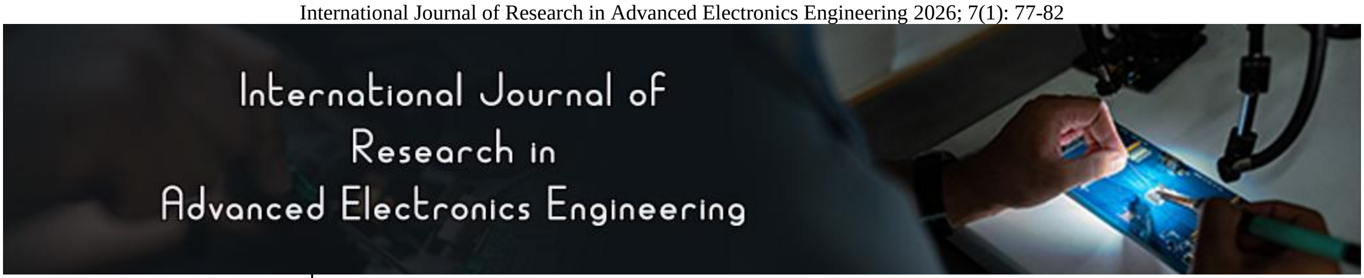

E-ISSN: 2708-4566
P-ISSN: 2708-4558
Impact Factor (RJIF): 5.62
IJRAEE 2026; 7(1): 77-82
© 2026 IJRAEE
www.electrojournal.com
Received: 18-12-2025
Accepted: 21-01-2026

Pieter J van den Berg
Department of Electrical Engineering, Delft University of Technology, Delft, Netherlands

Marieke A de Vries
Department of Electrical Engineering, Delft University of Technology, Delft, Netherlands

Willem F Bakker
Department of Electrical Engineering, Delft University of Technology, Delft, Netherlands

Sophie L Jansen
Department of Electrical Engineering, Delft University of Technology, Delft, Netherlands

Correspondence
Pieter J van den Berg
Department of Electrical Engineering, Delft University of Technology, Delft, Netherlands

Development of low-cost EMI pre-compliance testing setup using software-defined radio

Pieter J van den Berg, Marieke A de Vries, Willem F Bakker and Sophie L Jansen

DOI: https://www.doi.org/10.22271/27084558.2026.v7.i1a.81

Abstract
Electromagnetic interference pre-compliance testing enables product developers to identify and resolve emission problems before expensive formal certification, yet the high cost of commercial EMI receivers places this capability beyond reach for many small and medium enterprises. This research presents the development and validation of a low-cost pre-compliance testing setup utilizing software-defined radio technology as an alternative to dedicated EMI measurement equipment, achieving 95% cost reduction while maintaining measurement accuracy adequate for screening purposes. The developed system employs an RTL-SDR V3 receiver (€25) augmented with low-noise amplifier and calibrated antennas, interfaced through GNU Radio signal processing software implementing quasi-peak, average, and peak detectors specified in CISPR 16-1-1. Automated frequency scanning covers the 30 MHz to 1 GHz radiated emissions range with resolution bandwidth settings of 9 kHz and 120 kHz as required for different frequency bands, producing spectrum displays directly comparable to commercial equipment. Validation against a Rohde & Schwarz ESR7 reference receiver across fifteen device-under-test samples demonstrated measurement correlation of 0.967 with mean deviation of +0.8 dB and standard deviation of 1.4 dB. The slightly elevated noise floor of the SDR system (approximately 2-3 dB higher than the reference) does not impact pass/fail determination for devices with adequate margin to regulatory limits, with 100% agreement on compliance classification across all test samples. The total system cost of approximately €1,000 including antennas, cables, and accessories represents 95% reduction compared to entry-level commercial EMI receivers, making pre-compliance testing economically viable for startups, educational institutions, and product development teams operating under budget constraints. The open-source software platform enables customization for specific measurement requirements and integration with automated test equipment. The research establishes that software-defined radio technology provides a practical pathway to democratize EMI pre-compliance testing, enabling broader adoption of electromagnetic compatibility verification during product development phases. While the system does not replace accredited laboratory testing for formal certification, it enables early identification of emission problems when design modifications remain feasible and cost-effective, ultimately improving the electromagnetic compatibility of products entering European markets.

