

Coherent and Envelope OOK Performance Comparisons with BPSK and Orthogonal BFSK in AWGN and Coherent OOK Analysis in Flat Rayleigh Fading

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Abstract:

Binary amplitude shift keying in the form of on-off keying (OOK) provides a simple signal format, but its reliability depends on the receiver and channel conditions. MATLAB simulations compared coherent and envelope OOK detection in additive white Gaussian noise (AWGN) and examined coherent OOK under independent flat Rayleigh fading. A separate AWGN comparison evaluated OOK, binary phase shift keying (BPSK), and orthogonal binary frequency shift keying (BFSK), all with coherent detection. All comparisons used equal average bit energy and five million bits per scheme at each test point. Analytical and numerical reference curves were used to determine the ratio of average bit energy to noise power spectral density (E_b/N_0) required to reach a bit error rate of 1×10^{-3} . In AWGN, coherent OOK required 9.80 dB, compared with 10.51 dB for the modeled envelope receiver. Coherent BPSK required 6.79 dB, about 3.01 dB less than coherent OOK and orthogonal BFSK. Rayleigh fading raised the coherent OOK requirement to 26.98 dB, despite ideal channel information and gain compensation. Under the selected pulse and tone-spacing assumptions, OOK and BPSK also had narrower first-null spectral spans than BFSK. These results support initial modulation and receiver selection under the stated assumptions. Hardware cost and total power consumption still require practical measurements.

Keywords: On-off keying; Coherent detection; Envelope detection; Additive white Gaussian noise; Rayleigh fading.

1. Introduction

Wireless links must carry digital information reliably while meeting limits on bandwidth, energy use, and hardware cost. The modulation method determines how the information is represented in the transmitted signal and affects the receiver needed to recover it. Amplitude shift keying (ASK) represents information by changing the amplitude of a carrier signal. This paper focuses on binary ASK in the form of on-off keying (OOK). In OOK, one bit is represented by the presence of a carrier, and the other is represented by its absence. Its simple structure makes it a useful option for communication systems with limited hardware resources.

The simplicity of OOK is attractive, but it does not guarantee reliable communication. The receiver must distinguish between the two signal levels after transmission through a noisy channel. Noise can make an absent carrier appear to be present or make a weak carrier difficult to detect. Changes in the received amplitude can also affect the decision threshold. D'Angelo and Fischione examined OOK threshold selection under fading and interference [1]. These detection problems motivate examining OOK together with its receiver design and channel conditions. A simple transmitter alone is not enough to determine whether the whole system meets its requirements.

The demodulation method has a direct effect on detection performance. Coherent demodulation uses a local carrier that is synchronized with the received signal [2]. This reference allows the receiver to use phase information when detecting the transmitted bits. For OOK under ideal synchronization, coherent detection can provide a lower bit error rate than envelope detection. However, maintaining the carrier reference requires additional receiver functions. Errors in phase or frequency synchronization can reduce the expected benefit. Therefore, the advantage of coherent detection must be considered alongside its synchronization requirements and implementation complexity.

Noncoherent demodulation offers a different balance between performance and complexity. The envelope receiver considered here detects OOK data without an accurate carrier phase reference. This can simplify the receiver, although bit timing and a suitable decision threshold are still needed. The comparison between coherent and noncoherent receivers should use the same bit rate and average energy per bit. Performance can be measured by the bit error rate (BER), which is the proportion of incorrectly detected bits. The ratio of average energy per bit to noise power spectral density, written as E_b/N_0 , provides a common basis for comparing BER under different noise levels.

Channel variations can further limit OOK detection performance. An additive white Gaussian noise (AWGN)

channel provides a simple starting point for studying the effect of noise. However, it does not describe the amplitude variations caused by multipath fading. A flat Rayleigh fading model can represent these variations in a simplified wireless environment without a dominant direct path [2]. During a deep fade, the received signal becomes weak and is more difficult to detect. Comparing AWGN and Rayleigh fading helps show the limits of conclusions based only on noise. Ideal channel information allows the receiver to correct phase and amplitude, but it does not recover the signal quality lost during a deep fade.

