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SPREAD SPECTRUM MODULATION TECHNIQUE INVESTIGATION FOR PLL LESS CLOCK GENERATOR USING MATLAB/SIMULINK ENVIRONMENT

Electromagnetic interference (EMI) is a major design challenge in modern communication and embedded systems. Spread spectrum clock generation (SSCG) reduces peak EMI by spreading energy over a wider band via intentional, low-rate frequency modulation.

This paper presents the analytical foundations of SSCG, including detailed mathematical derivations for triangular and Hershey–Kiss (HK) modulation profiles and analyzes of main parameters that have impact on performance of EMI reduction.

To verify analytical approaches Matlab/Simulink model for spread spectrum clock generation system was developed. The model is based on approach of RC-based relaxation oscillator to which modulation signal applied. Developed model allow quickly evaluate commonly used modulation profiles (triangular, piecewise linear, Hershey-Kiss) and influence of modulation frequency, depth on EMI reduction level. To comply standards EMI receiver model is used for evaluation spectra of modulated signal. Accurate evaluation of electromagnetic interference (EMI) is essential for ensuring compliance with international standards such as CISPR, ISO, and FCC. While simple FFT-based spectrum analysis can provide a general view of signal spectra, it lacks the precision, repeatability, and standard-compliance required for EMI testing.

Comparative simulations of spectra for different modulation profiles shows that Hershey-Kiss profile the most effective, but require complex implementation in real hardware. Piecewise linear profile typically achieves greater peak reduction than linear triangular modulation at equal spread depth and modulation rate, while maintaining moderate level of complexity for implementation. The proposed model enables fast pre-silicon evaluation of SSCG parameters, offering guidelines for selecting optimal modulation strategies to balance EMI performance, implementation complexity, and regulatory compliance.

Key words: *EMI, spread spectrum, SSCG, triangular modulation, Hershey-Kiss modulation, piecewise linear profile, EMI receiver.*

Formulation of the problem. Electromagnetic Interference (EMI) is defined as emission from a device or a system that interrupt normal operation of the own or neighbor system. Emission could either being radiated (i.e. propagated through space) or conducted (i.e. propagated through a wires of ground, power or signal). EMI has become one of the most critical challenges in modern electronics and communication systems. As devices become faster, denser, and more integrated, they emit stronger harmonic components, increasing the risk of interference with nearby systems. The industry, therefore, faces the dual challenge – keep high data integrity and mitigate EMI to meet stringent regulatory standards for safety and performance.

EMI-related problems have received nowadays considerable attention, as proven by the presence of many international regulations, such as International Electrotechnical Commission (IEC), Society of Automotive Engineers (SAE) and the International Organization for Standardization (ISO) which are automotive Electromagnetic compatibility (EMC) standards [1]. Special Committee on Radio Interference (CISPR) 25 standard is to ensure that receivers used in vehicles such as boats and internal combustion engines are protected with compliance [2].

According to these regulations, EMC is meaning: the ability to fit the power spectrum of any interfering signal radiated/conducted by a circuit/system under a prescribed level; the ability of a circuit/system to be immune to incoming electromagnetic interference at a given level. In other words, any electronic equipment must not generate EMI above specified level, and must be not susceptible to EMI if it's below specified level. From stated above, the role of EMI source is not limited just to high power circuits and power transmission lines, but applicable for all circuits that have a non-negligible switching activity (for example any digital circuits have this switching activity). At the same time, this circuits are susceptible to interference, which can comprise signal integrity and even destroy correct application of circuit or system.

Classic and general purpose approaches for EMI reduction are about reduction between source and victim with shielding [3] or filtering [4]. Nevertheless, in many situations these approaches are not applicable, especially for mixed-mode and system-on-chip circuits, as in this case source and victim belong to the same integrated circuit [5, 6]. In this case, layout strategies can be applied to mitigate EMI, but all of them are case specific including particular applications.

A promising approach to addressing this issue is the use of spread spectrum modulation techniques, also known as dithering or spread spectrum clocking, firstly proposed in early 90s [7]. This technique can be applied to any circuit, that consist of non-negligible switching activity, such as digital circuits, switching power converters, communication protocols and can significantly reduce power density of transmitted signals, minimize potential for interference with other electronic systems. By deliberately spreading the signal's spectral energy over a wider frequency band, spread spectrum modulation reduces peak emission levels and ensures better compliance with EMI standards – without requiring additional hardware filtering. This capability is particularly important in the automotive sector, where the dense and complex electronic environment can exacerbate the effects of EMI. Robust, EMI-resistant communication is essential for advanced driver-assistance systems (ADAS), infotainment, and other critical vehicle functions. Using spread-spectrum modulation to improve EMI performance is both a practical necessity and a driver of technological advancement: it delivers more reliable in-vehicle data transfer and deepens the scientific basis of EMI mitigation, ultimately improving safety, efficiency, and the user experience.

Another problem is that design of spread spectrum clock generator (SSCG) not trivial task. The relationship between modulation profile, deviation (depth), and rate on one side, and the measured EMI reduction under CISPR receiver settings (resolution bandwidth, detector type) plus the induced timing/jitter penalties on the other, is highly nonlinear and platform-dependent. Therefore, a reproducible, configurable clock-generator model with spread spectrum is needed to support multiple modulation profiles (triangular, sinusoidal, Hershey–Kiss, random) and center/down/up spread modes. Also possibility to map time-domain parameters to frequency-domain compliance metrics (peak/quasi-peak vs. resolution bandwidth) and signal-integrity metrics (period and cycle-to-cycle jitter) is important during development cycle. Finally yet importantly, benefit from model is ability to enable pre-silicon exploration of EMI vs. timing trade-offs for different communication protocols. Such a model reduces hardware iteration risk, accelerates standards compliance, and yields practical guidelines for selecting SSCG parameters in required data-transmission systems.

Analysis of recent research and publications. In recent years, spread spectrum techniques have been used in many applications to improve electromagnetic interference (EMI), such as class D amplifiers [8], microprocessor clock generators [9], LCD display panels [10]. Also this technique has been adopted in lot of communication protocols like Serial ATA, Display Port and PCI Express.

Won-Young Lee and Lee-Sup Kim [11] propose a spread spectrum clock generator for DisplayPort main link. Their solution based on PLL implementation with two possible frequencies of operation, with controllable spreading of output frequency, but frequency of modulation fixed on 33kHz. And also modulation depth is limited.