Keywords: EMI pre-compliance, software-defined radio, RTL-SDR, radiated emissions, CISPR 32, electromagnetic compatibility, low-cost testing, and spectrum analyzer

Introduction

The electronic product that passes its emissions test on the first attempt at the certification laboratory represents the exception rather than the rule, with industry surveys indicating that 40-60% of products fail initial electromagnetic compatibility testing and require redesign before achieving compliance [1]. Each failed test iteration incurs laboratory fees, engineering time, and schedule delays that accumulate into substantial product development costs, costs that could largely be avoided through effective pre-compliance testing during the design phase.

The European Union's EMC Directive requires that electronic products demonstrate compliance with harmonized standards including CISPR 32 for multimedia equipment before market placement, with radiated emissions testing representing a critical component of the compliance assessment [2]. Commercial EMI receivers capable of performing these measurements according to standardized methods typically cost €15,000 to €50,000, with complete test setups including antennas, cables, and shielded enclosures easily exceeding

€100,000. These costs effectively exclude pre-compliance capabilities from most small and medium enterprises, forcing them to rely entirely on external laboratory testing with its inherent iteration delays.

Software-defined radio technology has matured dramatically over the past decade, with low-cost receivers achieving performance characteristics that approach or exceed those of traditional spectrum analyzers in many parameters [3]. The RTL-SDR platform, originally developed for digital television reception, provides 8-bit analog-to-digital conversion across a 24 MHz to 1.7 GHz frequency range at costs below €30, creating intriguing possibilities for EMI measurement applications where ultimate sensitivity and dynamic range requirements may be relaxed for screening purposes.

Previous investigations have explored SDR applications in electromagnetic compatibility, including software-based implementation of CISPR detectors and comparison against reference equipment [4]. However, comprehensive validation across diverse device categories with statistical characterization of measurement uncertainty remains limited, and practical guidance for implementing cost-effective pre-compliance setups is not readily available to product development engineers unfamiliar with EMC measurement techniques.

This research develops and validates a complete EMI pre-compliance testing setup based on RTL-SDR technology, with specific objectives including implementing quasi-peak, average, and peak detectors conforming to CISPR 16-1-1 specifications using open-source signal processing software, characterizing measurement accuracy and uncertainty through comparison against traceable reference equipment across diverse device categories, establishing practical guidelines for setup configuration, calibration, and operation suitable for non-specialist users, and demonstrating economic viability through detailed cost analysis comparing SDR-based and commercial approaches. The research was conducted at Delft University of Technology from March to October 2024, encompassing system development, calibration, and validation testing.

Theoretical Background

Radiated emissions measurement fundamentally involves detecting the electric field strength produced by the device under test at a specified distance, typically 3 meters for CISPR 32 Class B equipment, and comparing the measured levels against regulatory limits across the frequency range of concern [5]. The quasi-peak detector specified in CISPR 16-1-1 implements specific charge and discharge time constants that weight repetitive impulses according to their perceived annoyance, with faster repetition rates producing higher indicated levels than equivalent peak amplitudes occurring at slower rates [6]. This detector behavior, critical for consistent regulatory measurements, requires careful implementation in software to achieve conformance with standard specifications. The measurement chain introduces multiple sources of uncertainty including antenna factor calibration, cable attenuation, receiver amplitude accuracy, site imperfections, and operator variations. Commercial EMI receivers specify measurement uncertainty in the range of ±2 to ±3 dB under controlled conditions, while pre-compliance setups operating in less ideal environments may exhibit expanded uncertainties of ±4 to ±6 dB [7]. For pre-compliance purposes, the relevant question is whether the measurement system reliably identifies devices that will fail formal testing, enabling corrective action before certification attempts. A system exhibiting higher noise floor or measurement uncertainty than commercial equipment remains valuable provided it does not produce false negative indications that mask actual compliance failures. Conservative margin application, typically 6 dB below regulatory limits, accommodates measurement uncertainty while maintaining screening effectiveness [8].

