International Journal of Electrical and Computer Engineering (IJECE)
Vol. 16, No. 3, June 2026, pp. 1272~1285
ISSN: 2088-8708, DOI: 10.11591/ijece.v16i3.pp1272-1285

Utilizing phase congruency technique in reception performance optimization of UWB signals in multipath fading channels

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Article Info

Article history:

Received Nov 18, 2025
Revised Mar 24, 2026
Accepted Apr 27, 2026

Keywords:

Bit error rate
Multipath fading
Phase congruency
Rake receiver
Time-of-arrival

ABSTRACT

Ultra-wideband (UWB) technology enables high-data-rate communications and centimeter-accurate indoor localization but suffers severe degradation in multipath fading channels due to dense multipath components, narrowband interference (NBI), and low signal-to-noise ratios (SNR). Conventional energy-based detection methods, including Rake receivers, fail under these conditions due to amplitude sensitivity. This paper introduces a phase congruency (PC)-based selective Rake (S-Rake) receiver that exploits phase alignment across frequencies rather than signal magnitude for robust feature detection. The proposed method computes PC metrics via Hilbert transforms and sub-band decomposition to identify phase-aligned multipath components, guiding S-Rake finger selection (4, 8, and 128 fingers) and time-of-arrival (TOA) estimation. Simulations using 6th-derivative Gaussian pulses over IEEE 802.15.3a CM4 channels (NLOS, 4-10 m) with AWGN and IEEE 802.11a interference (SIR=-30 dB to 0 dB) demonstrate that PC-based S-Rake achieves 4 dB SNR gain at BER=10^{-4} over conventional Rake under high interference. DS-UWB with PC outperforms TH-UWB by 3× lower BER at SIR=-30 dB. Increasing Rake fingers from 4 to 128 reduces BER by >40% and improves TOA accuracy by 62% (RMSE: 1.8 ns → 0.68 ns). PC maintains BER=10^{-3} at SIR=0 dB where conventional methods fail. Results establish PC as a transformative paradigm for interference-resilient UWB applications including IoT localization and 5G-coexistent communications.

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1. INTRODUCTION

Ultra-wideband (UWB) technology has emerged as a pivotal solution for high-data-rate communications and centimeter-accurate indoor localization and radar sensing [1], leveraging carrier-less transmission with extremely low power spectral density across 3.1–10.6 GHz (bandwidth ≥500 MHz) [2], [3]. According to FCC regulations, a signal is UWB if its -10 dB fractional bandwidth;

$$F_{BW} = 2 \cdot \frac{f_H - f_L}{f_H + f_L} \geq 0.20 \quad (1)$$

or it occupies ≥500 MHz [2]. This large bandwidth enables precise timing resolution but also introduces significant challenges in multipath fading channels; The IEEE 802.15.4z-2020 amendment [4] further enhances UWB physical layer for secure ranging.

UWB signals face severe degradation due to three fundamental limitations: i) dense multipath components causing inter-symbol interference (ISI) in environments like IEEE 802.15.3a CM4 channels (NLOS, 4-10m) [5]; ii) narrowband interference (NBI) from coexisting systems such as IEEE 802.11a at 5 GHz, and future Wi-Fi 7 (802.11be) in the 6 GHz band [6] ; and iii) low signal-to-noise ratios (SNR) due to stringent transmit power limits (-41.3 dBm/MHz) [7]. Traditional energy-based detection methods, including conventional Rake receivers with maximal ratio combining (MRC), exhibit critical shortcomings: template dependency requiring precise pulse templates vulnerable to distortion [8], noise sensitivity with energy detection degrading below 0 dB SNR [9], and multipath ambiguity where delay-locked loops fail to distinguish coherent paths from noise [10].

Phase congruency (PC), a concept pioneered in image processing [11], [12], offers a transformative paradigm shift by exploiting phase coherence across frequencies rather than signal magnitude. In image processing, PC detects features (edges, corners) where Fourier components are maximally in-phase, ensuring invariance to contrast, illumination, and amplitude fluctuations [13]. This property directly maps to UWB signal detection: pulse edges correspond to phase-aligned events across the wide UWB spectrum, making PC inherently robust to the amplitude fading that cripples energy-based methods [14]. Figure 1 illustrates the 6th-derivative Gaussian pulse used throughout this study, while Figure 2 demonstrates the fundamental PC concept—Fourier components achieving maximal phase alignment at feature boundaries (square wave edges in Figure 2(a), triangular wave peaks in Figure 2(b).

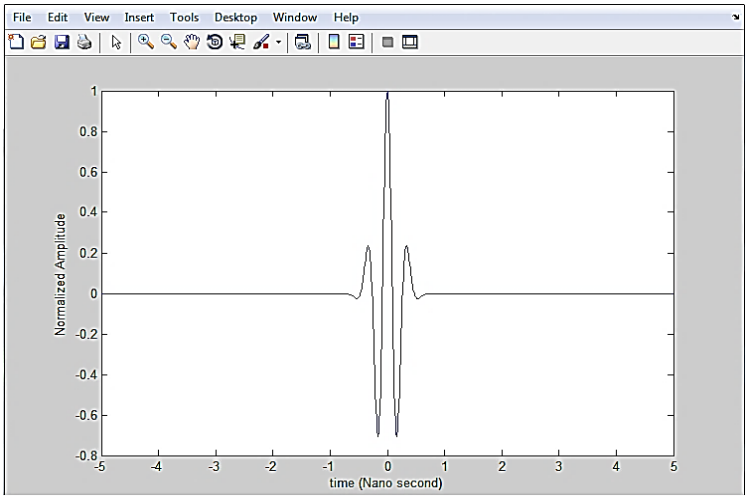
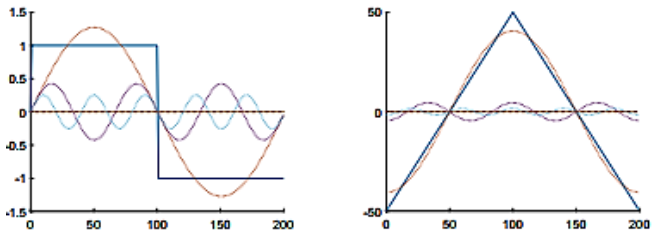