Hyuk Ryu et al. [12] presents a fractional N phase-locked loop based spread spectrum clock generator (SSCG) using programmable linear frequency modulator. The SSCG provides a programmable frequency deviation and modulation frequency with triangular profile regardless of its operation frequency. The ranges of frequency deviation ratio and modulation frequency are 0-80% and 0-100kHz, and operation frequency configurable from 400MHz to 2GHz. The proposed solution support serial-link standards such as SATA, Display Port, PCI Express and can be applied to various switching circuits such as Class-D power amplifiers or switching converters.

Ray A. et al. introduce an active EMI cancellation technique that achieves a significant reduction in conducted EMI of LIN drivers, demonstrating the effectiveness of active methods in automotive contexts [13]. The proposed active EMI cancellation circuit synthesizes a phase synchronized cancellation pulse which is then injected onto the LIN driver output using an on-chip tunable capacitor array to cancel the switching noise injected via substrate. The proposed EMI reduction technique can track and cancel substrate noise independent of process technology and device parasitics, input voltage, duty cycle and loading conditions of the DC-DC switching regulator.

Minyoung Song et al. [14] propose piecewise linear modulation profile that can significantly reduce EMI with relatively simple implementation. The proposed solution based on PLL with sigma-delta modulator to provide spread spectrum modulation. Output frequency is fixed for 2 cases, modulation frequency and depth also have just few fixed options.

In-Young Lee et al. [15] presents a robust spur reduction technique using a switched-capacitor feedback differential phase-locked loop (PLL) and a delay-locked-loop (DLL)-based spread-spectrum clock generation in a UHF-band RF identification transmitter (TX). The proposed differential PLL is characterized by adopting a switched-capacitor common-mode feedback and distributed varactor biasing scheme to the differential charge pump and voltage-controlled oscillator designs, respectively, which results in down to 94 dBc in reference spur rejection with all digital parts off. Additionally, by adopting an 8-bit DLL and Hershey-Kiss modulated profile together, the proposed spread-spectrum clock generator shows more than 20-dB electromagnetic-interference reduction while providing up-, down– , and center-spread modes.

Hong-Yi Huang et al. [16] proposed a PLL-less realization of spread spectrum clock generator with triangular profile. The problem here – relatively low frequency of operation, 65kHz, that is not relevant for most modern applications.

Mei-Ling Yeh et al. [17] proposed relaxation oscillator architecture with dual sawtooth modulation profile.

X. Wu et al. [18] presents also relaxation oscillator, but charging and discharging current of oscillator change randomly in the set range, which allow to get better EMI reduction. Also proposed solution has option of configuration of output frequency and modulation depth.

Another important part of investigation is a developing model for spread spectrum clock generation systems for fast evaluation performance of EMI reduction and developing and checks of new modulation profiles and parameters. W. A. Ayoub et al. [19] describes a developed Simulink model for PLL based SSCG with sigma delta modulator that provides triangular modulation profile. Model allows to configure modulation profile's parameters such as depth, frequency and evaluate impact of them on EMI reduction level.

S. Rajamanickam et al. [20] propose MATLAB based program for spread spectrum modulation technique evaluation with several modulation parameters, profiles, including test measurement setup in EMI analysis for DC-DC converters.

Selection of previously unresolved parts of the general problem. Despite the fact that spread spectrum technique topic already well studied, there remains a need for further research to develop spread spectrum clock generation system with architecture that allow different configuration of output frequency, modulation profiles and parameters. The studies mentioned above highlights that for fast protocols, spread spectrum clocking is typically integrated with PLL. However, it's challenging due to fact that PLL bandwidth must be carefully designed to avoid jitter amplification. It's also require advanced digital control loops, carefully balancing between EMI reduction and signal integrity. All of this come to high complexity of overall system.

For slower communication protocols like SPI, I2C, RS-232, RS-485, CAN, LIN the constraints are less strict, which give more freedom in developing spread spectrum clock generator. Lower operating frequencies in range of tens of MHz, give opportunity to develop fully analog solution with configurable profile, depth, frequency of modulation. And from literature study this part of topic not covered well.

Another problem that require additional investigation is in need to develop well defined model of oscillator that reflect real architecture of clock generator including part that is responsible for spread spectrum modulation.

The purpose of this article is to investigate the effectiveness of different modulation profiles and their parameters in spread spectrum modulation technique and their impact on EMI performance. The article seeks to identify the optimal parameters for spread spectrum techniques that can reduce electromagnetic interference while maintaining low complexity of implementation.

To achieve this aim, the article sets the following *objectives*:

1. Conduct a review of current methods and approaches to spread spectrum techniques used to mitigate EMI in data transmission systems.

2. Identify most commonly used modulation profiles and their parameters, and analyze their impact on EMI reduction level.

3. Develop a model of clock generator with configurable spread spectrum modulation that mimic real operation of oscillator and include EMI measurement unit according to standards.

4. Perform modeling and experimental studies to asses the impact of various modulation profiles and parameters on EMI performance.

5. Analyze the obtained results and provide recommendations for the optimal selection of spread spectrum modulation profiles and parameters depending on requirements.

Basic principles of spread spectrum modulation technique. Any digital circuits or switching converters have narrow-band characteristics of the spectrum of their typical signals, for which energy mainly located around fundamental tone and its harmonics. Spread spectrum techniques reduce EMI by lowering the power of main tone at the cost of adding additional spectrum components in some frequency band. This is achieved by introducing in time domain a controlled jitter in the reference clock signal by changing instantaneous working frequency (Figure 1).

Modulation is the process of modifying the characteristics of a carrier wave by another signal to achieve certain advantages. This process is widely used in telecommunications for information transmission. The carrier characteristics that are modulated usually include amplitude and/or angle (phase or frequency). A simple modulator can vary the carrier's characteristics in proportion to the modulating waveform (analog modulation). More sophisticated modulators first convert the modulating signal into a digital format and encode it (digital modulation). The modulator can be represented as a "black box" with three inputs and one output (Fig. 2).

In the modulation process three signals and one parameter are involved:

– Carrier frequency $f_c(t)$: a periodic waveform with constant frequency f_c and a constant amplitude profile;

– Modulating signal $\xi(t)$: the waveform responsible for changing (modulating) the original constant characteristics of the carrier;

– Δf_c : parameter; which response for frequency deviation;

– Modulated output signal F(t): the waveform that results from the modulation process.