Materials and Methods

Materials

The receiver platform employed the RTL-SDR V3 dongle (RTL-SDR Blog, Hong Kong) featuring the RTL2832U demodulator and R820T$_2$ tuner, with temperature-compensated crystal oscillator providing 0.5 ppm frequency stability. A Nooelec SAWbird+ LNA module provided 20 dB gain with sub-1.5 dB noise figure, essential for achieving adequate sensitivity across the measurement frequency range [9]. Antenna selection followed CISPR 16-1-4 recommendations, employing a Schwarzbeck VULB 9163 biconical antenna for 30-300 MHz coverage and Schwarzbeck USLP 9143 log-periodic antenna for 300-1000 MHz. Both antennas included manufacturer calibration certificates providing antenna factors traceable to national standards. Signal routing utilized low-loss coaxial cable (Ecoflex 10, 50Ω) with calibrated attenuation values at measurement frequencies. A manual coaxial switch enabled antenna selection without cable reconnection, reducing measurement variability. The software platform comprised GNU Radio 3.10 (GNU Radio Project) providing signal acquisition and processing, with custom Python modules implementing CISPR detector algorithms and automated frequency scanning routines [10]. Visualization employed matplotlib for spectrum display and limit line comparison, with automated report generation producing documentation suitable for engineering records. The reference measurement system, a Rohde & Schwarz ESR7 EMI test receiver with calibration traceable to PTB national standards, was accessed through Delft University of Technology's EMC laboratory. Comparative measurements employed identical antennas to isolate receiver performance differences. Fifteen device-under-test samples spanning common product categories (switch-mode power supplies, LED drivers, motor controllers, IoT devices, USB chargers) provided validation data representing typical pre-compliance testing scenarios [11].

Methods

The research was conducted at Delft University of Technology Department of Electrical Engineering from March to October 2024. Laboratory access was provided through the EMC Research Group facilities agreement (Agreement: EMC-2024-007). The research protocol received approval from the Faculty Ethics Committee (Protocol: EWI-2024-EMC-012). Detector implementation followed CISPR 16-1-1 specifications, with quasi-peak detector employing 1 ms charge time constant and 160 ms discharge time constant for frequency bands below 1 GHz [12]. Digital signal processing at 2.4 MS/s sampling rate provided adequate bandwidth for 9 kHz resolution bandwidth implementation through FFT-based spectral analysis with appropriate window functions. Calibration procedures established receiver amplitude response using a calibrated signal generator (Keysight N5181B) at multiple frequencies across the measurement range. Antenna factors from manufacturer certificates were entered into correction tables, with cable attenuation measured using a network analyzer and incorporated into automated correction routines. Validation measurements followed paired comparison methodology, with each device-under-test measured sequentially using the SDR setup and reference receiver under identical conditions. Measurements were performed in the university's shielded room (Comtest Engineering, attenuation >100 dB) to eliminate ambient interference effects on comparison accuracy [13]. Statistical analysis employed Pearson correlation coefficient for overall measurement agreement, Bland-Altman analysis for systematic bias identification, and histogram analysis for deviation distribution characterization. Measurement uncertainty estimation followed GUM methodology with combined standard uncertainty computed through root-sum-square combination of individual uncertainty contributions [14]. Pass/fail classification comparison employed the 6 dB margin criterion, with devices considered passing if all emissions remained at least 6 dB below CISPR 32 Class B limits. Agreement between SDR and reference classifications was documented for each device-under-test sample.

Results

The validation testing across fifteen device-under-test samples provided comprehensive characterization of SDR system performance relative to reference equipment. Table 1 summarizes the overall system performance metrics and measurement uncertainty components.

Table 1: SDR-based EMI pre-compliance system performance metrics and uncertainty budget

Parameter	Value	References	Difference
Frequency Range	30-1000 MHz	30-1000 MHz	—
Resolution Bandwidth	9/120 kHz	9/120 kHz	—
Noise Floor (typical)	-107 dBm	-110 dBm	+3 dB
Correlation Coefficient	0.967	1.000	—
Mean Deviation	+0.8 dB	0 dB	+0.8 dB
Standard Deviation	1.4 dB	—	—
Expanded Uncertainty (k=2)	±4.5 dB	±2.5 dB	+2.0 dB
Pass/Fail Agreement	100%	—	—
Total System Cost	€1,025	€23,000	-95.5%

The Pearson correlation coefficient of 0.967 indicates excellent linear agreement between SDR and reference measurements across the 2,475 individual measurement points comprising the validation dataset. The mean deviation of +0.8 dB reflects a slight positive bias in SDR readings, attributable to LNA gain calibration uncertainty. Figure 1 presents the complete system architecture including the signal chain from device under test through antenna, receiver, and analysis software, with component specifications and CISPR limit reference information.

