A DECOUPLED APPROACH TO COMPENSATION FOR NONLINEARITY AND INTERSYMBOL INTERFERENCE

Raphael J. Lyman and Qingsong Wang
New Mexico State University

ABSTRACT

To achieve good efficiency in a space-based radio transmitter, its final amplifier must be operated near the saturation point, in its nonlinear region. Because of strict band limitations, this nonlinear operation is combined with the problem of intersymbol interference. Normally, these problems are addressed using a combination of equalization and power back-off, resulting in reduced power efficiency. Many proposed receiver-based methods, such as Volterra equalization, attempt to compensate for the nonlinearity and ISI in a single block before the detector, allowing higher efficiency operation, but introducing a great deal of complexity. We propose a receiver-based method in which the two effects are dealt with in separate blocks, an equalizer and a linearizer, resulting in considerable simplification. We go further and place the detector before the linearizer, achieving improved performance by eliminating the errors introduced by the linearizer. Simulation results compare favorably with the performance of a linear AWGN channel.

KEYWORDS

Nonlinear, intersymbol interference, equalizer.

INTRODUCTION

Space-based radio transmitters are subject to severe power and bandwidth constraints. To increase power efficiency, the operating point of the transmitter's high-power amplifier is often pushed far into the nonlinear region, near saturation, causing significant distortion. In addition, to control out-of-band emissions, strong bandpass filtering is applied after the HPA, leading to intersymbol interference. The receiver must therefore deal with a signal affected by a combination of nonlinear distortion and ISI, as well as Gaussian thermal noise.

Many approaches for dealing with these effects focus on eliminating or reducing the nonlinearity at the transmitter. Often, the transmitter power is backed off several decibels from the saturation point, which reduces the amount of distortion, but also decreases the power efficiency of the HPA. An alternative is to predistort the input to the amplifier so that the cascade of the predistortion with the amplifier is more nearly linear [1]. This allows for more power-efficient operation of the HPA, but adds complexity and weight to the spacecraft, and also consumes some power on its own.

Transmitter-based compensation of HPA nonlinearity has a strong appeal, because it deals with the problem at the source, leaving the receiver to deal with a more tractable linear ISI problem. In fact, many space-based transmitters incorporate some form of linearization in the HPA. On the other hand, linearization of the transmitter amplifier makes it possible to push the operating point even closer to saturation, so that the receiver is still left with the problem of dealing with the residual nonlinearity.

Thus, it makes sense to consider ways of compensating for nonlinear ISI at the receiver. Previously proposed approaches include the use of Volterra series equalizers [2], as well as maximum-likelihood sequence detection [3]. These techniques attempt to compensate for both nonlinearity and ISI in a single signal-processing block, leading to a great deal of complexity.

We propose a receiver-based approach that deals with the problems of nonlinearity and ISI in separate blocks. A conventional linear equalizer handles the ISI, and a memoryless linearizer deals with the distortion introduced by the HPA. This leads to considerable simplification of the compensating blocks. Unfortunately, if the equalizer is cascaded with the linearizer before the detector, this allows the linearizer to amplify the effects of the Gaussian thermal noise introduced at the receiver front end, resulting in poor performance. To eliminate this problem, we place the detector after the equalizer but *before* the linearizer. In this case, the detector is matched to a signal alphabet that is distorted by the HPA nonlinear characteristic, and chooses the *distorted* symbol that is closest to the received pulse. Because detection comes before linearization, this eliminates the possibility of the linearizer introducing additional errors. In this way, we achieve a receiver performance that is comparable to an optimal receiver in a linear, Gaussian-noise channel.

NONLINEARITY AND INTERSYMBOL INTERFERENCE

Consider the channel model of Figure 1. Here a traveling wave tube serves as the active device in the HPA of the space-based transmitter. A bandpass filter follows the amplifier, in order to limit out-of-band emissions. Finally, the additive Gaussian white noise models thermal effects at the input of the receiver.

Depending on the amplitude of the input signal, the TWT introduces both amplitude and phase distortion. These effects may be modeled as [4]

$$A(r) = 2r/\left(1 + r^2\right) \tag{1}$$

$$\phi(r) = 60° r^2/\left(1 + r^2\right) \tag{2}$$

where r is the amplitude of the input, normalized to the saturation point, $A(r)$ is the normalized output amplitude and $\phi(r)$ is the phase shift. Graphs of (1) and (2) are shown in Figure 2. We see that the nonlinear effects are increased as the TWT is pushed closer to saturation.

