

20TH INTERNATIONAL CONFERENCE on Communications, Electromagnetics and Medical Applications (CEMA'26)

Sofia, Bulgaria
19th – 20th October, 2026



Organized by:
Faculty of Telecommunications of TU-Sofia, Bulgaria



NATIONAL
TECHNICAL UNIVERSITY
OF ATHENS,
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SCHOOL OF
ELECTRICAL AND
COMPUTER ENGINEERING



PROCEEDINGS

OF 20TH INTERNATIONAL CONFERENCE ON
COMMUNICATIONS, ELECTROMAGNETICS AND MEDICAL
APPLICATIONS (CEMA'26)



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SCHOOL OF ELECTRICAL
AND COMPUTER
ENGINEERING

Sofia, Bulgaria
19th-20st October, 2026

KING 2001, Sofia

Edited by Prof. Dr. Eng. **Dimiter Tz. Dimitrov**

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ISSN: 1314-2100

SCOPUS Indexing <http://suggestor.step.scopus.com/progressTracker>, ID: 6B4F77263D276412.

Printed in Bulgaria
KING 2001, Sofia



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Dear Colleagues,

It is our privilege to thank all of you for your contributions submitted at 20th regular International Conference on 'Communication, Electromagnetic and Medical Applications' CEMA'26. This is a conference which should help future collaboration in the area of engineering, especially in the area of communication technologies and medical applications. This is an important scientific event not only in Balkan region, but in Europe, also. The International Conference on Communication, Electromagnetism and Medical Applications CEMA'26 is dedicated to all essential aspects of the development of global information and communication technologies, and their impact in medicine, as well. The objective of Conference is to bring together lecturers, researchers and practitioners from different countries, working on the field of communication, electromagnetism, medical applications and computer simulation of electromagnetic field, in order to exchange information and bring new contribution to this important field of engineering design and application in medicine. The Conference will bring you the latest ideas and development of the tools for the above mentioned scientific areas directly from their inventors. The objective of the Conference is also to bring together the academic community, researchers and practitioners working in the field of Communication, Electromagnetic and Medical Applications, not only from all over Europe, but also from America and Asia, in order to exchange information and present new scientific and technical contributions.

Many well known scientists took part in conference preparation as members of International Scientific Committee or/and as reviewers of submitted papers. We would like to thank all of them for their efforts, for their suggestions and advices.

On behalf of the International Scientific Committee, we would like to wish you successful presentations of your papers, successful discussions and new collaborations for your future scientific investigations.

Engineering and medicine should provide high level of living for all people.

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REGISTRATION

October, 19th, 2026, 11h - 14h

The conference registration desk will be
in the Library of Technical University - Sofia
or on-line at Technical University - Sofia

CONFERENCE PROGRAM

October 19, 2026, Monday

OPENING CEREMONY

11h – 11h 30min

The Opening Ceremony will be on-line

SCIENTIFIC PROGRAM

FIRST SESSION

11h 30min – 12h 30min

CHAIRMEN: *Prof. Panayiotis Frangos, Dr. Nektarios Moraitis,*
School of Electrical and Computer Engineering, National Technical University of Athens, Greece

**1. COMPARATIVE NUMERICAL ASSESMENT OF HUMAN
ELECTROMAGNETIC EXPOSURE AT SLECTED FREQUENCIES**

*Tamar Nozadze, Ivane Javakhishvili Tbilisi State University, Department of Electric
and Electronic Engineering, Laboratory of Applied Electrodynamics and Radio Engineering,
Tbilisi, Georgia*

Ivliane Nozadze, Ivane Beritashvili Center of Experimental Biomedicine, Tbilisi, Georgia

**2. TEXTURE ANALYSIS OF ULTRASOUND IMAGES IN DETECTING THYROID
DISEASES**

Veska Georgieva, Faculty of Telecommunications, Technical University of Sofia, Bulgaria

*Raya Apostolova, Faculty of German Engineering Education and Industrial
Management, Technical University of Sofia, Bulgaria*

*Diana S. Tsvetkova, Faculty of Telecommunications, Technical University of Sofia,
Bulgaria*

**3. SPARSE ACOUSTIC SIGNAL PROCES SING – CHARACTERIZATION OF
ENTROPY VARIATION**

Ivan Simeonov, Vasil Levski National Military University, Veliko Tarnovo, Bulgaria

BREAK

12h 30min – 13h

SECOND SESSION

13h – 14h

CHAIRMAN: *Assoc. Prof. Ivan Simeonov,*
Vasil Levski National Military University, Veliko Tarnovo, Bulgaria

1. NONLINEAR DYNAMICS METHODS IN THE ANALYSIS OF ACOUSTIC SIGNALS

A. Kadomski, Saint Petersburg State University, Petersburg, Russia

N. Ampilova, Saint Petersburg State University, Petersburg, Russia

I. Soloviev, Saint Petersburg State University, Petersburg, Russia

2. CALIBRATION-AWARE ANDIOMETRIC SCREENING WITH LOW-COST HEADPHONES: A PYTHON-BASED EDUCATIONL APPROACH FOR MEDICAL INFORMATION TECHNOLOGY TRAINING

Tsvetan Valkovski, Technical University of Sofia, Sofia, Bulgaria

Kalin Dimitrov, Technical University of Sofia, Sofia, Bulgaria

3. INTEGRATED CYBERSECURITY FRAMEWORK FOR TELEMEDICINE: STANDARTS, RISK MANAGEMENT AND SECURE IMPLEMENTATION

Tsvetan Valkovski, Technical University of Sofia, Sofia, Bulgaria

Elena Nikolova, Technical University of Sofia, Sofia, Bulgaria

4. ADDRESSING TECHNICAL, PRACTICAL AND ADMINISTRATIVE LEGAL CHALLENGES IN OCCUPATIONAL MEDICAL PRACTICE

Antonya Ilieva, Faculty of Physics and Technology, University of Plovdiv Paisii

Hilendarski, Plovdiv, Bulgaria

Megi Dakova, Faculty of Law, University of Plovdiv, Paisii Hilendarski, Plovdiv, Bulgaria

October 20, 2026, Tuesday

THIRD SESSION

11h – 12h30min

CHAIRMAN: *Assoc. Prof. Kalin Dimitrov,*
Technical University of Sofia, Bulgaria

1. A TWO-TIER CRYPTOGRAPHIC FRAMEWORK FOR SECURE MARITIME COMMUNICATION

Dilyana Dimitrova, Nikola Vaptsarov Naval Academy, Varna, Bulgaria

Nadezhda Vladimirova, Nikola Vaptsarov Naval Academy, Varna, Bulgaria

2. THREAT MODELLING, TAXONOMY AND RISK ASSESSMENT OF LoRa MESH-BASED MARITIME SAFETY SYSTEMS

Nadezhda Vladimirova, Nikola Vaptsarov Naval Academy, Varna, Bulgaria

Dilyana Dimitrova, Nikola Vaptsarov Naval Academy, Varna, Bulgaria

3. DISTRIBUTION AND IMPACT OF RADIATIVE HEAT TRANSFER IN FIRES OF ELECTRIC VEHICLES IN UNDERGROUND GARAGES

Teodosi Tsankov, Academy of the Ministry of Internal Affairs, Sofia, Bulgaria

Svetlin Antonov, Technical University of Sofia, Bulgaria

4. ENVIRONMENTAL AND HEALTH RISKS OF ELECTRIC VEHICLE FIRES IN ENCLOSED SPACES: ANALYSIS AND RECOMMENDATION

Teodosi Tsankov, Academy of the Ministry of Internal Affairs, Sofia, Bulgaria

Svetlin Antonov, Technical University of Sofia, Bulgaria

5. GREEN'S FUNCTION AND ITS USE FOR FINDING APPROXIMATE SOLUTION TO NONLINEAR DIFFERENTIAL EQUATIONS IN OPTICAL COMMUNICATION SYSTEMS

Kostadin G. Sheiretsky, Technical University of Sofia, Bulgaria

Svetlin I. Antonov, Technical University of Sofia, Bulgaria

BREAK

12h30min – 13h

FOURTH SESSION

13h – 14h

CHAIRMAN: *Dr. Tamar Nozadze, Ivane Javakhishvili Tbilisi State University, Department of Electric and Electronic Engineering, Laboratory of Applied Electrodynamics and Radio Engineering, Tbilisi, Georgia*

1. PROTOTYPING OF AN INTELLIGENT RECYCLE BIN

Aleksandar Hristov, Department "Intelligent Technologies in Industry", Technical University of Sofia, Bulgaria

Roumen Trifonov, Department "Intelligent Technologies in Industry", Technical University of Sofia, Bulgaria

2. ACTIVE COMMUNICATION FOR DISTRIBUTED POWER GENERATORS

Hristo Hristov, Telecommunication faculty, Technical University of Sofia, Bulgaria

Antonio Trichkov, Electrotechnical faculty, Technical University of Sofia, Bulgaria

Bozhidar Zlatanov, Electrotechnical faculty, Technical University of Sofia, Bulgaria

3. METHODS FOR ACTIVE AND PASSIVE RECONNAISSANCE IN GRID SUBSTATION CONTROL SYSTEMS

Hristo Hristov, Telecommunication faculty, Technical University of Sofia, Bulgaria

Antonio Trichkov, Electrotechnical faculty, Technical University of Sofia, Bulgaria

Bozhidar Zlatanov, Electrotechnical faculty, Technical University of Sofia, Bulgaria

4. PARTICULATE MATTER RESUSPENSION AROUND AN IDLING VEHICLE AND ITS IMPLICATIONS FOR AIR QUALITY IN PUBLIC PARKING AREAS

Iliyan Damyanov, Technical University of Sofia

Rosen Miletiev, Technical University of Sofia

Kalin Dimitrov, Technical University of Sofia

CLOSING OF THE CONFERENCE

14h -14h30min

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COMPARATIVE NUMERICAL ASSESSMENT OF HUMAN ELECTROMAGNETIC EXPOSURE AT SELECTED FREQUENCIES

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Abstract

This study presents a comparative evaluation of electromagnetic (EM) exposure on the human body at 2.1 GHz and 6 GHz frequencies using numerical simulations. The radiofrequency (RF) source was modeled as a sinusoidal plane wave to represent far-field exposure conditions. Simulations were conducted with FDTDLab, a finite-difference time-domain (FDTD) based tool, employing a child anatomical model to quantify EM field interactions. Specific absorption rate (SAR) metrics including 1 g and 10 g mass-averaged SAR as well as whole-body SAR were computed, alongside corresponding tissue temperature elevations resulting from dielectric heating. Regional and whole-body thermal responses were analyzed to delineate frequency dependent differences in EM absorption. The findings were systematically compared with international safety guidelines to assess compliance with established SAR thresholds and permissible thermal effects, providing a rigorous evaluation of potential health risks associated with Wi-Fi exposure at these frequencies.

1. INTRODUCTION

Wireless communication has become deeply integrated into daily life, with devices such as smartphones, tablets, and laptops relying heavily on Wi-Fi networks for connectivity. Wi-Fi systems operate across several frequency bands, most notably the traditional 2.4 GHz band, newer 5 GHz bands, and the emerging 6 GHz band used in Wi-Fi 6E [1]. In addition, some mobile and wireless services operate near 2.1 GHz [2]. Each of these frequencies exhibits unique propagation characteristics, penetration depth, and energy absorption behavior in human tissues, which are critical factors for assessing electromagnetic field (EMF) exposure [3]-[4]. Understanding these differences is essential, especially as humans and other living organisms increasingly spend time in environments with multiple overlapping wireless signals [5]-[6], such as homes, offices, vehicles, and public spaces [7]-[11].

Exposure assessment at different frequencies relies on metrics like the specific absorption rate (SAR) and incident power density. SAR measures the rate at which RF energy is absorbed by biological tissues, expressed in watts per kilogram (W/kg), and is most relevant for frequencies below approximately 6 GHz where energy can penetrate

tissues and cause localized heating. Incident power density, measured in watts per square meter (W/m^2), is typically used for higher frequencies, such as 6 GHz and above, where energy absorption occurs primarily at the surface of tissues. Regulatory agencies such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and national authorities provide SAR and power density limits to ensure human safety and prevent thermal damage [11]-[15].

The penetration depth of RF energy is inversely related to frequency. Lower frequencies, such as 2.1 GHz, can penetrate more deeply into tissues, including muscles and internal organs, whereas higher frequencies, like 6 GHz, are mostly absorbed by superficial tissues, such as the skin and subcutaneous layers. This distinction has significant implications for both thermal effects and potential biological interactions, as energy deposition patterns determine local temperature rises and tissue responses. Comparative analysis between 2.1 GHz and 6 GHz frequencies can therefore reveal differences in energy distribution, local heating, and exposure levels in various organs and systems [16].

This study presents a comparative evaluation of electromagnetic (EM) exposure on the human body at 2.1 GHz and 6 GHz frequencies using

numerical simulations. The radiofrequency (RF) source was modeled as a sinusoidal plane wave to represent far-field exposure conditions. Regional and whole-body thermal responses were analyzed to delineate frequency-dependent differences in EM absorption. The findings were systematically compared with international safety guidelines to assess compliance with established SAR thresholds and permissible thermal effects, providing a rigorous evaluation of potential health risks associated with Wi-Fi exposure at these frequencies.

2. METHODOLOGY

The incident EM wave was applied from three spatial orientations: front, back, and left side of the body, with two orthogonal polarizations tested for each direction. Simulations were conducted with FDTDLab, a finite-difference time-domain (FDTD) based tool, employing an anatomical model to quantify EM field interactions. Specific absorption rate (SAR) metrics including 1 g and 10 g mass-averaged SAR as well as whole-body SAR were computed, alongside corresponding tissue temperature elevations resulting from dielectric heating. This well-established computational technique is widely applied to analyze interactions between electromagnetic fields and biological tissues due to its ability to accurately represent geometrically complex and compositionally heterogeneous structures. Such capabilities are essential for modelling the human body, which exhibits intricate anatomical features and frequency-dependent tissue properties.

The FDTD method captures key electromagnetic phenomena, including wave propagation, penetration, reflection, and absorption within biological media. This is achieved by discretizing the computational domain in both space and time, subdividing it into small volumetric cells and advancing the solution in discrete time steps. As mentioned, all simulations were carried out using FDTDLab, a numerical simulation platform developed at Tbilisi State University (LAE, Georgia). The software employs the FDTD method to calculate SAR distributions and corresponding temperature elevations in tissues. As with other FDTD-based solvers, FDTDLab utilizes the Yee algorithm for solving Maxwell's equations and integrates Pennes' bio-heat equation to model heat diffusion and perfusion effects within the human body.

An anatomically realistic human model (child model-“Thelonious”) was adopted from the Virtual Pop-

ulation (ViP) database developed by the IT'IS Foundation (Zurich, Switzerland) [17]. Specifically, the child model was used. This high-resolution three-dimensional model includes up to 80 distinct tissue types and was implemented with a spatial resolution of 2 mm. Frequency-dependent electromagnetic and thermal tissue parameters were obtained from the IT'IS tissue property database [18].

For all simulations, the initial tissue temperature was set to 37 °C, while the ambient air temperature was assumed to be 22 °C. Heat exchange between the skin surface and the surrounding environment was modeled using a convective heat transfer coefficient of $h = 8$.

3. SIMULATION RESULTS AND COMPARATIVE EVALUATION OF EM EXPOSURE

RF exposure was modelled using sinusoidal plane waves operating at 2.1 GHz and 6 GHz, representing far-field exposure conditions. 2.1 GHz and 6 GHz were identified as the exposure frequencies and were subsequently used for a comparative analysis of electromagnetic absorption and thermal response.

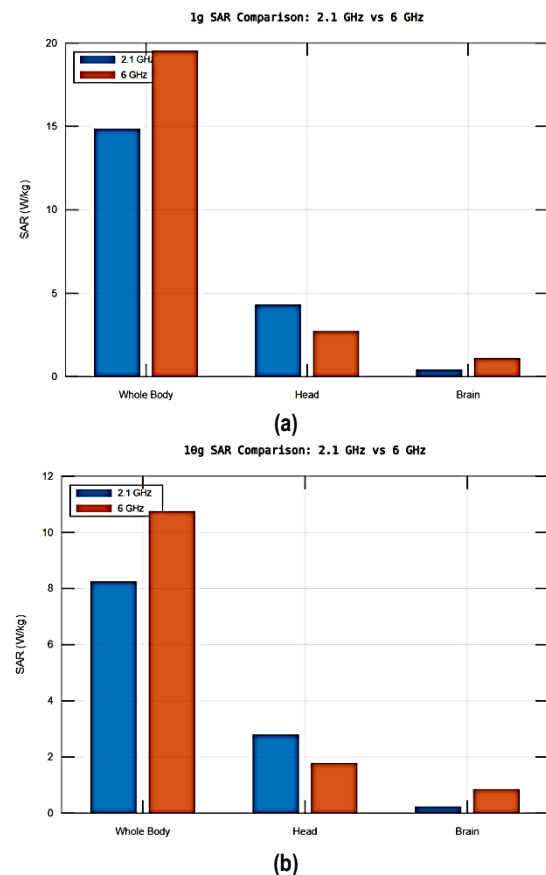


Figure 1. Maximum SAR1g (a) and SAR10g (b) for the child (Thelonious) model at 2.1 GHz and 6 GHz, normalized to an incident power density of 10 mW/cm²

The comparative simulations demonstrated clear frequency-dependent differences in field penetration, SAR distribution, and temperature elevation (Fig.1-Fig.3). At 2.1 GHz, electromagnetic waves penetrated deeper into biological tissues, producing a more spatially distributed SAR pattern and temperature increase across internal regions.

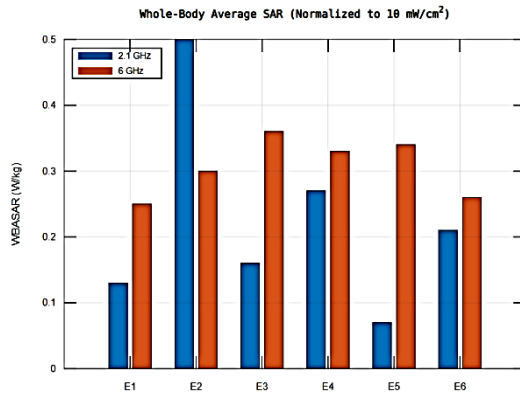


Figure 2. Whole-body averaged specific absorption rate (WBA-SAR) values for the Thelonious anatomical model at 2.1 GHz and 6 GHz frequencies.

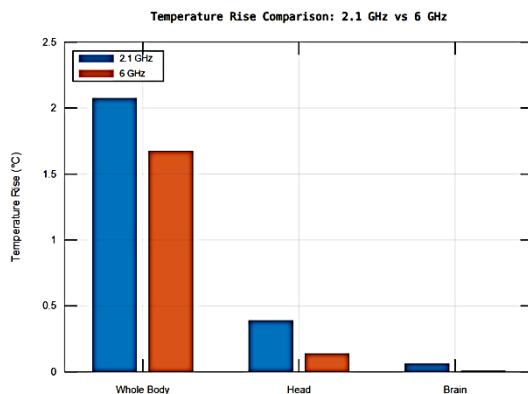


Figure 3. Temperature increase (ΔT) in the Thelonious anatomical model at 2.1 GHz and 6 GHz for an incident power density of 10 mW/cm^2 .

In contrast, exposure at 6 GHz resulted in more superficial energy absorption, with higher SAR values concentrated near the skin and subcutaneous tissues due to reduced penetration depth at higher frequencies Fig.1, Fig.2. Correspondingly, temperature elevations at 6 GHz were localized primarily at the tissue surface, whereas 2.1 GHz exposure caused a broader but less localized thermal response (Fig.1-Fig.3).

4. CONCLUSION

This study numerically evaluated electromagnetic exposure effects at 2.1 GHz and 6 GHz using FDTD simulations and a child anatomical model under far-field conditions. The results revealed

clear frequency-dependent differences in electromagnetic penetration, SAR distribution, and thermal response. Exposure at 2.1 GHz produced deeper tissue penetration with a more spatially distributed SAR and broader internal temperature elevation, whereas 6 GHz exposure led to superficial energy absorption with higher localized SAR and surface-confined heating. All computed SAR values and temperature increases complied with international safety guidelines. These findings emphasize the importance of frequency in determining electromagnetic absorption characteristics and support numerical modelling as an effective approach for RF exposure assessment.

5. ACKNOWLEDGMENTS

Financial support for this study was provided by the Shota Rustaveli National Science Foundation of Georgia (SRNSFG), grant YS-23-131..

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TEXTURE ANALYSIS OF ULTRASOUND IMAGES IN DETECTING THYROID DISEASES

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Abstract

Thyroid ultrasound imaging is used to obtain qualitative information about the structure and abnormalities of the thyroid gland. In this paper, we present texture analysis of thyroid ultrasound images based on second-order statistic through Gray-Level Co-occurrence Matrices to extract and analyze some texture features for hyperthyroidism, hypothyroidism, thyroid nodule, anaplastic thyroid cancer and healthy thyroid gland. Since the predominant presence of speckle noise usually masks the fine details of the ultrasound image and makes its interpretation for medical diagnosis difficult, we suggest image preprocessing. This stage includes contrast enhancement and noise reduction. By analyzing textural features we can infer their behavior both in normal thyroid gland and in cases of different types of thyroid disorders, as well as in the evaluation of thyroid nodules for successfully treatment of these diseases.

Our study could be a first step towards creating a model that extracts an optimal combination of GLCM features. The optimal combination of features should be trained with some of the known classification models in order to aid in the diagnosis thyroid diseases.

1. INTRODUCTION

Thyroid ultrasound (US) imaging is a non-invasive, real-time test with no known side effects. It is significantly less expensive and easier to perform than other medical imaging tests. It is a preferred method in the medical diagnosis of various thyroid diseases because it allows for measuring the size of the gland, detects the presence of a tumour mass or cysts, and can assess the structure and echogenicity of the parenchyma. Thyroid texture characterization based on statistical parameters can provide an objective diagnostic assessment of the condition of the gland and contribute to the use of computer-assisted applications in thyroid disorders [1, 2].

Most publications are related to testing computer-aided diagnosis (CAD) systems in differentiating benign from malignant thyroid nodules [3, 4, and 5]. These systems use various textural features and machine learning algorithms for classification, as well as various parameter optimization tech-

niques, in order to achieve increased classification accuracy [3, 6]. Another group of studies is related to classifying only hypo- and hyper function of the thyroid gland [1]. For this purpose, algorithms based on Fourier power spectrum, first or second-order gray-level statistics, co-occurrence statistics, and gray-level run-length statistics are used [1, 7]. In recent years, some research has used the deep learning method, which has the advantage, compared to traditional machine learning methods, that it does not require the identification of image features as a first step. The biggest problem with deep learning is that "it only finds rules, but often without leaving an audit trail to explain its decisions" [3, 8, 9], which is very important in medicine.

In this paper, we present texture analyses of thyroid US images for detecting of normal gland and four thyroid disorders: hyperthyroidism, hypothyroidism, thyroid nodule, anaplastic thyroid carcinoma. We use the second-order texture analysis through Grey-Level Co-occurrence Matrices (GLCM) to extract and analyse some texture fea-

tures, such as contrast, correlation, homogeneity, energy. Despite the higher quality of the obtained images, due to the application of high-frequency ultrasound (5-10.5 MHz) there is speckle noise, which usually masks the fine details of the ultrasound image and makes its interpretation for medical diagnosis difficult. We propose a pre-processing of the original image in terms of contrast enhancement and speckle noise reduction.

2. MAIN STAGES OF ALGORITHM FOR IMAGE PROCESSING

The block diagram of the proposed algorithm is presented in Fig.1.

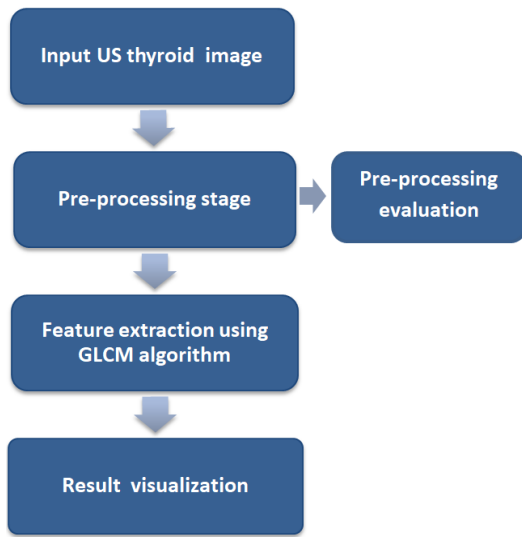


Figure 1. Block diagram of proposed algorithm

2.1. Pre-processing stage

Due to the characteristics of ultrasound images, noise reduction is an important step in pre-processing to improve their quality. This noise can be represented “as the combined effect of two components: one is additive, such as electronic and thermal noise, and the other is multiplicative,” the so-called “speckles” [10, 11]. Therefore, we can present the generalized noise model as in (1):

$$g(x,y)=f(x,y)+m_n(x,y)+a_n(x,y) \quad (1)$$

where $g(x,y)$ is the real image, $f(x,y)$ is the perfect image without noise, $m_n(x,y)$ is the multiplicative speckle noise, and $a_n(x,y)$ is the additive noise. It is assumed that the effect of multiplicative noise is significantly larger compared to additive noise (such as sensor noise) [10, 12]. Another feature of speckle noise is that it can reduce image contrast, resolution, as well as fine details and edges [10,

13]. Additionally, when modeling an ultrasound image with speckle noise, we used the generalized Gaussian distribution and the generalized gamma distribution, which is more general to approximate the speckle statistics [14].