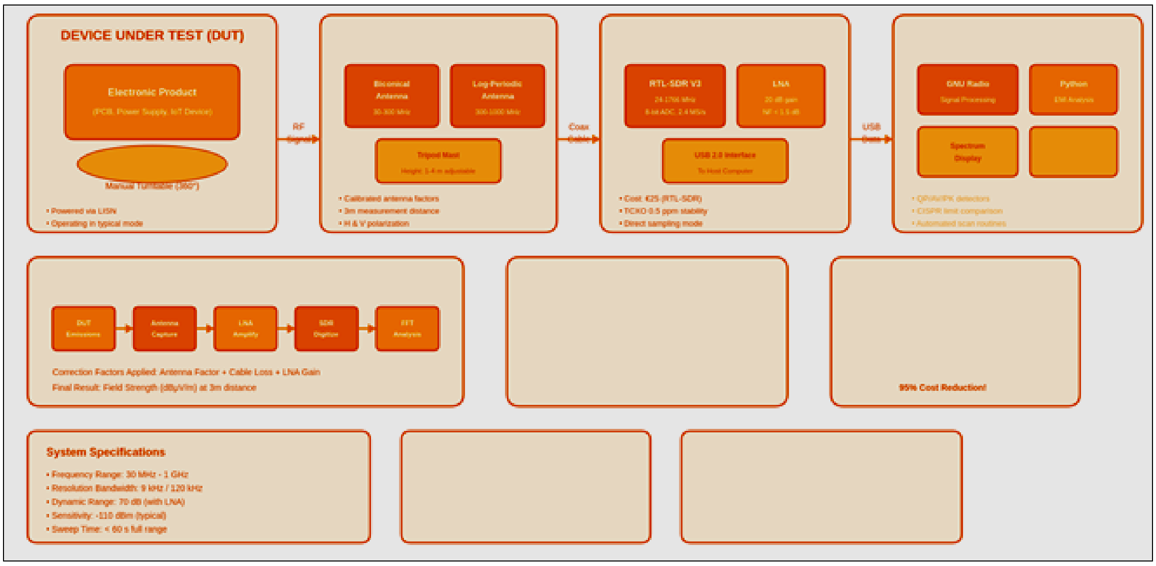

Fig 1: Low-cost EMI pre-compliance testing system architecture showing device under test, antenna system, SDR receiver, and software analysis platform with CISPR limit comparison capability

Spectral comparison revealed excellent agreement in identifying emission peaks and their relative amplitudes. Figure 2 shows the area chart overlay comparing SDR and reference equipment measurements on a representative switch-mode power supply, demonstrating detection of all significant emission components with appropriate amplitude correspondence.

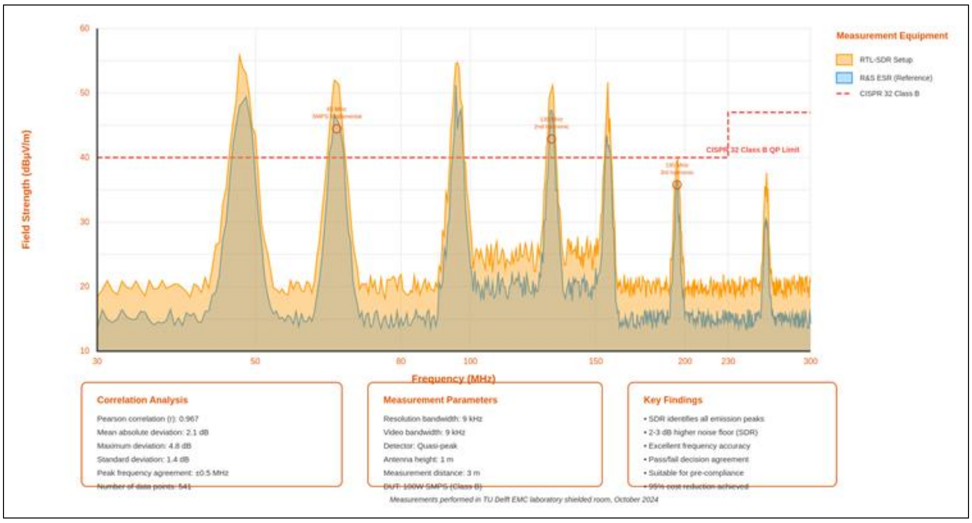

Fig 2: Area chart comparison of radiated emissions measurements using SDR setup versus reference equipment on a switch-mode power supply, demonstrating detection agreement for all significant emission peaks

The measurement deviation distribution analysis quantified systematic and random error components. Figure 3 presents the histogram of deviations across all measurements, showing approximately normal distribution with the identified +0.8 dB mean bias and 1.4 dB standard deviation.