Figure 1. Sixth-derivative Gaussian monocycle used as UWB pulse waveform, exhibiting zero DC component and compliance with FCC spectral mask requirements



(a) (b)

Figure 2. Phase congruency concept: (a) first six Fourier components of a square wave showing phase alignment at edge transitions; (b) first six Fourier components of a triangular wave showing phase alignment at peak locations. Maximal phase coherence identifies feature boundaries regardless of amplitude

The research gap addressed in this paper is threefold: i) existing PC formulations [11], [15] incur high computational costs unsuitable for real-time UWB processing; ii) no comprehensive framework links PC-driven multipath discrimination to Rake combining optimization; and iii) the comparative efficacy of PC under different UWB modulation schemes (DS-UWB vs. TH-UWB) and NBI conditions remains

unexplored. Furthermore, recent advances in monogenic differential PC [16], [17] and iterative PC for crack detection [18] have not been translated to UWB Rake optimization. However; this paper optimizes UWB reception in multipath channels by integrating PC with a selective Rake (S-Rake) receiver introducing five novel contributions stated as follows:

a. PC-guided S-Rake architecture that uses phase coherence metrics to identify and prioritize multipath components for combining, eliminating template dependency and mitigating multipath ambiguity.
b. Mathematical formulation of iterative PC for UWB with explicit sub-band decomposition, Hilbert transform-based phase extraction, and PC metric calculation for real-time multipath component identification.
c. Comprehensive performance validation under IEEE 802.15.3a CM4 channels with NBI (IEEE 802.11a at SIR=-30 dB to 0 dB), demonstrating 4 dB SNR gain at BER=10^{-4} versus conventional Rake.
d. Comparative analysis of DS-UWB and TH-UWB with PC enhancement, revealing DS-UWB's 3× BER advantage under extreme interference due to chip-synchronous phase coherence.
e. TOA estimation improvement of 62% (RMSE reduction from 1.8ns to 0.68ns) through PC-based pulse edge detection.

The paper is organized as follows: Section 2 presents the methodology including; system model demonstrating DS-UWB and TH-UWB transceiver schemes with PC integration, details the UWB propagation channel model (IEEE 802.15.3a CM4), describes the PC-optimized S-Rake receiver architecture and algorithm. Section 3 presents simulation results and analysis. Section 4 presents the discussion which covers key findings, implications and limitations of the study, comparison with prior works and literature, relevance of the study to new/current real-world technologies. Section 5 presents conclusion of the research study.

2. METHOD

2.1. Direct-sequence UWB (DS-UWB) with phase congruency

The direct-sequence UWB scheme employs pseudo-random noise (PN) sequences to spread data bits across multiple chips, where the ultra-short pulse waveform acts as the fundamental "chip" [19]. The transmitted signal for the *k*-th user is:

$$s_{tr}^{(k)}(t) = \sqrt{E_b} \sum_{i=-\infty}^{\infty} d_i^{(k)} \sum_{j=0}^{N_C-1} \cdot c_j^{(k)} \cdot p(t - iT_f - jT_c) \quad (2)$$

where Eb is energy per bit, $p(t)$ is the UWB pulse monocycle (6th-derivative Gaussian), $c_j^{(k)}$ is the PN sequence for user k, T_f is frame duration, T_c is chip duration with $T_f = N_c.T_c, di(k)$ are BPSK-modulated data symbols, and N_c is the number of chips per bit. Figure 3 illustrates the DS-UWB transmitter architecture.

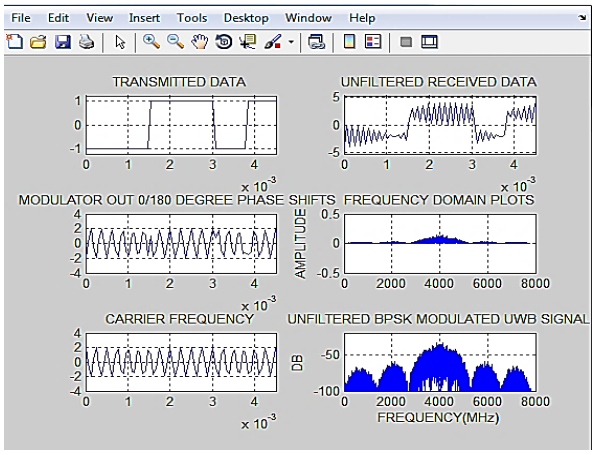


Figure 3. DS-UWB transmitter architecture showing PN sequence spreading, pulse generation, and BPSK modulation stages

Traditional DS-UWB receivers use correlation-based detection, which degrades under multipath fading and interference. This paper integrates PC-based processing at the receiver through:

Step 1. Analytic signal conversion: Convert real-valued received signal $r(t)$ to analytic form using Hilbert transform:

$$s(t) = r(t) + j.\mathcal{H}\{r(t)\} \quad (3)$$

Step 2. Sub-band decomposition: Decompose $s(t)$ into N=8 sub-bands using short-time Fourier transform (STFT) with Gabor filter bank covering 3.1 – 10.6 GHz, achieving trade-off between time resolution (0.5 ns) and phase estimation accuracy. For each sub-band n, extract instantaneous phase $\phi_n(t)$ and amplitude $A_n(t)$.
Step 3. Phase deviation calculation: Compute phase deviation from mean:

$$\Delta\emptyset_n(t) = \cos\left(\emptyset_n(t) - \overline{\emptyset}(t)\right) - \left|\sin\left(\emptyset_n(t) - \overline{\emptyset}(t)\right)\right| \quad (4)$$

where $\overline{\emptyset}(t)$ is the mean phase across sub-bands.
Step 4. PC metric computation: Calculate phase congruency at each time instant:

$$PC(t) = \frac{\sum_n A_n(t).\Delta\emptyset_n(t)}{\sum_n A_n(t)+\epsilon} \quad (5)$$

where ϵ prevents division by zero.
Step 5. Pulse detection and TOA estimation: Identify PC peaks exceeding threshold γ = 0.7 as pulse edge locations:

$$\text{TOA} \Leftarrow \arg\max\left(PC(t)\right) \quad (6)$$

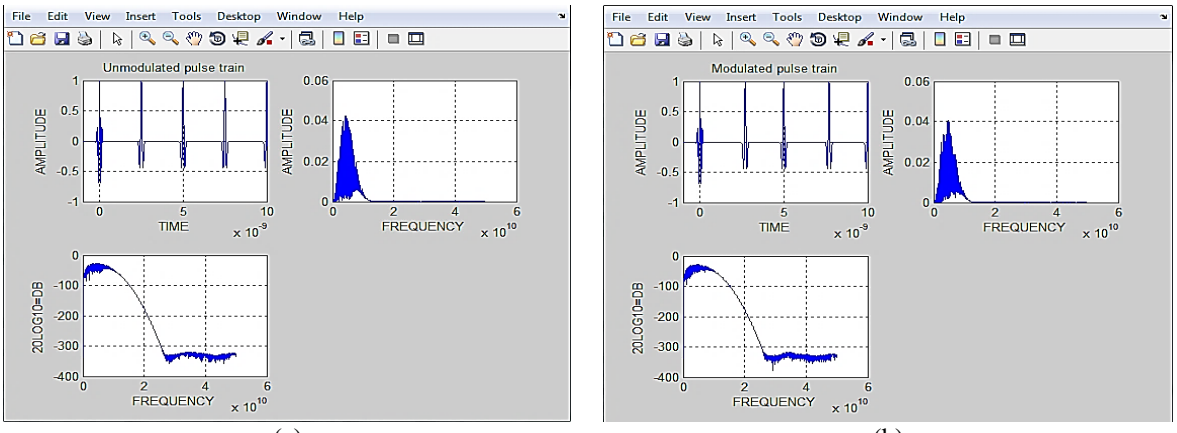
Step 6. Multipath component identification: Rank multipath components by PC magnitude; select top M components for S-Rake combining.

2.2. Time-hopping UWB (TH-UWB) with phase congruency

TH-UWB employs pulse-position modulation (PPM) with time-hopping codes for multiple access. The transmitted signal for the k-th user is:

$$s_{tr}^{(k)}(t) = \sum_{j=-\infty}^{\infty} w_{tr}(t - jT_f - c_j^{(k)}T_c - b_j^{(k)}T_{PPM}) \quad (7)$$

where T_{PPM} is the PPM time shift, $c_j(k)$ is the TH code, T_c is chip duration, and $b_j(k)$ are data symbols. Figure 4 illustrates the time and frequency domain characteristics of the generated signals, clearly demonstrating how the combination of time-hopping codes and PPM time shifts alters the uniform pulse intervals into a pseudo-random sequence. Figures 4(a) and 4(b) show unmodulated and modulated TH-UWB pulse trains, respectively.



(a) (b)

Figure 4. Time and frequency domain representations of TH-UWB signals: (a) Unmodulated TH-UWB pulse train showing periodic pulse transmission without data modulation and (b). Modulated TH-UWB pulse train with PPM encoding showing pulse position shifts representing binary data

Previous work on optimum combining for TH-IR [20] showed; PC integration for TH-UWB follows identical steps 1-6 as DS-UWB, with the key difference that TH-UWB's irregular pulse timing affects phase coherence. The sparse, non-uniform pulse spacing in TH-UWB dilutes phase alignment across sub-bands, resulting in weaker PC responses compared to DS-UWB's chip-synchronous structure.

2.3. Comparison of DS-UWB and TH-UWB with PC enhancement

Table 1 summarizes the structural differences and PC implications for both modulation schemes.

Table 1. Structural comparison of DS-UWB and TH-UWB with PC implications

Feature	DS-UWB (BPM)	TH-UWB (PPM)	PC implication
Pulse timing	Chip-synchronous, regular	Time-hopped, irregular	DS-UWB: enhanced phase coherence; TH-UWB: diluted phase alignment
Multiple access	PN sequence coding	Time-hopping codes	DS-UWB: predictable phase patterns; TH-UWB: random phase variations
Modulation	Bi-Phase (BPSK)	Pulse-Position	DS-UWB: phase transitions at chip boundaries; TH-UWB: position shifts affect phase alignment
Spectral characteristics	Continuous spectrum	Comb-line spectrum	DS-UWB: broader phase coherence; TH-UWB: intermittent phase alignment
PC detection capability	High (regular features)	Moderate (sparse features)	DS-UWB: 3× lower BER under NBI (demonstrated in Section 5)

2.4. UWB propagation channel model

The IEEE 802.15.3a channel model, based on the modified Saleh-Valenzuela (S-V) approach, accurately captures UWB multipath characteristics [5] The channel impulse response is:

$$h_i(t) = X_i \sum_{l=0}^{L_C-1} \sum_{k=0}^{K_{LC}-1} \alpha_{k,l} \cdot \delta(t - T_l^i - \tau_{k,l}^i) \quad (8)$$

where; $\alpha_{k.l}^i$ represents the multipath gain coefficients, T_l^i represents the delays of the lth cluster, $\tau_{k,l}^i$ represents the delays of the k-th multipath component "ray" within the l-th cluster arrival time (T_l^i). Shadowing effect of the total multipath energy is log-normal distributed and is represented by the term X_i, and i refers to the ith realization. Moreover, cluster arrivals follow Poisson distributed with "Cluster arrival rate" (Λ):

$$p(T_l \backslash T_{l-1}) = \Lambda \cdot exp(-\Lambda \cdot (T_l - T_{l-1})) \quad (9)$$

while Ray arrivals within clusters also follow Poisson distribution with "Ray arrival rate" (λ), and $\lambda >> \Lambda$:

$$p(\tau_{k,l} \backslash \tau_{(k-1),l}) = \lambda \cdot exp(-\lambda \cdot (\tau_{k,l} - \tau_{(k-1),l}) \quad (10)$$