Note that the TWT model reflected by (1) and (2) is *memoryless*. That is, the output depends only on the current value of the input, and not on any past values. In contrast, the bandpass filter has

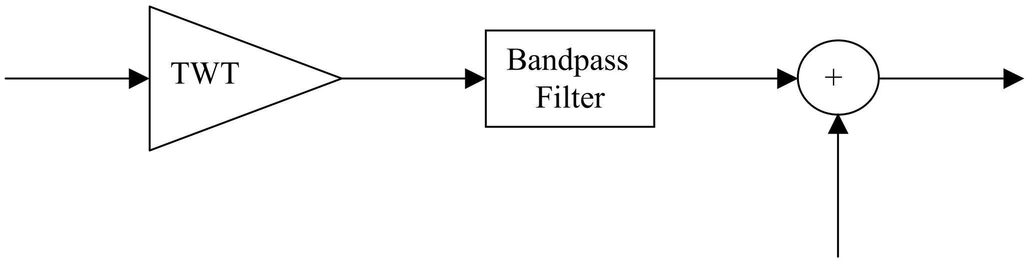


Figure 1. Radio channel.

memory, but is well modeled as a *linear* device. The memory of the filter causes a dispersion or "smearing out" of the transmitted symbols, leading to intersymbol interference.

It is important to note that the channel model of Figure 1 does not account for pulse shaping or spectral shaping before the TWT amplifier. Instead, square pulses are assumed. This simplifies the design of the receiver's matched filter because the pulse shape at the output of the bandpass filter is constant (see, e.g., Pupolin and Greenstein [5]). Ordinarily, a transmitter includes some filtering of the HPA input in order to improve the amplifier power efficiency. We choose the simpler model for this demonstration of our approach, and defer detailed modeling of the effects of HPA input filtering for future research.

The effect of the radio channel on a 16-QAM transmitted sequence is shown in Figure 3. The first graph shows the signal constellation of transmitted symbols, with the horizontal axis representing the

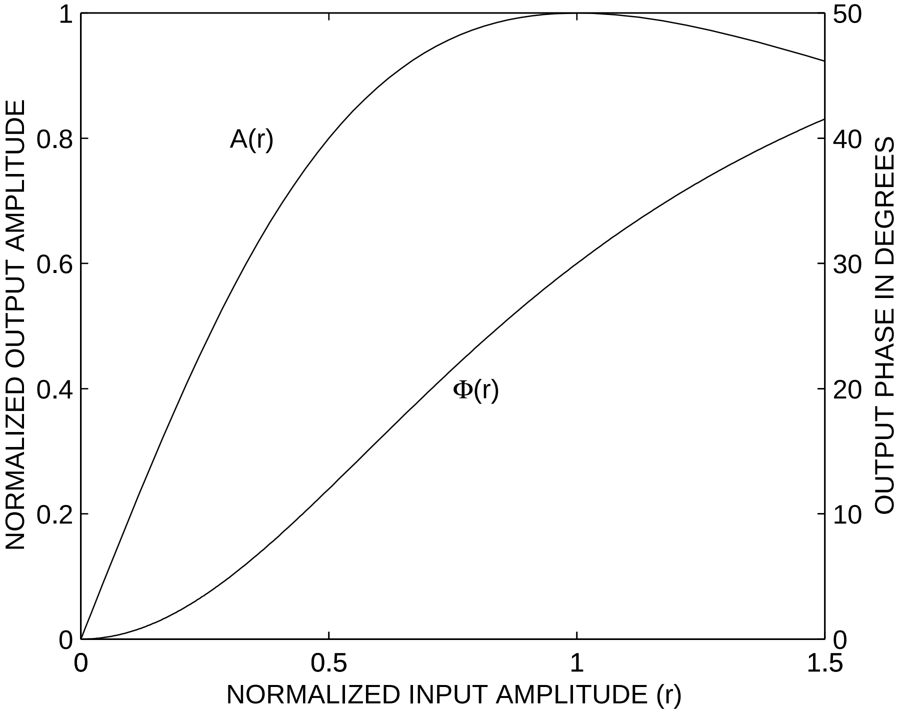


Figure 2. Nonlinear TWT characteristic.