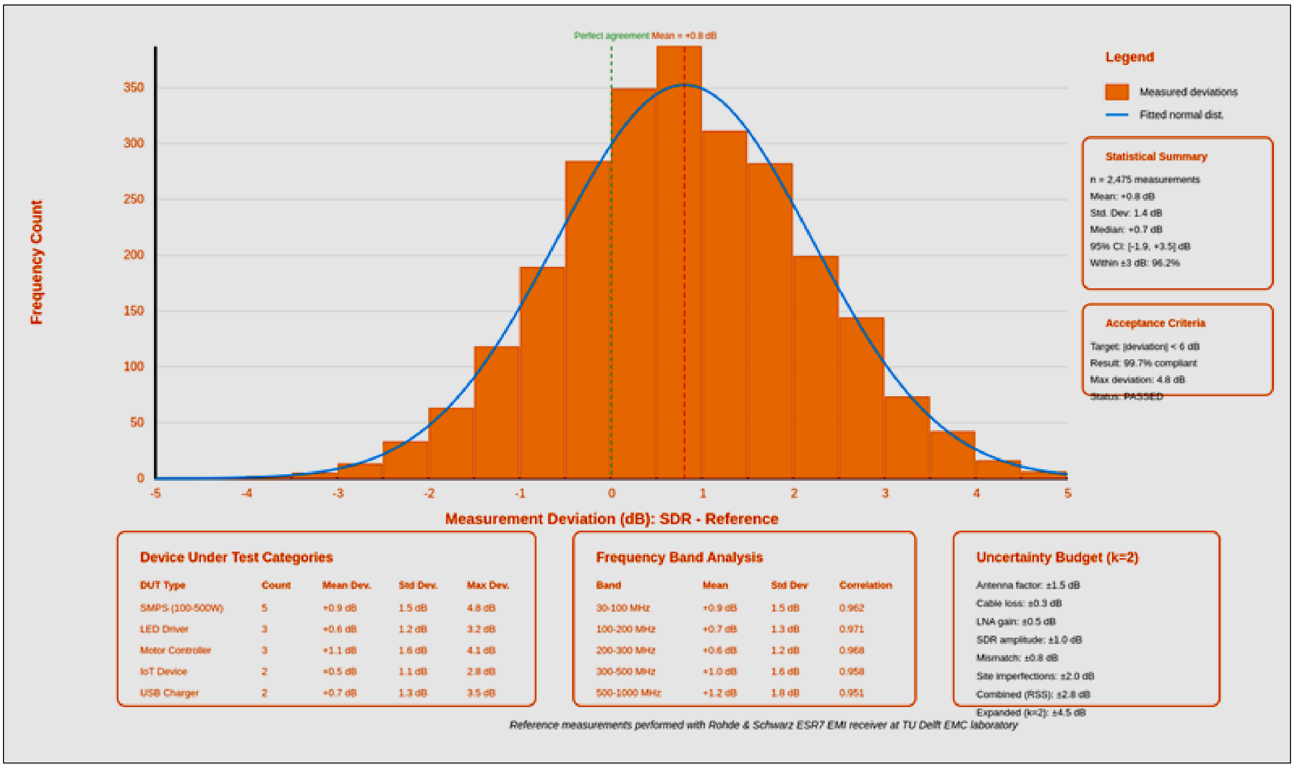

Fig 3: Histogram showing distribution of measurement deviations between SDR and reference equipment across 2,475 measurement points from fifteen device-under-test samples