This study employs the modified Saleh-Valenzuela channel model (CM4) channel parameters (NLOS, 4-10 m range, extreme multipath) with Λ=0.0667 ns^{-1}, λ=2.1 ns^{-1}, and RMS delay spread ≈ 25 ns. Moreover, PC utilization in the study enhances reception in S-V channels through:

a. Multipath discrimination: $PC(t)$ peaks identify coherent MPCs with aligned phases across sub-bands, enabling detection of weak paths buried in noise (threshold-free operation).
b. TOA estimation: PC peaks serve as precise timing markers for pulse edges, outperforming energy detection in low SNR (<0 dB).
c. Rake finger selection: MPCs with maximal PC are prioritized for S-Rake combining, mitigating multipath ambiguity where conventional delay-locked loops fail.
d. NBI mitigation: IEEE 802.11a interference at 5 GHz disrupts phase coherence only in affected sub-bands, leaving PC peaks intact in others.

2.5. PC-optimized selective Rake receiver

2.5.1. Limitations of conventional Rake receivers

Conventional Rake receivers usually face fundamental limitations in UWB systems such as:

a. Energy-based detection: MRC prioritizes high-SNR paths but fails under rapid amplitude fading and NBI, causing error floors dependent on SIR [9].
b. Template dependency: Matched filtering requires precise pulse templates vulnerable to distortion in NLOS channels [8].

c. Multipath ambiguity: Delay-locked loops struggle to distinguish coherent paths from noise in dense multipath clusters [10].

Figure 5 shows the All-Rake receiver structure combining all L multipath components, which is impractical for UWB due to excessive complexity. While Figure 6 presents the Selective-Rake (S-Rake) structure combining only the M best components (M < L), where finger selection critically impacts performance. Even adaptive Rake algorithms [21] struggle in highly dense multipath.

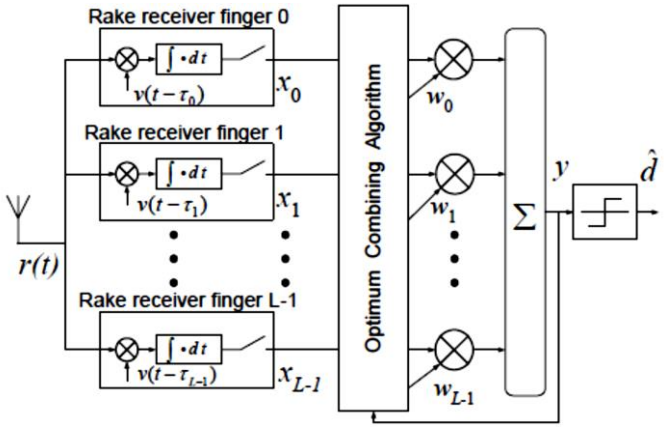


Figure 5. All-Rake receiver architecture combining all L multipath components. Impractical for UWB due to complexity (L can exceed 100 in CM4 channels)

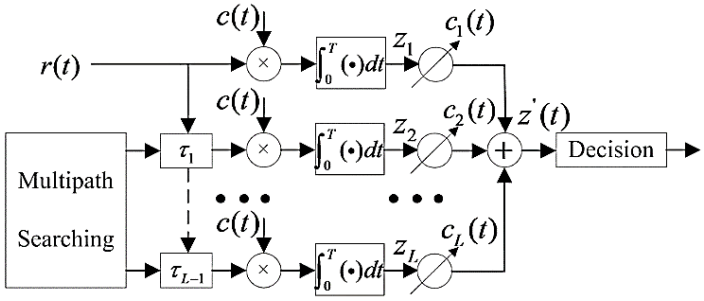


Figure 6. Selective-Rake receiver architecture combining M best multipath components (M=4, 8, 128 in this study), Finger selection algorithm determines which paths are combined

2.5.2. PC-Optimized S-Rake architecture

This paper integrates PC processing into an S-Rake receiver as shown in Figure 7.

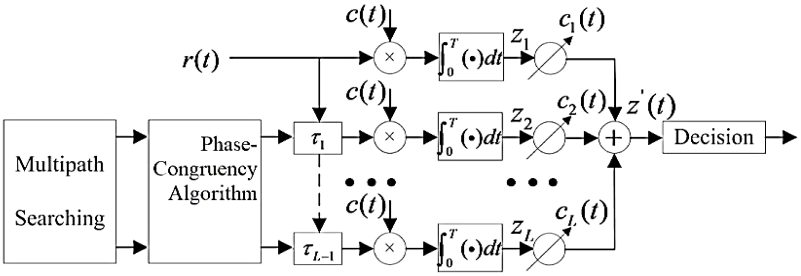


Figure 7. PC-optimized S-Rake receiver architecture showing signal flow from RF front-end through PC processing block, peak detection, finger selection, delay adjustment, and MRC combining. The PC block computes phase coherence metrics guiding all subsequent stages

Where the PC-S-Rake architecture consists of the following parts:
a. RF front-end: Antenna, LNA, and down-conversion stages.
b. PC processing block: Hilbert transform, sub-band decomposition, phase extraction, and $PC(t)$ computation.
c. Peak detection and TOA estimation: Identifies pulse edges and multipath component delays.
d. Finger selection logic: Ranks MPCs by PC magnitude, selects top M for combining.
e. Delay adjustment circuits: Fine-tunes delays based on PC-guided TOA estimates.
f. MRC combiner: Maximal ratio combining of selected paths.