In this preprocessing stage, we first increase the contrast of the image through gamma correction and then use an adaptive Wiener filter to reduce noise. The adaptive filter has a significant advantage over other filters in accounting for the local statistical properties of the image, and accordingly speckle noise can be greatly reduced [10, 15]. The gamma correction values and filter sizes are determined adaptively taking into account the PSNR parameter and the visual quality of the thyroid US image in order to preserve information details of the gland.

2.2. Features Extraction using GLCM

The next important step in the processing is the texture analysis of the enhanced images. It is related to feature extraction through the Gray Level Co-occurrence Matrix, also known as the Gray Level Spatial Dependence Matrix (GLSDM). This is a second-order statistical method. GLCM functions characterize the texture of an image by calculating how often pairs of pixels with a certain value and in a certain spatial ratio occur in the US image. Using this algorithm, a GLCM is formed and various statistical measurements are extracted from it [16, 17]. We calculate the co-occurrence matrices in the four directions, namely 0° , 45° , 90° , and 135° and thus obtain the texture information of the corresponding thyroid US image. The structural information from the studied texture is obtained by using the texture properties. Fourteen local properties were proposed by Haralick et al. for this purpose [18]. We used the following textural features such as contrast, correlation, homogeneity and energy, which proved to be very useful for our study. By analyzing these textural features, we can conclude about their behavior in normal thyroid gland, hyperthyroidism, hypothyroidism, thyroid nodule and anaplastic thyroid carcinoma which is very useful for their early detection and treatment.

3. EXPERIMENTS AND DISCUSSION

The proposed algorithm is implemented in Python 3.11.11, using Spyder powerful scientific environment. For the experiments, we used 20 transversal US images with size 500x375 of the thyroid gland

in jpeg and png-format. For the processing they are converted in bmp. They included an equal number of images from the considered cases [19]. Fig. 2 shows 1 representative from each group of original thyroid ultrasound images examined.

In the pre-processing stage, we used gamma correction values less than 1 to increase the contrast in the dark parts of the image. In this case, even the small dark details could be better detected. The filter sizes are also determined adaptively, taking into account the PSNR parameter. The most suitable size was the 3x3 of the adaptive Wiener filter. In this case, the PSNR values are around 30 dB. With a larger filter size, noise reduction is greater, but the image becomes blurry. The results obtained are significantly better compared to using a median filter, binomial Gaussian filter or anisotropic diffuse filter in the preprocessing stage.

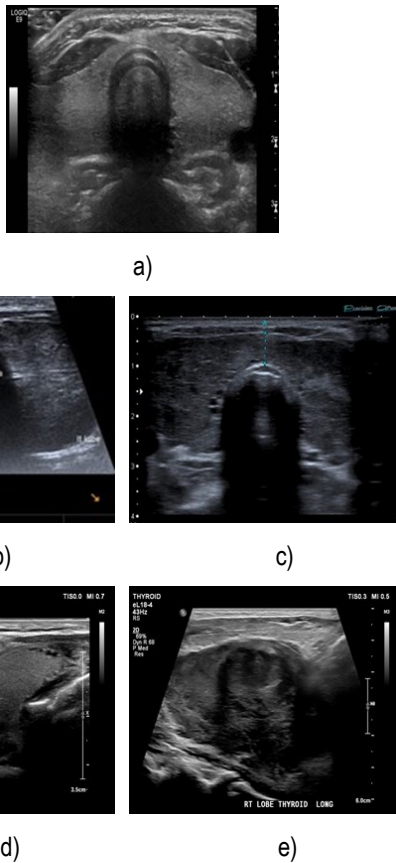


Figure 2. Thyroid images:
a) Normal gland; b) Hyperthyroidism; c) Hypothyroidism;
d) Thyroid nodule; e) Anaplastic thyroid carcinoma

Fig. 3 shows the original image from Fig. 2 and the processed image in the case of anaplastic thyroid carcinoma as an example for visual comparison of the effect of preprocessing.

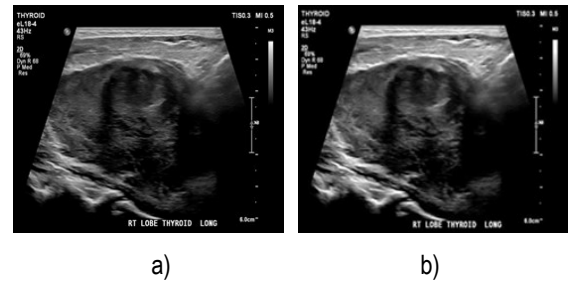


Figure 3. US images from anaplastic thyroid carcinoma:
a) original; b) enhanced image

The averaged results of selected textural characteristics obtained for the considered groups of thyroid diseases are presented in the following 5 tables.

Table 1. Texture Features of Normal Gland

Features	0°	45°	90°	135°
Contrast	93.7868	183.4105	89.2563	182.3599
Homogeneity	0.4730	0.3338	0.4117	0.3381
Energy	0.0626	0.0558	0.0639	0.0561
Correlation	0.9656	0.9309	0.9670	0.9313

Table 2. Texture Features of Hyperthyroidism

Features	0°	45°	90°	135°
Contrast	36.2942	131.7625	102.8664	132.0533
Homogeneity	0.6394	0.5334	0.5654	0.5310
Energy	0.3141	0.3114	0.3136	0.3112
Correlation	0.9913	0.9685	0.9754	0.9684

Table 3. Texture Features of Hypothyroidism

Features	0°	45°	90°	135°
Contrast	50.4885	99.1005	57.2277	99.2158
Homogeneity	0.5522	0.4412	0.4830	0.4336
Energy	0.1939	0.1904	0.1948	0.1904
Correlation	0.9888	0.9780	0.9873	0.9780

Table 4. Texture Features of Thyroid Nodule

Features	0°	45°	90°	135°
Contrast	137.9766	398.5488	280.7351	391.2683
Homogeneity	0.6267	0.5243	0.5555	0.5314
Energy	0.4245	0.4191	0.4235	0.4193
Correlation	0.9801	0.9425	0.9594	0.9435

Table 5. Texture Features of Anaplastic thyroid carcinoma

Features	0°	45°	90°	135°
Contrast	247.0391	405.7612	220.4663	429.6687
Homogeneity	0.6369	0.5530	0.5814	0.5506
Energy	0.4343	0.4282	0.4328	0.4281
Correlation	0.9559	0.9277	0.9607	0.9234

The graphical interpretation of the studied textural features from all ultrasound images obtained for the different thyroid diseases is presented in Fig. 4, Fig. 5, Fig. 6 and Fig. 7, respectively.

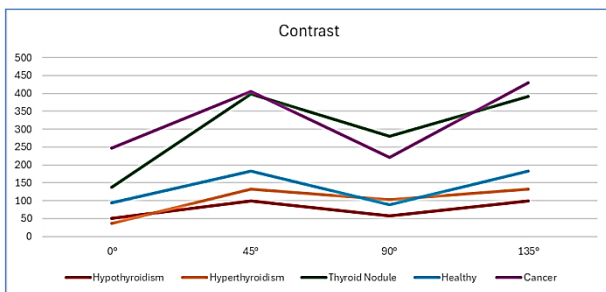


Figure 4. Graphical presentation of the contrast

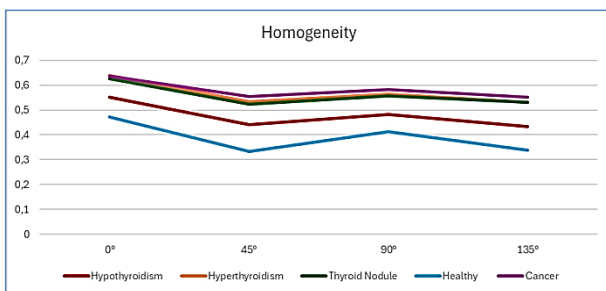


Figure 5. Graphical presentation of the homogeneity

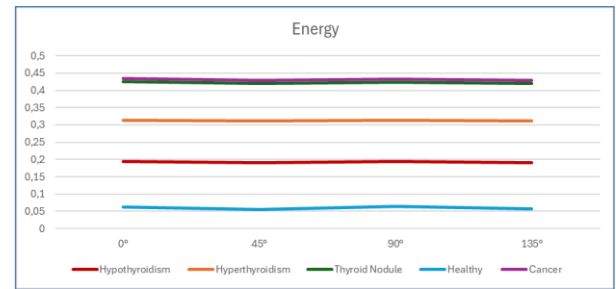


Figure 6. Graphical presentation of the energy

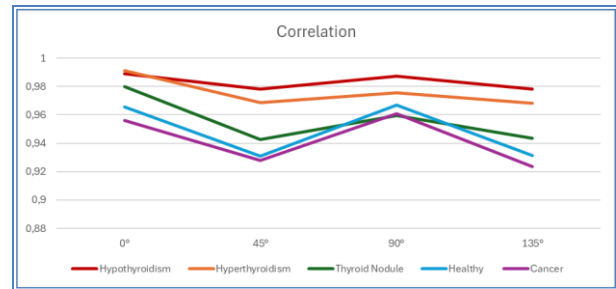


Figure 7. Graphical presentation of the correlation

The obtained experimental results proved to be stable and within a very narrow range of variation for all textural characteristics in the studied groups of ultrasound thyroid images. Therefore, we can make some conclusions regarding changes in textural characteristics for different disease groups.

Compared to the normal gland, the highest contrast values were obtained in the images from the anaplastic thyroid carcinoma group, followed by the thyroid nodule. In the cases of hypothyroidism and hyperthyroidism, lower contrast values are observed compared to the normal gland. Furthermore, the lowest contrast values are obtained in hypothyroidism. The maximum contrast values for all groups are obtained at 45° and 135°, i.e. in the diagonal direction, and the minimum in the vertical direction. Moreover, the contrast values at 135° are slightly increased compared to 45° in anaplastic thyroid carcinoma group, less in hyperthyroidism and hypothyroidism compared to the healthy gland, where a slight decrease is observed. High contrast is associated with higher entropy, which defines an image with a wide range of pixel values [20]. This indicates the presence of an uneven structure in the images from the anaplastic thyroid carcinoma group and thyroid nodule groups.

The energy values were again highest in images with anaplastic thyroid carcinoma and nodule, and lower in hyper- and hypothyroidism, respectively.

The lowest energy value was obtained in a normal gland.

Correlation is related to the degree of connection between neighboring pixels. All values for feature correlation are close to 1, indicating that there are no significant changes in the gray values, and a relatively smooth gradient of gray values is present. However, peaks are found at angles 0° and 90° . This indicates that the different gray values smoothly flow in these directions. The maximum correlation value was obtained in the groups of ultrasound images for hypothyroidism and hyperthyroidism, respectively. The higher correlation indicates a strong dependence between two pixels and therefore a more uniform structure. And the minimum value for the correlation was obtained in the groups of ultrasound images with anaplastic thyroid carcinoma.

The homogeneity measures the closeness of the distribution of elements in the GLCM to the GLCM diagonal [8]. The obtained values for homogeneity are in a very close range of variation for carcinoma, thyroid nodule and hyperthyroidism.

4. CONCLUSION

In this paper, a texture analysis of thyroid US images for detecting of normal gland and four common thyroid disorders, such as hyperthyroidism, hypothyroidism, thyroid nodule and anaplastic thyroid carcinoma is presented. The implemented study and obtained results show the effectiveness of the proposed algorithm in terms of applying pre-processing of the US images and subsequent texture analysis based on second-order statistics through GLCM.

By analyzing textural features such as contrast, correlation, energy and homogeneity, entropy, we can infer their behavior both in normal thyroid gland and in cases of hyperthyroidism, hypothyroidism, thyroid nodules and anaplastic thyroid carcinoma or other thyroid diseases. This is very useful and can help the doctors in:

- early diagnosis and appropriate treatment of various thyroid diseases
- in screening
- in monitoring changes in the structure of the gland and degeneration into a cancerous formation

Our study could be a first step towards creating a model that extracts an optimal combination of GLCM features, for example, a combination of 2 or 3 features. And the optimal combination of features should be trained with some of the known classification models in order to aid in the diagnosis of various thyroid diseases. The goal will be to tune the model in such a way that we achieve high classification accuracy and low computation time. Therefore, our future work will be related in this direction.

5. ACKNOWLEDGMENTS

The authors would like to thank the Research and Development Sector at the Technical University of Sofia for the financial support.

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SPARSE ACOUSTIC SIGNAL PROCESSING – CHARACTERIZATION OF ENTROPY VARIATIONS

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Abstract

Signal sparsity offers opportunities for optimization, not only for data compression, but also for data processing. Recently, the entropy variations observation of empiric acoustic data has been carried out. This paper generalizes previously obtained results for analyzing entropy variations in the studied real-world signals, like drone acoustic signal signatures, gunfire noises etc. The results reveal that, in many instances, compressive sensing method and entropy estimations offers a way to improve the detection and estimation of acoustic signals in the real world at low signal-to-noise ratios.

1. INTRODUCTION

In the 4th century BC, Democritus proposed that an infinite space existed in which an infinite number of atoms moved, forming the physical world. These atoms were considered eternal and invisible, absolutely small, so small that their size cannot be further reduced diminished (hence the name atomon, or “indivisible” [12]. Democritus considered that atoms were too small to be detected by the senses.

Analogically may be considered small parts of bandlimited noise, that Heisenberg's Uncertainty Principle-HUP will guarantee that these parts will not described in classical way.

It is known that Shannon entropy is one of the fundamental measures used for evaluating entropy. Initially entropy was introduced as an abstract mathematical property in thermodynamics. Verdú, 2019 [4] provides a literature review on empirical estimation of entropy.

Some concepts of entropy have been proposed as an interesting approach used in the field of compressed sensing, based on Shannon's theorems (see the work of Zbili and Rama, 2021, [5]).

Well known Approximate Entropy (ApEn) was initially developed to analyze medical data, in 1991 [6] and it was proposed by Steve M. Pincus to address the limitations related to the data's volume and the possibility of system noise influence, [7].

Some recent team works have addressed the study of signal processing of the acoustic signals in the presence of noise as well as the applications

and analyses using Approximate Entropy [1, 2, 3, 4, 11].

2. ACOUSTIC DATA DESCRIPTION

Previous studies [2,3] have demonstrated the analysis of a set of experimental data for pulse signals and for quadcopter noise [10].

In work CEMA'24, [3] raw data, that consists of time signals recorded from the blasts from 122 mm 2S1 howitzer (“Gvozdika”), has been analyzed in MatLab and evaluated with calculations of the ApEn. [2], [8].

In the same works [2], [8] it has been demonstrated that the presence of a strong energy and a noise-like component does not significantly change the spectral entropy picture.

The approximate entropies for these blast signals, have been calculated.

In all these works the approximate entropy have been found in MatLab and the calculating steps have been described in the works of Delgado-Bonal et al. [9].

Some experiments were conducted using a compact quadcopter (Teleoperated compact quadcopter DJI Mavic Air 2s), as described in CEMA'2025, [10]; in the area in order to register the sound picture in the area during takeoff and landing. In that study, we focus on the analysis of drone acoustic signatures, particularly the noise generated during landing.

In the following experiment with tailsitter vertical take-off and landing-VTOL drone WingtraRAY on

the Sep 7th 2025, the microphone is mounted at a height of 1.7 meters above the surface. The terrain is a flat grassy area. The air temperature was 27 degrees Celsius, wind speed 2.2 m/s, the humidity 43%, see Fig. 1.

The experimental setup consists of the following hardware:

Bruel and Kjaer 5-channel PULSE Data Acquisition Unit 3560B; 1/2" low frequency pressure field microphone BK 4193; laptop, and accessories, see [10].

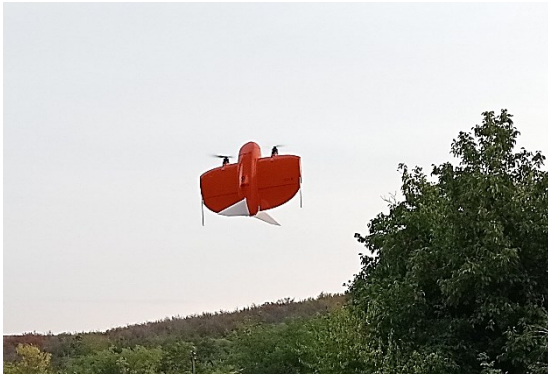


Figure 1. Experimental set up view, vertical takeoff and landing-VTOL drone WingtraRAY, Sep 7th 2025.

Fig. 2 illustrates the recorded signal, approximately one minute in duration, presented as a spectrogram generated using Audacity software, corresponding to the takeoff and landing of the Wingtra-Ray drone. Low-frequency components caused by the wind are noticeable, a high-pass filter 0.7 Hz was used in the recording. Here, the propellers harmonics are also clearly distinguished.

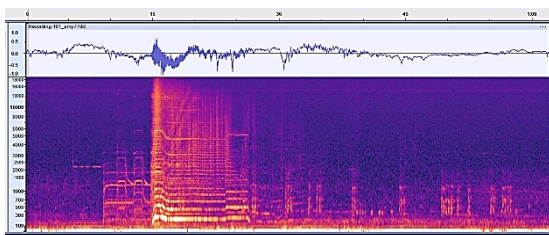


Figure 2. a) Spectrogram around takeoff, VTOL WingtraRAY drone, totally 62 seconds

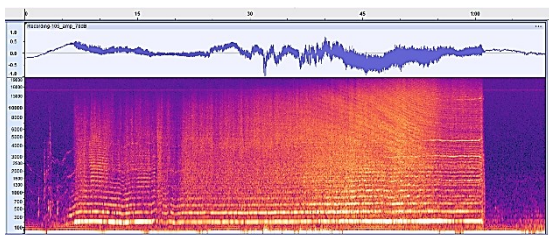


Figure 2. b) Spectrogram around landing, VTOL WingtraRAY drone, totally 65 seconds

It's known that the environmental sounds can be generated by a variety of sources under multiple contexts and no assumptions can be made about their spectral or temporal structure. Due to their non-stationary time nature, environmental sound signals can be considered locally stationary only over short time intervals, typically on the order of tens of milliseconds [11].

This implies that the time and frequency behaviour of the audio signal can be considered practically homogeneous in a time range of few milliseconds and it can have regarded two different temporal scales during the analysis phase of environmental sound.

Following Bernardini's work, [11], the audio segments could be processed on a short time basis of tens ms to discriminate which set of temporal and frequency features is effective in the drone identification problem and subsequently discarding the local detail, made a mid-term time analysis on hundreds ms.

The following section describes the analysis of a set of experimental data, following the approaches presented in [2] and [10], and assesses the unpredictability of signal fluctuations using Approximate entropy calculations.

Simeonov and Yordanov work 2025, [10] demonstrates that statistics of fluctuations' unpredictability of a specific acoustic signal can be evaluated using approximate entropy. The ApEn calculations show that, for the empirical acoustic data, ApEn values increase as the SNR decreases.

3. ENTROPY VARIATIONS OF SIGNAL

This section presents, mid-term "time slices", of 8192 samples (0.125 s), cut from the initial 0.5 s signal "date126p8" and the calculated ApEn in MatLab.

The signal "dn10m_p8_r126" is noise of quadcopter DJI Mavic Air landing – the 0.5 s part of the entire 54 s record "date126all", see Simeonov and Yordanov work 2025, [10].

Signal waveform (0.125 s) and corresponding reconstruction the phase space of the signal for second slice (second quarter) are illustrated on fig. 3.

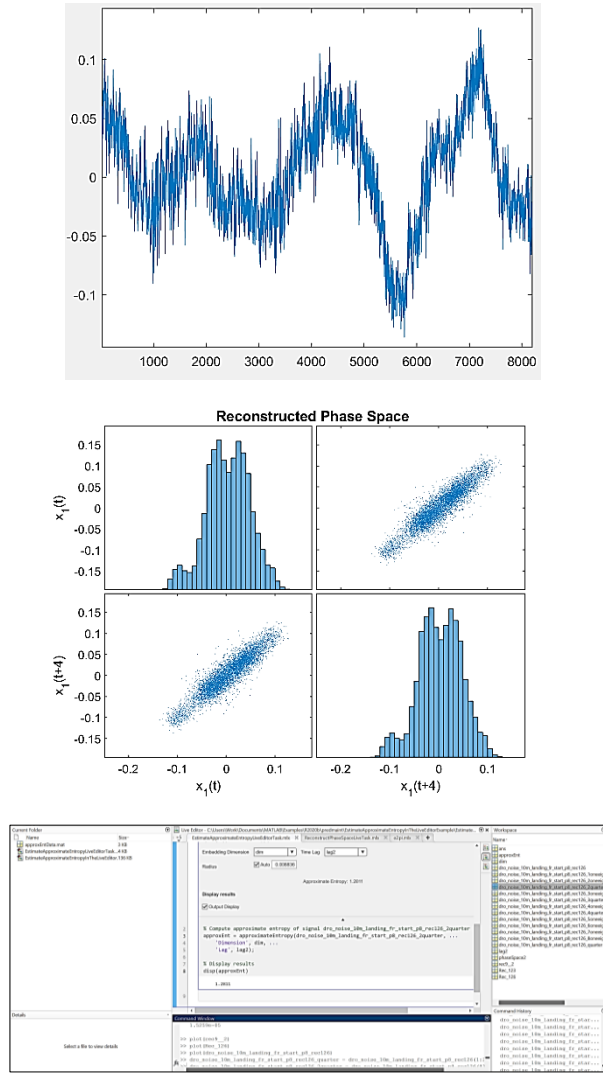


Figure 3. Signal waveform and reconstruction the phase, for time slice 0.125 s, quadcopter DJI Mavic Air landing, “date126” is last 4.7 s from entire 54 s record “date126all”, App. Ent. = 1.2811, dim = 2, lag = 10

In Table 1 are shown results for ApEn for this four 0.125 s ‘time slices’, mid-term, where Dim = 2, Lag = 10, and consist 8192 samples.

Table 1. ApEn for four 0.125 s ‘time slices’, mid-term

Name of signal	Approximate Entropy	N samples
dn10m_p8_r126_q	1.6628	2^{13}
2q	1.2811	2^{13}
3q	1.0468	2^{13}
4q	1.0468	2^{13}

In the following section are presented, eight ‘time slices’, of 2048 samples (0,03125 s), cut from the same initial signal

“dro_noise_10m_landing_fr_start_p8_rec126”, and the calculated ApEn in MatLab. The signal waveform and the corresponding reconstruction of the

phase space of the signal for seventh slice (7 eight) are illustrated on fig. 4.

Table 2 illustrates short-time, eight time slots of the landing drone’s signal

“dro_noise_10m_landing_fr_start_p8_rec126”, with respectively time periods of 0,03125 s i.e.1/32 s, for which ApEn values were calculated in MatLab.

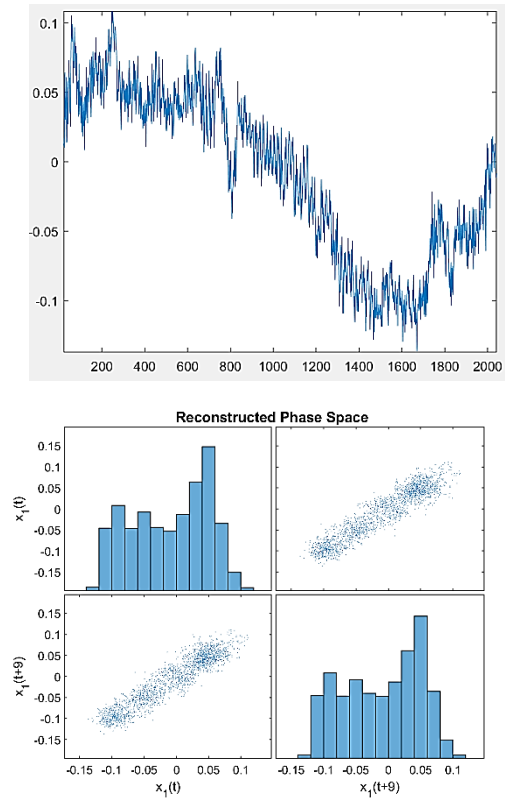


Figure 4. Signal waveform and reconstruction the phase for time slice 0,03125 s, moment of quadcopter landing, App. Ent. = 0.9943, dim = 2, lag = 10.