As a result output modulated signal F(t) can be represented as follow:

$$F(t) = A_0 \cos\left(2\pi f_c t + 2\pi\Delta f_c \int_{-\infty}^{t} \xi(\tau)d\tau\right) \quad (1)$$

where f_c – carrier frequency;

Δf_c – carrier frequency deviation;

A_0 – amplitude of the signal;

$\xi(t)$ – normalized driving signal, $-1 \le \xi(t) \le 1$.

The power of F(t) is unchanged with respect to unmodulated signal power and equal to $\frac{A_0^2}{2}$, and it is approximately consists of in the Carson's bandwidth [21] (2):

$$B = 2 \cdot f_m \cdot (1 + m_f) = 2 \cdot (\Delta f_c + f_m) \quad (2)$$

where f_m – frequency of modulating signal;

m_f – modulation index.

Modulation index is defined as ratio of carrier frequency deviation to frequency of modulating signal (3):

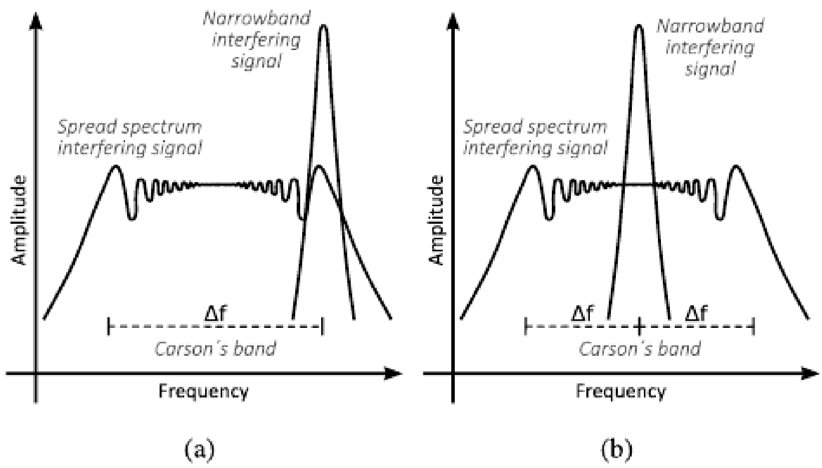

Fig. 1. Illustration of comparison between the power spectra of an unmodulated narrow-band interfering signal and of a spread spectrum modulated one: a – down-spread modulation; b – center-spread modulation

$$m_f = \frac{\Delta fc}{fm}, \tag{3}$$

Also important parameter that characterize spread spectrum modulation is modulation depth or modulation coefficient (4):

$$\delta = \frac{\Delta fc}{fc} \ (or\ \delta\% = (\frac{\Delta fc}{fc}) \cdot 100) \tag{4}$$

For fast link communication protocols like SATA, Display Port or PCI Express modulation depth is not more than 2.5% typically due to high timing requirements at high data rate. But for slower communication protocols this parameter could be bigger up to 10-15%, which is increase a performance of EMI reduction.

Considering square signal to which frequency modulation applied, it's equal to applying (1) to each signal harmonics, taking into account that the *n*th harmonic is spread within the bandwidth of amplitude $2n\Delta f_c$.

Modulation index m_f define spread of spectrum and amplitude of carrier frequency power. Assuming modulation index is small ($m_f = \Delta f_c * T_m$), only a few among of the resulted components are part of spectrum bandwidth which is interested. From other side, when modulation index is large, the resulted spectrum of F(t) has many components very close to each other in Carson's bandwidth, which is better for EMI reduction. But in practical implementation there are limitations for minimum and maximum modulation frequency and modulation depth.

For the frequency modulation reduction in EMI could be expressed as [22] :

$$\gamma = -10 log\omega_c + 10\log\omega_m - 10\log\delta + 3(dB) \tag{5}$$

From (5) EMI reduction coefficient depend on carrier frequency ω_c, modulation frequency ω_m, and modulation depth δ.

The key parameter that determines the shape of the resulting modulated spectrum is closely tied to the modulation profile, i.e., the waveform used for modulation. In practice, three profiles are commonly used for modulation: sinusoidal, triangular (including modifications of it like sawtooth or piecewise linear) , and exponential, also known as Hershey-Kiss. (fig. 3) [23].

In table 1 mathematical representation of commonly used profiles are presented.

The latter provides a very flat spectral characteristic, maximizing harmonic suppression. Sinusoidal modulation is simpler to analyze but not optimal. A

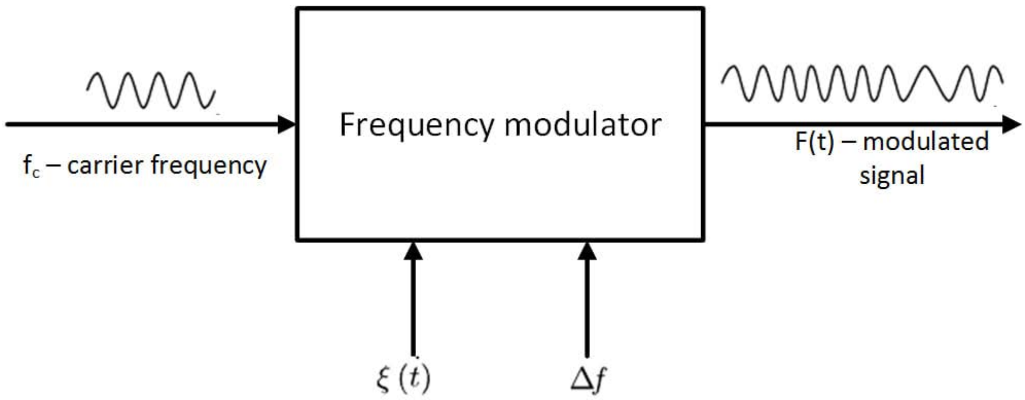

Fig. 2. Model of the frequency modulator

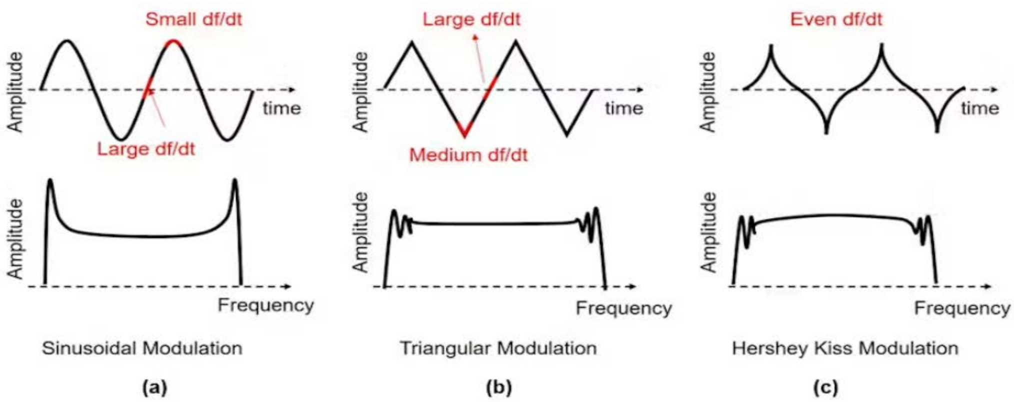

Fig. 3. Modulation profiles representation and their power spectrum

Table 1

Sinusoidal, triangular and exponential modulation profiles mathematical representation, where f_m and T_m are the modulating signal frequency and period, respectively