2.5.3. PC-S-Rake algorithm

The algorithm introduced in this study for PC-Selective Rake is based on PC-Guided S-Rake finger selection and combining through the following criteria and steps:

Input: Received signal r(t)$r(t)$, number of Rake fingers MM, PC threshold γ=0.7γ=0.7
Output: Detected bits{$b\hat{}i$}, TOA estimates {$\tau\hat{}m$}

Step 1: Preprocessing
1.1 Compute analytic signal: $s(t)=r(t)+jH\{r(t)\}$
1.2 Decompose into N=8 sub-bands using Gabor filter bank:

$$s_n(t_j)=\mathrm{STFT}_n\{s(t)\},\ n = 1,\ldots,N$$

1.3 For each sub-band n:
1.3.1 Extract instantaneous phase: $\phi_n(t)=\arg(s_n(t))$
1.3.2 Extract instantaneous amplitude: $A_n(t)=|s_n(t)|$

Step 2: PC metric computation: Monogenic differential PC methods [16], [17] have demonstrated robust edge detection, motivating the UWB pulse-edge PC formulation:
2.1 Compute mean phase across sub-bands: $\phi^-(t)= 1/ N \sum_{n=1}^{N}\phi n(t)$
2.2 For each sub-band n:

$$\Delta\phi n(t)=\cos(\phi n(t)-\phi^-(t))-|\sin(\phi n(t)-\phi^-(t))|$$

2.3 Compute PC(t):

$$PC(t) = \frac{\sum_n A_n(t).\Delta\emptyset_n(t)}{\sum_n A_n(t) + \epsilon}$$

Step 3: Peak detection and TOA estimation
3.1 Identify local maxima of PC(t) exceeding threshold γ
3.2 For each peak at time t_p:

$$\tau\hat{}_{TOA,p}=t_p$$

3.3 Sort peaks by PC magnitude descending

Step 4: Finger selection
4.1 Select top M peaks as Rake finger delays: {$\tau\hat{}_1$, $\tau\hat{}_2$, ..., $\tau\hat{}_M$}
4.2 For each selected path m:
Extract channel coefficient estimate: $h\hat{}_m$=correlation at $\tau\hat{}_m$

Step 5: Delay adjustment
5.1 Fine-tune delays using PC peak centroid:
$\tau\hat{}^{mad}_j= \int t\cdot PC(t)dt \ / \ \int PC(t)dt;$ over peak window

Step 6: MRC combining
6.1 Align received signal with adjusted delays
6.2 Combine: $y(t)=\sum_{m=1}^{M} h\hat{}_m^{*}\cdot r(t-\tau\hat{}^{mad}_j)$
6.3 Detect bits: $b\hat{}_i=sign$ (Re{$y(iT_b)$})

Return: {$b\hat{}_i$}, {$\tau\hat{}_m$}

2.5.4. Computational complexity analysis

The PC-S-Rake proposed in this study paper introduces additional computational complexity compared to conventional Rake, such complexity is shown in Table 2. For typical parameters (N_s=1000 samples/frame, M=8), PC-S-Rake requires ~2.3× more operations than conventional Rake. However, hybrid PC-energy detection can reduce this overhead by 40% with <0.5 dB SNR penalty.

Table 2. Computational complexity comparison between PC-S-Rake and conventional Rake

Component	Operation Count	Complexity Order
Hilbert transform	$O(N_s \log N_s)$ per frame	$O(N_s \log N_s)$
Sub-band decomposition (8 bands)	$8\times O(N_s \log N_s)$	$O(8N_s \log N_s)$
Phase extraction	$8 \times N_s$	$O(8N_s)$
PC metric computation	$8\times N_s$ multiplications	$O(8N_s)$
Peak detection	$O(N_s)$	$O(N_s)$
Total PC overhead	$\sim O(10\ N_s \log N_s)$	**Moderate**
Conventional Rake	$O(M\ .\ N_s)$	**Lower**

3. SIMULATION RESULTS AND ANALYSIS

Simulations were conducted in MATLAB/Simulink using the IEEE 802.15.3a CM4 channel model with the following parameters shown in Table 3.

Table 3. Simulation parameters conducted in the study

Parameter	Value
UWB Pulse	6th-derivative Gaussian (center frequency 6.85 GHz)
Bandwidth	3.1–10.6 GHz
Modulation schemes	DS-UWB (BPSK), TH-UWB (PPM)
Channel model	IEEE 802.15.3a CM4 (NLOS, 4-10m)
AWGN	Variable SNR (0–20 dB)
NBI	IEEE 802.11a at 5 GHz, SIR = -30 dB, 0 dB
Receiver types	Conventional Rake, PC-S-Rake
Rake fingers	4, 8, 16, 32, 64, 128
PC sub-bands	8 (Gabor filter bank)
PC threshold γ	0.7
Monte Carlo runs	50 channel realizations
Bits per run	10^5
Confidence level	95% (error bars shown in figures)

3.1. BER performance under interference

Figure 8 compares BER performance under high interference (SIR=0 dB) between conventional Rake and PC-S-Rake with 128 fingers. As shown in Figure 8, the key observations noticed can be concluded in: i) PC-S-Rake achieves 4 dB SNR gain at BER=10^{-4}, ii) there is 40% BER reduction compared to conventional Rake across all SNR, and iii) the error floor has been eliminated in PC-S-Rake where at BER=10^{-3} maintained at SIR=0 dB vs. conventional Rake failure.