Table 2. App entropy for eight 0.0125 s ‘time slices’, short-term

Name of signal (slots)	App. Entropy	Number of samples	Dim; Lag
dn10m_p8_r126_1oveight	1.6235	2^{11}	2; 10
2oveight	1.7458	2^{11}	2; 10
3oveight	1.5890	2^{11}	2; 10
4oveight	1.4598	2^{11}	2; 10
5oveight	1.5237	2^{11}	2; 10
6oveight	1.5019	2^{11}	2; 10
7oveight	0.99427	2^{11}	2; 10
8oveight	1.1004	2^{11}	2; 10

As shown in fig. 5, and fig. 6, that illustrates ApEn Table1 (mid-term) and Table 2 (short-term), that App entropy varies for different time portions.

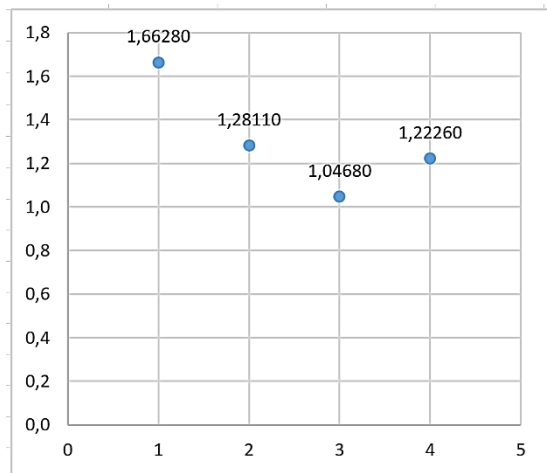


Figure 5. ApEn for four 0.125 s 'time slices', mid-term

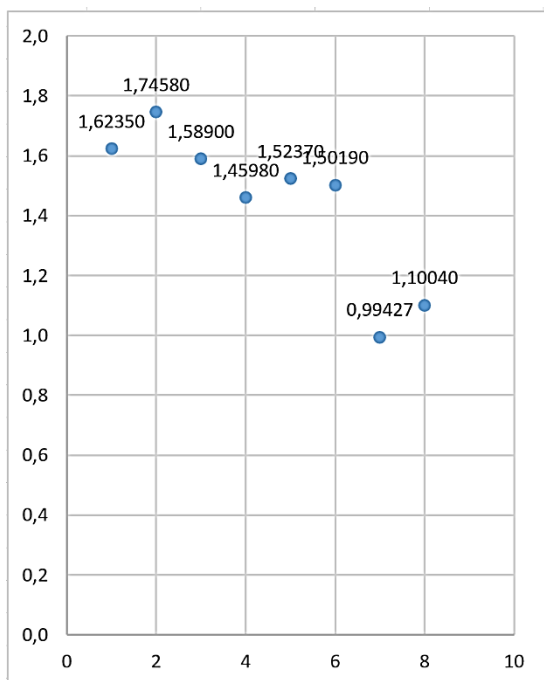


Figure 6. App entropy for eight 0.013125 s 'time slices', short-term

The Approximate Entropy variations through different time signal parts can be seen as a tool for estimating the unpredictability of signal fluctuations.

The likelihood that similar patterns of observations are not followed by additional similar observations corresponds to a higher value of approximate entropy.

If the duration of signal time slices is reduced, making it too small, a limit will be reached where

the minimal slice duration will correspond to the HUP.

4. CONCLUSION AND FUTURE RESEARCH

In conclusion, it can be assumed that a decrease in the rate of entropy change as the registered acoustic signal and noise are divided into increasingly shorter intervals indicates that the durations of time intervals are sufficient. This may be analogous to reaching indivisible units ("atoms") in the case of specific acoustic noise.

ACKNOWLEDGEMENTS

I would like to thank my colleagues from dep. of CIS, prof. Dimiter Tsvetkov, assoc.prof. Ralitsa Slavova, from Vasil Levski National Military University for their collaboration. I would also like to extend my thanks to prof. Tihomir Trifonov and doctor Georgi Dimkov for their collaboration and for providing the hardware PULSE

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NONLINEAR DYNAMICS METHODS IN THE ANALYSIS OF ACOUSTIC SIGNALS

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Abstract

The methods of analysis and classification of complex acoustic signals are based on both special forms of representation (spectrograms or mel-spectrograms) and distinctive peculiarities of signals which may be obtained by various ways. To classify signals one apply both base algorithms (SVM, Random forest, MLP) and neural networks. In some cases obtained signs allow us to use only base methods without complex classifiers.

In this work, we consider the problem of classification of acoustic signals of 3 types of engine — working, broken and overloaded ones. To obtain classifying signs nonlinear dynamics method was used. We assume that each numerical series corresponding to the given type of record is generated by a complex dynamical system and analyze it by the gliding window method. For each segment (window) we estimate the correlation dimension D_c of the restored attractor by the Grassberger-Procaccia algorithm, and calculate the Shannon entropy H on the amplitude covering of the signal.

Further, we use histograms of the distribution of D_c and H . As these signals are generated by a deterministic dynamical system, different states of the engine formed nonintersecting clusters in the space of obtained signs (D_c, H). Hence, the application of deep learning structures is computationally abundant, and for classification, we use base algorithm of machine learning. Accuracy of the classification is 99.9%..

1. INTRODUCTION

It is well known that spectrograms [1] and mel-spectrograms [2] are traditional forms of acoustic signals. We used them when designed the methods for detection and classification of quadcopters by their signals. The analysis showed that the application of network architectures based on CNN (ResNet-50) and mel-spectrogram permits to reveal the appearance of Quad on the background of city and natural noises with high precision (up to 99.5%). [3]

However, mel-spectrograms seemed to be not very effective when differentiating types of quadcopters (DJI Phantom 3, Mavic Pro, FPV 250, etc.) in one class. Generally speaking, the classification of different models not always may be realized because many apparatus have similar engines and propellers generating audios signals in the same frequency diapasons. Acoustic resemblance of the signals under study and strong background distortions led to the result when network did not catch a

difference between models (for some models the completeness metric decreased to 2.6%). [4]

It was shown in [5] that classical methods gave a failure in the conditions of strong noise when background noise and signal power are similar.

To overcome the restrictions of spectral analysis, in [6] we applied the methods of nonlinear dynamics [7]. In assumption that an acoustic signal is generated by a complex dynamical system the correlation dimension D_c of the restored system attractor was estimated by the Grassberger-Procaccia algorithm [8]. The signal of a given length was divided on 100 parts, and for each part correlation dimension was calculated. Experiments showed that for a given model of quadcopter the histogram of the distribution of the obtained dimensions is a unique characteristics, which keeps high classifying ability in the conditions of strong noise.

The problem of practicality of nonlinear dynamics methods for the analysis of arbitrary stochastic and mechanical signals is very important and requires further investigations. In this work we use histograms of the distribution of correlation dimension and the Shannon entropy calculated on an amplitude covering of the signal to examine acoustic emissions of electrical engines in three different states. These signals are generated by a deterministic dynamical system. In the space of obtained signs (D_c, H) different states of the engine formed nonintersecting clusters, hence the classification problem was solved with the precision $> 99.9\%$

2. MAIN NOTIONS AND DEFINITIONS

2.1. The idea of reconstruction

The analyzed time series is considered as the result of a process determined by a dynamical system.

These systems are usually defined on manifolds, which are represented as surfaces in n -dimensional Euclidean space R^n . A manifold may be imbedded in the space (placed without self-intersections) or immersed (placed with self-intersections). The first case is more preferable for studying, we need only to find an appropriate dimension. The Yitni theorem guaranties that any N -dimensional manifold of class C^r , where $r > 1$, may be embedded in R^{2N+1} .

Thus, if the dynamical system acts on N -dimensional manifold and has an attractor, we may reconstruct this attractor in $(2N+1)$ -dimensional Euclidean space.

2.2. Takens method

Scalar time series is an array of K numbers, which are values of a variable $x(t)$ at the moments $t_i = t_0 + \tau(i - 1)$. The value τ is called the period of sample.

Consider $\varphi_t(x)$ - n -order dynamical system defined on N -dimensional manifold M . Time series as records of the system states may be obtained for all n coordinates. It is important that the reconstruction of the attractor (if it exists) may be performed only by one coordinate. If an attractor $A \subset M$, we can reconstruct it in $(2N+1)$ -dimensional Euclidean space.

Define the map $F: M \rightarrow R^{2N+1}$ as follows

$$F(x) = (\varphi_0(x), \varphi_\tau(x), \dots, \varphi_{2N\tau}(x)),$$

where τ is the sample period.

We construct vectors from the data of a time series on a chosen coordinate taken with interval τ . On assumption, these data are on the surface M . Then their images under the map F are on the copy of attractor A considered as a surface in R^{2N+1} .

So, form the vectors by the following way

$$\begin{aligned} z_0 &= (\varphi_0(x), \varphi_1(x), \dots, \varphi_{2N}(x)), \\ &\dots, \\ z_i &= (\varphi_i(x), \varphi_{i+1}(x), \dots, \varphi_{i+2N}(x)), \\ z_{K-2N} &= (\varphi_{K-2N}(x), \varphi_{K-2N+1}(x), \dots, \varphi_K(x)), \end{aligned}$$

where K is the length of the segment of the time series. In other words, we construct our vectors as the points in the space R^{2N+1} .

By the Takens theorem the map F is embedding in R^{2N+1} (almost always)

Thus, we have 2 systems:

$\varphi: M \rightarrow M$ and $F: M \rightarrow R^{2N+1}$, which are connected by a non-degenerated change of variables $z = F(x)$, because F is embedding. Hence, for these systems the characteristics invariant regarding the change are the same, and correlation dimension of the attractor is such a characteristic.

2.3. Determination of embedding dimension

Attractor of a dynamical system is an invariant attracting set. The correlation dimension D_c of the attractor is defined by correlation integral. It estimates the number of pairs of points, which are close with a given precision. It is easy to understand that correlation integral is maximal when the attractor does not have self-intersections, i.e. lies in a space of appropriate dimension. On further increasing the space dimension correlation integral does not change, hence D_c stabilizes. Thus, correlation dimension is used as an indicator that the embedding dimension is achieved.

The Grassberger-Procaccia algorithm is based on this idea.

Construct vectors with the length $k = 2, 3, \dots$ as it was described above and calculate the correlation dimension of the attractor in the space of dimension k . The minimal value k beginning which D_c stabilizes is the embedding dimension. Otherwise,

the data analyzed may be a random noise, not the result of a system action.

Correlation integral is defined as

$$C(\varepsilon) = \lim_{K \rightarrow \infty} \frac{1}{K^2} \sum_{n,n1=1}^K \theta(\varepsilon - \rho(z_n, z_{n1})),$$

where K is the length of a sample, and θ is Hevy-side function

$$\theta(u) = 0, u < 0, \theta(u) = 1, u \geq 0,$$

and (z_n, z_{n1}) are points (vectors) in the space of dimension k .

The correlation dimension of reconstructed attractor is defined as follows

$$D_c = \lim_{\varepsilon \rightarrow 0} \frac{\log C(\varepsilon)}{\log \varepsilon}$$

and calculated approximately by Least Square Method as the tangent coefficient of the line in coordinates $(\log \varepsilon, \log C(\varepsilon))$.

Correlation dimension is invariant for map F .

3. EXPERIMENTS

The time of analyzed records is 1075 s, such that 316 s is the time for records of the engine in a good working order (W), 373 s – broken engine (B), and 386 s – for heavy load engine (HL).

All the acoustic signals were transformed to the frequency discretization 32 000 Hz.

The calculation of signs was performed by the gliding window method by the following algorithm:

In the cycle by step 320 do

1. *Choice of the window.* From the time series a local segment (window) by the length $L = 1024$ is chosen. (For the frequency discretization 32 000 hz such a window contains 32 millisecond of the record.)
2. *Reconstruction of an attractor for the chosen window.* For the part of the time series inside the window form vectors of increasing length k with $\tau = 2$. Determine the embedding dimension m and correlation dimension. Calculate the Shannon entropy on amplitude covering (the number of intervals is 20).

3. *Shift the window on the step 320 (shift with overlap).* Hence the second window contains data from 320 to 1343 position and overlap is 704 position (68.75%). It helps avoiding the loss of information on the window boarders.

4. Check the end of data and go to 2.

On obtained results for 3 regimes of the engine histograms for the distribution of correlation dimensions and Shannon entropy are constructed.

It should be remarked that the choice of parameters 1024 and 320 is traditional for digital acoustic signal processing and provides an optimal balance between frequency and time resolution [9]. In future we suppose to combine the characteristics of nonlinear dynamics with traditional time-frequency representation in the frame of common architecture.

When determining embedding dimension value k changed from 2 to 6. The results are given in Table 1.

Table 1. Dependence D_c on k

Regime	k=2	k=3	k=4	k=5	k=6
W	1.70	2.18	2.49	2.71	2.87
B	1.78	2.49	3.01	3.38	3.70
HL	1.62	1.93	2.08	2.16	2.21

For working and heavy load regime we can take embedding dimension $m=5$, but for the regime broken the signal is more complex and embedding dimension will be greater. However, we take embedding dimension as 5 because for this value correlation dimensions are significantly different. For $k=6$ the computation time greatly increases, but the result does not effect on the recognition quality.

The analysis of the results shows that the acoustic signals of engine are determined by the physical process, such that its different states form nonintersecting clusters in the space (D_c, H) .

Working engine: histogram of distribution of correlation dimension is bell-shaped and centered in the diapason [2.75–2.80], main interval is [2.4, 3.1], maximum of entropy is 4.06.

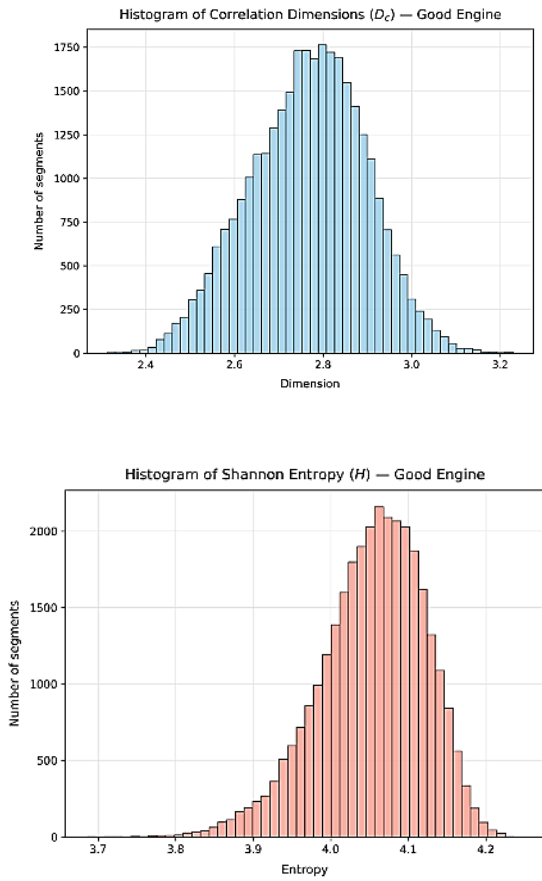


Figure 1. Histograms of the distributions of D_c and H for the regime Working

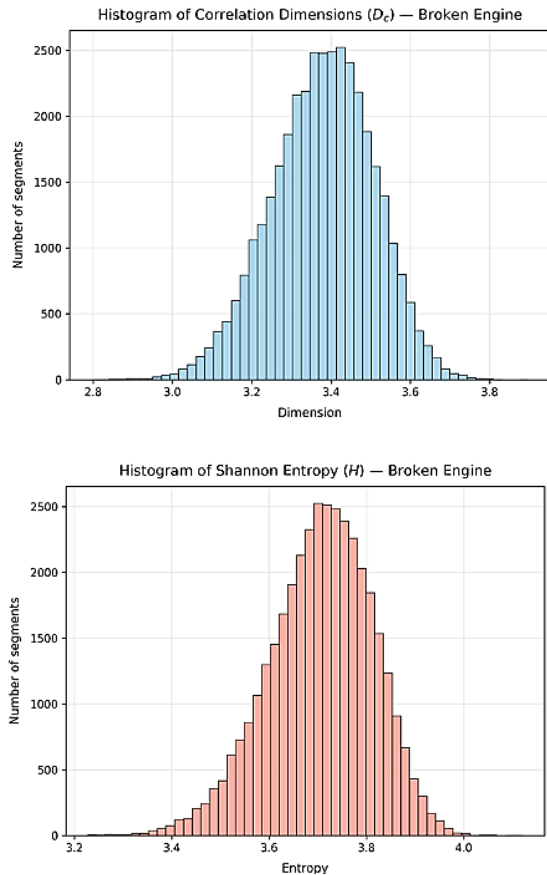


Figure 2. Histograms of the distributions of D_c , and H for the regime Broken

Broken engine: dimension is increasing (due to mechanical backlashes), and entropy is decreasing (due to the occurring rhythmic knocking). The histogram of D_c distribution is right-shifted and centered in the diapason 3.35–3.45 (main part of data is in the interval [3.0, 3.7]), the entropy maximum is near 3.70 (main part of data lies in the interval [3.4, 4.0]).

Heavy load: the histogram of D_c is left-shifted, maximum is in the diapason 2.18–2.22 (main part of data lies in the interval [1.9, 2.4]), entropy distribution is right-shifted with maximal value in the diapason 4.22–4.24 (main part of data is in the interval [4.15, 4.26]).

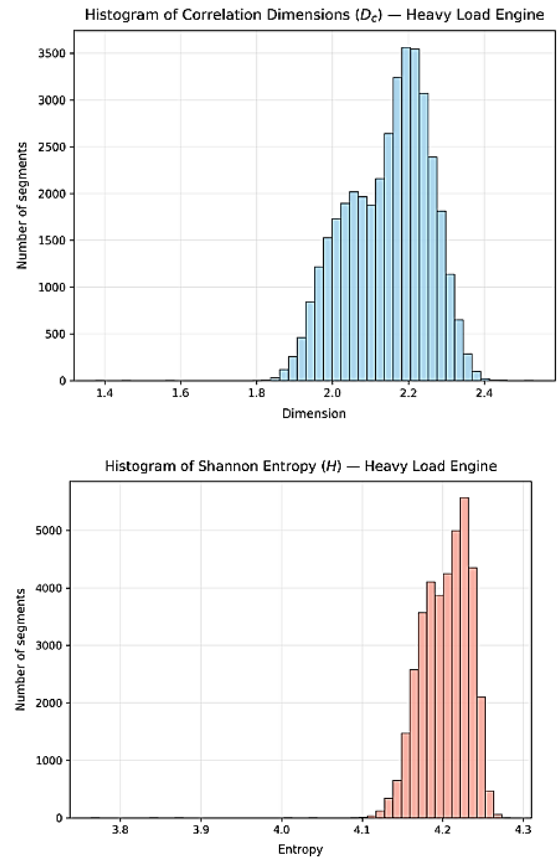


Figure 3 Histograms of the distributions of D_c and H for the regime Heavy load

4. CONCLUSION

The results obtained show that 3 states of the engine form in the space (D_c , H) of our signs nonintersecting clusters. Hence the application of deep learning structures is computationally abundant, and for classification we use base algorithm of machine learning: SVM, Random forest and MLP. Accuracy of classification is more than 99.9%. That means that in the problems of acoustic signal diagnostics adequate signs are more important than complex classifiers.

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CALIBRATION-AWARE AUDIOMETRIC SCREENING WITH LOW-COST HEADPHONES: A PYTHON-BASED EDUCATIONAL APPROACH FOR MEDICAL INFORMATION TECHNOLOGY TRAINING

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Abstract

Pure-tone audiometry requires precise hardware calibration to adhere to ISO and ANSI standards, usually necessitating expensive artificial ears and couplers. In educational laboratory environments, provisioning clinical-grade hardware for entire computer classes is financially prohibitive. This paper presents a calibration-aware, Python-based audiometric screening framework designed for Medical Information Technology student training using low-cost wired and wireless consumer headphones and microphones. The framework utilizes standard libraries (NumPy, SciPy, SoundDevice) to implement frequency-response equalization and Sound Pressure Level (SPL) estimation through loopback and baseline microphone measurement techniques. This approach exposes students to digital signal processing (DSP), electro-acoustic calibration challenges, and the limitations of consumer-grade hardware in medical screening contexts.

Keywords – Audiometric Screening, Headphone Calibration, Medical IT Education, Python, Pure-Tone Audiometry..

1. INTRODUCTION

Pure-tone audiometry is the gold standard for evaluating peripheral hearing thresholds. Traditional setups rely on calibrated audiometers and specific transducers (e.g., Telephonics TDH-39 or Sennheiser HDA 200) calibrated via artificial ears complying with IEC 60318 standards. In academic curricula training Medical Information Technology or Biomedical Engineering students, hands-on lab exercises are critical. However, equipping a computer cluster of 20–30 workstations with clinical hardware is cost-prohibitive. This paper fills this gap by introducing an educational framework that leverages standard commercial consumer headphones (wired and Bluetooth) alongside accessible Python scripts. The core pedagogical focus shifts from "performing a clinical test" to "understanding the acoustic and algorithmic boundaries of hardware calibration." [1-3]

2. MATHEMATICAL MODEL AND CALIBRATION

To deliver an accurate auditory stimulus via consumer headphones, the system must transform a digital signal amplitude into a predictable Sound Pressure Level (SPL) in decibels (dB).

- A. Sound Pressure Level Transformation - The relationship between the digital Root Mean Square (RMS) value of a generated sine wave (x_{rms}) and the acoustic output SPL is modeled as:

$$SPL = 20\log_{10}(P_{rms}/P_0) \quad (1)$$

$$SPL = S_v + 20\log_{10}(x_{rms}) + G_{sys} \quad (2)$$

Where: $p_0 = 2 \times 10^{-5}$ Pa is the reference sound pressure in air (threshold of human hearing). S_v is the voltage sensitivity of the headphone (dB SPL/V or dB SPL/mW converted to voltage equivalent). G_{sys} is the combined system gain (system software volume, DAC gain, and amplifier configuration). [4]

- B. Relative Equalization (Frequency Response Correction) - Consumer headphones have non-linear frequency responses. Let $H_{raw}(f)$ be the uncalibrated frequency transfer function of the headphone. To present a uniform auditory baseline, students implement an inverse filter $H_{inv}(f)$:

$$H_{inv}(f) = 1/(|H_{raw}(f)| + e) \quad (3)$$

Where ϵ is a small regularizing constant to prevent division by zero at deep acoustic nulls.[5]

- C. Discrete FIR Filter Design for Frequency Response Equalization - To compensate for the non-linear acoustic profiles of consumer-grade transducers, a Finite Impulse Response (FIR) equalization filter is applied. Let $d[n]$ be the digital input pure-tone signal, and $w[n]$ be the impulse response coefficients of the compensation filter of length M . The equalized output signal $y[n]$ is computed via discrete convolution:

$$y[n] = \sum \omega[k]d[n - k] \quad (4)$$

Students design the filter coefficients $\omega[n]$ using the frequency-sampling method or windowed inversion of the targets derived from experimental data. The target magnitude response $W(f)$ satisfies:

$$|W(f)| = 1/(|H_{raw}(f)|) \quad (5)$$

Where $H_{raw}(f)$ represents the specific baseline acoustic response profile of either the over-ear Anker Soundcore Life Q30 or the on-ear JBL T450BT transducers. To prevent unstable high-frequency boosting or over-amplification of acoustic nulls, a threshold brick-wall cap is mathematically enforced:

$$|W(f)|_{capped} = \min(|W(f)|, Gain_{max}) \quad (6)$$

Where $Gain_{max}$ is set to +12 dB within the student software environment to protect hearing safety and avoid digital clipping (0 dBFS).[6,7,8]

3. PYTHON SYSTEM ARCHITECTURE AND IMPLEMENTATION

The educational software architecture utilizes a modular Python design. The script fulfils two primary roles: Acoustic Calibration Loop and Audiometric Stimulus Generation.[9,10]

The following updated Python production code includes hardware structural metadata presets for both target headphones and implements an automated FIR filter convolution step using scipy.signal presented in Fig. 1.

```
1 import numpy as np
2 import sounddevice as sd
3 import scipy.signal as signal
4
5 class EducationalAudiometer:
6     def __init__(self, sample_rate=44100):
7         self.sample_rate = sample_rate
8         # Hardware specific calibration profiles (Target frequencies vs required relative attenuation dB)
9         # Derived from acoustic response tests
10        self.device_profiles = {
11            "Anker-Soundcore Life_Q30": {
12                "type": "Over-Ear (Closed)",
13                "codec_delay_ms": 180, # Estimated Bluetooth latency
14                "offsets": (250: -2.0, 500: -1.5, 1000: 0.5, 2000: 3.0, 4000: -4.5, 8000: 6.0)
15            },
16            "JBL_T450BT": {
17                "type": "On-Ear",
18                "codec_delay_ms": 140, # Estimated Bluetooth latency
19                "offsets": (250: 4.5, 500: 2.0, 1000: -1.0, 2000: -1.5, 4000: 2.5, 8000: 8.0)
20            }
21        }
22
23    def design_fir_equalizer(self, num_taps=101, device_name="JBL_T450BT"):
24        """
25        Designs a linear-phase FIR filter based on the headphone's unique offset profile.
26        """
27        if device_name not in self.device_profiles:
28            return np.array([1.0]) # Return identity filter if device unknown
29
30        profile = self.device_profiles[device_name]["offsets"]
31
32        # Define frequencies normalized to Nyquist
33        freqs = sorted(profile.keys())
34        gains = [10**(profile[f]/20.0) for f in freqs]
35
36        # Append boundary configurations for normalized frequency bands (0 to Nyquist)
37        nyquist = self.sample_rate / 2.0
38        bands = [0.0] + freqs + [nyquist]
39        amp_gains = [gains[0]] + gains + [gains[-1]]
40
41        # Design the FIR filter using frequency sampling
42        fir_coefficients = signal.firwin2(num_taps, bands, amp_gains, fs=self.sample_rate)
43        return fir_coefficients
44
45    def generate_calibrated_stimulus(self, frequency, duration, target_db_hl, device_name="JBL_T450BT"):
46        """
47        Generates pure tone and processes it through the structural FIR calibration filter.
48        """
49        t = np.linspace(0, duration, int(self.sample_rate * duration), endpoint=False)
50
51        # Raw stimulus scaling relative to 0 dBFS reference
52        amplitude = 10 ** ((target_db_hl - 70) / 20.0)
53        raw_wave = amplitude * np.sin(2 * np.pi * frequency * t)
54
55        # Apply 50ms Hann temporal windowing to eliminate transient acoustic clicks
56        fade_len = int(self.sample_rate * 0.05)
57        envelope = np.ones_like(raw_wave)
58        envelope[:fade_len] = np.hamming(fade_len * 2)[:fade_len]
59        envelope[-fade_len:] = np.hamming(fade_len * 2)[-fade_len:]
60        windowed_wave = raw_wave * envelope
61
62        # Convolve signal with the calculated FIR equalization matrix
63        fir_coefficients = self.design_fir_equalizer(num_taps=101, device_name=device_name)
64        equalized_wave = signal.lfilter(fir_coefficients, 1.0, windowed_wave)
65
66        # Ensure digital headroom safety check
67        if np.max(np.abs(equalized_wave)) > 1.0:
68            equalized_wave = equalized_wave / np.max(np.abs(equalized_wave))
69
70        return equalized_wave.astype(np.float32)
71
72 # Execution block within laboratory exercise
73 if __name__ == "__main__":
74     audiometer = EducationalAudiometer()
75     # Simulating standard screening stimulus for a student using Anker Life Q30
76     calibrated_signal = audiometer.generate_calibrated_stimulus(
77         frequency=1000, duration=2.0, target_db_hl=30, device_name="Anker-Soundcore Life_Q30"
78     )
79     # Output to audio channel
80     sd.play(calibrated_signal, samplerate=44100)
81     sd.wait()
82
```

Fig.1. Python based source code

4. LABORATORY ENVIRONMENT

The proposed curriculum incorporates a structured four-stage laboratory session tailored for computer classrooms containing mixed hardware topologies presented in Figure 2.