Sinusoidal	Triangular (with symmetry index, k_T)	Exponential (with concavity coefficient, p)
$\xi(t) = \sin(2\pi f_m t)$	$\xi(t) = \begin{cases} \frac{2}{k_T} * f_m t, & 0 \le t \le \frac{k_T T_m}{2} \\ \frac{1}{1-k_T} * (1 - 2f_m t), & \frac{k_T T_m}{2} \le t \le \left(1 - \frac{k_T}{2}\right) * T_m \\ \frac{2}{k_T} * (f_m t - 1), & \left(1 - \frac{k_T}{2}\right) * T_m \le t \le T_m \end{cases}$	$\xi(t) = \begin{cases} \frac{1}{e^{\frac{p}{4f_m}} - 1} * (e^{pt} - 1), 0 \le t \le \frac{T_m}{4} \\ \frac{1}{e^{\frac{p}{4f_m}} - 1} * (e^{\frac{p}{2f_m}} * e^{-pt} - 1), \frac{T_m}{4} \le t \le \frac{T_m}{2} \\ \frac{1}{e^{\frac{p}{4f_m}} - 1} * (1 - e^{-\frac{p}{2f_m}} * e^{pt}), \frac{T_m}{2} \le t \le \frac{3T_m}{4} \\ \frac{1}{e^{\frac{p}{4f_m}} - 1} * (1 - e^{\frac{p}{f_m}} * e^{-pt}), \frac{3T_m}{4} \le t \le T_m \end{cases}$

triangular waveform is often used as a good compromise. Triangular profile is the simplest and most common SSCG profile: the clock frequency ramps linearly from a minimum to a maximum, then linearly back, spreading harmonic energy over a wider band and lowering peak amplitudes. It's easy to implement, yields a relatively uniform spread, and is widely used to cut EMI from system clocks. A skew parameter k_T (0–1) shifts the break point within the half-period, allowing a seamless transition from symmetric triangle to sawtooth.

Exponential or Hershey-Kiss profile is more complex than triangular/sawtooth. The slope is shallow near the center frequency and steeper at the band edges, pushing more dwell toward the edges to better disperse high-harmonic energy. Variants such as Hershey-Kiss typically deliver the largest peak EMI reduction and a more even energy distribution, but they're harder to realize due to the required nonlinear modulation (specialized circuitry or DSP).

Matlab/Simulink model implementation and simulation. As mentioned above, spread spectrum modulation have different parameters and modulation profiles. During design phase it is important to have a quick check of influence of selected parameters for performance of systems and also a level of EMI reduction. For this purpose the model in which parameters can be tuned and evaluated quickly is needed.

As a core of oscillating block the relaxation RC based architecture is selected. The block diagram is showed on Fig. 4 [24].

This solution is easy to implement, not sensitive to element mismatch and allow changing operation frequency simply by changing RC time constant. Also this oscillator selected as reference for investigation of spread spectrum technique due to possibility to implement frequency modulation without effort, just by modifying bias current, that set reference frequency.

This oscillator consists of startup circuitry (which can be ignored for now), bias current generator, integrator, voltage-to-current converter, current comparison circuit and some output logics with latch.

Proposed model, implemented in Matlab/Simulink shown on Fig. 5. In this model to guarantee RC-only frequency choose the V-to-I and bias scaling so that the current comparator trips exactly when V_{INT} reached a fixed V_{GS} -equivalent, and make that "fixed" cancel via device matching. In model this can be done by setting Voltage-to-current converter gain $k_{VI} = I_B/V_{th}$. To set carrier frequency the value of IB2 and IB3 blocks, which are references for current comparators, should be set to proper value. Also model has spread spectrum modulation, which is implemented by block "Modulator". This block implement frequency modulation as described in (1). Modulation profiles generated by Matlab script and can be easily configured. In the developed model added EMI Receiver model [25] due to the fact that EMI levels should be measured according to standards [2]. Using a dedicated EMI receiver instead of a simple FFT analysis is crucial when measuring electromagnetic interference in

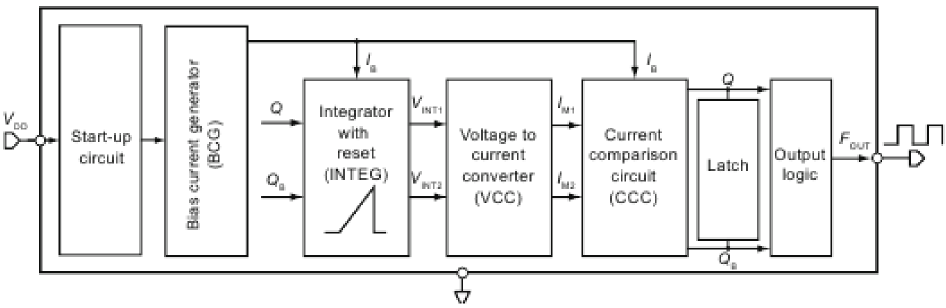

Fig. 4. Block diagram of RC based relaxation oscillator

compliance with international standards (e.g., CISPR, ISO, FCC). Unlike a basic FFT spectrum analyzer, an EMI receiver provides: standard-compliant measurements – EMI receivers implement specific detector types (peak, quasi-peak, and average) and resolution bandwidths required by standards, while FFT cannot replicate these accurately; better dynamic range and sensitivity – EMI receivers are optimized to detect very low-level emissions even in the presence of strong neighboring signals; preselection filtering – they include hardware filters to suppress out-of-band signals, preventing measurement errors common in FFT-based approaches; repeatability and certification readiness – results from EMI receivers are accepted in official compliance testing, while simple FFT data is often insufficient for regulatory approval.