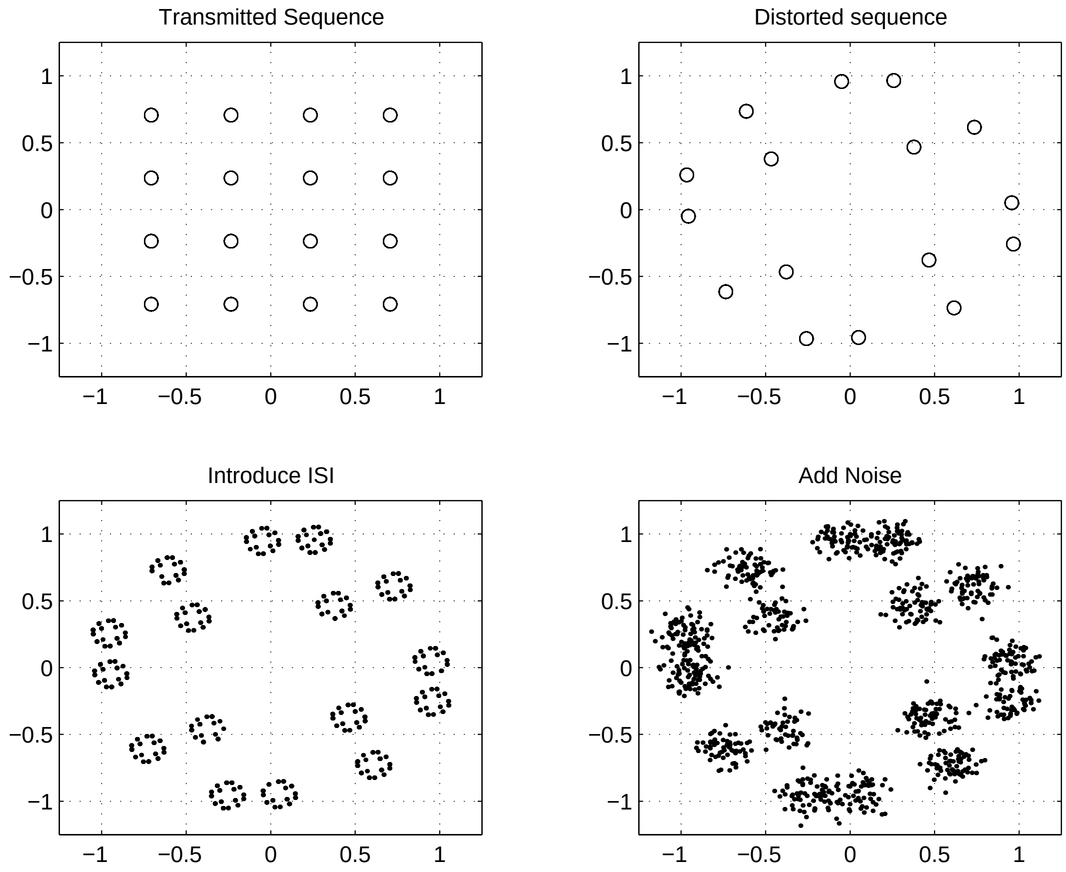


Figure 3. Effect of radio channel.

in-phase part and the vertical axis representing the quadrature part. The nonlinearity of the TWT causes a distortion of the constellation, as shown in the second graph. Note that some of the signal points are closer together. This makes them harder for the detector to distinguish.

The third graph of Figure 3 shows the effect of intersymbol interference introduced by the bandpass filter. Because of the time dispersion and delay of the filter, the value of the signal at a given sampling instant is influenced not only by the current transmitted symbol, but also by those that were transmitted before and after. This accounts for the spread that can be seen in the in the sampled signal about the distorted constellation points. Further dispersion of the signal points occurs when the Gaussian noise is added. The fourth graph shows how the combined effects of noise and ISI can make it difficult to determine which symbol was transmitted based on the received pulse.

Despite the need for power efficiency, the operating point of space-based transmitters is normally backed of several decibels from saturation in order to reduce the nonlinear effects. The sacrifice of efficiency is often tolerable for phase-shift keyed modulation, because the amplitude variations are small. But the need for increased bandwidth efficiency has stimulated interest in higher-order QAM alphabets, whose performance is more severely degraded by a reduction in transmitted power.