OOK should also be compared with other basic modulation methods. Binary phase shift keying (BPSK) represents bits through two opposite carrier phases. Binary frequency shift keying (BFSK) uses two different carrier frequencies. With suitable receivers, these methods offer different trade-offs between error performance and implementation requirements. BFSK often requires more bandwidth, depending on the frequency spacing and pulse shape. BPSK commonly uses coherent detection and therefore needs a reliable phase reference. A fair comparison must state the receiver assumptions and use consistent energy definitions. Otherwise, an apparent performance difference may come from unequal comparison conditions.

BER is important, but it cannot answer every engineering question. A system with strict bandwidth limits may require a different choice from a system that prioritizes simple hardware. Cui, Goldsmith, and Bahai evaluated modulation choices using both transmission and circuit energy [3]. Low transmitted energy therefore does not necessarily mean low total power consumption. For this reason, BER curves should be interpreted together with bandwidth use, synchronization needs, and implementation complexity. This distinction is important when using idealized BER results to guide a design that must also meet limits on device energy and hardware resources.

This paper uses MATLAB simulation to examine these trade-offs through three comparisons. First, coherent and envelope OOK receivers are compared in an AWGN channel. Secondly, coherent OOK is examined in AWGN and flat Rayleigh fading channels, with ideal channel information and gain compensation assumed for the fading case. Third, coherent OOK, BPSK, and orthogonal BFSK are compared in AWGN using the same bit rate and average energy per bit at each E_b/N_0 value. Receiver assumptions are stated to make the comparisons clear. The analysis considers BER trends and the E_b/N_0 needed to reach a selected BER, alongside bandwidth and receiver requirements. The aim is to clarify the conditions under which OOK is a suitable choice. The comparison uses established detection models and does not propose a new

modulation method.

2. System Model and Simulation Setup

An uncoded binary link is modeled in signal space to compare receiver and channel effects at equal average bit energy. Random bits are mapped to signal coordinates, passed through the selected channel, and detected at the receiver. Comparing the detected bits with the transmitted bits gives the BER.

2.1 Binary ASK Signal Model

The binary ASK system uses OOK, with independent zeros and ones generated with equal probability. A zero produces no transmitted signal during its bit interval. A one produces a carrier burst. Each bit occupies the same duration, and no channel coding is used. This model allows the effect of modulation and detection to be examined directly.

The simulation works with signal coordinates at the output of an ideal matched filter. Each coordinate represents a projection onto a unit-energy waveform [2]. This approach models ideal pulse reception without generating carrier samples for each bit. The OOK coordinate is defined as follows.

$$x_k = ab_k, a = \sqrt{2E_b} \quad (1)$$

Here, b is a binary variable with equally likely values of zero and one, k is the bit index, and a is the on-state signal coordinate. The average energy per bit, E_b , is normalized to one. The on-state energy is therefore two because, on average, half of the bits are transmitted in the on state. This normalization gives OOK the same average bit energy as BPSK and BFSK; assigning unit energy to the OOK on state would make the comparison unequal.

2.2 Demodulation Models

The coherent OOK receiver assumes perfect carrier phase and bit timing. In AWGN, it compares the real received coordinate with a threshold of $a/2$. A value above the threshold is detected as one; otherwise, it is detected as zero. The midpoint threshold is appropriate because the two bits are equally likely and have the same noise variance [2].

The noncoherent envelope receiver compares the magnitude of the complex received coordinate with a threshold calculated at each noise level. The on-state envelope has a Rician (Rice) distribution; the off-state Rayleigh distribution is its zero-signal special case [4]. Equating these two envelope probability densities, with equal bit probabilities and known on-state amplitude and noise variance, gives the following maximum-likelihood threshold equation.

$$I_0\left(\frac{a\tau}{\sigma^2}\right) = \exp\left(\frac{a^2}{2\sigma^2}\right) \quad (2)$$

In (2), I_0 is the modified Bessel function of the first kind and order zero. The symbol τ denotes the envelope threshold, and σ^2 is the noise variance in each real coordinate. Equation (2) is solved numerically to obtain the threshold, using a scaled Bessel function for numerical stability [5]. Envelope detection does not require a carrier phase reference, but it still assumes perfect bit timing and knowledge of the signal amplitude and noise variance.