In developed model modulation profile could be configurable to triangular with different value of symmetry index k_T, Hershey-Kiss, piecewise linear. Also in model easy to adjust carrier frequency f_c, modulation frequency f_m, modulation depth δ and modulation index m_f. To be complaint with standards EMI Receiver model added. Proposed model of oscillator could be easy portable to schematic as it's mimic real operation. Also model could be improved to reflect parasitic effects, like noise, delays, element mismatch.

The developed model was verified at frequency of 4MHz. For doing that capacitance value, that sets a frequency, was selected C_ramp = 500fF. From RC-time constant value for resistance was calculated as 250kOhms. Threshold voltage was selected 0.7V, because real values of threshold voltages for MOS and bipolar transistors are in this range. As a result calculated value of bias current IB equal to 2.8uA, and voltage to current converter gain kVI equal to 4 uA/V.

The setup of EMI receiver model was done accordingly to standard [2]. Resolution bandwidth

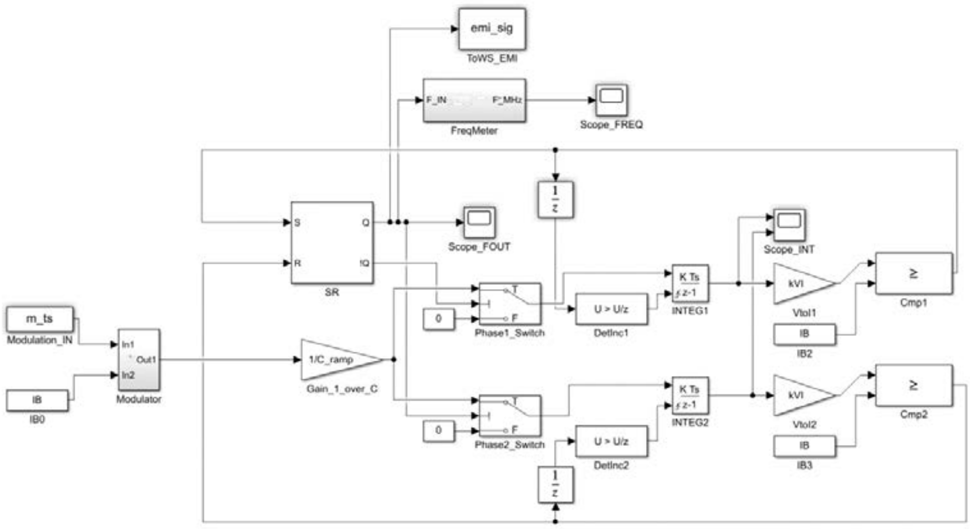

Fig. 5. Proposed model of oscillator including spread spectrum modulation

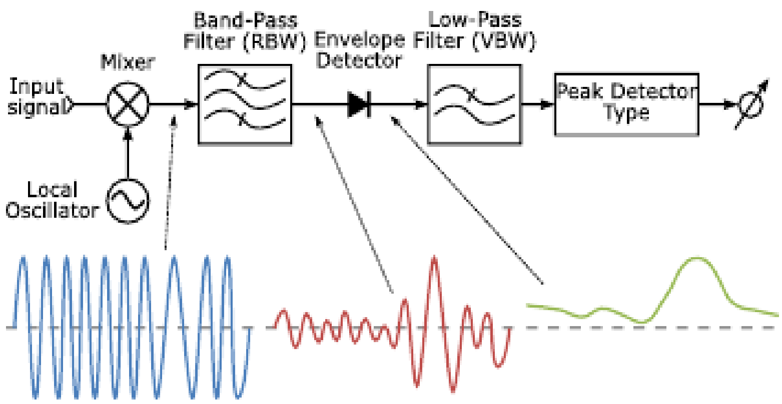

Fig. 6. Simplified block diagram of an analog spread spectrum analyzer (EMI receiver)

(RBW) was set to 9kHz, frequency band adjusted from 33kHz to 30MHz as specified. Frequency step was selected as 1kHz just to have enough resolution and as a compromise between simulation time and accuracy.

The simulation results of developed model of spread spectrum generation clock system are illustrated on figures 7-10. On figure 7 the spectrum of non-modulated clock signal is shown.

From this figure we see narrow-band carrier signal at frequency 4MHz and its harmonics. On carrier frequency the magnitude of signal is approximately -1dB, this is due to fact that EMI Receiver has built-in low-pass filter.

On the figure 8 a spectrum of modulated by triangular profile signal is shown. The symmetry index of k_T is selected as 0.5, which is equal to normal triangular wave. Modulation depth is selected as 10%, modulation frequency f_m equal 10kHz, and as a result modulation index m_f equal to 40. Resulted signal spectrum shows flat spectrum around Carson's bandwidth, with magnitude – 16.7dB, which equal to EMI reduction level, with this modulation profile and parameters. Also reduction of magnitude could be seen at the harmonics.

On the figure 9 a spectrum of modulated by piecewise linear profile signal is shown. The symmetry index of k_T is selected as 0.5. During rising edge three different slopes applied, which is configured inside model and could be adjusted, falling edge is symmetrical. All other parameters keep the same. With this modulation profile and parameters, resulted signal spectrum shows not so flat spectrum around Carson's bandwidth, but peak reduction is around 17dB, with even more reduc-