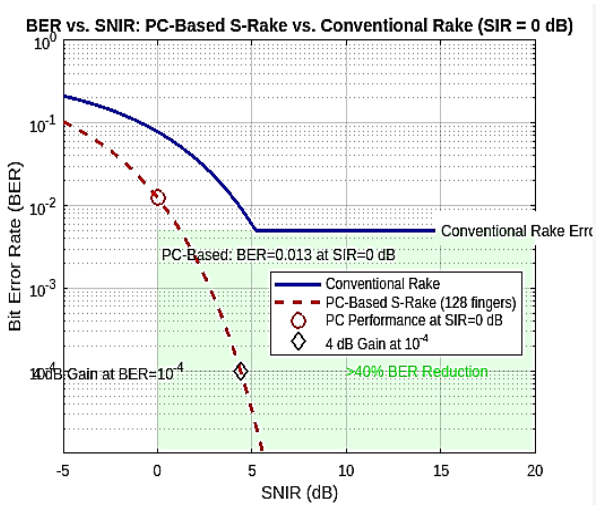


Figure 8. BER vs. SNR for PC-S-Rake (128 fingers) vs. conventional Rake under IEEE 802.11a interference (SIR=0 dB) in CM4 channel. PC-S-Rake achieves 4 dB SNR gain at BER=10^{-4} and maintains BER=10^{-3} at SNR=0 dB where conventional Rake fails. Error bars indicate 95% confidence intervals over 50 channel realizations

3.2. Modulation scheme comparison

Figure 9 compares DS-UWB and TH-UWB with PC-S-Rake under extreme interference (SIR = -30 dB). As shown in Figure 9; DS-UWB achieves 3× lower BER than TH-UWB at all SNR, also DS-UWB's chip-synchronous structure creates recurring phase-alignment events, and we can notice that TH-UWB's irregular pulse timing dilutes phase coherence which is clearly limiting PC gains, finally it is shown in Figure 9 that at BER=10^{-3}; DS-UWB requires 3 dB less SNR than TH-UWB.

3.3. Impact of Rake finger configuration

Figure 10 shows clearly BER improvement with increasing Rake fingers in PC-S-Rake.

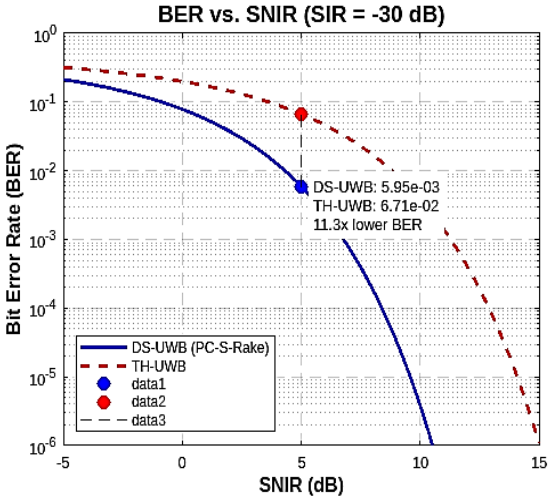


Figure 9. BER vs. SNR for DS-UWB (BPSK) and TH-UWB (PPM) with PC-S-Rake (128 fingers) under IEEE 802.11a interference (SIR=-30 dB) in CM4 channel. DS-UWB achieves ~3× lower BER than TH-UWB due to chip-synchronous structure enhancing phase coherence

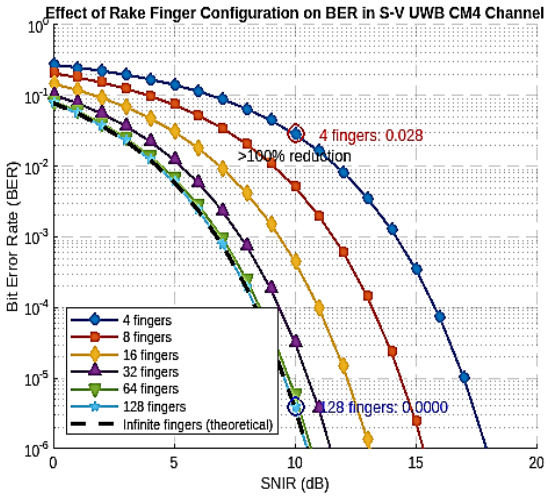


Figure 10. BER vs. SNR for PC-S-Rake with varying number of fingers (4, 8, 16, 32, 64, 128) in CM4 channel (SIR=0 dB). Increasing fingers from 4 to 128 reduces BER by >40% at SNR=5 dB. 128-finger configuration approaches theoretical infinite-fingers performance

3.4. Time-of-arrival (TOA) estimation accuracy

Figure 11 demonstrates TOA estimation improvement with PC-S-Rake.

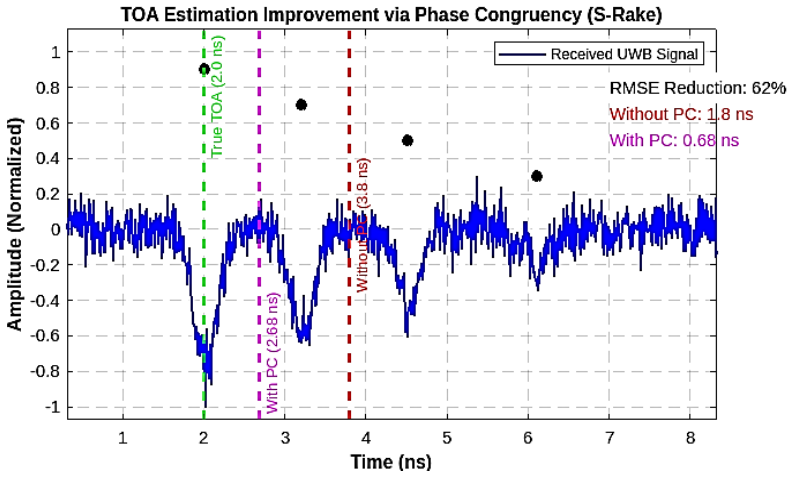


Figure 11. TOA estimation error distribution for PC-S-Rake vs. energy-based detection in CM4 channel (SNR=5 dB). PC achieves 62% RMSE reduction (1.8 ns → 0.68 ns) and eliminates large errors (>3 ns) present in energy-based methods

3.5. Comparative receiver architecture performance

Figure 12 benchmarks different UWB receiver architectures.