For the modulation comparison, BPSK maps the bits to minus one and plus one and uses a zero-decision threshold. Coherent orthogonal BFSK maps each bit to a unit-energy signal in one of two orthogonal branches. The receiver selects the branch with the larger real matched-filter output. All three coherent receivers assume ideal synchronization. Noncoherent BFSK is outside the scope of this comparison.

2.3 Channel Models

The AWGN model adds zero-mean Gaussian noise that is independent of the bits. The real and imaginary noise components are independent and have equal variance. The average transmitted bit energy is fixed while the noise variance changes with E_b/N_0 . In the following relation, N_0 is the one-sided noise power spectral density, and γ is the linear value of E_b/N_0 .

$$\sigma^2 = \frac{N_0}{2} = \frac{E_b}{2\gamma}, \gamma = \frac{E_b}{N_0} \quad (3)$$

$$r_k = h_k x_k + n_k \quad (4)$$

Equation (4) defines the complex received coordinate r , transmitted coordinate x , channel coefficient h , and additive noise n at bit index k . In AWGN, h equals one. In flat Rayleigh fading, the real and imaginary parts of h are independent Gaussian variables with zero mean and variance one half. The mean channel power is therefore one. The coefficient is constant within each bit and independent between bits; this is a simplified fading model without a dominant direct path.

The coherent fading receiver assumes perfect channel state information (CSI). It corrects the channel phase and applies gain compensation. The implementation uses an equivalent detection rule: the phase-corrected real coordinate is compared with $a/2$ multiplied by the channel magnitude. This avoids division by a very small gain. Channel estimates are assumed to be exact and require no pilot overhead in this model. Channel estimation errors, time-correlated fading, diversity, coding, and intersymbol interference are not evaluated.

2.4 Simulation Configuration

The Monte Carlo simulations were run in MATLAB R2025b with the settings in Table 1. Each scheme at each E_b/N_0 value was tested with five million bits, processed in blocks of 100,000 bits. A bit rate of 1 kbit/s is assumed for the bandwidth estimates, giving a bit duration of 1 ms. The signal-space simulation does not sample a radio-frequency carrier, and the assumed bit rate does not change

BER at a fixed E_b/N_0 .

For the bandwidth comparison, rectangular bit pulses are assumed. The two BFSK tones are separated by 1 kHz, which gives orthogonality over a 1 ms interval. This spacing is a defined setting for the present comparison, rather than the minimum spacing for every coherent BFSK implementation.

Table 1. Main simulation settings.

Parameter	Setting
Average energy per bit	1 for every modulation scheme
Bit probabilities and bit rate	Equal probabilities; 1 kbit/s
AWGN test range	0 to 12 dB in 2 dB steps
Rayleigh test range	0 to 28 dB in 2 dB steps, plus 27 dB
Bits per scheme and test point	5,000,000
Random seed and generator	20260905; Mersenne Twister
Target BER	1×10^{-3}
Receiver assumptions	Perfect timing; ideal phase for coherent detection

The simulated BER is the number of bit errors divided by the number of transmitted bits. Coherent and envelope OOK use the same received samples at each AWGN test point. Markers in the figures show BER estimates; lines show analytical results or numerical integration of the envelope error probabilities. The envelope reference averages the false-alarm and miss probabilities with equal weights. Target E_b/N_0 values are obtained from the reference curves, not by interpolation of the simulation grid. Reported two-sided 95% confidence intervals are Wilson score intervals for a binomial proportion [6]. They describe the sampling uncertainty of each BER estimate, not the uncertainty of model assumptions.