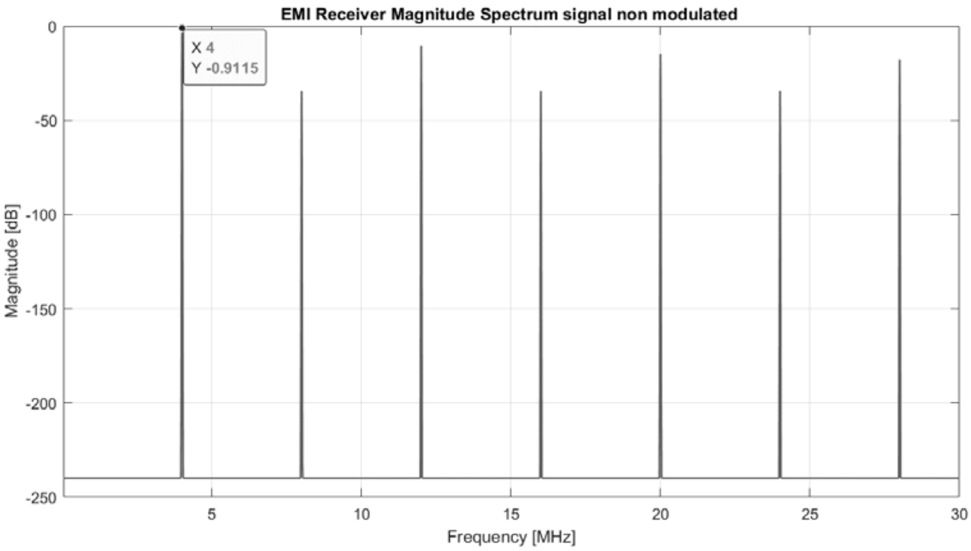

Fig. 7. Spectrum of non-modulated signal after EMI Receiver

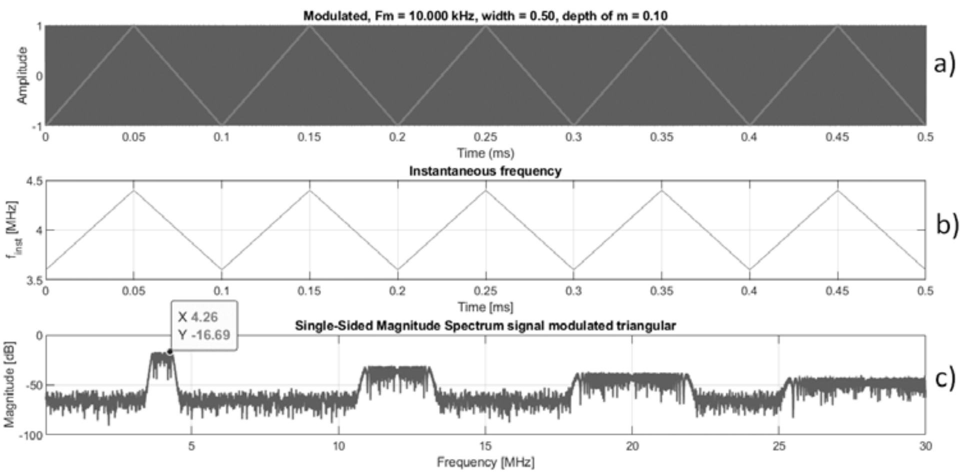

Fig. 8. Modulated by triangular profile with symmetry index 0.5 resulted signal: a) resulted and modulation signals in time domain; b) instantaneous frequency of modulated signal in time domain; c) resulted spectrum after EMI receiver

tion at carrier frequency up to -20dB. Also reduction of magnitude could be seen at the harmonics.

On the figure 10 a spectrum of modulated by Hershey-Kiss profile signal is shown. The envelope coefficient p is selected as 6, but could be configured inside model and could be adjusted. All other parameters keep the same. With this modulation profile and parameters, resulted signal spectrum shows the most flat spectrum around Carson's bandwidth, peak level reduction is -17.2dB, and at the carrier frequency reduction level achieve around -20dB level.

All of the performed simulations show expected theoretical behavior and look promising in terms of mitigation EMI.

The resulted behavior with performance metrics are summarized in table 2. Taking in to account complexity of realization of Hershey-Kiss modulation profile, which require complex digital control circuits, piecewise linear modulation profile looks promising to implement in spread spectrum clock generation systems, as performance in reduction EMI level is comparable with Hershey-Kiss profile. But for some application triangular profile could also be implemented, as doesn't require complex circuits for generating modulation signal.

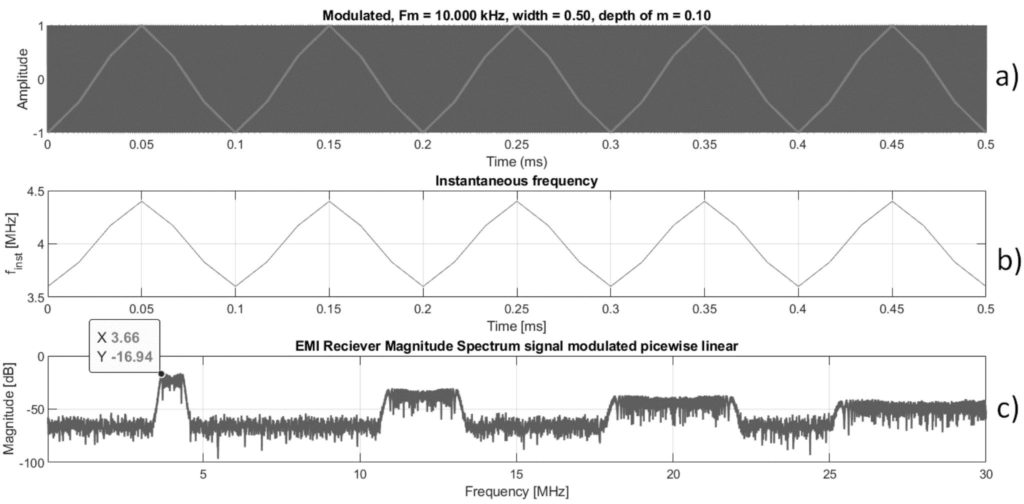

Fig. 9. Modulated by piecewise linear profile with symmetry index 0.5 resulted signal: a) resulted and modulation signals in time domain; b) instantaneous frequency of modulated signal in time domain; c) resulted spectrum after EMI receiver