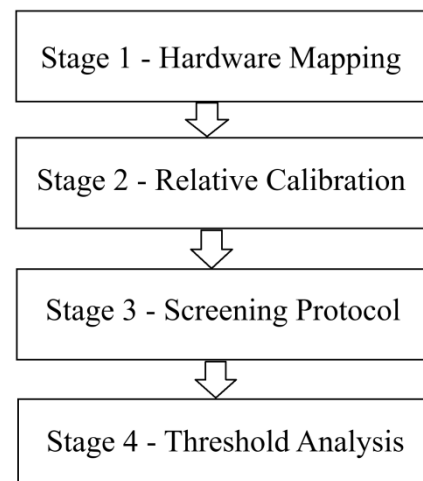


Fig.2. Principle block scheme of the laboratory environment.

Table I. Laboratory Training Workflow – Expanded Evaluation Setup

Step	Objective	Target	Outcome
Enclosure Isolation Analysis	Measurement of passive vs. active noise dampening.	Comparison of Anker Life Q30 (Over-Ear with ANC) and JBL T450BT (On-Ear).	Mapping ambient lab room noise floors against structural target thresholds.
Loopback Recording Matrix	Capturing output sweeps using integrated boom microphones.	Direct physical microphone capture from headphone cups via loops.	Calculating initial frequency attenuation profile $H_{raw}(f)$.
FIR Coefficients Extraction	Mapping frequency matrices into linear-phase FIR vectors.	Digital Python script pipeline (scipy.signal.firwin2).	Understanding limits of maximum safe gain boosts without clipping.
Threshold Screening Protocol	Simulating interactive user audiometry.	Dual device testing via Bluetooth connection profiles.	Collecting data on codec latency shifts and subjective test variances.

1. Hardware Topology Mapping -Students identify whether their workstation uses a wired analog audio jack (3.5mm driven by Realtek/Intel DACs) or a wireless Bluetooth headset (SBC/AAC codecs with inherent internal DSP latency). Latency profiles and sample rate limits (44.1kHz vs 48kHz) are evaluated.

2. Relative Calibration via Reference Microphones - Using standard computer microphones placed inside a 3D-printed coupler or makeshift acoustic chamber (foam-lined enclosure), students play a white noise signal to record the headphone's rough frequency response graph. They calculate the $H_{inv}(f)$ matrix to flatten the playback characteristics across standard audiometric bands (250Hz to 8000Hz).

3. Audiometric Screening Protocol - Students write a control script implementing a modified Hughson-Westlake up-down method (10dB down after positive response, 5dB up after no response). The script cycles through 500Hz, 1000Hz, 2000Hz and 4000Hz frequencies.

4. Variance and Error Threshold Analysis - Students aggregate data across different headphone models (e.g., budget over-ear vs. mobile earbuds). They analyse how hardware variations affect the resulting audiogram, mapping out the systematic errors introduced by consumer electronics in medical contexts.

On Table I are presented the expanded evaluation setup with target hardware focus and student outcomes.

By developing this system, students encounter real-world engineering trade-offs:

The Bluetooth Dilemma: Bluetooth headphones introduce packet latency

(100-250 ms) and internal compression algorithms that alter pure-tone fidelity, emphasizing why clinical systems strictly mandate wired hardware.

Acoustic Noise Floor: Standard computer labs suffer from an ambient noise floor of 40-50 dB SPL (due to PC fans and chatter). Students learn to quantify how this environment masks low-intensity thresholds, reinforcing the importance of sound-proof booths in professional audiology.

Transducer Typology Variations - The inclusion of Anker Soundcore Life Q30 and JBL T450BT headphones exposes Medical IT students to structural acoustic classification impacts:

The On-Ear vs. Over-Ear Coupling Challenge: The on-ear design of the JBL T450BT exhibits high user-to-user variability due to inconsistent ear-pad pressure and acoustic sealing leaks, which drastically alters low-frequency (250–500 Hz) validation accuracy. Conversely, the over-ear Anker Q30 offers a more stable seal, but its Active Noise Cancelling (ANC) digital engine introduces an artificial phase delay and high-frequency filtering that students must mathematically isolate in Python.

Bluetooth Latency Constraints: Bluetooth protocols force a substantial scheduling delay (up to 180 ms for SBC profiles). Students learn to compensate for this within their interactive Hughson-Westlake script logic, preventing false-negative responses caused by late user inputs.

7. CONCLUSION

This Python-based educational framework successfully converts cheap consumer audio hardware into a functional, highly informative teaching laboratory for Medical IT students. While the setup cannot replace medical-grade diagnostic audiome-

ters, it provides a deep, hands-on understanding of signal generation, digital calibration methods, and acoustic hardware constraints.

8. APPENDIX AND ACKNOWLEDGMENTS

The authors would like to thank the Research and Development Sector at the Technical University of Sofia for the financial support. The authors collective would like to express our sincere gratitude to the Faculty of Telecommunications at the Technical University of Sofia for providing the laboratory base

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INTEGRATED CYBERSECURITY FRAMEWORK FOR TELEMEDICINE: STANDARDS, RISK MANAGEMENT, AND SECURE IMPLEMENTATION

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Abstract

Telemedicine has become a critical component in the management of high-risk patient groups, including individuals with chronic conditions, older adults in remote locations, pediatric populations, and patients receiving palliative care. Despite the clear benefits of remote medical service delivery, concerns persist regarding the security, integrity, and confidentiality of processed personal bio-medical data. This paper examines key aspects of data protection in telemedicine systems by analyzing the associated technical, organizational, and ethical challenges. Furthermore, it outlines recommendations aimed at ensuring the sustainable and secure integration of telemedicine into contemporary clinical practice.

1. INTRODUCTION

Telemedicine has transitioned from a supplementary tool to a mainstream modality for clinical interaction, enabling remote consultations, continuous monitoring, and coordinated care for high-risk groups (e.g., chronic conditions, older adults in remote areas, pediatric and palliative care). The same digitalization that expands access also elevates exposure of sensitive health data—particularly in real-time settings—to sophisticated and evolving cyber threats. Sustained trust therefore hinges on robust security, privacy, and regulatory compliance (e.g., GDPR/HIPAA), without degrading clinical usability or availability [1-11].

This paper consolidates security controls across transport, identity, data, and operations, and proposes a reference security architecture for telemedicine platforms (Fig. 1). We highlight modern cryptographic and communication protocols (TLS 1.3, DTLS, SRTP/WebRTC), identity and authorization frameworks (OAuth 2.0/OIDC, SMART on FHIR), sector standards (ISO 27799, ISO/IEC 27001), Zero Trust policy enforcement, security logging and auditing, keys and certificates management (HSM/PKI), and privacy-preserving analytics with cross-border exchange within the EHDS.

Scope highlights:

- A) Reliable, secure connectivity for urgent consultations and continuous monitoring.

- B) Assured data integrity/quality via access control, audit logging, digital signatures, and resilient backup.
- C) Encryption in transit and at rest; least-privilege, role-based access (RBAC) with clinician-assistant segregation and admin data-content isolation.
- D) Defense-in-depth: MFA, vulnerability management and patching, regular penetration testing, SIEM-backed monitoring.
- E) Ethics and compliance: data minimization, transparency, informed consent, and full accountability/traceability.

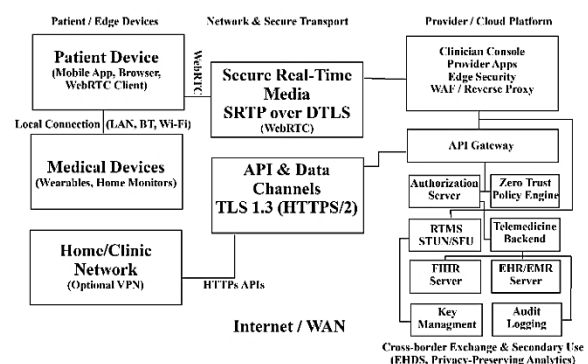


Fig. 1. Reference Security Architecture

The expanding impact of telemedicine creates new opportunities for significantly improving the quality and accessibility of healthcare services, while simultaneously introducing heightened requirements

for security and resilience of digital systems. An integrated approach—combining technical safeguards, regulatory compliance, and ethical oversight—remains the most effective mechanism for ensuring patient safety and data protection. [12-15]

The adoption of standardized protocols and internationally recognized guidance for cybersecurity in healthcare contributes to higher service quality, operational continuity, and broader adoption of telemedicine in modern clinical practice.

2.1. Widely Adopted International Information Security Standards – Several international standards play a key role in establishing robust information security governance across healthcare environments:

2.1.1. ISO/IEC 27001 — Information Security Management System (ISMS) - A globally recognized standard defining the requirements for implementing and maintaining an Information Security Management System. It provides the foundation for policies, processes, and controls needed to safeguard all forms of information, including sensitive medical data.

2.1.2. ISO/IEC 27002 — Security Controls Guidelines - A complementary standard to ISO/IEC 27001, offering detailed guidance on the practical implementation of security controls (e.g., access control, encryption, asset management).

2.1.3. ISO/IEC 27701 — Privacy Information Management System (PIMS) - An extension to ISO/IEC 27001/27002, focused specifically on privacy management. It provides control sets for the protection of personal data, making it especially relevant for healthcare organizations processing sensitive health information.

2.2. Sector Specific Frameworks and Standards for Healthcare

2.2.1. HIPAA (Health Insurance Portability and Accountability Act) - A U.S. regulatory framework that establishes administrative, physical, and technical safeguards for protecting electronic protected health information (ePHI). HIPAA defines mandatory requirements for confidentiality, integrity, and availability of health data.

2.2.2. HITECH Act - Enhances and expands HIPAA requirements, including obligations for breach notification and increased oversight of electronic health records (EHRs).

2.2.3. HITRUST CSF (Common Security Framework) - A widely adopted framework integrating elements from HIPAA, NIST, ISO/IEC 27001, and other standards into a unified risk management and certification model. HITRUST certification is frequently used as a benchmark for security maturity in healthcare organizations.

2.2.4. NIST Cybersecurity Framework (CSF) - A flexible and scalable model used internationally for cybersecurity risk management, structured around five core functions: Identify, Protect, Detect, Respond, Recover.

It is extensively applied in healthcare environments for evaluating risks, planning mitigation, and improving resilience.

2.2.5. NIST Special Publications (e.g., SP 800 53, SP 800 66)

NIST SP 800 53 provides a comprehensive catalogue of security and privacy controls that can be adapted for health information systems.

NIST SP 800 66 offers implementation guidance for complying with the HIPAA Security Rule within a risk based management context.

2.3. Additional Frameworks and Complementary Controls

2.3.1. CIS Critical Security Controls - A prioritized set of 18 actionable security controls that help organizations mitigate common cyber threats. These controls are often used to complement broader frameworks like ISO, NIST, and HITRUST.

2.3.2. COBIT (Control Objectives for Information and Related Technologies) - A governance framework supporting risk management, compliance, and strategic alignment of IT resources. It includes controls and practices relevant to cybersecurity and health data protection.

2.3.3. GDPR (General Data Protection Regulation — EU) - Although not a cybersecurity standard per se, GDPR establishes stringent requirements for personal data protection, including health data, and is often integrated into ISMS and PIMS strategies within healthcare organizations.

2.4. Application of Standards within the Healthcare Sector

2.4.1. Integrated Management Systems – Healthcare organizations frequently build ISMS programs based on ISO/IEC 27001 and extend

them with privacy controls from ISO/IEC 27701 to ensure holistic protection of health data.

2.4.2. Regulatory Compliance - In the United States, HIPAA and HITECH are legally binding for healthcare providers and their business associates. Frameworks like HITRUST CSF are used to demonstrate compliance and security maturity.

2.4.3. Risk Management and Operational Resilience - NIST CSF, often paired with SP 800 53, is used to assess cybersecurity risks, establish protective measures, and prepare for incident response and recovery, ensuring continuity of telemedicine services.

2. METHODS AND MATERIALS

Based on a comparative analysis of the most widely adopted international standards for information security management, the regulatory requirements for the protection of health data, and established best practices in telemedicine, the dependencies and relationships discussed in this paper were identified. [16,17]

The proposed concept follows the defense in depth principle (Fig.2), in which each layer provides an independent security mechanism. The integration and orchestration of these layers minimize the risk of compromising sensitive medical information and enhance the resilience of telemedicine systems against cybersecurity incidents

4. APPLICATIONS OF THE ISO STANDARDS SERIES IN PRACTICE

4.1. ISO/IEC 27001 – Practical applications of ISO/IEC 27001 in the healthcare and telemedicine sector include [18-21]:

- Establishing an Information Security Management System (ISMS) in hospitals and telemedicine centers.
- Conducting formal risk assessments for Electronic Health Records (EHR)
- Defining policies for:
 - to access management to patient records
 - incident management
 - data backup and disaster recovery
- Certifying healthcare institutions to demonstrate compliance and security maturity

4.2. ISO/IEC 27002 – ISO/IEC 27002 provides detailed technical and administrative controls, including:

- Role-Based Access Control (RBAC) for physicians, nurses, and administrative staff
- Logging and monitoring of access to patient information
- Policies for strong passwords and identity management
- Controls for mobile devices used in home-based monitoring scenarios

4.3. ISO/IEC 27701

Key privacy related applications of ISO/IEC 27701 include:

- Patient consent management
- Minimization of processed health data
- Formal procedures for breach notification
- Appointment of a Data Protection Officer (DPO)

5. REGULATORY FRAMEWORKS IN HEALTHCARE

5.1. HIPAA – Specific Requirements and Applications

The Health Insurance Portability and Accountability Act (HIPAA) impose several concrete technical and administrative safeguards relevant to telemedicine, including:

- Encryption of electronic Protected Health Information (ePHI)
- Multi factor authentication (MFA) for access to Electronic Health Records (EHR)
- Audit trails for tracking access to patient data
- Business Associate Agreements (BAA) with external providers of telemedicine platforms
- An established and tested incident response plan

5.2. HITECH Act – Practical Applications

The HITECH Act extends HIPAA and introduces additional operational and compliance obligations such as:

- Mandatory breach notification in cases of unauthorized disclosure of health data
- Enhanced penalties for violations of HIPAA requirements
- Incentives for implementing secure and interoperable electronic health systems

5.3. General Data Protection Regulation (GDPR) Applications Within the EU

The GDPR introduces specific requirements for processing health data within the EU, including:

- Conducting a Data Protection Impact Assessment (DPIA) for telemedicine services
- Implementing Privacy by Design principles during the development of medical software
- Pseudonymization and encryption of health data
- Limiting the retention period of medical information according to data minimization principles

5.4. European Health Data Space (EHDS) Regulatory Implications and Applications

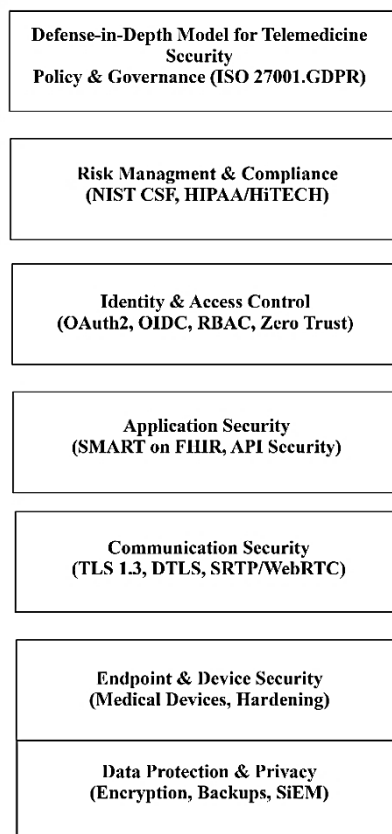


Fig. 2. Defense in Depth Model for Telemedicine Security

The European Health Data Space (EHDS) represents a comprehensive regulatory and infrastructural framework proposed by the European Union to enable secure, interoperable, and privacy preserving use of health data across Member States. Its applications in the context of telemedicine include:

- Cross border interoperability of electronic health records (EHRs) - Ensures that patient health data can be accessed securely across the EU, enabling continuity of care for remote consultations, second opinions, and emergency telemedicine services.
- Harmonized data sharing rules for primary use of health data - Establishes unified requirements for accessing and exchanging patient information in telemedicine platforms, aligned with GDPR and sector specific safeguards.
- Framework for secondary use of health data - Supports privacy preserving analytics, research, AI model development, and policy making without compromising individual patient confidentiality.
- Standardization and certification of digital health products - Promotes adoptions of interoperable formats such as HL7 FHIR, strengthens cybersecurity obligations, and introduces conformity assessment for telemedicine systems.
- Patient empowerment through digital rights - Grants patients' clearer control over their health data, including access rights, consent mechanisms, data portability, and visibility into how and where their information is used.

The EHDS thus provides a foundational regulatory environment for scaling secure and trustworthy telemedicine services across the European Union, while maintaining high levels of privacy, interoperability, and clinical safety.

6. RISK MANAGEMENT FRAMEWORKS

6.1. NIST Cybersecurity Framework — Applications in Hospital Environments

The NIST Cybersecurity Framework (CSF) can be applied in healthcare and telemedicine settings through its five core functions:

- Identify: Inventory and classification of medical IoT devices
- Protect: Deployment of network segmentation to isolate clinical subsystems
- Detect: Use of intrusion detection and prevention systems (IDS/IPS)
- Respond: Development of response plans for ransomware and other cyber incidents
- Recover: Implementing and testing backup and restoration procedures for EHR systems.

6.2. NIST SP 800 53 — Relevant Security Controls

NIST Special Publication 800 53 provides detailed security and privacy controls, including:

- AC (Access Control): Restricting access to clinical databases and sensitive medical information
- SC (System & Communications Protection): Implementing TLS encryption and secure communication channels
- IR (Incident Response): Formal procedures for incident handling, escalation, and reporting

6.3. NIST SP 800 66 — Practical Applications

NIST SP 800 66 offers guidance for implementing HIPAA requirements, with applications such as:

- Providing structured guidance for HIPAA Security Rule risk assessments
- Documenting technical and administrative safeguards for compliance auditing and verification

7. INTEGRATED SECTOR FRAMEWORKS

7.1. HITRUST CSF — Possible Applications

- Unified security assessment
- Certification of cloud based medical service providers
- Harmonization of ISO, NIST, and HIPAA requirements

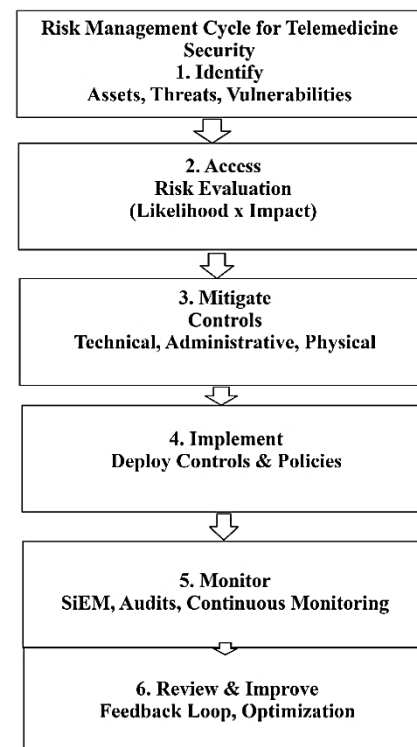


Fig. 3. Risk Management Cycle for Telemedicine Security

8. ADDITIONAL TECHNICAL STANDARDS USED IN THE PROTECTION OF MEDICAL DATA

8.1. CIS Critical Security Controls

- Protection against ransomware
- Control of administrative privileges
- Risk management and prioritization of mitigation actions

8.2. IEC 80001 — Specialized for Medical Technology

- Risk management for connecting medical devices to hospital networks
- Analysis of potential impact on patient safety resulting from device–network into

9. SECURE COMMUNICATION PROTOCOLS USED IN TELEMEDICINE

9.1. TLS 1.2 / 1.3 — Encrypted Communication

- IPsec — secure tunneling for protected network connections
- S/MIME – protection of medical electronic mail
- OAuth 2.0 / OpenID Connect — secure user authentication and authorization

- HL7 with encryption for secure exchange of health information
- DICOM Security Extensions — protection of medical imaging data and metadata

Based on a preliminary review of established cybersecurity practices and their application within international healthcare cybersecurity standards—particularly in the context of telemedicine—we derive a consolidated comparison of relevant aspects.

The analysis of the data examined leads to several conclusions regarding the practical application of security standards in the field of telemedicine. In real-world implementations, these standards are most often applied in a combined and complementary manner, as follows:

- ISO 27001 → organizational and governance framework
- ISO 27701 / GDPR → personal data protection and privacy controls
- NIST → cybersecurity risk management
- HIPAA → regulatory compliance for health information (U.S.)
- IEC 80001 → risk management for medical devices and clinical IT networks
- TLS / IPsec → practical encryption for secure communication channels

9.2. Organizational-Level Implementation –

At the organizational level, the management framework is established and formal certification becomes possible. This is typically achieved through the implementation of the following standards identified in the best practices reviewed:

- ISO 27001
- ISO 27701
- HITRUST CSF

These standards provide structured governance, privacy management, and unified security assessment models for telemedicine service providers.

9.3. Legal and Regulatory-Level Implementation – At the legal and regulatory level, mandatory requirements are defined by standards and regulations that set the minimum protection measures for health data, including:

- HIPAA (Health Insurance Portability and Accountability Act)

- HITECH Act
- GDPR (General Data Protection Regulation)

These frameworks establish legally binding expectations for confidentiality, patient rights, breach notification, and organizational accountability.

9.4. Technical-Level Implementation – At the technical level, concrete mechanisms for encryption, access control, network segmentation, and protection of medical equipment ensure the security of medical information. These safeguards are made possible through the practical application of standards such as NIST SP 800 53, IEC 80001, and CIS Critical Security Controls.

9.5. Summary of the Integrated Cybersecurity Model for Telemedicine – Summarizing the findings collected thus far, a theoretically integrated model for ensuring cybersecurity in telemedicine has been formulated. The most effective configuration in practical deployments typically includes:

- ISO 27001 → governance and management framework
- GDPR / HIPAA → regulatory compliance
- NIST CSF → risk management
- IEC 80001 → protection of medical devices and clinical networks
- HITRUST → unified and comprehensive certification

This combined model provides a holistic, multi-layered approach that aligns organizational governance, regulatory obligations, risk-based decision making, device level protection, and certification driven assurance.