The coherent BPSK and orthogonal BFSK reference expressions follow the standard AWGN results [7]. The coherent OOK expression follows from the binary signal-distance result in ref [2], using the normalization in (1). These expressions provide the baselines for checking the simulated BER.

3. Performance Comparison and Analysis

The following comparisons separate the effects of the

OOK receiver, the channel, and the modulation method. Each uses the assumptions and energy normalization in Section 2. Reference curves provide target energy requirements, while the simulations check the predicted BER trends.

3.1 Effect of the Demodulation Method

Coherent OOK has a lower BER than envelope detection throughout the tested AWGN range. At 8 dB, the simulated BER is 5.98×10^{-3} for coherent OOK and 1.335×10^{-2} for envelope detection. The 95% Wilson score intervals are approximately 5.92×10^{-3} to 6.05×10^{-3} for coherent OOK and 1.325×10^{-2} to 1.345×10^{-2} for envelope detection. The intervals are well separated, indicating that the BER difference is large relative to the uncertainty from finite sampling.

Figure 1 shows that both receivers improve as E_b/N_0 increases. The reference curves reach a BER of 1×10^{-3} at 9.80 dB for coherent detection and 10.51 dB for envelope detection. The resulting gap is about 0.71 dB. This value is specific to the target BER and the maximum-likelihood envelope threshold used here; it is not a universal penalty for noncoherent detection.

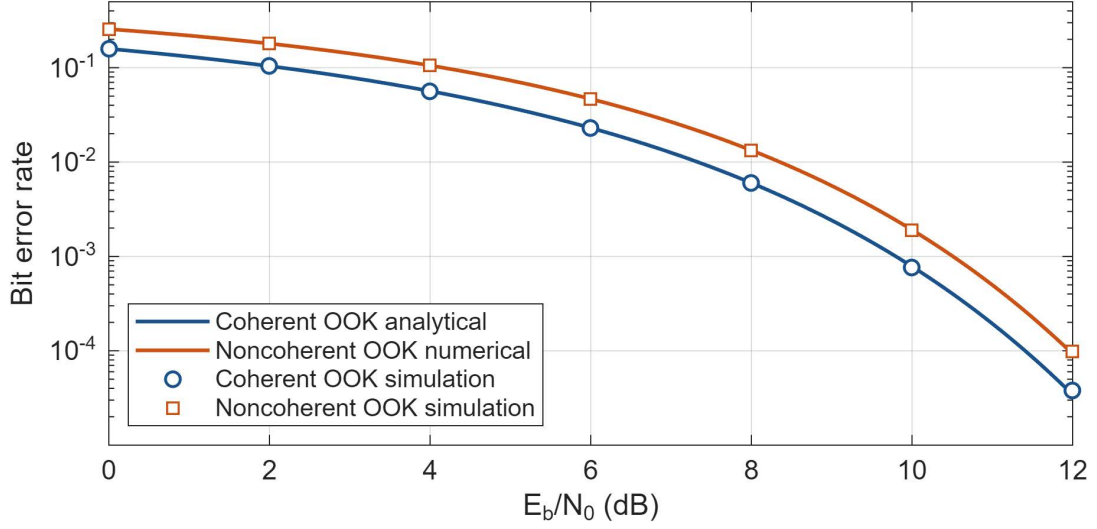


Fig. 1 Coherent and envelope OOK detection in AWGN. Markers show MATLAB simulation results; lines show the analytical coherent result and numerical envelope result.

The coherent receiver uses a known carrier phase to separate the two signal levels. Envelope detection uses magnitude alone and therefore loses useful phase information. Avoiding phase synchronization may simplify receiver implementation, although the simulation measures only its effect on BER. Knowledge of the amplitude and noise variance, as well as bit timing, is still required by the envelope model.