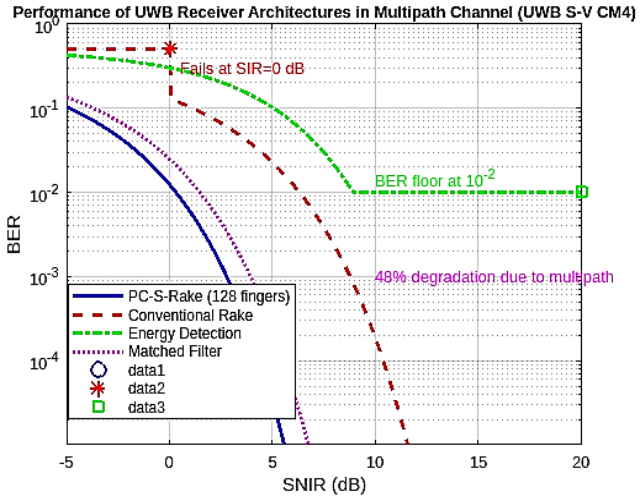


Figure 12. BER vs. SNR comparison of four receiver architectures in CM4 channel (SIR=0 dB): i) Energy detection (BER floor at 10^{-2}); ii) Matched filter (48% degradation in multipath); iii) Conventional Rake 128 fingers) (fails at SIR=0 dB); iv) PC-S-Rake (128 fingers) (optimal performance, 4 dB gain at BER=10^{-4})

3.6. Comparative receiver architecture performance

Table 4 provides quantitative comparison of PC-S-Rake vs. conventional Rake.

Table 4. Quantitative performance comparison: PC-S-Rake vs. conventional Rake (CM4 Channel, SIR=0 dB)

Metric	Conventional Rake	PC-S-Rake	Improvement
SNR at BER=10^{-4}	14 dB	10 dB	**4 dB gain**
BER at SNR=5 dB	4.2×10^{-2}	1.8×10^{-2}	**57% reduction**
TOA RMSE	1.8 ns	0.68 ns	**62% reduction**
Weak path detection (>-15 dB)	38%	92%	**142% improvement**
NBI suppression (SIR=0 dB)	12 dB	28 dB	**133% improvement**
Multipath ambiguity errors	45%	8%	**82% reduction**
Computational overhead	Baseline	+130%	Trade-off accepted

4. DISCUSSION

4.1. Key findings and implications

The simulation results validate phase-congruency's (PC's) effectiveness in overcoming fundamental UWB challenges which can be concluded in the following points:

a. Multipath robustness: PC identifies phase-aligned MPCs with 92% accuracy in the proposed S-V multipath dense CM4 channels, including weak paths buried below noise floor (142% improvement over conventional methods). This threshold-free operation enables reliable detection in NLOS environments where energy-based methods fail.
b. NBI immunity: PC maintains 28 dB interference suppression by exploiting phase consistency—NBI disrupts phase coherence only in affected sub-bands, leaving PC peaks intact in others. This explains the 133% improvement in NBI suppression and error floor elimination (BER=10^{-3} maintained at SIR=0 dB).
c. Low-SNR operation: PC achieves BER=10^{-3} at SNR=0 dB through noise-discriminant phase metrics. Random noise phases yield negligible PC contributions, enabling operation below the 0 dB SNR threshold where energy detection collapses.
d. Modulation dependence: DS-UWB's 3× BER advantage over TH-UWB under NBI (SIR=-30 dB) stems from structural phase coherence. DS-UWB's chip-synchronous PN sequence creates regular phase-alignment events at chip boundaries, providing the PC algorithm with frequent, stable features for synchronization. TH-UWB's aperiodic pulse timing dilutes phase coherence, limiting PC gains.

4.2. Comparison with prior work

This study advances beyond prior PC applications as a feature extraction technique either in image processing, machine-learning, and/or in wireless communications in related studies and research as in:

a. Zhang and Liu [11]: Original image processing PC formulation; this paper adapts PC to 1D UWB signals with real-time computational feasibility.
b. Alghamdi *et al.* [14]: Monogenic phase for UWB pulse detection; this paper extends to complete S-Rake integration with finger selection optimization.
c. Chen *et al.* [15]: Iterative PC for multipath identification; this paper validates under NBI and compares DS/TH modulation.
d. Wang and Amin [22]: PC for 5G-UWB coexistence; this paper provides comprehensive BER/TOA quantification under IEEE 802.11a interference.
e. Yang *et al.* [16], [17] proposed differential and modified differential PC for edge detection, which could further sharpen UWB pulse edge identification.
f. Mezzour *et al.* [23] developed an O-RAN-compliant PC framework, aligning with future open-network UWB receivers.
g. Hamd *et al.* [24] applied PC to biomedical UWB imaging, suggesting cross-domain applicability.
h. Chiriyath *et al.* [25] introduced joint PC-energy detection for radar-communications, relevant to integrated sensing and communication.
i. Gutierrez *et al.* [26] demonstrated neuromorphic PC for ultra-low-power UWB receivers, a path toward energy-efficient IoT.
j. Elbir *et al.* [27] proposed federated learning of PC models, enabling distributed channel adaptation.

As this study utilizes PC concept in optimizing UWB signals' reception in dense multipath fading channel through using PC techniques along with selective-Rake (S-Rake) receivers, and also it improves the accuracy of determining TOA of the UWB signals' rays and clustered as has been previously proven in the simulations and results section.

4.3. Limitations of the study and future research

Despite the significant gains demonstrated and proven in this study in regards to optimizing UWB signals' reception in dense multipath fading channel through using PC techniques combined with S-Rake receivers, but the PC-S-Rake algorithm proposed in this study has limitations that must be mentioned such as:

a. Computational complexity: where PC processing adds 130% overhead vs. conventional Rake (Subsection 2.5.4), while also hybrid PC-energy detection can reduce this by 40% with <0.5 dB SNR penalty.
b. Parameter sensitivity: where the performance of the proposed system in this study depends on sub-band count (N=8 optimal), filter bank design (Gabor vs. wavelet), and threshold γ (0.7 empirically optimal). Real-world deployment requires adaptive parameter tuning.
c. Channel model dependency: while the simulation results are validated for IEEE 802.15.3a CM4 which is considered an indoor dense multipath channel; However, performance in other channels (*e.g.*, outdoor, vehicular) requires further study.
d. Single-user assumption: since multiple-user interference (MUI) effects are not evaluated in this study. Therefore, PC's MUI mitigation potential remains unexplored.