The theoretically integrated model consists of five interrelated layers that collectively ensure a high level of security for medical data in the practical application of telemedicine within modern clinical practice:

- Clinical and telemedicine layer – the operational level at which medical data are generated, processed, and exchanged (electronic health records, telemetry, medical imaging, remote consultations).
- Technical security layer – implements cryptographic protection, access control, and monitoring through mechanisms such as

TLS encryption, multi factor authentication, and intrusion detection systems.

- Cyber risk management layer – structures the identification, assessment, and mitigation of threats in accordance with the NIST Cybersecurity Framework and NIST SP 800 53.
- Information security management layer – an organizational governance level based on ISO/IEC 27001 and expanded through ISO/IEC 27701, providing systematic control, internal auditing, and continuous improvement.
- Regulatory layer – the legal framework ensuring compliance with mandatory regulations, including the General Data Protection Regulation (GDPR) and HIPAA.

CONCLUSION

The connection between network security and telemedicine standards is critical and inseparable. If medical standards (such as FHIR or DICOM) define what is said and how it is structured, then network security defines who has access to the information and ensures that it has not been altered along the way. We can consider this connection in three main directions:

1. Data Encapsulation (Encryption in Transit) - Medical data standards by themselves do not always guarantee security - they need a network "tunnel". When you send a FHIR resource or a DICOM image, the network protocol TLS 1.3 (Transport Layer Security) encapsulates this data. Without network encryption, even the best structured HL7 packet can be intercepted and read by third parties (Man-in-the-Middle attack). In telemedicine, this is unacceptable due to the requirements of GDPR.

2. Identification and Authorization (Identity Management)

This is where security standards meet clinical workflow. Protocols such as OAuth 2.0 and OpenID Connect are used. They allow the telemedicine subsystem to confirm to the BIS: "This is really Dr. Ivanov, and he has the right to see this patient's file". In modern networks, no one is trusted "by default". Each request for data from a telemedicine device must be individually authenticated and authorized.

3. Data Integrity - In telemedicine, an error in a single bit of information can be fatal (for example, changing a drug dose from 0.1 mg to 10 mg). Network security uses hash functions and digital signatures to ensure that the data sent by the patient via ISO/IEEE 11073 is identical to that received in the BIS. Telemedicine traffic is often isolated in separate virtual networks (VLANs) to prevent the spread of malware from the hospital's administrative network to the medical equipment.

Security can also be enhanced with end-to-end encryption – from the patient's sensor to the hospital server. Using a secure gateway to manage FHIR requests. It acts as a "filter" that stops malicious requests before they reach the BIS database. Multi-factor authentication, which is a prerequisite for doctors to access telemedicine portals from external networks.

Telemedicine represents a significant advancement in the digital transformation of modern medical practice, particularly in the care of high risk and vulnerable patient groups. Alongside this technological progress and the expanding impact of telemedicine, however, raises a critical need to ensure the reliable protection of sensitive personal and health information.

Secure communication, guaranteed data integrity, encryption, role-based access, and proactive cyber threat prevention form the core pillars of effective protection. Only through a systematic and multidisciplinary approach can the sustainable development of telemedicine be achieved—one that combines accessibility and efficiency with a high level of personal data protection.

4. APPENDIX AND ACKNOWLEDGMENTS

The authors would like to thank the Research and Development Sector at the Technical University of Sofia for the financial support. The authors collective would like to express our sincere gratitude to the Faculty of Telecommunications at the Technical University of Sofia for providing the laboratory base

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ADDRESSING TECHNICAL, PRACTICAL AND ADMINISTRATIVE LEGAL CHALLENGES IN OCCUPATIONAL MEDICINE PRACTICE

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Abstract

This analysis examines the main technical, practical, and administrative-legal challenges in occupational health practice and their impact on ensuring safe and healthy working conditions. Particular attention is paid to the resources of occupational health services, the prevention of occupational risks, and the problems in the control and assessment of occupational accidents. In conclusion, the need to strengthen the approach to increase control effectiveness and strengthen institutional cooperation to improve the health and safety of workers is emphasized.

1. INTRODUCTION

Occupational medicine occupies a key place in the system for protecting the safety and health of workers. Its main function is aimed at preventing occupational risks, early detection of occupational diseases, and limiting the adverse consequences of occupational accidents. It is an essential element of public health, labor, and administrative law.

In the field of safe and healthy working conditions, the Republic of Bulgaria has built a relatively stable regulatory framework. The main act is the Health and Safety at Work Act (HSWA), adopted in 1997 and subsequently harmonized with European Union law [19].

Framework Directive 89/391/EEC introduces the fundamental principles of prevention, risk assessment, and shared responsibility between employer and employee. Despite the regulatory integrity and institutional arrangement, the practical implementation of the legislation reveals significant implementation gaps.

This article aims to analyse the technical, practical, and administrative-legal challenges in the activities of occupational health in the Republic of Bulgaria. Emphasis is placed on the role of occupational health services and control bodies, as well as on the need to strengthen the preventive approach and inter-institutional cooperation to increase the practical effectiveness of the system for safe and healthy working conditions.

Practitioners in the field face a range of interrelated technical, organizational and administrative-legal

difficulties: differentiating occupational from non-occupational conditions, securing workplace access for assessments, coordinating with employers and regulators under resource constraints, and complying with evolving regulatory and ethical requirements while managing legal risk [1,3,5,7, 10,12]. These challenges are addressed through continuous professional development, strong institutional partnerships, and strict adherence to legal and ethical standards [2,4,6,8,9,11].

2. A BRIEF OVERVIEW OF THE BASIC PRINCIPLES OF RULEMAKING IN THE REPUBLIC OF BULGARIA ON ISSUES RELATED TO SAFE AND HEALTHY WORKING CONDITIONS.

2.1. Legal framework

The legal framework governing safe and healthy working conditions in the Republic of Bulgaria was substantially developed with the adoption of the Health and Safety at Work Act (HSWA) in 1997 [19]. The national legislation has subsequently been progressively harmonized with the European Union regulatory framework, incorporating the standards and provisions of the relevant EU directives discussed below. This includes Council Directive 89/391/EEC on measures to encourage improvements in workers' safety and health, together with Directives 91/383/EEC, 92/29/EEC, 94/33/EC and 83/477/EEC, which extend protection to fixed-term and temporary workers, seafarers, young persons, and workers exposed to asbestos, respectively [22].

Other important international instruments related to the need to ensure health and safety at work are the ILO Conventions (Convention No. 81 of 1947 concerning Labor Inspection in Industrial Undertakings and Convention No. 161 of 1985 concerning Occupational Health Services). Part of the Global Strategy of the World Health Organization (WHO), adopted in May 1996 during the XXVI World Health Assembly "Health for All at Work", is also dedicated to ensuring healthy and safe working conditions [13].

The basic principles laid down in the HSWA can generally be summarized as follows:

- prevention of occupational risks;
- protection of safety and health;
- elimination of risks and causes of occupational injuries and occupational morbidity;
- information, consultations, training [19];

In the context of the basic principles stated, attention should be paid to the fact that the statutory liability provided for by law is distributed to a large extent equally between the subjects in the labor-law relationship. The variations of casuistry that arise in practice are heterogeneous in nature and do not allow for their imperative and explicit definition separately. In this context, when initiating cases before a court, the judicial panels are often faced with the need to interpret the legal norms in accordance with the realized harmful result for the parties and the normatively stipulated requirements when it comes to material damages suffered. This circumstance is logical and stems from the fact that the applicable legal regulation under the HSWA is framework, not detailed. A significant legal problem is also the normative assessment of the non-material damages that occur as a consequence of work-related incidents for the worker or employee [14]. There is no doubt about the psychosomatic element that is a consequence of the work accident, but its objective assessment in monetary value often does not correspond to the consequences that the injured person has to deal with [14]. Basic norms for ensuring safe working conditions are also contained in Chapter Thirteen of the Labor Code (LC), including Article 275, as well as in the subordinate regulations for its implementation [24].

According to Bulgarian legislation and in particular the Health and Safety at Work Act, compulsory insurance for occupational diseases and accidents

at work has been introduced, with insurance contributions being at the expense of employers (Art. 51, para. 1 Health and Safety at Work Act) [19]. The terms and conditions for insurance for occupational accidents and occupational diseases are regulated by a separate law. Compulsory insurance for the risk of "occupational accidents" has also been introduced: at the expense of the employer under the terms and conditions and in accordance with the procedure determined by an act of the Council of Ministers [15].

The Social Security Code sets out the statutory issues related to insurance for occupational accidents and occupational diseases, which are regulated in Part I of the Social Security Code "State Social Security", as well as the basic obligations of the parties to employment or service relationships. According to Art. 65 of the Social Security Code [20], the Occupational Accident and Occupational Disease Fund finances measures to prevent occupational accidents and occupational diseases:

- providing assistance, consultations and co-operation to insurers for the creation and implementation of an effective system for managing occupational safety and health protection at work;
- developing and participating in the development of national sectoral programs (strategies) in the field of occupational safety and health protection at work;
- checking the state of occupational safety and health protection at work;
- investigating independently or with other competent authorities of occupational accidents and occupational diseases;

2.2. Regulatory framework

A key element of the secondary legislation is the Organizational Regulations of the Ministry of Labor and Social Policy, adopted by Council of Ministers Decree No. 266 of 2009 (promulgated in State Gazette No. 91 of 2009, as subsequently amended) [23]. The Regulations determined the functions, organizational structure, and administrative units of the Ministry. For the purposes of this study, we will only indicate the most widely applicable regulation relating to all types of work activity; by sector, the legislator has regulated all activities

exercised on the territory of the Republic of Bulgaria in terms of safe working conditions.

Among the key secondary legislation is Ordinance No. 4/1998 on the training of representatives in committees and groups on working conditions [25]. Two other ordinances merit closer attention. Ordinance No. 3/1987 on mandatory preliminary and periodic medical examinations sets out the conditions for screening job applicants and employees, including under Art. 2(3) mandatory comprehensive examinations for workers under 18 by a therapist, neurologist, surgeon, otorhinolaryngologist, and ophthalmologist prior to employment approval [16]. Ordinance No. 3/2011 on drivers' physical fitness requirements completes the sector-specific framework [17]. In view of the spatial regulatory framework, we will limit ourselves to a brief presentation of the regulatory framework, which in our opinion is of key importance in the processes of establishing safe and healthy working conditions. For the successful implementation of the requirements established in the legal and regulatory framework, the bodies with control and supervisory functions are of key importance.

2.3. Bodies with key importance for implementing policy in the field of safe and healthy working conditions.

Chapter 4 of the HSWA lists the bodies with direct relevance to the issue under consideration [19]. The Council of Ministers determines and implements the policy for ensuring healthy and safe working conditions. The Minister of Labor and Social Policy develops, coordinates, and implements the state policy in the field of ensuring healthy and safe working conditions. In collaboration with the Minister of Health, they prepare analyses of the status, trends, and problems of the activity for ensuring healthy and safe working conditions and propose measures for their improvement. The Minister of Labor and Social Policy exercises integrated control through the Executive Agency "General Labor Inspectorate" over compliance with the legislation and the fulfilment of obligations for ensuring healthy and safe working conditions in all sectors and activities, regardless of the form of ownership. The Labor Code, in Article 276, also provides that the Minister of Labor and Social Policy, independently or jointly with other ministers, issues acts on ensuring healthy and safe working conditions [24].

According to Art. 38 of the HSWA, "the policy for ensuring healthy and safe working conditions is determined and implemented after coordination within the framework of permanent or temporary structures of tripartite cooperation at national, sectoral and regional levels" [19]. In this context, the National Council on Working Conditions is a key body. It includes representatives of the Council of Ministers, the National Social Security Institute, nationally representative employers' organizations, and nationally representative workers' organizations [19]. At territorial levels, sectoral and branch councils on working conditions have been established, as well as regional district and municipal sectoral and branch councils on working conditions. A key role in the activities of these organizations is the periodic analysis of the regulatory requirements related to safe working conditions, legislative proposals for amending and optimizing the existing regulatory framework, as well as the preparation of project proposals for improving conditions by industry sectors.

According to the requirements of the HSWA, the main administrative and control powers on issues related to safe working conditions are exercised by the Minister of Labor and Social Policy and the Chief Labor Inspectorate. The state health control bodies exercise control over the activities of the occupational health services [19].

Ordinance No. 3 of 25.01.2008 on the conditions and procedure for carrying out the activities of occupational health services sets out the regulatory requirements for registration and activity. A regulatory obligation has been introduced for employers to provide an occupational health service to serve employees in the establishment or enterprise. The services can be established both by the employers themselves and by natural or legal persons registered under the Commerce Act, the Cooperatives Act, or the Non-profit Legal Entities Act to serve employees [21].

3. CONCLUSION

Occupational health practitioners face significant challenges - from the complexity of occupational hazards and diagnostic difficulty to limited service resources and evolving regulatory demands. The analysis shows that Bulgaria's legal and regulatory framework for safe and healthy working conditions is conceptually aligned with European and international standards, with the principles of prevention,

information, training and institutional cooperation clearly laid down in the HSWA and the Labor Code [19,24]. Nevertheless, statistical data reveal a significant gap between regulation and practice [18], and the framework nature of the legislation continues to hinder administrative and judicial control over liability for occupational accidents. Future development should focus on strengthening the preventive approach, improving control efficiency, and reinforcing the role of occupational health services as a link between the health and labor law systems.

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A TWO-TIER CRYPTOGRAPHIC FRAMEWORK FOR SECURE MARITIME COMMUNICATIONS

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Abstract

Maritime communication systems rely on continuous data exchange among vessels, coastal stations, satellites, and maritime IoT devices. The heterogeneous nature of these networks and the limited resources of edge devices make efficient cryptographic protection challenging. This paper proposes a two-tier secure communication architecture that adapts encryption methods to device capabilities. The system is divided into a strategic security zone using AES-256-GCM and an edge security zone using ASCON-128 for resource-constrained devices. A gateway layer enables secure data transfer between zones while preserving confidentiality and integrity. The proposed architecture is designed to reduce computational overhead, improve energy efficiency, and enhance scalability in maritime environments. A simulation demonstrates secure data transmission across the system, including edge encryption, cryptographic processing at the gateway, and protection within the strategic domain.

Keywords: AES-256-GCM, ASCON-128, lightweight cryptography, maritime cybersecurity, secure communications, simulation, two-tier architecture.

1. INTRODUCTION

Maritime communication systems rely on continuous data exchange between onboard sensors, vessels, coastal stations, and maritime operation centres. The communications between them are usually performed over heterogeneous transmission infrastructures, which include satellite links, wireless ad hoc networks, VHF (Very High Frequency) radio channels, and emerging Internet of Ships (IoS) architectures. The digitalization of maritime operations has improved situational awareness, but it also has expanded the attack surface for cyber threats.

Existing security approaches frequently apply uniform cryptographic mechanisms throughout the network, regardless of device capabilities or communication requirements. This strategy simplifies deployment, but it may introduce excessive computational overhead and unnecessary communication costs for constrained maritime assets [1], [2].

To address this limitation, the paper proposes a two-tier secure communication architecture that separates strategic communication infrastructure from edge maritime sensing infrastructure. It applies two cryptographic algorithms according to the

computational resources and communication characteristics of each network segment and maintains confidentiality and integrity across communication domains through trusted gateway-based cryptographic processing.

2. RELATED WORK

The literature review was conducted using scientific publications published between 2021 and 2026. The initial search was performed in the Scopus database using the keywords “maritime cybersecurity”, “secure communications”, “satellite networks”, and “maritime IoT”. Additional relevant literature was also examined to provide broader context and support the analysis. The selected studies address security challenges in maritime communication infrastructures, including shipboard systems, satellite links, navigation services, and Internet of Ships (IoS) environments.

In paper [3] authors investigate routing security and anomaly detection in large-scale space information networks, demonstrating the impact of routing vulnerabilities and encryption overhead on communication performance. Authors in [4] propose a multi-layer security framework for Air-

Space-Ground-Maritime (ASGM) networks in 6G scenarios.

Maritime-specific cybersecurity challenges are comprehensively reviewed by the authors in [5], who identify vulnerabilities affecting shipboard systems, satellite communications, AIS infrastructures, and maritime IoT devices. Similarly, paper [6] introduces a cloud-edge architecture for the Internet of Ships, improving privacy protection and reducing communication latency through distributed data processing.

Navigation security is addressed by the authors in [7], who analyse GNSS jamming and spoofing threats, highlighting the need for robust authentication and integrity verification mechanisms. Lightweight security solutions are presented in [8] through a secret-sharing authentication protocol for marine communications and by authors in [9], who propose a hybrid hash-encryption scheme for secure marine data transmission.

Table 1. Comparison of relevant literature sources

Source	Year	Description	Relevance to the topic
[3]	2021	Evaluation of routing anomalies and secure transmission controls in space networks.	Addresses long-range payload protection and satellite link encryption.
[4]	2025	Multi-layered network security architectures utilizing advanced encryption frameworks.	Focuses on multi-sensor validation zones and marine network infrastructure.
[5]	2024	Comprehensive review of maritime cybersecurity threats and vulnerabilities.	Identifies key weaknesses in shipboard, IoT, and satellite maritime systems.
[6]	2025	Cloud-edge collaborative computing framework for the Internet of Ships (IoS).	Decentralizes computing resources to enable real-time anomaly detection and protect data privacy.
[7]	2024	Survey of jamming and spoofing detection methods in GNSS systems.	Mitigates location manipulation and timing falsification in vessel tracking.
[8]	2023	Secure marine communication using multi-object authentication and secret sharing.	Provides lightweight authentication for distributed maritime environments.
[9]	2026	Hybrid hash-encryption scheme for secure marine data transmission.	Ensures efficient integrity verification with low computational overhead.

The literature review and Table 1 show that significant progress has been made in maritime cybersecurity. However, existing research primarily focuses on individual functions, such as threat detection, edge computing, authentication, routing security, and GNSS spoofing mitigation, rather than providing an integrated approach to securing heterogeneous maritime communication environments. Despite these advances, limited research has examined the integration of lightweight and conventional encryption mechanisms across different maritime communication layers while maintaining interoperability between resource-constrained devices and strategic infrastructure. This gap motivates the framework proposed in this study.

3. TWO-TIER SECURE COMMUNICATION ARCHITECTURE

Maritime communications are challenged by the heterogeneity of connected assets, which operate with different protocols, capabilities, and roles, including vessels, satellite stations, sensors, and autonomous systems. Variations in processing power, energy resources, and bandwidth make the use of uniform cryptographic mechanisms inefficient, as they can introduce unnecessary overhead and latency. Therefore, they should be adapted to the capabilities of individual devices within a consistent and unified security framework.

Table 2. Encryption mechanisms assigned to maritime communication tiers

Communication tier	Components	Cipher
Strategic zone	MOCs, Coast Guard Centres, Satellite Gateways	AES-256-GCM
Edge zone	AIS, Smart Buoys, Sensors, ASVs	ASCON-128

The proposed architecture is divided into two security zones (Table 2): strategic zone and edge zone, each designed to address the specific operational and resource requirements of its components. The strategic security zone includes critical infrastructure like Maritime Command Centres (MOCs), Coast Guard Headquarters, Naval Operations Centres, Satellite Ground Stations, and Vessel Communication Gateways. Its aim is to protect critical operational data transmitted across high-capacity communication networks and strategic maritime information systems.

The edge security zone consists of resource-constrained devices operating in the maritime environment and includes AIS transceivers, smart buoys, environmental monitoring sensors, autonomous surface vehicles (ASVs), and other maritime IoT devices.

Table 3. Comparison of selected ciphers for maritime communication environments

Characteristics	AES-256-GCM	ASCON-128
Authenticated encryption (AEAD)	Yes	Yes
Security level	High	High
Computational overhead	Higher	Lower
Memory requirements	Higher	Lower
Energy consumption	Higher	Lower
Suitability for resource-constrained devices	Moderate	High
Suitability for critical infrastructure	High	High

The selection of cryptographic algorithms within the proposed framework considers the operational characteristics of the corresponding communication domains, as well as the cryptographic properties and implementation performance reported in

the literature [10], [11], [12], [13]. The comparison between the two choices is presented in Table 3.

Strategic maritime infrastructure has sufficient computational resources and stable power availability, making AES-256-GCM an appropriate choice for protecting critical communications [11]. On the other hand, maritime IoT devices, autonomous platforms, and distributed sensors operate under strict energy, processing, and bandwidth constraints, making ASCON-128 [14] a suitable choice.

By separating cryptographic responsibilities according to operational requirements, the proposed architecture aims to improve communication efficiency while maintaining a high level of security across the maritime surveillance network.

Based on the strategic zones, the framework is divided into two tiers, as presented in Fig. 1.

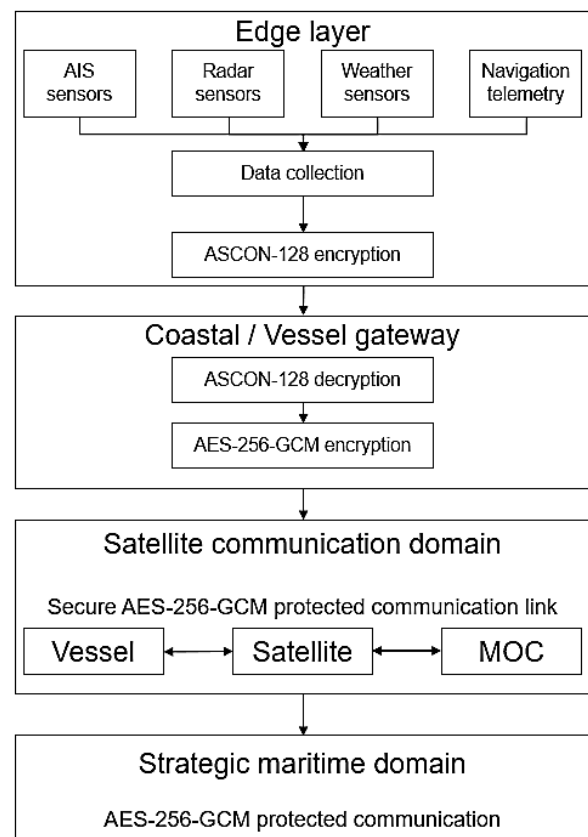


Figure 1. Hybrid maritime communication security architecture

The communication process begins at the edge layer, where maritime sensors collect surveillance information like vessel positions, environmental measurements, AIS transmissions, radar observations, and navigation telemetry. Prior to transmission, collected data are encrypted locally using

ASCON-128. This minimizes computational overhead while protecting sensitive information from eavesdropping and unauthorized modification.

Encrypted sensor data are then transmitted to a Coastal Gateway or Vessel Gateway responsible for aggregating information from multiple edge devices. The gateway acts as a security boundary between the edge domain and the strategic communication domain. It verifies and decrypts ASCON-128 protected traffic before establishing AES-256-GCM encryption for transmission within the strategic communication domain.

The use of AES-256-GCM within the strategic domain ensures that information exchanged between maritime operation centres, vessels, and satellite infrastructure benefits from strong cryptographic protection while remaining compatible with existing secure communication standards.

To demonstrate the proposed framework, a simulation environment is implemented using a lightweight web technology stack. The frontend is developed with React 18. Vite is used as the build tool and development server. The visual layer is

styled using Tailwind CSS. Interactive inline SVG rendering is used to create a tactical surveillance map for real-time visualization of nodes, links, and telemetry movement. The cryptographic logic is developed in TypeScript as custom simulation modules.

The simulation (Fig. 2) is designed to show how the combination of a lightweight cipher at the constrained edge and encryption using AES-256-GCM at a coastal gateway can protect critical telemetry data. It operates through an interactive tactical map and real-time cryptographic emulation components. Users can manually initiate telemetry transmissions from any edge sensor, triggering a step-by-step visualization of the ASCON-128 construction. As the telemetry packet moves across the harbour, it is received by the coastal gateway, where the lightweight integrity tag is verified. The gateway then decrypts the payload and encrypts it using AES-256-GCM. The secured data is subsequently forwarded via satellite links to the final command stations.

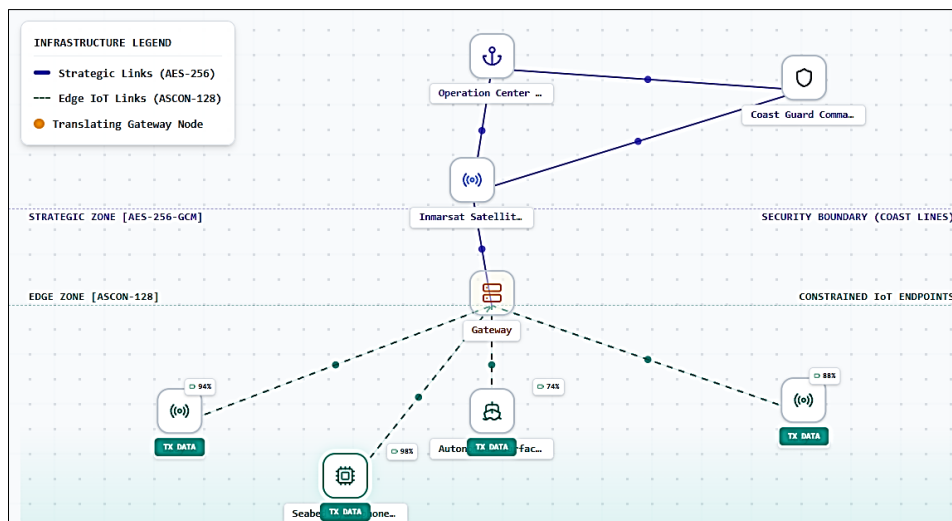


Figure 2. Simulation of the two-tier secure communication architecture

4. CONCLUSION

This paper presents a two-tier secure communication framework for maritime environments that combines conventional and lightweight cryptographic mechanisms according to the capabilities of different network components. The proposed framework separates strategic maritime infrastructure from resource-constrained edge devices and applies AES-256-GCM and ASCON-128 encryp-

tion, respectively, to balance security and communication efficiency.