3.2 Effect of the Channel Environment

The Rayleigh fading results show that ideal channel knowledge does not restore AWGN performance. At 10 dB, the simulated BER rises from 7.66×10^{-4} in AWGN to 4.356×10^{-2} in Rayleigh fading. At 20 dB, the fading BER is still about 4.93×10^{-3} . Figure 2 shows the slower decrease of the fading curve, even though the receiver has

ideal channel information.

For the independent flat Rayleigh model, the conditional coherent OOK error probability depends on the instantaneous channel power. Applying the standard fading-average method to the OOK signal distance gives (5) [2]. Here, γ is the average E_b/N_0 rather than its instantaneous value.

$$P_{b, \text{Rayleigh}} = \frac{1}{2} \left(1 - \sqrt{\frac{\gamma}{\gamma + 2}} \right) \quad (5)$$

The reference curve based on (5) reaches a BER of 1×10^{-3} at approximately 26.98 dB, about 17.18 dB above the AWGN target of 9.80 dB. At 27 dB, the simulation gives a BER of 1.008×10^{-3} and a 95% Wilson score interval of approximately 9.80×10^{-4} to 1.036×10^{-3} . This estimate is consistent with the reference curve near the target.

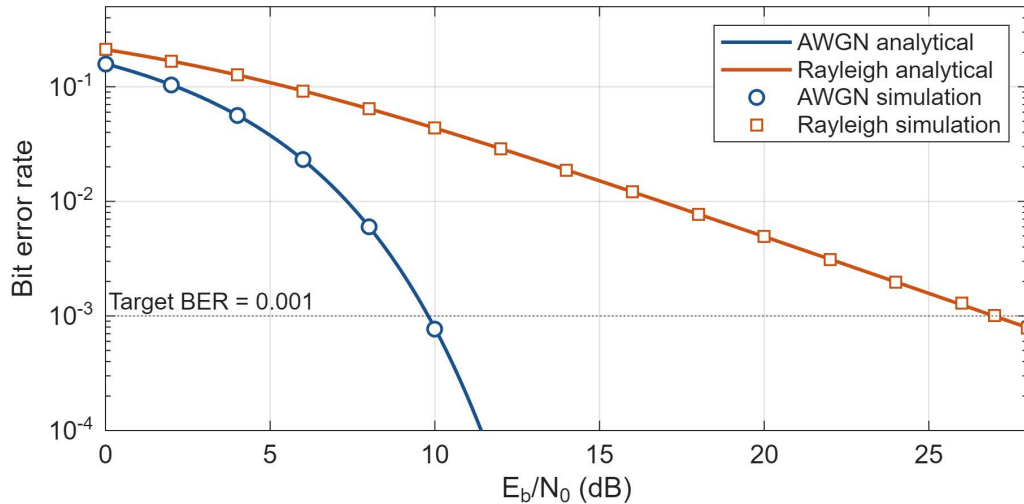


Fig. 2 Coherent OOK in AWGN and independent flat Rayleigh fading. The fading receiver uses ideal phase correction and gain compensation.

Gain compensation restores the signal scale for detection, but it does not recover signal quality lost during a deep fade. When the channel magnitude is small, the noise remains large relative to the useful signal. The BER continues to decrease as average E_b/N_0 increases, so these results do not indicate a fixed error floor. An energy requirement calculated for AWGN therefore cannot be applied directly to this uncoded fading link.

3.3 Comparison of Modulation Methods

As shown in Figure 3, BPSK has the lowest BER in the coherent AWGN comparison. At 8 dB, its simulated BER is 1.86×10^{-4} , whereas OOK and orthogonal BFSK both give approximately 5.99×10^{-3} . The OOK expression in

(6) follows from the binary signal-distance result [2]. The BPSK and BFSK expressions are the standard coherent AWGN results [7]. Here, Q is the upper-tail probability of a standard normal variable, and all schemes use the same average bit energy.

$$P_{b,OOK} = P_{b,BFSK} = Q(\sqrt{\gamma}), P_{b,BPSK} = Q(\sqrt{2\gamma}) \quad (6)$$

BPSK places its two signal points on opposite sides of zero. At the same average bit energy, their separation is larger than the separation of the OOK points or the orthogonal BFSK points. BPSK therefore reaches the target BER at about 6.79 dB, giving an energy advantage of approximately 3.01 dB over the other two coherent schemes.