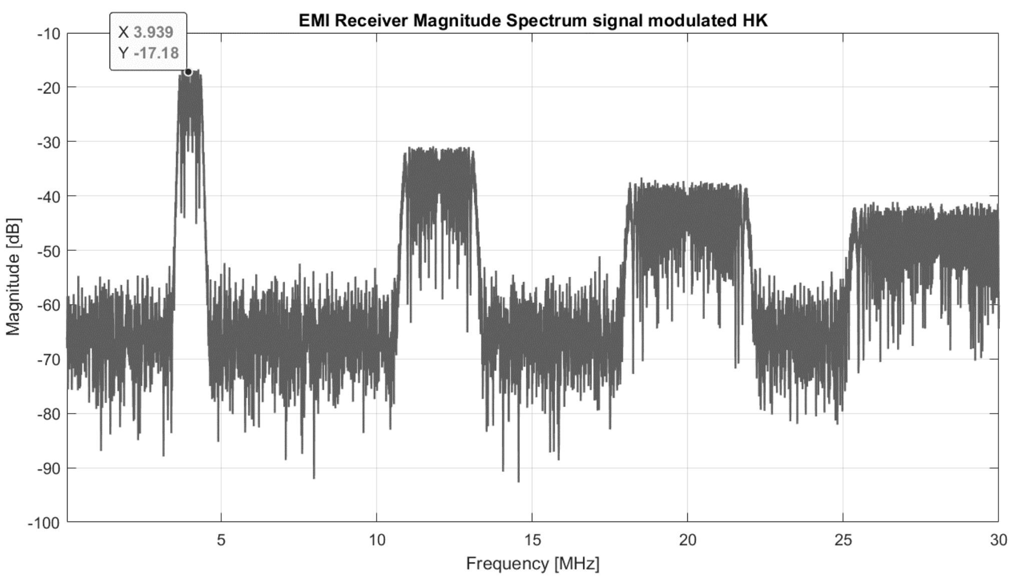

Fig. 10. Modulated by Hershey-Kiss profile with concavity coefficient equal to 6 resulted signal

Table 2

EMI reduction level for triangular, piecewise linear and Hershey-Kiss modulation profiles in spread spectrum clock generator

Modulation shape	Peak EMI Reduction	Complexity of implementation
No modulation	~ -1 dB	Basic
Triangular	-16.7 dB	Low
Piecewise linear	-20 dB	Medium
Hershey-Kiss	-20 dB	High

Conclusions. In conducted study the use of spread spectrum modulation technique is investigated in terms of improvement electromagnetic compatibility performance in data transmission systems. It could be stated that it's promising approach with significant potential to enhance the reliability and efficiency of modern communication systems. By expanding the signal spectrum, the power density of the transmitted signal is reduced, minimizing the likelihood of interference with other electronic systems.

The theoretical basic principles of spread spectrum modulation were analyzed and main parameters were derived. It can be stated, that level of reduction in EMI depends on modulation profile type, modulation frequency and depth.

Theoretical results were proved by model in Matlab/Simulink environment. Developed model for spread spectrum clock generation system allow to predict EMI levels and compare performance for different modulation profiles with adjustable parameters. This is useful during developing real system to make fast exploration of spread spectrum modulation parameters and achieve required levels of EMI suppressions.

From the conducted simulations, it could be stated that Piecewise linear modulation profile looks like the most optimal for hardware implementation as it gives uniform spectrum in Carson's bandwidth and peak level of reduction up to -20dB simultaneously have moderate level of complexity for implementation comparing to Hershey-Kiss profile, which is comparable in terms of performance, but require much more complex implementation in hardware.

Further study could be aimed to firstly optimize parameters for piecewise linear modulation profile. Also model of oscillator could be improved in terms of different parasitic effects that present in hardware implementation like noise, propagation delays, component mismatches. Lastly more complex modulation profiles could be added to model for further investigation of performance in EMI reduction. Random and pseudo random modulation profiles look promising in terms of investigation using developed model.

Bibliography:

1. Code of Federal Regulations 47 (47CFR), Part 15, Subpart B:Unintentional Radiators. URL: http://www.ecfr.gov/ (дата звернення: 01.09.2025).
2. CISPR 25:2021: Vehicles, boats and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of on-board receivers. URL: https://webstore.iec.ch/en/publication/64645 (дата звернення: 01.09.2025).
3. Li M., Nuebel J., Drewniak J., Dubroff R., Hubing T., Van Doren T. (2000). EMI from cavity modes of shielding enclosures – FDTD modeling and measurements. *IEEE Transactions on Electromagnetic Compatibility*. 2000. Vol. 42. P. 29–38. DOI: 10.1109/15.831702.
4. Hartmann M., Ertl H., Kolar J.W. (2011). EMI filter design for a 1 MHz, 10 kW three-phase/level PWM rectifier. *IEEE Transactions on Power Electronics.* 2011. Vol. 26, № 4. P. 1192–1204. DOI: 10.1109/TPEL.2010.2070520.
5. Sudo T., Sasaki H., Masuda N., Drewniak J.L. (2004). Electromagnetic interference (EMI) of system-on-package (SOP). IEEE Transactions on Advanced Packaging. 2004. Vol. 27, № 2. P. 304–314. DOI: 10.1109/TADVP.2004.828817.
6. Ramdani M., Sicard E., Boyer A., Ben Dhia S., Whalen J., Hubing T., Coenen M., Wada O. (2009). The electromagnetic compatibility of integrated circuits – past, present, and future. IEEE Transactions on Electromagnetic Compatibility. 2009. Vol. 51. P. 78–100. DOI: 10.1109/TEMC.2008.2008907.
7. Lin F., Chen D.Y. (1994). Reduction of power supply EMI emission by switching frequency modulation. IEEE Transactions on Power Electronics. 1994. Vol. 9, № 1. P. 132–137. DOI: 10.1109/63.285504.
8. Ming X., Chen Z., Zhou Z.-k., Zhang B. (2011). An advanced spread spectrum architecture using pseudo-random modulation to improve EMI in class D amplifier. IEEE Transactions on Power Electronics. 2011. Vol. 26. P. 638–646. DOI: 10.1109/TPEL.2010.2063440.
9. Chang H.-H., Hua I.-H., Liu S.-I. (2003). A spread-spectrum clock generator with triangular modulation. IEEE Journal of Solid-State Circuits. 2003. Vol. 38, № 4. P. 673–676. DOI: 10.1109/JSSC.2003.809521.
10. Kim M.-W., Kim D.-W., Koo B.-S., Kim Y.-B., Choi O.-S., Kim N.-D. (2009). Chip level techniques for EMI reduction in LCD panels. Proceedings of the 20th International Zurich Symposium on Electromagnetic Compatibility. Zurich, Switzerland, Jan. 2009. P. 441–444. DOI: 10.1109/EMCZUR.2009.4783485.

11. Lee W.-Y., Kim L.-S. (2011). A spread spectrum clock generator for DisplayPort main link. IEEE Transactions on Circuits and Systems II: Express Briefs. 2011. Vol. 58. P. 361–365. DOI: 10.1109/TCSII.2011.2149670.

12. Ryu H., Park S., Sung E.-T., Lee S.-G., Baek D. (2015). A spread spectrum clock generator using a programmable linear frequency modulator for multipurpose electronic devices. IEEE Transactions on Electromagnetic Compatibility. 2015. Vol. 57. P. 1447–1456. DOI: 10.1109/TEMC.2015.2442618.