The architecture enables secure integration between heterogeneous maritime communication domains through gateway-based cryptographic processing while maintaining data confidentiality and integrity. Based on the established properties of the two algorithms, the proposed approach is expected to reduce computational overhead and

energy consumption for critical maritime communication infrastructure.

The simulation presents the proposed architecture in a proof-of-concept setting, demonstrating secure maritime data transmission across the defined communication layers.

The proposed framework is suitable for deployment in Internet of Ships (IoS), maritime surveillance networks, vessel monitoring systems, and distributed maritime sensor environments. Future work will focus on implementing the proposed architecture in a real-world maritime testbed and evaluating its performance in terms of latency, energy consumption, bandwidth efficiency, and resilience against cyberattacks under realistic operational conditions, as well as mechanisms to secure the gateway boundary itself and mitigate the risk of its compromise.

ACKNOWLEDGEMENTS

This report was financed by the Ministry of Education and Science under the National Science Program "Security and Defense", carried out in implementation of the National Strategy for the Development of Scientific Research 2017-2030 and adopted by Decision of the Council of Ministers No. 731 of October 21, 2021. The material reflects only the author's opinion, and the Ministry of Education and Science is not responsible for the content.

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THREAT MODELLING, TAXONOMY AND RISK ASSESSMENT OF LORA MESH-BASED MARITIME SAFETY SYSTEMS

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Abstract

LoRa mesh networks are increasingly used in maritime safety systems due to their long-range communication capabilities and low power consumption. However, their multi-hop architecture introduces additional security vulnerabilities that may affect emergency communications and personnel tracking. This paper presents a threat modeling, taxonomy, and risk assessment study of LoRa mesh-based maritime safety systems. Seven threat categories are identified and classified according to their impact on confidentiality, integrity, availability, and trust. A quantitative risk assessment framework based on likelihood and severity is applied to evaluate the most relevant threats. The results indicate that replay attacks and spoofing represent the highest-risk threats, while flooding/DoS, eavesdropping, and message tampering are classified as medium-risk threats impacting network availability, confidentiality, and integrity. The analysis provides a foundation for improving the security and resilience of future maritime LoRa mesh deployments.

Keywords: authentication, LoRa, maritime IoT, mesh, risk assessment, security vulnerabilities, taxonomy, threat modeling

1. INTRODUCTION

LoRa-based maritime IoT systems are increasingly used to support sailor safety, emergency signaling, and personnel tracking in offshore environments. By utilizing low-power long-range communication and mesh networking, wearable devices can maintain connectivity beyond the coverage of conventional maritime communication infrastructure [1], [2].

The decentralized nature of LoRa mesh networks introduces security challenges that may affect the reliability of distress communications. Unlike conventional LoRaWAN deployments, the proposed LoRa-based mesh topology in [1], [2] relies on peer-to-peer forwarding and dynamic multi-hop routing.

This paper investigates the security vulnerabilities of LoRa mesh-based maritime safety systems through structured threat modelling, domain-specific threat taxonomy, and quantitative risk assessment. The identified threats are analysed according to their likelihood and operational impact within a maritime operational context, considering the additional risks introduced by decentralized multi-hop routing and forwarding. A set of targeted countermeasures is proposed to address the

threats, thereby enhancing the security, reliability, and resilience of emergency communications. The novelty of the work lies in extending security analysis from conventional LoRaWAN star-topology systems to decentralized maritime mesh networks, introducing a threat taxonomy and risk assessment framework specifically designed for wearable IoT safety applications in offshore environments. The presented framework provides practical guidance for the secure design and deployment of future maritime IoT safety networks.

2. RESEARCH BACKGROUND

2.1. LoRa mesh technology in maritime systems

LoRa is a low-power long-range physical-layer wireless technology based on Chirp Spread Spectrum (CSS) [3], [4]. Operating in unlicensed ISM (Industrial, Scientific, and Medical) bands (e.g., 868 MHz in Europe, 915 MHz in North America), LoRa supports connectivity over several kilometres, making it well-suited for maritime environments with sparse infrastructure [3], [5].

In a LoRa mesh network, nodes act as transmitters, receivers, and relays, forwarding messages through multiple hops until the data reaches its

destination. This topology can extend communication coverage in maritime environments where direct line-of-sight links or gateway connectivity cannot always be guaranteed [6], [7]. When integrated into wearable devices, LoRa mesh networks can support periodic position reporting and distress alerts in remote maritime areas [1], [2].

2.2. LoRaWAN security model and limitations

LoRaWAN defines a star-of-stars network architecture consisting of end devices, gateways, and a network server. It includes AES-128 encryption and separate network and application session keys to provide message integrity, authentication, and data confidentiality [4], [8]. In LoRaWAN 1.0.x, they are represented by the Network Session Key (NwkSKey) and the Application Session Key (AppSKey). The protocol also includes frame counters to mitigate replay attacks and Message Integrity Codes (MICs) to verify message authenticity and integrity [9]. However, standard LoRaWAN relies on centralized infrastructure, whereas the proposed mesh architecture uses decentralized, multi-hop peer-to-peer forwarding. Consequently, LoRaWAN's security mechanisms may not address mesh-specific threats. Several studies have identified vulnerabilities affecting LoRaWAN systems at the physical, MAC, and application layers [3], [9], [10].

The main limitations of LoRaWAN security for maritime mesh systems include:

- Lack of peer-to-peer authentication – nodes cannot verify the legitimacy of neighbouring devices without centralized infrastructure [11].
- Static key management – pre-shared keys are vulnerable if any node is compromised [12].
- Replay vulnerability – limited nonce or time-stamp usage allows repeated message injection [10].
- No dynamic trust propagation – malicious nodes cannot be effectively isolated in real time [5].

Given these weaknesses, maritime LoRa mesh systems require a domain-specific security framework that accounts for ad hoc connectivity, intermittent communication, and operational safety priorities.

3. THREAT MODELING AND TAXONOMY

The threat model for the proposed LoRa-based wearable system for maritime tracking [1], [2] considers a multi-hop wireless environment where nodes may act as both sensing devices and forwarding relays. Compared to traditional LoRaWAN star topologies, the mesh extension introduces additional vulnerabilities at the routing and packet-forwarding level, increasing the overall attack surface.

The proposed taxonomy in Table 1 classifies threats into seven categories: replay attacks, spoofing/impersonation, message tampering, routing attacks, flooding/DoS, node capture, and eavesdropping, based on their impact on identity assurance, data integrity, network availability, trust, and confidentiality in maritime safety scenarios.

Replay attacks reuse previously transmitted packets [13], [14], potentially causing duplicate distress or man-overboard (MOB) alerts and inconsistent state propagation. Spoofing and impersonation attacks enable unauthorized nodes to participate in routing or inject false information, leading to route manipulation and false alerts [14]. Message tampering affects data integrity by altering sensor or positional information, degrading vessel tracking accuracy [13].

Routing attacks are particularly relevant in LoRa mesh networks, where intermediate nodes are responsible for packet forwarding. They can disrupt search-and-rescue (SAR) coordination by dropping or redirecting critical messages [13]. Flooding and denial-of-service (DoS) attacks exploit the limited bandwidth and duty-cycle constraints of LoRa systems, leading to congestion and delayed emergency communication [13].

Node capture represents a physical/device-level threat where compromised devices allow extraction of cryptographic keys and long-term network impersonation [3]. Eavesdropping attacks involve passive interception of wireless transmissions, exposing sensitive maritime location and operational data [13].

The mitigation techniques for the identified threats in LoRa-based maritime mesh systems include frame counters, nonces, and freshness validation for replay protection; mutual authentication, message authentication codes (MACs), secure key-identity binding, and node verification for spoofing

and impersonation prevention; authenticated encryption and integrity checks for message tampering; multipath routing, trust-based routing, neighbour verification, and anomaly detection for routing attacks; rate limiting, duty-cycle enforcement, and congestion-aware MAC protocols for flooding and DoS mitigation; secure elements, key revocation, periodic re-keying, and intrusion detection for node capture; and lightweight encryption together with

secure key management and, where required, hop-level re-encryption for protection against eavesdropping.

The taxonomy highlights that while conventional IoT threats remain applicable, LoRa mesh systems introduce additional risks at the routing and relay layers due to their multi-hop architecture.

Table 1. LoRa mesh maritime threat taxonomy

Attack type	Description	Impact on maritime safety	Mitigation
Replay attack	Reuse of previously transmitted legitimate packets in a multi-hop LoRa mesh network, violating message freshness guarantees.	False distress/MOB alerts; duplicate SAR actions; inconsistent emergency state propagation.	Frame counters, nonces, freshness validation.
Spoofing / impersonation	Malicious node forges an identity or acts as a legitimate relay in the LoRa mesh.	Unauthorized network participation; false alerts; routing manipulation.	Mutual authentication, MACs, secure key-identity binding, node verification.
Message tampering	Unauthorized modification of sensor/GPS/status data during transmission or forwarding.	Incorrect vessel tracking; degraded situational awareness; unsafe SAR decisions.	Authenticated encryption, integrity checks.
Routing attacks	Malicious nodes manipulate multi-hop routing by attracting, dropping, or tunnelling packets.	Loss/interception of emergency messages; disrupted SAR coordination; mesh partitioning.	Multipath routing, trust-based routing, neighbour verification, anomaly detection.
Flooding / DoS	Excessive transmissions or routing requests overwhelm constrained LoRa mesh bandwidth and duty-cycle limits.	Network congestion; delayed emergency communication; node energy depletion.	Rate limiting, duty-cycle enforcement, congestion-aware MAC.
Node capture / physical compromise	Physical access to LoRa mesh node enables extraction of cryptographic keys or firmware compromise.	Long-term impersonation; persistent malicious routing; full trust breakdown of mesh segment.	Secure elements, key revocation, periodic re-keying, intrusion detection.
Eavesdropping	Passive interception of LoRa physical layer transmissions across mesh hops.	Vessel location leakage; operational privacy risks; exposure to targeted maritime threats.	Lightweight encryption, secure key management, optional hop-level re-encryption.

4. RISK ASSESSMENT FRAMEWORK

The risk assessment considers only five of the seven identified threats, focusing on those most relevant to operational maritime safety and communication reliability, while routing attacks and node capture are discussed qualitatively due to their dependency on specific deployment assumptions.

To evaluate the relative importance of the identified threats, a quantitative risk assessment framework is developed (Table 2) based on two criteria:

- Likelihood (L) – probability of the attack occurring.
- Severity (S) – operational or safety impact if exploited.

The assessment follows a 3x3 likelihood-severity matrix, where likelihood and severity are assigned numerical values from 1 to 3. Likelihood levels are defined as **Low (1)**, **Medium (2)**, and **High (3)**, while severity levels are defined as **Minor (1)**, **Major (2)**, and **Critical (3)**.

The overall risk score (R) is calculated as:

$$R = L \times S, \quad (1)$$

where L represents the likelihood of occurrence and S represents the severity of the potential impact.

Based on the calculated score, risk levels are classified as follows:

- **Low Risk:** 1–2
- **Medium Risk:** 3–4
- **High Risk:** 6
- **Critical Risk:** 9

As shown in Table 2 and Figure 1, replay attacks and spoofing represent the highest-risk threats to the proposed system. Replay attacks can trigger false distress alerts and disrupt search-and-rescue operations, while spoofing can compromise trust in identities and safety-critical communications. Flooding/DoS, eavesdropping, and message tampering are assessed as medium-risk threats that affect network availability, confidentiality, and message integrity.

Table 2. Risk evaluation matrix for maritime LoRa mesh threats

Threat	Likelihood (L)	Severity (S)	Risk level (R)	Notes
Replay attack	High	Major	High	Can trigger false distress alerts and disrupt SAR operations.
Spoofing	Medium	Critical	High	Can fully compromise trust in identity and safety messages.
Flooding / DoS	Medium	Major	Medium	Causes congestion, delays, and energy depletion.
Eavesdropping	High	Minor	Medium	Enables location leakage and operational exposure.
Message tampering	Low	Critical	Medium	Less frequent but high impact if successful.

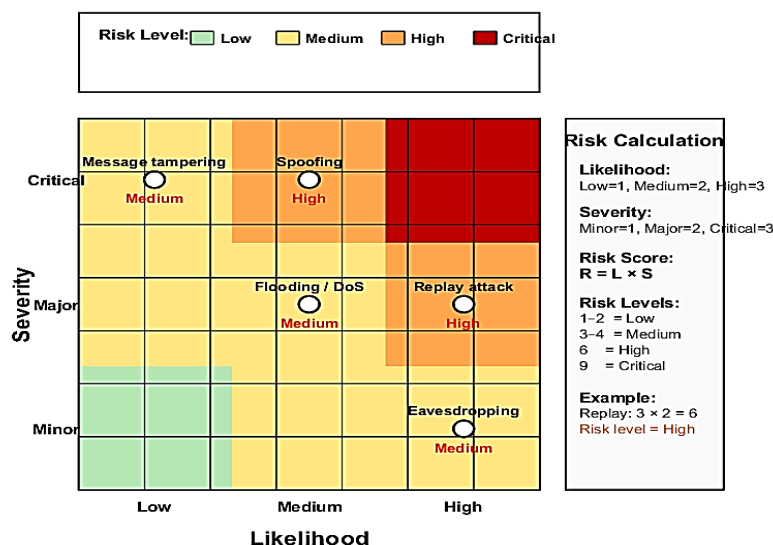


Figure 1. Risk assessment matrix for LoRa mesh maritime communication threats

The results indicate that authentication, replay protection, and message integrity verification

should be prioritized when designing secure maritime LoRa mesh safety systems.

5. CONCLUSION

This paper presented a structured security analysis of LoRa mesh-based maritime safety systems through threat modelling, a domain-specific threat taxonomy, and a quantitative risk assessment framework. The study identified key security threats - replay attacks, spoofing/impersonation, message tampering, routing attacks, flooding/DoS, node capture, and eavesdropping, and evaluated their impact on maritime safety-critical functions such as distress signalling and personnel tracking. The risk assessment results identify replay attacks and spoofing as the most significant threats, while flooding/DoS attacks, eavesdropping, and message tampering are assessed as medium-risk threats that may still adversely affect the availability, confidentiality, and integrity of maritime communications.

The findings highlight that the decentralized and multi-hop nature of LoRa mesh networks significantly increases the attack surface compared to traditional LoRaWAN star topologies, particularly at the routing and packet-forwarding level. To address these vulnerabilities, the paper proposed a set of targeted countermeasures, emphasizing authentication mechanisms, replay protection, message integrity verification, and lightweight encryption techniques adapted for constrained maritime IoT environments.

The proposed framework provides a systematic approach for understanding, classifying, and prioritizing security threats in maritime LoRa mesh systems and offers practical guidance for designing more secure and resilient wearable IoT safety networks in offshore environments.

ACKNOWLEDGEMENTS

This report was financed by the Ministry of Education and Science under the National Science Program "Security and Defense", carried out in implementation of the National Strategy for the Development of Scientific Research 2017-2030 and adopted by Decision of the Council of Ministers No. 731 of October 21, 2021. The material reflects only the author's opinion, and the Ministry of Education and Science is not responsible for the content.

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DISTRIBUTION AND IMPACT OF RADIATIVE HEAT TRANSFER IN FIRES OF ELECTRIC VEHICLES IN UNDERGROUND GARAGES

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Abstract

Electric vehicle (EV) fires in underground garages pose a high risk of rapid fire spread because intense radiative heat transfer can ignite adjacent vehicles within a short time. This paper evaluates the role of radiation in this process and estimates the ignition time of neighboring vehicle components under a representative heat flux of 40 kW/m². The authors apply radiative heat-transfer and thermal-energy accumulation models to tires and interior materials located approximately 1 m from the fire source. The calculations show ignition times of about 3.51 min for tires and 4.29 min for interior components, considerably shorter than values reported for conventional vehicle fires. The results confirm that radiative transfer is a critical mechanism in confined parking structures and support stronger fire-protection measures, including water-based suppression and smoke-control systems in underground garages. The proposed analysis is also relevant to telecommunications-based fire safety systems, where wireless sensor networks and real-time communication links can support early detection, continuous thermal monitoring, and automated activation of fire-protection systems in underground garages.

1. INTRODUCTION

Over the past decade, electric vehicles (EVs) have become a cornerstone of sustainable transportation. However, their large-scale adoption introduces specific risks that differ significantly from those associated with conventional internal combustion engine (ICE) vehicles. These risks stem primarily from the unique characteristics of EV powertrains, particularly the presence of high-energy lithium-ion batteries, which exhibit distinct fire dynamics compared to liquid-fuel systems.

The global transition towards electrification has accelerated rapidly, driven by stringent environmental regulations and the pursuit of reduced greenhouse gas emissions. This trend is evident not only worldwide but also in Bulgaria, where the adoption of electric vehicles has shown remarkable growth. In fact, the number of registered light EVs increased by 55% compared to 2024, reaching a total of 17,826 units as of January 1, 2025. Such expansion underscores the urgency of addressing safety challenges associated with EV fires, particularly in confined spaces such as underground parking facilities. Future research must therefore focus on identifying the mechanisms of fire propagation in EV-related incidents and developing effective mitigation strategies. [14].

Table 1. Temp and growth of electric car sales
[10] [11] [12] [13]

Year	New electric cars in BG	Decline/ Growth compared to the previous	Comment
2015	~21	–	Initial steps
2018	~194	+824%	194 sales
2023	over 19000 (everything - light, medium and heavy duty)	+9694 %	Exceptional growth
2024 (until September)	1 249	–10.9 %	Decrease compared to 2023
May 2025	197 (only in May)	–	–

Fires involving electric vehicles are characterized by extremely high temperatures, intense heat release rates, and the emission of toxic gases. These incidents pose a particularly severe hazard in enclosed spaces such as underground parking garages, where limited natural ventilation and the close proximity of vehicles create conditions for rapid fire growth and heat accumulation [10,11]. The complexity of fire dynamics in such scenarios is further exacerbated by the interaction of structural elements and the confined nature of the envi-

ronment, which significantly impedes firefighting operations.

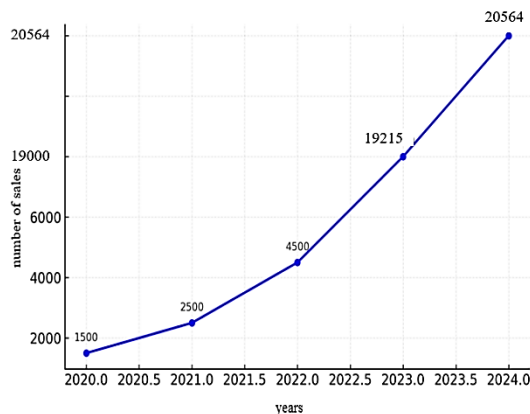


Figure 1. Sales of electric vehicles in Bulgaria by year

In these conditions, radiative heat transfer emerges as the dominant mechanism of thermal energy propagation. During a thermal runaway event in a lithium-ion battery pack, temperatures can exceed 1000 °C, producing a substantial radiative heat flux. This heat flux is capable of igniting adjacent vehicles within a relatively short time frame, initiating a chain reaction that can escalate the fire to a multi-vehicle conflagration. Additionally, the release of flammable gases during cell venting not only intensifies the combustion process but also introduces the risk of secondary explosions.

These factors collectively highlight the necessity for comprehensive studies on radiative heat transfer in EV fires, particularly in confined parking structures, where the potential for catastrophic damage is considerably higher.

2. SPECIFICATIONS AND MECHANISM OF RADIATION HEAT TRANSFER BETWEEN VEHICLES

Radiative heat transfer in vehicle fires, particularly within enclosed environments such as underground parking structures and garages, represents a primary factor contributing to the rapid propagation of flames. The high heat release rate generated during combustion, in conjunction with the close spatial arrangement of vehicles, results in intense radiative flux, which constitutes a critical ignition source for adjacent vehicles. This circumstance underscores the necessity of in-depth research on radiative heat transfer mechanisms under these conditions, as they exert a substantial influence on the overall fire dynamics and are essential for the prevention of cascading fire spread events.

The dynamics of a fire reflect a spatio-temporal evolution process, where in confined spaces the heat balance is predominantly governed by radiation. As the temperature of burning surfaces increases, the intensity of radiative emission rises proportionally to the fourth power of the absolute temperature, according to Stefan–Boltzmann's law. This exponential growth significantly amplifies the heat flux impacting nearby objects. In addition to emitting energy, each surface concurrently absorbs radiant energy from neighboring heated or burning surfaces, accelerating its thermal loading and potentially leading to ignition temperatures being reached within a short timeframe.

Conversely, in open-air scenarios, the process evolves differently due to the absence of heat accumulation within the combustion zone. In such cases, the spread of flames and the burning rate are primarily influenced by wind conditions and convective flows. In enclosed environments, however, restricted ventilation facilitates considerable heat retention, which, in combination with radiative heat transfer, creates an exceptionally aggressive environment for fire escalation. The extent of the burning zone and flame spread rate are determined by the combustible load, spatial geometry, and the behavior of developing convective gas streams. Nevertheless, radiative heat transfer remains the dominant mechanism for rapid heat transfer between adjacent vehicles. Heat exchange occurs within the surrounding unconfined environment, as illustrated in Fig. 2.

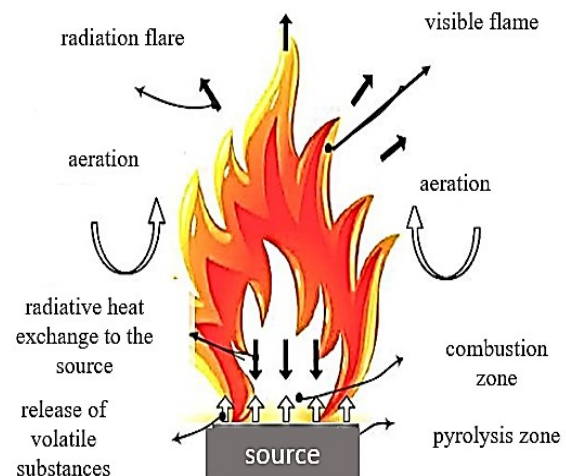


Figure 2. Heat transfer in an unbounded environment [6]

The distinct characteristic of this heat transfer mechanism lies in the fact that even short-term exposure to intense radiative heat can trigger igni-

tion in nearby combustible objects, such as vehicles, wooden structures, temporary shelters, or building elements. In the specific context of parking facilities and garages, where the spacing between vehicles is minimal, this phenomenon assumes critical importance, as only a few minutes of exposure to elevated thermal radiation may result in the ignition of an adjacent automobile. Continuous heat radiation from a burning vehicle leads to a gradual accumulation of thermal energy in surrounding objects, thereby accelerating the attainment of ignition-critical temperatures.

According to the principles of radiative heat transfer, the amount of heat energy transmitted depends on the difference between the energy emitted by the hot body and the energy absorption capacity of the receiving body. In the case of a burning vehicle, the surface temperature increases significantly, which intensifies radiation emission in accordance with Stefan–Boltzmann’s law. The emitted thermal energy propagates through the air to adjacent objects, whose surfaces absorb a portion of the radiative flux, progressively increasing their temperature until the ignition point of combustible components is reached. This phenomenon explains the mechanism behind the so-called “chain propagation” of fires in environments with high vehicular density.

Additional factors influencing this mechanism include the emissivity of surfaces, the distance between vehicles, and the presence of barriers capable of reflecting or absorbing part of the radiative energy. In real-world scenarios, particularly within enclosed parking structures where reflections from walls and ceilings amplify the overall heat flux, the risk of fire propagation through radiation increases substantially. Consequently, when developing fire models and designing fire safety measures, it is essential to account not only for convective heat transfer but also for radiative mechanisms as a dominant parameter for predicting fire dynamics (see Fig. 3) [6].