Some form of predistortion is often used in the transmitter HPA in order to render the cascade characteristic more nearly linear. The most effective of these schemes are adaptive and use feedback

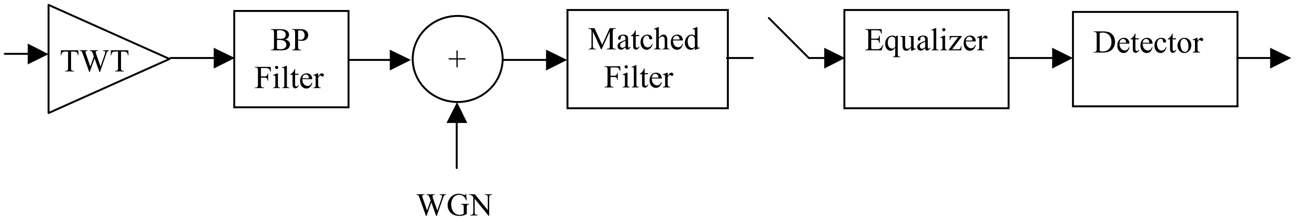


Figure 4. Typical receiver structure.

of the transmitted signal [1]. Unfortunately this requires the addition of demodulator circuitry on the spacecraft, which adds weight, consumes power and results in increased complexity, with its attendant reliability issues. Also, as mentioned in the introduction, even when linearization is used, there will remain some residual nonlinearity for the receiver to deal with.

A DECOUPLED, RECEIVER-BASED APPROACH

A typical receiver includes a matched filter, a detector and possibly an equalizer, as shown in Figure 4. Normally, the equalizer is used to compensate for the effects of intersymbol interference, and does nothing to counteract the nonlinear characteristic of the transmitter HPA. It is possible, though, to model the cascade effect of the TWT with pre- and post filtering as a Volterra series, and then attempt to invert this model in the equalizer [2]. Unfortunately, the resulting signal-processing algorithm is so complicated that some simplified version is always used. Another approach is to use the output of the matched filter as the input to a maximum-likelihood sequence detection algorithm, which combines the functions of the equalizer and detector [3]. This approach offers the possibility of optimal performance, but is even more complicated than the Volterra approach.

We propose a decoupled approach, as shown in Figure 5. The linear equalizer handles the intersymbol interference, while the linearizer compensates for the effects of the transmitter nonlinearity. Because the linear bandpass filter at the transmitter introduces the ISI, it is reasonable to try to equalize the signal using a linear device. Also, because the transmit amplifier's nonlinear characteristic is memoryless, the linearizer must simply invert the amplitude and phase distortion described by (1) and (2).

Because the detector is placed after the linearizer in Figure 5, we call this *outside detection.* Its effects are illustrated in Figure 6. The first graph shows the received signal, with the combined effects of nonlinearity, ISI and Gaussian noise. After the equalizer has removed the ISI, the dispersion of the signal about the distorted signal points is reduced. Next the linearizer inverts the

