r)}}$$
$$F_P[\rho] = 0$$

    - $v = 1$ is the small signal gain of the amplifier
    - $r = 3$ smoothes the transition from linear operation to saturation
    - $V_{sat} = 1.4V$ is the saturation voltage of the amplifier

The effect of the output back-off (OBO)

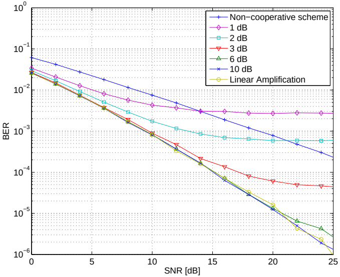

Fig. 3. BER for different OBO with regular MRC.

- Without modifying the MRC
- NLD at the relay impacts the performance of the system significantly

The benefit of the NLD-aware MRC

- $OBO = 1\text{dB}$:

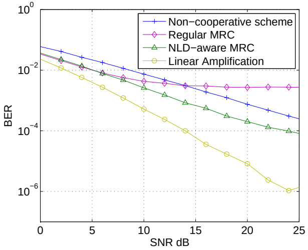

Fig. 4. Performance results for non-cooperative scheme, regular MRC, NLD-aware MRC, and MRC in case of linear power amplifier in the relay.

- The performance of the NLD-aware MRC is significantly enhanced when compared to the regular MRC
- NLD-aware MRC outperforms the noncooperative scheme but its performance is still inferior to the linear amplifier

The benefit of PANC

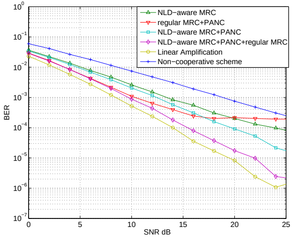

Fig. 5. Performance results for NLD-aware MRC, different PANC techniques, non-cooperative scheme, and MRC with linear power amplifier in the relay.

- The performance is improved significantly with PANC
- The BER curve is not only close to the linear case but it also shows a similar behavior (diversity order)
- PANC and MRC should be combined properly

Conclusion

- The nonlinear effects are significant for cooperative OFDM systems
- Increasing the output backoff of the amplifier improves the performance but it makes the system inefficient from the power resources point of view
- Introduction of the maximal ratio combiner (MRC) that properly includes the nonlinear distortion effects
- A modification to the power amplifier nonlinearity cancellation (PANC) technique
- Proper combining of the MRC with PANC yields performance close to the case of linear amplifiers
- Simulations verified that the proposed schemes work

Thank you!

- Questions?
- Discussion?