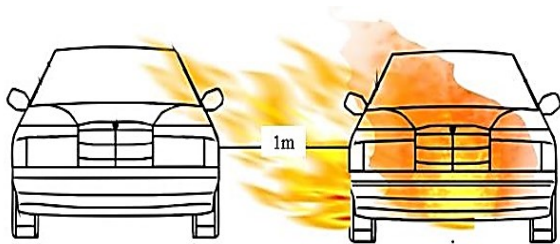


Figure 3. Spread of fire to a neighboring vehicle

3. MODELING AND EVALUATION OF VEHICLE IGNITION TIME WITH INTENSIVE RADIATION HEAT FLOW

To determine whether a vehicle located at a distance of 1 meter from a fire source will ignite when exposed to a radiative heat flux of 40 kW/m² (according to [7], during an electric vehicle fire, the radiative heat transfer can range between 40 and 60 kW/m²), it is necessary to apply appropriate thermodynamic equations and consider the ignition temperature of the materials composing the adjacent vehicle (e.g., plastics, rubber, metals).

Knowledge of the ignition temperature of flammable materials likely to be present in the neighboring vehicle is crucial, such as:

- Tires: approximately 250°C – 300°C
- Plastics: approximately 300°C – 350°C
- Textile materials: approximately 200°C-250°C [9]

Given the radiative heat flux from the burning vehicle (40 kW/m²), to assess whether the adjacent vehicle will ignite, the following heat flux equation should be applied [3]:

$$q = \sigma \cdot \varepsilon \cdot T^4, \quad (1)$$

where: q is the heat flux (40 kW/m²); σ is the Stefan-Boltzmann constant; ε denotes the emissivity of the object (≈ 1 for a black body); T is the object’s temperature in Kelvin.

The next step involves computing the temperature T of the object using the known radiative heat flux and emissivity values [3]

$$T = \left(\frac{q}{\sigma \cdot \varepsilon} \right)^{1/4} \quad (2)$$

This calculation provides the equilibrium temperature to which the adjacent object will heat under sustained radiative exposure. Consequently:

$$T = \left(\frac{40000}{5.67 \times 10^{-8}} \right)^{1/4} = 916.5 \text{ K} \approx 643.5^\circ\text{C} \quad (3)$$

The obtained temperature is significantly higher than the ignition threshold of most common automotive materials, such as tires, plastics, and textiles, which typically ignite at around 250°C – 350°C. Therefore, under a radiative heat flux of 40 kW/m², the adjacent vehicle will reach ignition conditions after a certain time interval.

To estimate the self-ignition time of vehicles located 1 meter away, the principle of thermal energy accumulation on combustible surfaces is applied. Assuming a combined exposed area of approximately 2 m² (including tires and interior), an average specific heat capacity of 1.5 kJ/(kg·K) for rubber and plastics, and a total mass of about 50 kg for tires and interior components, the accumulated heat energy will be used to raise the material's temperature. The ignition time can be calculated as follows [9]:

First, compute the energy required to increase the temperature [5]:

$$Q_{\text{necessary}} = m \cdot c \cdot \Delta T, \quad (4)$$

where: m- material mass (50 kg); c - specific heat capacity (1.5 kJ/(kg·K)); ΔT - difference between initial temperature and ignition temperature (approx. 250°C for tires and 300°C for interior materials).

Next, apply the heat accumulation relationship to determine time:

$$Q = q \cdot A \cdot t, \quad (5)$$

where: q – heat flux (40 kW/m²);

A- surface area (2 m²); t – time in seconds.

Following these calculations ((4) and (5)), the results indicate that:

- Tires ignite after approximately 3.51 minutes of exposure to a 40 kW/m² radiative heat flux.
- The interior ignites after approximately 4.29 minutes under the same conditions.

These ignition times are remarkably short, highlighting the rapid rate at which a fire can propagate in the vicinity of a burning vehicle when the radiative heat flux is sufficiently high. For comparison, in [4], during an internal combustion engine (ICE) vehicle fire, an adjacent vehicle located at a distance of 0.8 m and exposed to a heat flux of 26.66 kW/m² ignites in approximately 8 minutes—almost twice the time calculated in the present analysis. This discrepancy is primarily attributed to the higher energy release associated with electric vehicle (EV) fires compared to ICE vehicles.

The escalation of fire in an underground garage involving multiple vehicles can result not only in severe material losses but also in substantial structural damage. Prolonged exposure of reinforced

concrete elements to elevated temperatures causes a significant reduction in load-bearing capacity, primarily due to the degradation of concrete strength and the loss of bond between steel reinforcement and concrete. Numerous studies emphasize that in confined garage fires, temperatures may exceed 800–1000 °C, which is critical for structural stability [2][6][8]. Such thermal conditions create a potential for partial structural failure and even progressive collapse of the building, posing a severe risk to human life and safety.

Recommendations for Future Research:

Full-Scale Experimental Testing – Evaluation of the performance of various sprinkler technologies and advanced suppression methods under real-world EV fire scenarios.

Development of Innovative Battery Cooling Techniques – To arrest thermal runaway propagation and reduce re-ignition risks.

Computational Fluid Dynamics (CFD) Simulations – For predicting smoke and toxic gas dispersion in confined environments and optimizing ventilation strategies.

4. CONCLUSION

The findings of this study reveal that in the event of an electric vehicle (EV) fire in an underground parking facility, ignition of an adjacent vehicle can occur within 3–4 minutes, posing a critical threat to life safety, property integrity, and structural stability. This extremely short ignition window underscores the necessity for enhanced fire protection strategies and immediate regulatory action.

Recommended Engineering and Regulatory Measures:

Amendments to Bulgarian Fire Safety Regulations – Specifically, revisions to Regulation No. I3-1971 of October 29, 2009, and in particular Chapter IX, Article 113, paragraph 5, item 2, which currently mandates the installation of automatic water-based sprinkler systems and smoke control systems only for underground garages with 10 or more parking spaces. This requirement creates a significant safety gap: for example, in a garage with only 9 vehicles, if a fire starts in the central one, all surrounding vehicles could ignite within approximately 12 minutes, as demonstrated by the rapid heat propagation documented in this study. Therefore, it is critical to extend this requirement to all under-

ground garages, regardless of capacity, to effectively mitigate the risk of multi-vehicle fire escalation.

Deployment of Automated Cooling and Gas Detection Systems – To prevent thermal runaway escalation and mitigate hazardous concentrations of toxic and flammable gases.

Specialized Firefighter Training – Focused on lithium-ion battery hazards, suppression techniques, and strategies for preventing secondary ignition events.

The study highlights that addressing the unique challenges posed by EV fires requires an integrated approach combining advanced engineering solutions, updated fire codes, and specialized emergency response protocols. Without such measures, the growing penetration of EVs in urban infrastructure could significantly increase fire risk in confined parking environments.

From a telecommunications perspective, the short ignition interval identified in this study (approximately 3 – 4 minutes for an adjacent vehicle under intense radiative exposure) highlights the need for rapid and reliable information exchange in underground fire safety systems. Wireless sensor networks integrating thermal, infrared, smoke, and gas detectors could provide continuous monitoring of parking areas and transmit a real time data to a centralized fire safety control system. Low-latency communication between distributed sensors, control units, and automated suppression and smoke management systems could reduce detection and response times and enable protective measures to be activated before fire propagation reaches neighbouring vehicles. Therefore, the presented thermal analysis can serve as a basis for defining a communication-response requirements in future cyber-physical fire protection systems for underground garages.

5. ACKNOWLEDGMENTS

The authors would like to thank the Research and Development Sector at the Technical University of Sofia for the financial support.

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ENVIRONMENTAL AND HEALTH RISKS OF ELECTRIC VEHICLE FIRES IN ENCLOSED SPACES: ANALYSIS AND RECOMMENDATIONS

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Abstract

The rapid adoption of electric vehicles (EVs) introduces specific fire-safety and environmental risks in enclosed spaces, particularly underground parking facilities, where limited ventilation can accelerate the accumulation of heat, smoke, and toxic combustion products. This paper analyses the hazards associated with lithium-ion battery fires, with particular attention to thermal runaway and emissions of hydrogen fluoride (HF), carbon monoxide (CO), hydrogen chloride (HCl), and fine particulate matter. Based on experimental data and published studies, the authors identify the increased toxicity of EV fire effluents and the resulting risks to occupants, emergency responders, and the environment. The paper proposes engineering and regulatory measures, including automated emergency ventilation, gas detection, and revised Bulgarian requirements for underground garages. Such systems may also be integrated with optical telecommunications infrastructure through fiber-optic sensing and reliable data transmission for real-time fire detection and emergency control.

1. INTRODUCTION

In recent years, electric vehicles (EVs) have gained prominence as a sustainable alternative to internal combustion engine (ICE) vehicles, primarily due to their reduced operational emissions and alignment with global decarbonization strategies. Their rapid adoption has been driven by stringent environmental regulations, technological advancements, and increasing societal awareness of climate change. However, alongside these undeniable advantages, EVs introduce new and complex challenges in the field of fire safety and environmental risk management.

One of the most critical concerns relates to the unique characteristics of EV fires, which differ significantly from those involving conventional vehicles. Unlike ICE vehicles, EVs are powered by high-energy lithium-ion battery systems that can undergo thermal runaway – a self-propagating reaction that leads to rapid temperature escalation, gas release, and in many cases, violent combustion. These incidents are difficult to suppress using traditional firefighting techniques, often requiring specialized cooling methods and extended intervention times.

Furthermore, the chemical composition of the smoke generated during EV fires presents a distinct hazard. In addition to common combustion by-

products such as carbon monoxide (CO) and particulate matter, EV fires emit a wide range of toxic and corrosive compounds, including hydrogen fluoride (HF), phosphorous-based compounds, and various organic fluorides, which can severely impact human health and corrode structural elements. The situation becomes even more critical in enclosed environments, such as underground parking facilities, where limited ventilation exacerbates smoke accumulation, heat retention, and toxic gas concentration.

These factors collectively underscore the urgent need for a systematic analysis of the environmental and health risks associated with EV fires in enclosed spaces, as well as the development of robust preventive measures and regulatory frameworks. This paper addresses these concerns by examining the mechanisms of fire propagation, quantifying associated risks, and proposing engineering and legislative interventions to mitigate their impact.

2. BACKGROUND AND LITERATURE REVIEW

According to the comprehensive study by [1] published by the RISE Research Institutes of Sweden, the combustion of lithium-ion batteries generates a complex mixture of hazardous substances, including hydrogen fluoride (HF), carbon monoxide (CO),

carbon dioxide (CO₂), as well as significant amounts of fine aerosol particles and organic compounds with carcinogenic potential. Among these, HF poses a particularly severe threat due to its high toxicity and corrosive nature. Research indicates that, for certain battery chemistries, HF concentrations can exceed permissible exposure limits (PEL) within only a few minutes after ignition, creating a critical hazard for occupants and first responders.

Time-resolved spectroscopic measurements using FTIR and FID, illustrate the dynamic evolution of these emissions. Table 2 summarizes cumulative emissions data, including polycyclic aromatic hydrocarbons (PAHs) from supplementary gas sampling. Notably, normalized values (per kilogram of mass loss) reveal the disproportionately high toxicity of emissions from EV fires compared to their internal combustion engine (ICE) counterparts.

Table 1. Quantity of gas released by battery cells [1]

Study	Cathode	Cell type, size	Gas volume [L]	Energy [Wh]	[L/Wh]
ICAO [36]	LCO	Cylindrical 18650, small	8.00	17.64	0.45
Golubkov et al.	LFP	Cylindrical 18650, small	0.72	3.65	0.20
	NCA	Cylindrical, small	6.20	12.33	0.50
Golubkov et al.	LMO	Prismatic, large	133	185.3	0.72
	LMO	Prismatic, large	67.2	185.3	0.36
	LFP	Cylindrical 18650, small	1.12	3.85	0.29
Golubkov et al.	NMC	Cylindrical 18650, small	3.34	6.15	0.54
	NMC-LCO	Cylindrical 18650, small	5.94	10.5	0.57
Sturk et al.	LCO	Pouch, small	0.77	7.7	0.10
	LFP	Pouch, small	50.0	115.5	0.43
	NMC-LMO	Pouch, small	1500	287	5.2
Nedjalkov et al.	NMC	Pouch, large	200	172	1.2

Table 2. Gas compounds measured from the exhaust duct [1]

Gas measurements	ICEV A	BEV A	BEV B
CO ₂ [kg] / [g/lost g]	344 / (1.4)	335 / (1.4)	438 / (1.1)
CO [g] / [mg/lost g]	6420 / (25.5)	7790 / (31.5)	9510 / (23.8)
THC [g] / [mg/lost g]	2370 / (9.4)	3130 / (12.7)	2750 / (6.9)
HF [g] / [mg/lost g]	11 / (0.04)	573 / (2.3)	859 / (2.1)
HCl [g] / [mg/lost g]	1100 / (4.4)	1590 / (6.4)	1800 / (4.5)
HBr [g] / [mg/lost g]	18 / (0.1)	115 / (0.5)	88 / (0.2)
HCN [g] / [mg/lost g]	-	-	155 / (0.4)
SO ₂ [g] / [mg/lost g]	479 / (1.9)	575 / (2.3)	-
NO [g] / [mg/lost g]	452 / (1.8)	371 / (1.5)	617 / (1.5)
NO ₂ [g] / [mg/lost g]	44 / (0.2)	25 / (0.1)	145 / (0.4)
PAH [g] / [mg/lost g]	112 / (0.4)	29 / (0.1)	334 / (0.8)

A recent study published in Fire Safety Journal [2]; [3] offers a direct comparative analysis between EV and ICE vehicle fires. While the overall heat release rate (HRR) and total heat release (THR) were found to be broadly similar across both vehicle types, the toxicity profile of EV fire effluents was markedly higher. This discrepancy is primarily attributed to the electrolyte decomposition and fluorinated additives in lithium-ion batteries, combined with polymeric insulation and other synthetic components in EV systems. Despite similar peak HRR values, the qualitative composition of smoke introduces additional hazards unique to EV fires.

Further investigations, including those by [4] and [2] underscore the compounding risk in enclosed environments such as underground parking garages, where the absence of natural ventilation fosters rapid accumulation of toxic gases. These studies emphasize that such conditions significantly increase the threat not only to nearby occupants but also to emergency response personnel, who frequently operate under incomplete information regarding battery configuration, chemistry, and the current stage of thermal runaway.

Regulatory frameworks, such as the NFPA EV Emergency Response Guidelines, recognize the need for updated safety measures, including enhanced ventilation standards and specialized training protocols. However, many national regulations—including those in Bulgaria—remain insufficiently adapted to these emerging challenges. For example, existing provisions do not mandate additional ventilation capacity or early detection systems in underground garages where EV charging and storage occur, leaving a critical gap in fire safety infrastructure.

3. COMPOSITION AND TOXICITY OF SMOKE IN ELECTRIC VEHICLE FIRES

Fires involving electric vehicles release a variety of hazardous substances, the quantity and composition of which primarily depend on the type of battery, the combustion phase, and the volume of electronic and polymer components. The main source of toxic emissions is lithium-ion batteries, which contain a wide range of metals, electrolytes, and organic compounds that are prone to thermal decomposition at high temperatures.

3.1. Gaseous Emissions

According to a study by [5], the combustion of lithium-ion batteries results in the release of the following hazardous gases:

- Hydrogen fluoride (HF): A highly toxic and corrosive gas that causes severe burns to mucous membranes and lungs, even at low concentrations. Depending on the battery type, the released amount can reach up to 200–400 mg/Wh [5].
- Carbon monoxide (CO): A well-known combustion product that poses a serious poisoning risk by inhibiting the body's ability to transport oxygen.
- Hydrogen chloride (HCl) and sulfur dioxide (SO₂): Released from the combustion of PVC cables and other polymer components in the vehicle's electrical systems [6].

According to a report by [1], it has been found that during a battery module fire in an electric vehicle, the concentration of hydrogen fluoride (HF) in the air can exceed 50 ppm - more than 10 times higher than the permissible exposure limit for workplace

environments set by OSHA (Occupational Safety and Health Administration – USA).

Hydrogen fluoride (HF), which may be released during an electric vehicle fire - especially from lithium-ion batteries - is extremely toxic and hazardous to human health. HF is a highly corrosive gas that reacts aggressively with human tissue (eyes, skin, lungs), causing severe chemical burns. It penetrates deeper into tissues than most other acids because the fluoride ion binds with calcium and magnesium in the body. Even short-term exposure to concentrations above 30 ppm can be fatal. HF exposure may lead to chemical pneumonitis (inflammation of the lungs), pulmonary edema, and in severe cases - acute respiratory failure [7, 8]. Safe exposure thresholds according to OSHA and NIOSH (National Institute for Occupational Safety and Health - USA) are shown in Table 3.

Table 3. Safety thresholds (as per osha and niosh; ref.: Watanabe et al., Lam et al. INERIS)

Vehicle studied	Mass	Stored energy	PHRR [MW]	THR [GJ]	AEHC [MJ/kg]
2003 Honda Fit ICEV	1275	10 L gasoline	2.1	4.3	22
Toyota sedan ICEV		10 L gasoline	5.1	5.3	
Nissan minivan ICEV		10 L gasoline	5.2	5.1	
Subaru station ICEV		10 L gasoline	5.6	5.6	
Toyota minivan ICEV		10 L gasoline	3.3	4.8	
2011 Nissan Leaf BEV	1520	24 kWh 100% SOC	6.3	6.4	22
Toyota luxury sedan ICEV		10 L gasoline			
2015 Vehicle A ICEV	1096	Full tank gasoline	7.1	3.3	12
2013 Vehicle B ICEV	1344	Full tank gasoline	10.8	5.0	15

2013 Vehicle C PHEV	1466	<10 kWh 85% SOC + full tank gasoline	6	4.6	11
2014 Vehicle D PHEV	1711	<20 kWh 100% SOC + full tank gasoline	7.9	5.4	11
2014 Vehicle A BEV	1448	>20 kWh 100% SOC	6.0	5.2	10
2013 Vehicle B BEV	1475	>20 kWh 85% SOC	5.9	4.9	9
2013 Vehicle B BEV	1659	>20 kWh 100% SOC	6.9	5.6	10
Manufacturer 1 ICEV	1128	Full tank Diesel		9.4	35.7
Manufacturer 2 ICEV	1122	Full tank Diesel		6.6	39.5
Manufacturer 1 BEV	1122	16.5 kWh 100% SOC	4.0	4.3	29.8
Manufacturer 2 BEV	1501	23.5 kWh 100% SOC	4.7	8.5	30.7

3.2. Aerosols and particulate matter

In addition to gases, the combustion of batteries also releases aerosol particles with diameters below 1 micron, carrying heavy metals such as:

- Cobalt (Co), Manganese (Mn), Nickel (Ni) - present in the cathode material.
- Lithium (Li) - although in smaller amounts, it can cause infrastructure corrosion when reacting with water.

These particles can penetrate deep into the respiratory system and are associated with an increased risk of respiratory and neurological diseases, especially with prolonged exposure [5, 6].

3.3. Thermal instability and "Thermal runaway"

The phenomenon of "thermal runaway" in batteries is another source of hazardous emissions. It is a chain reaction in which each battery cell begins to heat up and decompose, releasing flammable and toxic gases. During this phase, additional substances such as hydrocarbons, acetonitrile, and organofluorides are emitted. These not only pose a toxic threat but also create conditions for explosive reactions upon contact with air [9].

3.4. Comparison with internal combustion engine vehicle fires

Although fires involving internal combustion engine (ICE) vehicles also emit toxic gases (primarily CO, NOx, and smoke from plastics and fuel), the presence and quantities of fluorine-containing compounds and metal aerosols are significantly lower. Furthermore, the risk of re-ignition is higher in electric vehicles, which further increases exposure risks for rescue teams and the environment.

4. HEALTH AND ENVIRONMENTAL RISKS IN CASE OF FIRE IN ENCLOSED SPACES

An electric vehicle fire in an enclosed space, such as an underground garage, creates a particularly hazardous environment due to limited air circulation, low ceilings, and slow removal of smoke and toxic gases. Such incidents pose potentially fatal risks both to people nearby and to the environment.

4.1. Health Risks to Humans

4.1.1. Acute inhalation poisoning

The toxic combustion products released during an electric vehicle fire - especially hydrogen fluoride (HF), carbon monoxide (CO), acetonitrile, and irritant gases such as HCl and SO₂ - pose an immediate danger when inhaled. According to OSHA, the permissible exposure limit for HF is 3 ppm, while fire scenarios can exceed 50–100 ppm within minutes, especially without active ventilation [1].

These substances can cause:

- Acute respiratory irritation - coughing, shortness of breath, laryngospasm
- Pulmonary edema - a life-threatening condition that may develop hours after exposure
- Neurotoxic effects - dizziness, headaches, loss of consciousness

- Cardiac complications - due to carbon monoxide in the bloodstream (carboxyhemoglobin)

4.1.2. Long-term exposure

Without adequate ventilation and decontamination, fine particulate matter and chemical residues from the fire may persist in the air and on surfaces in enclosed areas for extended periods. This presents a risk of:

- Chronic respiratory illnesses (e.g., asthma, COPD)
- Increased carcinogenic risk - especially from organofluorides and heavy metals
- Damage to eyes and skin - particularly through contact with electrolyte residues

4.1.3. Hazards for rescue teams

Firefighters face significant risks even when using personal protective equipment. The difficulty in determining the exact battery type, the combustion phase, and the possibility of secondary ignitions creates a situation of high uncertainty and extreme stress on protective systems.

4.2. Environmental impact

4.2.1. Air pollution

Toxic gases - especially HF, HCl, CO, and organic compounds - not only harm human health but also contribute to the degradation of the ozone layer and can accumulate in the atmosphere around the fire site. This is particularly dangerous in urban environments.

4.2.2. Soil and water contamination

Fire residues (such as leftover electrolytes, molten metals, and reaction products with water) often contain toxic metals and acids that can enter the sewage system or seep into groundwater. This poses a threat to:

- Aquatic ecosystems – particularly due to the presence of lithium and nickel
- Soil biodiversity – due to high acidity and heavy metals
- Human health through secondary exposure-via the food chain or drinking water.

4.2.3. Summary of environmental impact

In enclosed environments such as underground parking garages, electric vehicle fires create an

extremely aggressive toxic atmosphere that poses serious immediate and long-term risks to human health. At the same time, the environmental footprint of such incidents should not be underestimated - especially in terms of air, water, and soil pollution.

5. THE CRITICAL NEED FOR EMERGENCY VENTILATION IN ENCLOSED PARKING FACILITIES

5.1. Gaseous real risks in the absence of emergency ventilation:

The absence of dedicated emergency ventilation systems in enclosed parking structures, particularly those accommodating electric vehicles, creates an environment where hazardous conditions develop within minutes. Empirical studies and full-scale fire tests demonstrate the following key risks:

- Rapid atmospheric saturation with toxic and corrosive compounds: During thermal runaway and subsequent combustion of lithium-ion batteries, gases such as hydrogen fluoride (HF) and carbon monoxide (CO) can reach concentrations far exceeding permissible exposure limits (e.g., HF > 50 ppm, CO > 500 ppm within several minutes of ignition). These levels pose an immediate threat to human life and severely restrict safe evacuation timelines.
- Reduced evacuation capability: Due to the accelerated accumulation of smoke and high-temperature gases, visibility in enclosed garages can drop below 5 meters in less than 3 minutes, rendering traditional evacuation routes ineffective.
- Severe operational constraints for emergency responders: Entry into the contaminated zone without self-contained breathing apparatus (SCBA) and full chemical protective suits becomes impossible, delaying firefighting intervention and increasing property loss.
- Secondary hazards from combustible gas buildup: Decomposition products of electrolytes, including flammable hydrocarbons and hydrogen, can accumulate in poorly ventilated areas, creating a potential for secondary ignition or explosion when exposed to ignition sources or during firefighting operations.

5.2. Recommended parameters and design considerations for emergency ventilation

To mitigate these risks, modern fire protection strategies advocate the integration of high-capacity, automatically activated emergency ventilation systems designed to manage both thermal energy and toxic emissions. The primary objectives include maintaining tenable evacuation conditions, reducing gas concentrations below critical thresholds, and ensuring a controlled environment for firefighting operations.

Specific design recommendations include:

- **Minimum extraction rates:** Systems should be capable of achieving 12–15 air changes per hour (ACH) during emergency mode, in compliance with best practices outlined in international standards such as NFPA 88A and European directives.
- **Use of jet fan systems:** European standard EN 12101 recommends longitudinal ventilation with jet fans, which generate directional airflow, pushing hot gases and smoke towards designated exhaust points or filtration and scrubbing units to minimize environmental discharge of harmful substances.
- **Redundancy and fail-safe mechanisms:** Ventilation systems should be powered by independent emergency generators and include automated control logic based on inputs from heat and gas sensors capable of detecting HF, CO, and flammable vapors.
- **Zonal compartmentalization:** Employing fire-resistant partitions and controlled airflow pathways can significantly reduce cross-contamination of toxic gases between different garage sections, enhancing overall containment efficiency.

These engineering controls, combined with regulatory enforcement, are essential to bridge the current safety gap in underground parking structures storing or charging electric vehicles. With the increasing use of electric vehicles, the risks associated with fire safety are transforming, including new threats – highly toxic emissions, unpredictable battery behavior, and danger to people and the environment in case of fire in enclosed spaces [10, 11, 12].