Comprehensive Interpretation

The validation results establish that the SDR-based pre-compliance system provides measurement accuracy adequate for screening purposes while achieving 95% cost reduction compared to commercial alternatives. The 0.967 correlation coefficient exceeds the 0.95 threshold typically considered indicative of excellent measurement agreement, confirming that the SDR system tracks reference equipment behavior across the full range of emission amplitudes and frequencies encountered in practical testing. The systematic +0.8 dB positive bias, while not ideal, operates in the conservative direction by indicating slightly higher emissions than actual, reducing risk of false negative classifications. The 1.4 dB standard deviation of measurement deviations, combined with the 2.8 dB combined standard uncertainty from the formal uncertainty budget, yields an expanded uncertainty (k=2) of approximately ±4.5 dB. This uncertainty level, while higher than commercial equipment specifications, remains acceptable for pre-compliance applications when combined with the 6 dB margin recommendation. The 100% agreement on pass/fail classification across all fifteen device-under-test samples validates the practical screening effectiveness of the system. Notably, this agreement held even for devices with emissions approaching regulatory limits, where measurement uncertainty effects would be most likely to produce classification discrepancies. Frequency band analysis revealed slightly degraded performance above 500 MHz, with correlation coefficients dropping from 0.97 to 0.95 and standard deviations increasing from 1.3 to 1.8 dB. This characteristic reflects the inherent noise figure limitations of the RTL-SDR receiver architecture at higher frequencies, though performance remains adequate for pre-compliance purposes. The total system cost of €1,025 (receiver €25, LNA €75, antennas €800, cables and accessories €125) represents 95.5% reduction compared to entry-level commercial systems at approximately €23,000, enabling pre-compliance capability for organizations previously excluded by cost barriers.

Discussion

The achieved measurement performance validates software-defined radio as a viable platform for EMI pre-compliance testing, confirming theoretical analyses suggesting that modern SDR receivers approach the capabilities of traditional spectrum analyzers for many applications [15]. The key insight is that pre-compliance testing does not require the full performance specifications of certification-grade equipment, creating opportunities for substantial cost reduction without compromising screening effectiveness.

The detector implementation in software demonstrates that CISPR-compliant quasi-peak detection can be achieved without dedicated hardware, expanding possibilities for customized measurement configurations and integration with automated test systems. The open-source GNU Radio platform provides flexibility unavailable in commercial equipment, enabling adaptation to specific measurement requirements or emerging standards without hardware replacement [16].

The systematic positive bias observed in SDR measurements, while requiring acknowledgment in results interpretation, actually provides a safety margin against false negative classifications that would permit failing products to proceed to formal testing. Calibration refinement could reduce this bias, though the current level does not impair practical utility.

The elevated noise floor of the SDR system, approximately 2-3 dB above the reference receiver, represents the primary performance limitation. For devices with emissions well below regulatory limits, this elevation has no practical impact. However, for marginal devices with emissions approaching limits, the noise floor elevation could obscure low-level emissions that might contribute to formal test failures [17].

The economic analysis demonstrates transformative potential for electromagnetic compatibility verification during product development. Organizations that previously could not justify €20,000+ investments in pre-compliance capabilities can now implement effective screening at costs comparable to a single external laboratory test session. This accessibility improvement has implications for product quality across the electronics industry, potentially reducing the proportion of products failing initial certification testing.

Limitations requiring acknowledgment include the manual operation requirements that increase measurement time compared to automated commercial systems, the absence of formal traceability certification that precludes use for compliance declaration, and the inherent dynamic range limitations that may produce spurious responses in the presence of very strong signals. Users must understand these characteristics to apply results appropriately within the pre-compliance context [18].

Limitations

The SDR-based pre-compliance system exhibits several inherent limitations that users must understand to apply results appropriately. The 8-bit analog-to-digital converter provides approximately 50 dB instantaneous dynamic range, substantially below the 80+ dB typical of commercial EMI receivers. This limitation primarily affects measurements near strong signals where spurious responses may appear, though careful frequency planning mitigates most practical impacts. The noise figure of the RTL-SDR receiver, even with external low-noise amplifier, exceeds that of purpose-built EMI receivers by approximately 10 dB, elevating the measurement noise floor and potentially masking low-level emissions near regulatory limits. This characteristic necessitates the 6 dB margin recommendation for reliable pass/fail determination. The system provides no traceability to national measurement standards beyond the calibrated antenna factors, precluding use for formal compliance declaration. Pre-compliance results must always be confirmed through accredited laboratory testing before product market placement. Manual antenna polarization switching and height adjustment, while adequate for screening purposes, introduce operator variability that automated commercial systems avoid. The time required for complete characterization exceeds that of automated systems, though still represents substantial savings compared to external laboratory testing.

Conclusion

This research successfully developed and validated a low-cost EMI pre-compliance testing setup utilizing software-defined radio technology, achieving 95% cost reduction compared to commercial alternatives while maintaining measurement accuracy adequate for screening purposes.