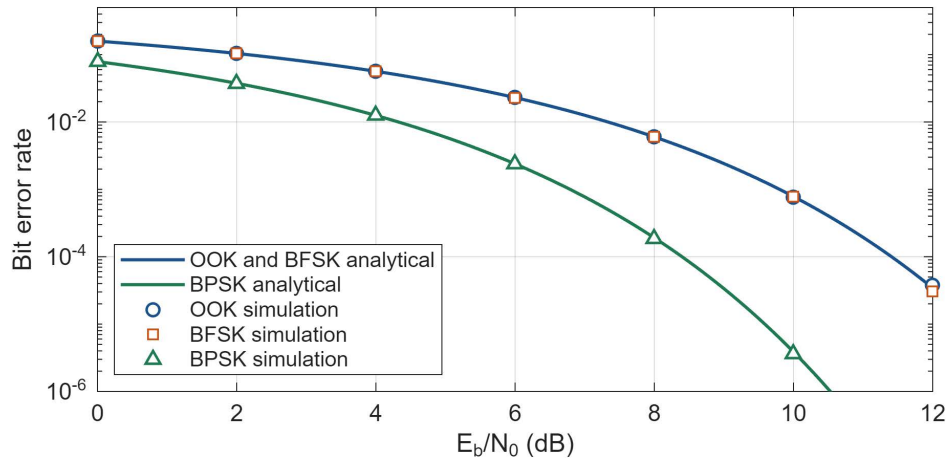


Fig. 3 Coherent OOK, BPSK, and orthogonal BFSK in AWGN. OOK and BFSK share the same theoretical BER curve. The zero-error BPSK point at 12 dB is omitted from the logarithmic plot.

Table 2. Coherent AWGN comparison at equal average bit energy.

Scheme	Simulated BER at 8 dB	Reference E_b/N_0 (dB) at $BER = 1 \times 10^{-3}$
OOK	5.984×10^{-3}	9.80
BPSK	1.856×10^{-4}	6.79
Orthogonal BFSK	5.994×10^{-3}	9.80

As shown in Table 2, the small difference in the simulated BER between OOK and BFSK is consistent with sampling variation; their theoretical BERs are identical under the stated assumptions. At 12 dB, BPSK records no errors in five million bits. This does not imply a zero-error probability. Exact binomial inversion gives a one-sided 95% upper bound of approximately 6×10^{-7} [8]. The zero-error point is therefore omitted from the logarithmic plot.

The bandwidth comparison uses first-null widths estimated from the assumed pulse shapes, not simulated spectra. For the 1 ms rectangular bit pulses used here, the first

spectral nulls lie 1 kHz on either side of the carrier frequency. The two-sided first-null main-lobe width is therefore about 2 kHz for OOK and BPSK. The span between the outer first nulls of the two BFSK tone spectra is about 3 kHz at the selected 1 kHz spacing. These widths exclude sidelobes and are not regulatory occupied-bandwidth measurements. The selected BFSK configuration therefore has a wider first-null span while sharing the coherent OOK error curve.

4. Engineering Tradeoffs and Modulation Selection

Modulation selection depends on which constraint is most important for the link. The results in Section 3 quantify the required bit energy and estimate spectral width. These findings are considered alongside receiver requirements. Hardware cost and total device power were not evaluated.

4.1 Main Engineering Tradeoffs

Coherent OOK offers better error performance than envelope detection, but its gain depends on accurate carrier phase synchronization. The reference curves in Figure 1 show a difference of about 0.71 dB in required E_b/N_0 at a BER of 1×10^{-3} in AWGN. The design question is whether this gain justifies carrier phase recovery. Envelope detection avoids that function but still requires reliable bit timing and estimates of signal amplitude and noise variance for threshold selection.