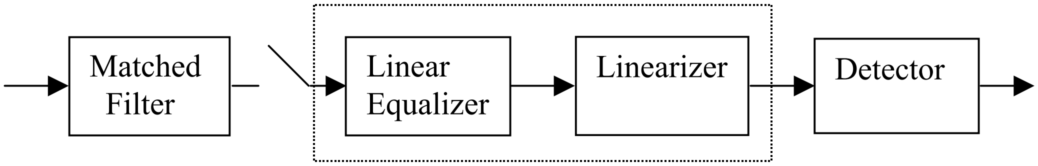
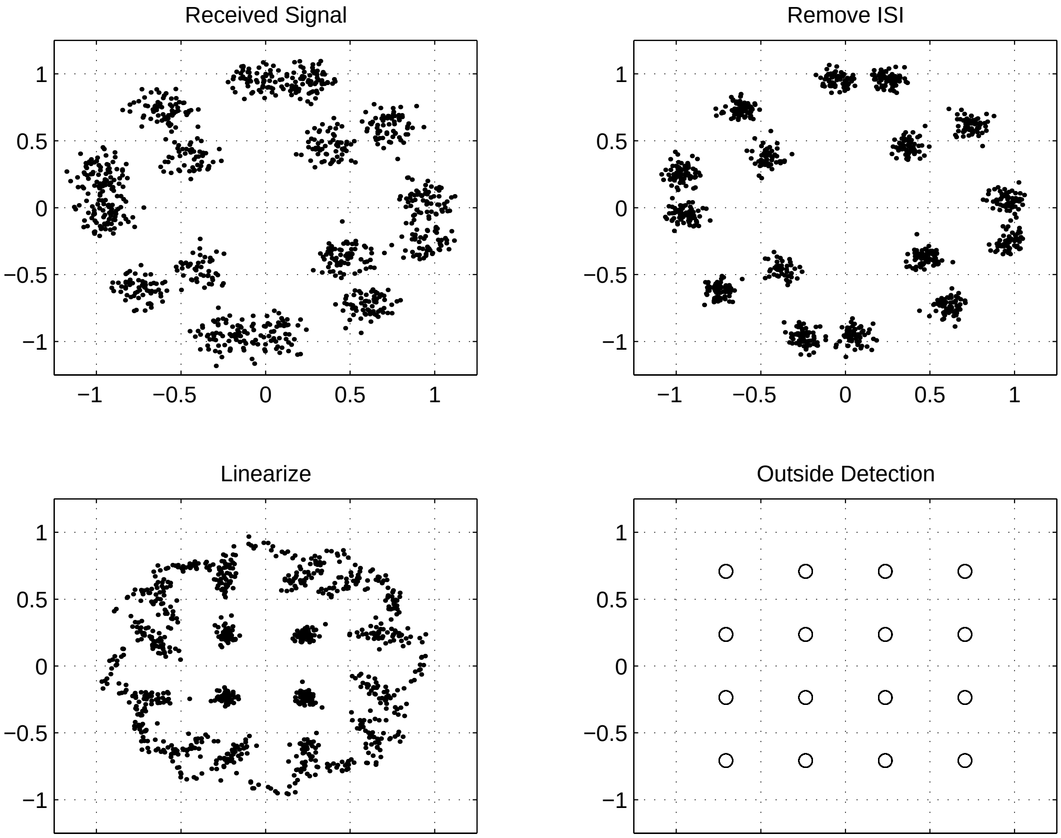


Figure 5. A decoupled approach.



Received Signal

Remove ISI

Linearize

Outside Detection

Figure 6. Effect of outside detection.

TWT characteristic of (1) and (2), as shown in the third graph. This removes the warping of the distorted signal constellation, returning it to a shape that is more nearly, square. Unfortunately, it also has the effect of increasing the dispersion of the signal about the constellation points. This is especially true for signal values close to saturation. The reason for this is that inverting the TWT characteristic has the effect of amplifying the residual noise at the linearizer input. This makes it more likely that the detector will make an error.

To eliminate this problem, we place the detector after the equalizer, but *before* the linearizer, as shown in Figure 7. We call this arrangement "inside detection." In this case the detector is matched to a signal alphabet that is distorted by the nonlinear HPA characteristic, and chooses the *distorted* symbol that is closest to the received pulse.