13. Ray A., et al. (2022). An active EMI cancellation technique achieving a 25-dB reduction in conducted EMI of LIN drivers. IEEE Transactions on Circuits and Systems I: Regular Papers. 2022. Vol. 69, № 9. P. 3829–3840. DOI: 10.1109/TCSI.2022.3187068.

14. Song M., Ahn S., Jung I., Kim Y., Kim C. (2013). Piecewise linear modulation technique for spread spectrum clock generation. IEEE Transactions on Very Large Scale Integration (VLSI) Systems. 2013. Vol. 21. P. 1234–1245. DOI: 10.1109/TVLSI.2012.2210290.

15. Lee I.-Y., Kim S., Lee S.-S., Choi J., Ko J., Lee S.-G. (2015). Spur reduction techniques with a switched-capacitor feedback differential PLL and a DLL-based SSCG in UHF RFID transmitter. IEEE Transactions on Microwave Theory and Techniques. 2015. Vol. 63, № 4. P. 1202–1210. DOI: 10.1109/TMTT.2015.2405536.

16. Huang H.-Y., Palencia G.F., Chen D.-K., Huang W.-H. (2015). Triangular modulation using switched-capacitor scheme for spread-spectrum clocking. 2015 IEEE 18th International Symposium on Design and Diagnostics of Electronic Circuits & Systems (DDECS). Belgrade, Serbia, 2015. P. 87–90. DOI: 10.1109/DDECS.2015.41.

17. Yeh M.-L., Liou W.-R., Hsieh H.-P., Lin Y.-J. (2010). An electromagnetic interference (EMI) reduced high-efficiency switching power amplifier. IEEE Transactions on Power Electronics. 2010. Vol. 25, № 3. P. 710–718. DOI: 10.1109/TPEL.2009.2035622.

18. Wu X., Yang B., Wei Q., Li P. (2024). Current spread spectrum clock oscillator with adjustable output mode. 2024 International Conference on Electronic Components and Integrated Engineering (ECIE). 2024. P. 70–76. DOI: 10.1109/ECIE61885.2024.10627468.

19. Ashraf Ayoub W., Dessouky M., Sharaf K. (2010). Modeling of spread-spectrum clock generation system using Simulink. International Conference on Microelectronics : proceedings, Cairo, Egypt, 2010. P. 88–91. DOI: 10.1109/ICM.2010.5696213.

20. Rajamanickam, Sivanyanam. (2020). Spread spectrum modulation investigation using MATLAB developed tool on automotive DC-DC converter. International Journal of Advanced Trends in Computer Science and Engineering. Vol. 9. P. 6631-6639. DOI: 10.30534/ijatcse/2020/355942020.

21. H. S. Black, Modulation Theory. Bell Telephone Laboratories series. New York, NY, USA: Van Nostrand, 1953. 363p.

22. Xia, T. (2012). Analytic model for spread-spectrum clock generator circuit characterization. International Journal of Circcuit Theory and Applications. Vol. 40, №6. P. 617-626. DOI: https://doi.org/10.1002/cta.746

23. FAQ on spread spectrum for switching-supply EMI management Part 2: details. URL: https://www.analogictips.com/faq-on-spread-spectrum-for-switching-supply-emi-management-part-2-details/ (дата звернення: 21.05.2025).

24. H. Asano *et al*. (2016). A fully integrated, 1-μs start-up time, 32-MHz relaxation oscillator for low-power intermittent systems. *14th IEEE International New Circuits and Systems Conference (NEWCAS)*. Vancouver. BC. Canada. 2016. P. 1-4, DOI: 10.1109/NEWCAS.2016.7604819.

25. MATLAB/Octave function to evaluate time-domain signals according to the measurement bandwidth and average/peak detector of EMI test receivers Virtual EMI test receiver. (Version 1.0.0). A. Bendicks. URL: https://www.mathworks.com/matlabcentral/fileexchange/109119-virtual-emi-test-receiver (дата звернення: 21.05.2025).

Цимбал О.В., Антонюк О.І. ДОСЛІДЖЕННЯ ТЕХНІКИ МОДУЛЯЦІЇ З РОЗШИРЕННЯМ СПЕКТРА ДЛЯ ГЕНЕРАТОРА ТАКТОВИХ СИГНАЛІВ БЕЗ PLL У СЕРЕДОВИЩІ MATLAB/SIMULINK

Електромагнітні завади (EMI) є однією з основних інженерних проблем у сучасних комунікаційних та вбудованих системах. Технологія генерації тактових сигналів із розширенням спектра (SSCG) дозволяє зменшити піковий рівень EMI шляхом розподілу енергії сигналу на ширший частотний діапазон за допомогою навмисної низькочастотної модуляції.

У статті представлено аналітичні основи SSCG, включаючи детальні математичні виведення для трикутного та Hershey–Kiss (HK) профілів модуляції, а також аналіз основних параметрів, що впливають на ефективність зменшення EMI. Для перевірки аналітичних результатів було розроблено модель у середовищі Matlab/Simulink на основі RC-релаксаційного генератора з можливістю підключення різних модулюючих сигналів. Створена модель дає змогу швидко оцінювати поширені профілі модуляції (трикутний, кусково-лінійний, Hershey-Kiss) та досліджувати вплив частоти та глибини модуляції на рівень зменшення EMI.

Для відповідності міжнародним стандартам (CISPR, ISO, FCC) у модель інтегровано віртуальний EMI-приймач для точного аналізу спектра модульованих сигналів. Звичайний спектральний аналіз на основі FFT надає лише загальне уявлення про спектр, але не забезпечує необхідної точності, повторюваності та відповідності стандартам.

Порівняльне моделювання показало, що профіль Hershey-Kiss забезпечує найкраще зниження пікових рівнів EMI, але вимагає складної апаратної реалізації. Кусково-лінійний профіль досягає близьких результатів зі значно простішою апаратною реалізацією та перевершує класичну трикутну модуляцію при однакових параметрах розширення спектра.

Запропонована модель забезпечує швидку оцінку параметрів SSCG, пропонуючи практичні рекомендації щодо вибору оптимальних стратегій модуляції для досягнення балансу між ефективністю зменшення EMI, складністю реалізації та відповідністю міжнародним стандартам.

Ключові слова: *електромагнітні завади, модуляція розширеним спектром, трикутна модуляція, Hershey-Kiss модуляція, кусково-лінійний профіль, EMI приймач.*

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