The energy comparison must distinguish average signal energy from total device energy [3]. Table 2 shows that coherent BPSK has an advantage of about 3.01 dB over coherent OOK and orthogonal BFSK at the target BER. This corresponds to roughly half the average bit energy at the same noise level. With equally likely zero and one bits, the OOK on-state energy is twice its average bit energy. Its off state therefore does not itself establish an energy advantage. Circuit energy is excluded, so the BER results alone cannot predict battery life.

Bandwidth limits can narrow the choice even when BER performance is similar. The 2 kHz first-null spans of OOK and BPSK are narrower than the 3 kHz span of the selected BFSK configuration. This gives BFSK no bandwidth advantage in the present comparison. These pulse-based estimates exclude sidelobes and cannot establish compliance with an occupied-bandwidth limit. A design using different pulse shapes or tone spacing would need a new spectral analysis.

The fading results show that the channel assumption can matter more than the OOK detection method at the selected BER target. As shown in Figure 2, independent flat Rayleigh fading raises the required E_b/N_0 for coherent OOK by about 17.18 dB relative to AWGN. This difference is much larger than the 0.71 dB receiver gap in AWGN. Under the tested conditions, selecting a representative channel model is therefore more important to the energy estimate than choosing between the two OOK detectors.

4.2 Selection for Different Link Conditions

Envelope OOK is a candidate for an AWGN-like link

when avoiding carrier phase recovery is a priority and enough bit energy is available to meet the required BER. The receiver must still maintain reliable timing and a suitable threshold. Before this choice is adopted, the threshold should be tested across the expected range of signal amplitudes and noise levels.

For an AWGN-like link, BPSK is the strongest candidate among the tested coherent schemes when average bit energy is the main constraint and reliable phase synchronization is available. It reaches the target BER at the lowest E_b/N_0 and has the same estimated two-sided first-null main-lobe width as OOK. This preference is limited to the tested coherent receivers and pulse assumptions; noncoherent BFSK was not evaluated.

Coherent OOK is relevant when a system must retain an OOK signal format but can support carrier phase recovery. A coherent receiver could improve BER while retaining that signal format. However, the predicted improvement assumes ideal synchronization. Phase and timing errors must be tested before applying the gain to a practical receiver.

For a link affected by strong fading, the channel model should be examined before choosing a modulation method. The coherent OOK result shows that ideal channel information and gain compensation are not enough to reproduce AWGN performance. It does not identify the best modulation for a fading link, because BPSK and BFSK were not evaluated in that channel. A suitable follow-up comparison would use the expected fading conditions and realistic channel estimates, with the same energy normalization for every scheme.

5. Conclusion

This study compared OOK receiver types, channel conditions, and modulation alternatives using MATLAB simulations and reference curves. Equal average bit energy provided a consistent basis for comparison. At a target BER of 1×10^{-3} in AWGN, the reference curves showed that coherent OOK required about 0.71 dB less E_b/N_0 than the modeled envelope receiver. Coherent BPSK required about 3.01 dB less than coherent OOK and orthogonal BFSK.

The channel model had a larger effect on the coherent OOK energy requirement. Independent flat Rayleigh fading raised the reference target from about 9.80 dB to 26.98 dB, even with ideal channel information and gain compensation. An AWGN-only assessment therefore understates the energy needed under this fading model.

The preferred option depends on the receiver functions that the link can support. Envelope OOK avoids carrier phase recovery, while BPSK provides the lowest BER

among the tested coherent AWGN schemes. The bandwidth estimates also favor OOK and BPSK over the selected BFSK configuration. These findings guide initial selection but do not establish the lowest hardware cost or total power consumption.

These conclusions are limited to uncoded signal-space models with ideal timing and the stated assumptions about synchronization and channel knowledge. Future work should test phase and threshold estimation errors, compare all three modulation methods under fading, and evaluate coding or diversity as possible improvements. Hardware power and signal spectra should then be measured to determine whether the simulated advantages remain useful in a practical link.

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