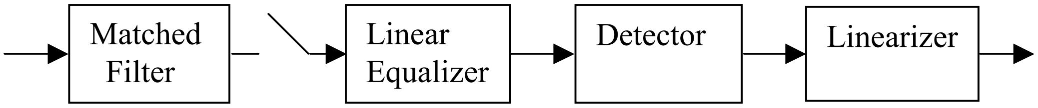
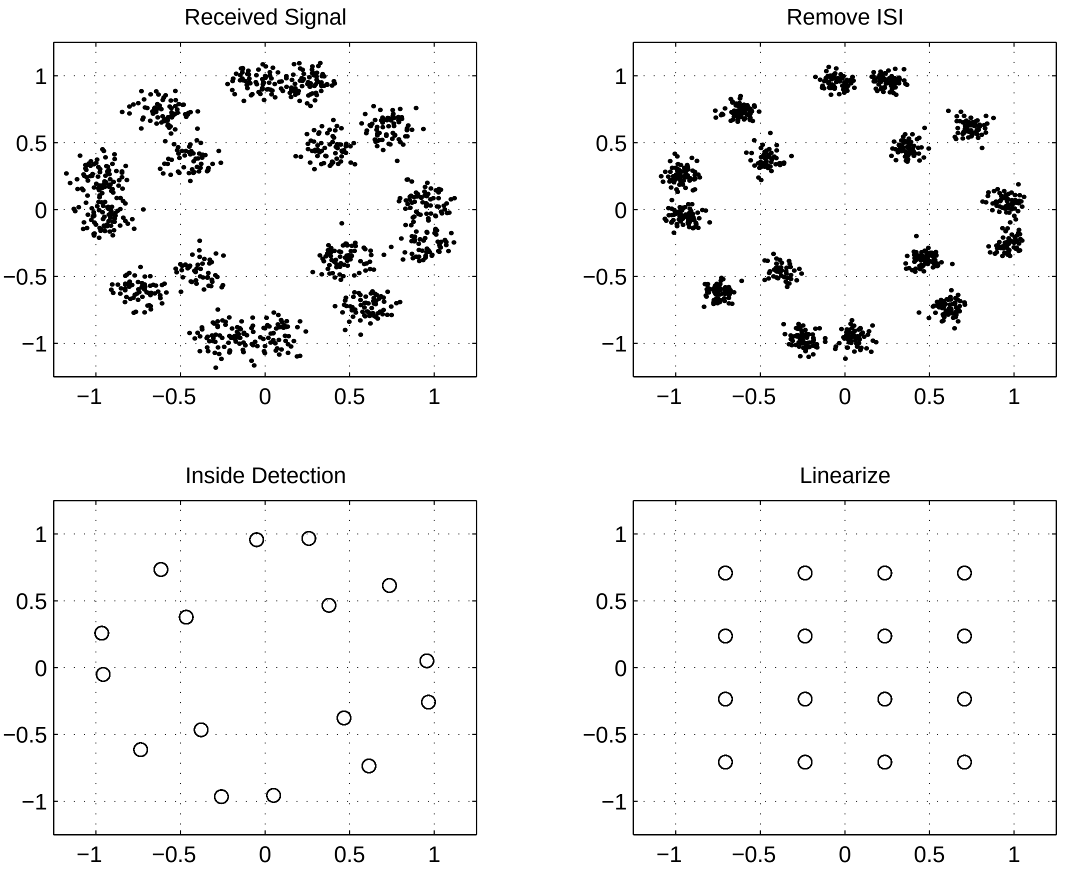


Figure 7. Inside detection.


Received Signal

Remove ISI

Inside Detection

Linearize

Figure 8. Effect of inside detection.

This effect is illustrated in Figure 8. We see again that, after the equalizer removes the intersymbol interference, the dispersion of the received signal about the distorted signal points is small. This makes it easier for the detector to decide which symbol was transmitted, as shown in the third graph. The linearizer then removes the distortion introduced at the transmitter. The advantage of this arrangement is that, because the linearizer comes after the detector, there is no more residual noise for it to amplify. It will therefore not introduce any additional errors, although it cannot, of course, correct any errors already made by the detector.

SIMULATIONS

We evaluated the performance of our decoupled approach by simulating a matched-filter detector for a 16-QAM modulated signal. The carrier frequency is 6 GHz, with a bandwidth of 30 MHz and a symbol rate of $1/T = 22.5$ Mbaud. The transmit bandpass filter is a fourth-order Butterworth with a 3-dB bandwidth of $B = 1.1/T \cong 24.8$ MHz, which would be sufficient to satisfy the FCC emission mask [5]. The receiver input filter is matched to the square transmitted pulse shape. This is followed by a five-tap, zero-forcing equalizer.