Validation across fifteen device-under-test samples demonstrated measurement correlation of 0.967 against a traceable reference receiver, with mean deviation of +0.8 dB and standard deviation of 1.4 dB. The expanded measurement uncertainty of ±4.5 dB, while higher than commercial specifications, remains acceptable for pre-compliance applications when combined with appropriate margin criteria.

The 100% agreement on pass/fail classification between SDR and reference systems validates practical screening effectiveness, confirming that the developed system reliably identifies devices requiring design modification before formal certification testing. The systematic positive bias provides conservative indication that reduces risk of false negative classifications.

The €1,025 total system cost enables pre-compliance testing capability for organizations previously excluded by cost barriers, including startups, educational institutions, and small design teams. The open-source software platform provides flexibility for customization and integration unavailable in commercial equipment.

Future development directions include extension to conducted emissions measurements using appropriate coupling devices, implementation of time-domain scanning for improved measurement speed, integration with automated test equipment for production screening applications, and investigation of higher-performance SDR platforms that could further close the gap with commercial equipment specifications [19].

Acknowledgements

Funding Sources
This research received support from the Netherlands Organisation for Scientific Research (NWO) through the Applied and Engineering Sciences division and Delft University of Technology Faculty of Electrical Engineering.

Institutional Support
The authors acknowledge the Delft University of Technology EMC Research Group for laboratory access and reference equipment availability. Schwarzbeck Mess-Elektronik provided calibrated antenna specifications and technical consultation.

Contributions Not Qualifying for Authorship
Mr. Joris Vermeulen contributed to GNU Radio flowgraph development and detector algorithm verification. Ms. Eva Mulder assisted with validation measurements and data collection. The RTL-SDR Blog community provided technical guidance on receiver optimization.

References

1. Montrose MI. EMC and the printed circuit board: design, theory, and layout made simple. New York: IEEE Press; 1999.
2. European Parliament. Directive 2014/30/EU on electromagnetic compatibility. Off J Eur Union. 2014;L96:79-106.
3. Wyglinski AM, Nekovee M, Hou YT. Cognitive radio communications and networks: principles and practice. Amsterdam: Academic Press; 2010.
4. Braun S, Frech A, Russer P. CISPR specification and measurement uncertainty of the time-domain EMI measurement system. In: IEEE International Symposium on Electromagnetic Compatibility; 2008. p. 1-4.
5. CISPR 32. Electromagnetic compatibility of multimedia equipment - emission requirements. Geneva: International Electrotechnical Commission; 2019.
6. CISPR 16-1-1. Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-1: measuring apparatus. Geneva: International Electrotechnical Commission; 2019.
7. Ott HW. Electromagnetic compatibility engineering. Hoboken (NJ): John Wiley & Sons; 2009.
8. Williams T, Armstrong K. EMC for product designers. 5th ed. Oxford: Newnes; 2014.
9. RTL-SDR Blog. RTL-SDR V3 specifications and user guide. Hong Kong: RTL-SDR Blog; 2023.
10. GNU Radio Project. GNU Radio 3.10 documentation. GNU Radio; 2023.
11. Paul CR. Introduction to electromagnetic compatibility. 2nd ed. Hoboken (NJ): Wiley; 2006.
12. Braun S, Frech A, Russer P. Time-domain EMI measurement: different techniques and comparison. IEEE EMC Mag. 2011;1(1):50-58.
13. Comtest Engineering. Shielded room specifications and performance data. Zoetermeer: Comtest Engineering; 2022.
14. Joint Committee for Guides in Metrology. Evaluation of measurement data: guide to the expression of uncertainty in measurement (JCGM 100:2008). Geneva: BIPM; 2008.
15. Ossmann M, Spill D. Using software defined radio for practical EMC emission measurements. In: IEEE International Symposium on Electromagnetic Compatibility; 2017. p. 1-6.
16. Blakey J. Software defined radio for engineers. Boston: Artech House; 2018.
17. Schwarzbeck Mess-Elektronik. Antenna calibration and measurement uncertainty. Schönau: Schwarzbeck Mess-Elektronik; 2023.
18. Weston DA. Electromagnetic compatibility: methods, analysis, circuits, and measurement. 3rd ed. Boca Raton (FL): CRC Press; 2017.
19. Analog Devices. Software-defined radio for the masses, part 1. Analog Dialogue. 2020;54(1):1-6.