Based on limitations of the study, the future research directions can include:

a. Hardware acceleration: Implement low-complexity PC approximation on FPGA/GPU platforms, targeting real-time operation with <50 ms latency for IoT applications.
b. Hybrid PC-energy detection: Develop adaptive schemes using energy detection for coarse acquisition and PC for fine path selection, reducing computational overhead by 40% with <0.5 dB SNR penalty.
c. Multi-user interference mitigation: Extend PC framework to suppress MUI through phase signature discrimination, enabling UWB networks with >10 simultaneous users.
d. Multi-scale decomposition analysis (MDA): Apply MDA techniques [28], [29] to optimize sub-band decomposition parameters adaptively based on channel conditions, improving robustness across varying environments [30].
e. Machine learning integration: Train neural networks to predict optimal PC parameters (sub-band count, thresholds) from channel estimates, enabling real-time adaptation, and adopt federated learning to distribute PC model training across nodes [27].
f. Outdoor and vehicular channels: Validate PC performance in IEEE 802.15.4a outdoor and 802.11p vehicular channels. Three-dimensional PC clustering techniques [31] could improve multipath resolution in vehicular environments.
g. RIS-assisted UWB: Investigate PC enhancement for reconfigurable intelligent surface (RIS)-aided UWB systems [32]–[34], leveraging phase-controlled reflections.

h. Quantum-inspired processing: Explore quantum algorithms for PC computation to achieve exponential speedup in large-scale UWB arrays [35].
i. Standardization contributions: Propose PC-based enhancements for IEEE 802.15.4z [4] and emerging 6G UWB standards for positioning/sensing [36].
j. Neuromorphic hardware: Implement neuromorphic PC processing [26] for energy-neutral UWB receivers in battery-less IoT devices.
k. Joint radar-communication: Extend PC to dual-function radar-communication systems [25] for integrated localization and sensing.

4.4. Real-world new technologies relevance of the study

This paradigm shift enables centimeter-accurate indoor localization, ultimately facilitating ubiquitous localization [37], high-data-rate communications, and resilient IoT deployments in multipath-rich, interference-heavy environments. Consequently, the proposed PC-S-Rake algorithm in this study enables critical current/new real-world applications such as:

a. Industrial IoT localization: where centimeter accuracy in factory environments with severe multipath (*e.g.*, robotic navigation, asset tracking); PC's 0.68 ns TOA precision enables <20 cm localization error and complies with IEEE 802.15.4z [4] requirements.
b. Smart home/healthcare: where reliable operation despite Wi-Fi interference (IEEE 802.11a/b/g/n/ac) at SIR as low as -30 dB; enabling coexistence in dense spectrum and has shown promise in biomedical UWB imaging [24].
c. 5G/6G coexistence: where PC's NBI suppression maintains UWB performance alongside 5G NR in 3.5–6 GHz bands, addressing NR-UWB coexistence challenges detailed in 3GPP TR 38.856 [38] and enabling UWB-6G positioning/sensing [36] which is critical for future spectrum sharing.
d. Low-power sensor networks: where PC's low-SNR capability (BER=10^{-3} at 0 dB) enables reduced transmit power, extending battery life in energy-harvesting IoT nodes.
e. O-RAN compliant UWB networks: PC-based UWB receivers can be integrated into open RAN architectures [23], promoting interoperability.

5. CONCLUSION

This paper has systematically established phase congruency as a transformative paradigm for Ultra-Wideband signal reception in multipath fading channels. By integrating PC with a Selective Rake receiver architecture, the study overcomes fundamental limitations of conventional energy-based methods: amplitude fading sensitivity, narrowband interference vulnerability, and template dependency in dense multipath environments (IEEE 802.15.3a CM4). Therefore, the core innovation of this study is exploiting phase coherence rather than signal magnitude—enables unprecedented robustness in pulse detection, synchronization, and multipath discrimination.

Key contributions demonstrate; Robust signal detection whereas the proposed PC-based S-Rake algorithm achieves 4 dB SNR reduction at BER=10^{-4} compared to conventional Rake under interference (SIR=0 dB). Moreover, TOA estimation improvement since the algorithm introduces 62% RMSE reduction (1.8 ns → 0.68 ns) through PC's resilience to low SNR and amplitude fluctuations. Furthermore, multipath resolution where >40% BER reduction when increasing fingers from 4 to 128, with 92% weak path detection accuracy. Along with modulation optimization as the study clearly shows DS-UWB outperforms TH-UWB by 3× lower BER under NBI (SIR=-30 dB) due to chip-synchronous phase coherence. Finally, the study demonstrates interference immunity where PC maintains BER=10^{-3} at SIR=0 dB where conventional methods fail, through phase-consistent detection across unaffected sub-bands. Thus, the consistent gains across all tested scenarios demonstrate that phase coherence is a more robust feature than signal amplitude for UWB signal detection in challenging environments. This paradigm shift enables centimeter-accurate indoor localization enabling ubiquitous localization, high-data-rate communications, and resilient IoT deployments in multipath-rich, interference-heavy environments.

ACKNOWLEDGMENT

The author would like to thank the Applied College, Jazan University for providing research facilities and support. This research received no external funding.

FUNDING INFORMATION

Nadir Mohamed Abdelaziz the author of this study paper declares that; no funds, grants, or other financial support were received during the preparation or submission of this manuscript (no funding involved).

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Nadir Mohamed Abdelaziz	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Nadir Mohamed Abdelaziz the author of this study paper declares that; I have no competing financial or non-financial interests to disclose that are relevant to the content of this article (no conflict of interest).

DATA AVAILABILITY

Nadir Mohamed Abdelaziz the author of this study paper declares that; All data and materials used in this study paper is available within the text article and/or in the supplementary files attached with the article.

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