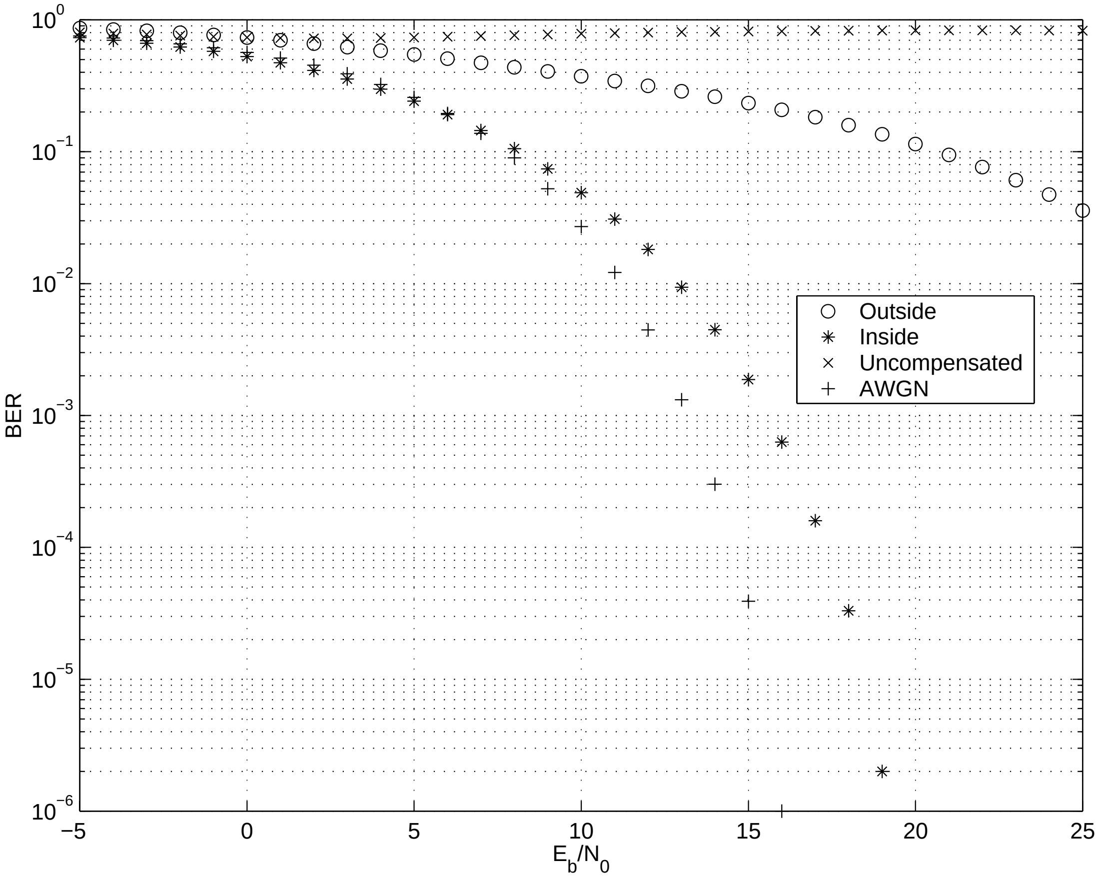


Figure 9. Performance of decoupled approach.

The graph of Figure 9 shows the bit-error-rate performance of the receiver as a function of E_b / N_0. The curve labeled "Outside" shows the performance of the decoupled arrangement of Figure 5. We can clearly see the poor performance caused by noise amplification in the linearizer. The curve labeled "Inside" shows the large improvement that can be achieved by using inside detection, as shown in Figure 7, with the detector matched to the 16-QAM alphabet after being distorted by the transmitter HPA characteristic (1) and (2). In this case, performance approaches that of a linear additive white Gaussian noise channel. For reference, the performance of a receiver with no compensation for transmitter nonlinearity is included in Figure 9. This uses the receiver structure of Figure 4, with the detector matched to the square 16-QAM alphabet.

By looking at Figure 3, it is not difficult to see that the performance of an AWGN channel cannot be approached arbitrarily closely. This is because the distortion of the transmitter amplifier causes the transmitted signal points to be closer together, making it harder for the detector to distinguish them after dispersion and noise are factored in. Thus, the amount of improvement possible using only receiver-based compensation is limited.

CONCLUSIONS

In general, a nonlinear, dispersive, noisy communication channel poses a very difficult problem. The simplicity of our decoupled approach follows from the fact that, in the channel model of Figure 1, the effects of transmitter nonlinearity and bandpass-filter induced intersymbol interference are separable. Indeed, we see that after the transmitter amplifier the channel is completely linear. Thus, conventional techniques can be applied effectively to all parts of the problem except the nonlinearity itself. In addition, the fact that the transmitter amplifier characteristic is memoryless simplifies the task of correcting for the nonlinearity.

As discussed in the previous section, the performance of a linear AWGN channel cannot be approached arbitrarily closely using only receiver-based techniques. Instead, it would seem that some sort of predistortion is necessary before the transmitter amplifier to keep the distorted signal points sufficiently far apart. Thus, it seems likely that effective compensation procedures will necessarily involve both receiver-based and transmitter-based methods.

The model of Figure 1 does not account for pulse shaping before the transmit amplifier. It is clear that this would complicate the problem because the linear and nonlinear effects would no longer be so easily separable. How it would affect the performance of our approach is not yet clear. This is a topic for further study.

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