The proposed fire-safety framework can be extended through the integration of fiber optic sens-

ing and communication technologies. Distributed temperature sensing (DTS) along optical fibers can provide continuous temperature monitoring over large underground parking areas and can support the early identification of abnormal thermal conditions associated with battery overheating and thermal runaway. Fiber optic communication links can also provide reliable transmission of data from gas sensors, thermal imaging systems, and ventilation controllers to centralized fire-management and emergency-response systems. Due to their immunity to electromagnetic interference and suitability for distributed monitoring, optical fiber networks represent a promising infrastructure for integrating real-time fire detection, environmental monitoring, and automated emergency ventilation in enclosed parking facilities [13, 14].

6. CONCLUSION

The introduction of emergency ventilation is not only technically justified, but also a necessary precaution that should be included in any modern concept of fire protection in urban environments. Without it, efforts towards sustainable transport and electrification of mobility remain incomplete from a security perspective.

As a recommendation, the following measures should be indicated:

- Introduction of a regulatory requirement for emergency ventilation in indoor parking lots, especially in facilities with the capacity to charge or store electric vehicles. It is necessary to change the regulatory regulation in Bulgaria and in particular Regulation No. Iz-1971 of October 29, 2009, in particular Chapter IX Art. 113 para. 5 item 2, and emergency ventilation should be designed for all underground and windowless garages, regardless of the number of parking spaces/cars.
- Provision of gas sensors and automated control of ventilation systems for the detection and removal of toxic gases such as HF, CO and HCl.
- Training of personnel and rescue teams for working in an environment with possible toxic and corrosive emissions in the event of an electric vehicle fire.

These measures not only enhance the resilience of urban infrastructure but also align with broader sustainability objectives by ensuring that the transition to electric mobility does not compromise public safety.

Future implementations may further enhance these safety measures by integrating fiber-optic sensing and optical communication networks for continuous temperature monitoring and reliable real-time transmission of fire-related data to automated ventilation and emergency control systems.

7. ACKNOWLEDGMENTS

The authors would like to thank the Research and Development Sector at the Technical University of Sofia for the financial support.

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GREEN'S FUNCTION AND ITS USE FOR FINDING APPROXIMATE SOLUTIONS TO NONLINEAR DIFFERENTIAL EQUATIONS IN OPTICAL COMMUNICATION SYSTEMS

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Abstract

The paper presents a Green-function formulation for approximate solutions of weakly nonlinear differential equations. A linear differential operator is inverted through its Green kernel, and the resulting integral representation is combined with the Lindstedt-Poincare expansion to remove secular terms. The method is demonstrated for a softening Duffing-type oscillator, for which the first-order waveform correction and the nonlinear frequency shift are obtained. The same operator structure is then transferred to optical telecommunication systems governed by dispersive propagation and weak Kerr nonlinearity. For the nonlinear Schrodinger equation, the linear fiber response is represented by a Green function, while the cubic nonlinear term acts as a distributed source. This provides a direct framework for estimating nonlinear distortion, modelling dispersive optical links, and constructing reduced-order models of optical resonators and optoelectronic feedback systems.

1. PROBLEM DEFINITION AND MAIN OBJECTIVE

Many communication and physical systems are represented by differential equations whose linear part is well understood, whereas a weak nonlinear term prevents an exact closed-form solution. Direct expansion in the physical time variable often produces secular terms that grow with time and destroy the validity of the approximation. The Green-function method and the Lindstedt-Poincare procedure address complementary parts of this problem: the former gives an integral inverse of the linear operator, and the latter corrects the oscillation frequency so that the perturbation series remains bounded [1-4].

The main objective is to construct a concise analytical procedure for a weakly nonlinear oscillator and to show that the same procedure is applicable to optical telecommunications. The contribution is not a claim that a lumped oscillator is identical to a distributed optical fiber. The connection is structural: in both cases, the solution is separated into a linear response described by a Green kernel and a weak nonlinear correction generated by a cubic source term.

2. GREEN-FUNCTION REPRESENTATION OF A LINEAR PROBLEM

The operator $\hat{L} = L(D) = \sum_{k=0}^n a_k D^k$, $D = \frac{d}{dt}$ and $a_k = a_k(t)$, $t \in \mathbb{R}$ is a linear differential

operator. In general, a non-homogeneous differential equation can be represented in operator form as:

$$\hat{L}x = y \quad (1)$$

Let us assume that there exists an inverse operator $\hat{L}^{-1}$ of $\hat{L}$ such that $\hat{L} \cdot \hat{L}^{-1} = \hat{L}^{-1} \hat{L} = \hat{I}$, where $\hat{I}x = x$ is the identity operator. Then:

$$x = \hat{L}^{-1}y = \int G(t, \tau)y(\tau)d\tau \quad (2)$$

Consequently, returning to the original differential equation and utilizing the fact that the order of integration and differentiation can be interchanged, we obtain:

$$\hat{L} \int G(t, \tau)y(\tau)d\tau = \int \hat{L}G(t, \tau)y(\tau)d\tau = y(t) \quad (3)$$

For the last equality to hold, it is necessary that:

$$\hat{L}G(t, \tau) = \delta(t - \tau), t \in \mathbb{R} \quad (4)$$

The function $\delta(t - \tau)$ represents the Dirac delta function, and $G(t, \tau)$ is called the fundamental solution or the influence function of a point source. The fundamental solution is determined up to the solution of the homogeneous equation [1].

Related integral-representation techniques have also been applied to autonomous linear neutral fractional systems with distributed delay, where they provide a useful analytical tool for studying stability properties [5].

3. NONLINEAR AUTONOMOUS DIFFERENTIAL EQUATION

Let an equation of the following form be given [2]:

$$\frac{d^2}{dt^2}x + \omega_0^2x - \varepsilon\omega_0^2x^3 = 0 \quad (5)$$

with initial conditions $x(0) = A, x\left(\frac{\pi}{2}\right) = 0$. The parameter ε is positive, dimensionless, and less than unity, while ω_0^2 is a positive constant.

Let us assume that the solution is a function of $\theta = \omega t$, which transforms (5) into the equation:

$$\omega^2 \frac{d^2}{d\theta^2}x + \omega_0^2x - \varepsilon\omega_0^2x^3 = 0 \quad (6)$$

We seek the solution by expanding the quantities in a series with respect to the small parameter:

$$\begin{aligned} x &= x_0 + \varepsilon x_1 \\ \omega &= \omega_0 + \varepsilon \omega_1 \end{aligned} \quad (7)$$

By equating the terms corresponding to the same powers of the small parameter, we arrive at the system:

$$\begin{aligned} \frac{d^2}{d\theta^2}x_0 + x_0 &= 0 \\ \frac{d^2}{d\theta^2}x_1 + x_1 &= x_0^3 - 2\frac{\omega_1}{\omega_0} \frac{d^2}{d\theta^2}x_0 \end{aligned} \quad (8)$$

Let the solution to the first equation of system (8) satisfy the initial conditions $x_0(0) = A, x_0\left(\frac{\pi}{2}\right) = 0$, and let the solution to the second equation satisfy $x_1(0) = 0, x_1\left(\frac{\pi}{2}\right) = 0$. Then, considering the solution to the first equation:

$$x_0 = A \cos \theta \quad (9)$$

we obtain the differential equation for the first approximation:

$$\begin{aligned} \frac{d^2}{d\theta^2}x_1 + x_1 &= \frac{A^3}{4} \cos 3\theta + \\ &+ \left(\frac{3A^3}{4} + 2\frac{\omega_1}{\omega_0} \right) \cos \theta \end{aligned} \quad (10)$$

To eliminate the secular term, we set $\omega_1 = -\frac{3}{8}A^2\omega_0$.

Finally, we obtain the equation:

$$\begin{aligned} \frac{d^2}{d\theta^2}x_1 + x_1 &= \frac{A^3}{4} \cos 3\theta \\ x_1(0) &= 0, x_1\left(\frac{\pi}{2}\right) = 0 \end{aligned} \quad (11)$$

In the next section, we will describe the Green's function method for solving equation (11).

4. GREEN'S FUNCTION METHOD

Let us start with the differential equation:

$$\frac{d^2}{dt^2}x + \omega_0^2x = f(t), \quad (12)$$

with initial conditions $x(a) = 0, x(b) = 0$.

We formulate the equation:

$$\frac{d^2}{dt^2}G(t, \tau) + \omega_0^2G(t, \tau) = \delta(t - \tau). \quad (13)$$

We shall prove the validity of the formula:

$$\begin{aligned} &\int_a^t G(t, \tau)f(\tau) d\tau + \\ &+ \int_t^b G(t, \tau)f(\tau) d\tau = x(t) \end{aligned} \quad (14)$$

here $x(t)$ is the solution to (12). It can be concluded that $G(t, \tau)$ will have a different mathematical form within the integrands of the two integrals.

Let:

$$\begin{aligned} \varphi(t) &= \int_a^t G(t, \tau)f(\tau) d\tau + \\ &+ \int_t^b G(t, \tau)f(\tau) d\tau. \end{aligned}$$

Then,

$$\begin{aligned} \frac{d}{dt}\varphi(t) &= \int_a^t f(\tau) \frac{d}{dt}G(t, \tau) d\tau + G(t, t)f(t) + \\ &+ \int_t^b f(\tau) \frac{d}{dt}G(t, \tau) d\tau - G(t, t)f(t). \end{aligned}$$

This leads to the expression:

$$\frac{d}{dt}\varphi(t) = \int_a^t f(\tau) \frac{d}{dt}G(t, \tau) d\tau + \int_t^b f(\tau) \frac{d}{dt}G(t, \tau) d\tau.$$

It can be shown analogously that:

$$\frac{d^2}{dt^2}\varphi(t) = \int_a^t f(\tau) \frac{d^2}{dt^2}G(t, \tau) d\tau + \int_t^b f(\tau) \frac{d^2}{dt^2}G(t, \tau) d\tau.$$

Let us construct the equation:

$$\begin{aligned} \frac{d^2}{dt^2}\varphi(t) + \omega_0^2\varphi(t) &= \\ &= \int_a^t f(\tau) \left[\frac{d^2}{dt^2}G(t, \tau) + \omega_0^2G(t, \tau) \right] d\tau + \\ &+ \int_t^b f(\tau) \left[\frac{d^2}{dt^2}G(t, \tau) + \omega_0^2G(t, \tau) \right] d\tau = \\ &= \int_a^t f(\tau) \delta(t - \tau) d\tau + \int_t^b f(\tau) \delta(t - \tau) d\tau = \\ &= \int_a^{t-\varepsilon} f(\tau) \delta(t - \tau) d\tau + \int_{t-\varepsilon}^{t+\varepsilon} f(\tau) \delta(t - \tau) d\tau + \\ &+ \int_{t+\varepsilon}^b f(\tau) \delta(t - \tau) d\tau \end{aligned}$$

Taking into account the properties of the delta function, it follows that:

$$\begin{aligned} \int_a^{t-\varepsilon} f(\tau) \delta(t - \tau) d\tau &= \int_{t+\varepsilon}^b f(\tau) \delta(t - \tau) d\tau = 0, \\ \int_{t-\varepsilon}^{t+\varepsilon} f(\tau) \delta(t - \tau) d\tau &= f(t), \varepsilon > 0, \varepsilon \rightarrow 0. \end{aligned}$$

This was the objective of our proof; that is, $\varphi = x$ given the chosen initial conditions for equation (12).

Let us find the solution to equation (13) for $\tau \neq t$:

$$\frac{d^2}{dt^2}G(t, \tau) + \omega_0^2G(t, \tau) = 0.$$

In general, this solution can be written as follows:

$$G(t, \tau) = \{C_1(\tau) \sin \omega(b - t)\}_{\tau < t} + \{C_2(\tau) \sin \omega(t - a)\}_{\tau > t} \quad (15)$$

Indeed, the functions $\sin \omega(t - a)$ and $\sin \omega(b - t)$ are solutions to (15), and the Wronskian:

$$W = \begin{vmatrix} \sin \omega(t - a) & \sin \omega(b - t) \\ \omega \cos \omega(t - a) & -\omega \cos \omega(b - t) \end{vmatrix} = -\omega \sin \omega(b - a)$$

is non-zero for $\omega(b - a) \neq k\pi$. Thus, (14) can be written in the form:

$$x(t) = \int_a^t f(\tau) C_1(\tau) d\tau \sin \omega(b - t) + \int_t^b C_2(\tau) f(\tau) d\tau \sin \omega(t - a) \quad (16)$$

We can summarize that the Green's function has the form:

$$G(t, \tau) = \begin{cases} G(t, \tau) = G_1(t, \tau) = C_1(\tau) \sin \omega(b - t), & \tau < t \\ G_2(t, \tau) = C_2(\tau) \sin \omega(t - a), & \tau > t \end{cases} \quad (17)$$

Integrating (13) with respect to t from $\tau - \varepsilon$ to $\tau + \varepsilon$ as $\varepsilon \rightarrow 0$ yields:

$$\frac{d}{dt}G_1(\tau, \tau) - \frac{d}{dt}G_2(\tau, \tau) = 1. \quad (18)$$

Furthermore, for the Green's function to be continuous, the following condition is required [3]:

$$G_1(\tau, \tau) = G_2(\tau, \tau). \quad (19)$$

In this specific case, the following system is obtained:

$$\begin{aligned} C_1(\tau) \cos \omega(b - \tau) + C_2(\tau) \cos \omega(\tau - a) &= -\frac{1}{\omega}, \\ C_1(\tau) \sin \omega(b - \tau) - C_2(\tau) \sin \omega(\tau - a) &= 0. \end{aligned}$$

The solutions are:

$$\begin{aligned} C_1(\tau) &= -\frac{\sin \omega(\tau - a)}{\omega \sin \omega(b - a)}, \\ C_2(\tau) &= -\frac{\sin \omega(b - \tau)}{\omega \sin \omega(b - a)}. \end{aligned}$$

Finally, the solution to (12) is obtained as:

$$\begin{aligned} x(t) &= \\ &= -\frac{1}{\omega} \int_a^t f(\tau) \frac{\sin \omega(\tau - a)}{\sin \omega(b - a)} d\tau \sin \omega(b - t) - \\ &- \frac{1}{\omega} \int_t^b \frac{\sin \omega(b - \tau)}{\sin \omega(b - a)} f(\tau) d\tau \sin \omega(t - a) \end{aligned} \quad (20)$$

5. FINDING THE FIRST APPROXIMATION OF THE NONLINEAR DIFFERENTIAL EQUATION

Let us seek a solution to equation (11) using the theory discussed so far. For Green's function, we obtain:

$$G(t, \tau) = \begin{cases} G_1(\theta, \tau) = -\sin \tau \cos \theta & \tau < \theta; \\ G_2(\theta, \tau) = -\cos \tau \sin \theta & \tau > \theta. \end{cases} \quad (21)$$

Substituting into the integral (20):

$$x_1(\theta) = -\frac{A^3}{4} \int_0^\theta \sin \tau \cos 3\tau d\tau \cos \theta - \frac{A^3}{4} \int_\theta^{\frac{\pi}{2}} \cos \tau \cos 3\tau d\tau \sin \theta.$$

The final result takes the form:

$$x_1(\theta) = -\frac{A^3}{16} \cos 3\theta + \frac{A^3}{16} \cos \theta. \quad (22)$$

The final form of the solution to equation (5) is:

$$x(t) = A \left(1 + \varepsilon \frac{A^2}{16} \right) \cos \omega t - \varepsilon \frac{A^3}{16} \cos 3\omega t, \quad (23)$$

$$\text{and } \omega = \omega_0 \left(1 - \varepsilon \frac{3}{8} A^2 \right).$$

For the type of equation considered here, the Green's function method offers no particular advantage over other calculation methods; however, the value of this approach lies in the fact that it is applicable to differential equations with variable coefficients, as well as to equations involving dissipation and non-autonomous differential equations with nonlinear terms [4]. The choice to present the method using this specific type of equation is motivated by the clarity and elegant form of the results—qualities that would remain obscured in more complex cases.

6. APPLICATION TO OPTICAL TELECOMMUNICATIONS

In optical telecommunication systems, the same Green-function approach can be applied to the mathematical modelling of optical pulse propagation in dispersive and weakly nonlinear fibre links [6]. The linear part of the propagation equation

describes the response of the optical channel, including chromatic dispersion and attenuation, and its Green function can be interpreted as the impulse response of the fibre. The nonlinear part, mainly associated with the Kerr effect, may then be treated as a distributed perturbation source acting along the transmission path. In this sense, the solution is constructed as a superposition of the linear propagation response and a nonlinear correction term, in the same way as the weakly nonlinear oscillator considered above. Such a formulation is useful for estimating waveform distortion, nonlinear phase shift, pulse broadening, and the limits of analytical approximation in high-speed optical communication systems. It can also support simplified models for dispersion compensation, nonlinear impairment analysis, and the design of optical links where full numerical simulation is not required at the preliminary stage.

7. CONCLUSION

This paper presented a Green-function formulation for constructing approximate solutions of weakly nonlinear differential equations. The method was demonstrated for a nonlinear autonomous second-order differential equation, where the linear part was solved by means of the corresponding Green function and the nonlinear term was treated as a perturbation. In combination with the Lindstedt-Poincare procedure, the approach makes it possible to remove the secular term and to obtain a bounded first-order approximation of the solution.

The example considered in the paper shows that, for simple weakly nonlinear oscillators, the Green-function method does not necessarily provide a shorter calculation than classical perturbation techniques. Its main advantage is methodological: it gives a clear integral representation of the solution and separates the linear response of the system from the nonlinear correction. This makes the approach applicable to more complex problems, including systems with variable coefficients, dissipation, non-autonomous excitation, distributed effects, and weak nonlinear perturbations.

From the viewpoint of optical telecommunications, the same mathematical structure is relevant to the modelling of dispersive and weakly nonlinear optical fibre links. The linear part of the propagation model can be interpreted through a Green function corresponding to the impulse response of the opti-

cal channel, while the Kerr nonlinear term can be treated as a distributed perturbation source.

Therefore, the presented approach may be used as an analytical basis for estimating pulse distortion, nonlinear phase shift, and the influence of weak nonlinearities in optical communication systems. Although detailed fibre-link modelling requires further development, the Green-function framework provides a useful bridge between perturbation theory and practical analytical models in optical telecommunications.

8. ACKNOWLEDGMENTS

The authors would like to thank the Research and Development Sector at the Technical University of Sofia for the financial support.

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PROTOTYPING OF AN INTELLIGENT RECYCLE BIN

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Abstract

The aim of this paper is to demonstrate the steps for prototyping and implementing an intelligent system for automated waste separation based on artificial intelligence methods and edge image processing. The proposed solution is built around a microcontroller, Tiny Machine Learning, and a convolutional neural network, which performs image classification locally without requiring a continuous Internet connection and/or cloud-based services.

1. INTRODUCTION

Worldwide, the management of the solid waste has become one of the most critical environmental, engineering, and socio-economic challenges of the twenty-first century. Due to the intensive growth of urban populations and global consumption, the amount of generated waste is increasing at a rate that exceeds the capacity of conventional and waste collection methods.

Recycling is a key prerequisite for sustainable development and for the transition towards a circular economy; however, its overall effectiveness depends directly on accurate, precise, and timely waste sorting at the point of the generation. The integration of artificial intelligence into local waste collection points transforms waste disposal from a passive action with uncertain result into a precise, controlled, and automated process. By applying real-time computer vision, the system not only reduces the risk of human error, but also functions as an educational tool for the user. This way, the Zero Waste concept becomes practically accessible and applicable in dynamic urban environments, while mitigating negative impacts that would otherwise cause significant damage.

Local waste collection and separation systems can generally be divided into two main categories: commercial Reverse Vending Machines (RVMs) and intelligent recycle bins based on sensor or software architectures. RVM machines represent the most widely used commercial technology for collecting high-quality materials that could be recycled, primarily PolyEthylene Terephthalate (PET) bottles and aluminium cans. Those machines are the backbone of the deposit-return systems in several European countries. After a successful identification, the machine physically compresses the

bottle and directs it to the corresponding internal container. Nevertheless, their wide-range usage is limited by their high cost - an industrial RVM machine [1] costs thousands of euros, and by the need of constantly updating the software databases containing the packaging, since they typically operate using barcode recognition.

Sensor-based intelligent recycle bins [2] use combinations of low-cost hardware sensors, such as ultrasonic sensors for volume-fill measurement, infrared sensors for proximity detection, and capacitive and inductive sensors for identifying metals and moisture. In vision-based cloud AI systems [3], a camera is integrated into the bin. When waste is deposited, the system captures an image and sends it over the network to a remote cloud platform, such as AWS, Google Cloud Vision, or a dedicated server, where a computationally intensive deep learning model classifies the object and returns a command for its mechanical distribution.

The aim of the current paper is to demonstrate the steps for prototyping and implementing a functional prototype of an intelligent device for automated recognition and mechanical sorting of municipal solid waste – more specifically PET plastic bottles and aluminium cans, using the edge computer vision (Edge AI) and Internet of Things (IoT) technologies.

2. HARDWARE IMPLEMENTATION

The practical implementation of the intelligent system for automated waste sorting requires the appropriate selection of electronic and mechanical components. The main selection criteria are aimed at achieving an optimal balance between computational power for real-time deep learning inference based on Convolutional Neural Networks (CNN),

energy efficiency, compact physical dimensions, and low prototype cost.

The smart recycle bin is constructed as a 20-litre plastic container with a vertical partition that divides the internal volume into two isolated sections for the separate collection of plastic and aluminium. The second main element is the platform, which serves as a base on which the object is placed for recognition and includes a flap for directing the waste. A servo motor ensures the platform movement from 0° to 180° .

A perpendicular support structure is mounted on the outer side of the bin for the fixed installation of the two microcontrollers (ESP32-CAM and Arduino Uno), the LCD display, and the breadboard. This arrangement provides portability and a good layout of the components, while giving a completed engineering form to the overall prototype. The following components are used for the smart recycle bin hardware implementation:

- ESP32-CAM microcontroller module by Ai-Thinker [4]. This microcontroller is a compact and low-cost Edge AI solution. It is based on a 32-bit dual-core Xtensa LX6 processor operating at up to 240 MHz and is capable of executing optimized algorithms for deep learning inference;
- Arduino Uno, used as a programming interface and power-supply module, since the ESP32-CAM does not include an integrated USB ports for direct programming and power-supply;
- SG90 servo motor, which physically directs the waste to the corresponding internal section of the recycle bin, similarly to [5]. In this implementation, the surface of the intelligent bin rotates through an angle from 0° to 180° , providing a torque of 1.8 kg·cm. It is controlled directly by the ESP32-CAM through Pulse-Width Modulation (PWM) signals, which determine the precise rotation angle of the bin surface according to the classified waste category;
- 16x2 Liquid-Crystal Display (LCD), which provides real-time visual feedback and communication with the user by displaying two rows of 16 characters each. Text messages indicating the current process state are displayed, such as “Detecting...”, “Plastic”, or “Can”. The ESP32-CAM has a limited number of available General Purpose Input/Output (GPIO) pins due to the parallel camera interface and the display uses an I²C adapter for connection to the controller. Communication

with the display is implemented through a software-based I²C bus. The Serial Data Line (SDA) line is connected to GPIO 14, while the Serial Clock Line (SCL) line is connected to GPIO 15 of the ESP32-CAM, enabling screen information to be refreshed.

The connection of the two microcontrollers and the other components is shown in Fig.1.

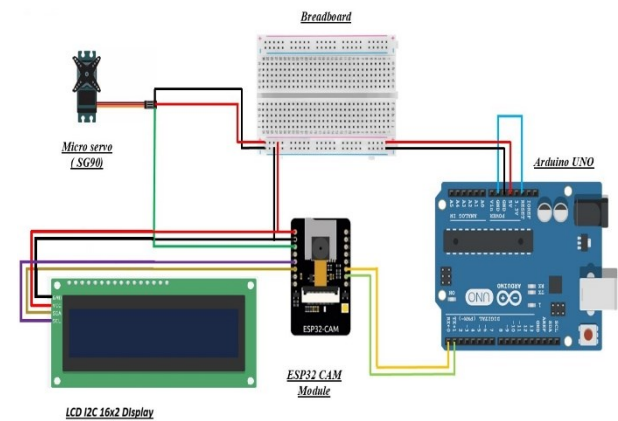


Fig.1 Structural diagram

The physical implementation of the intelligent automated waste sorting system is divided into two stages: initial hardware configuration and image dataset acquisition, followed by the assembly of the final engineering prototype.

The first stage of the development involves the construction of a dedicated hardware configuration intended for capturing and streaming images of plastic bottles and aluminium cans. These digital images are fundamentally required for the subsequent training of the convolutional neural network in the Edge Impulse platform.

After the deployment of the compressed Edge AI model on the ESP32-CAM, the system is reconfigured into its final autonomous topology (Fig. 1). In this configuration, the ESP32-CAM controls the SG90 servo motor and the LCD 16x2 display in real time, while the Arduino UNO board is used solely as a stable power source.

3. SOFTWARE IMPLEMENTATION

The software implementation of the intelligent recycle bin is based on the concept of edge artificial intelligence (Edge AI) and the application of machine learning on microcontrollers, commonly referred to as Tiny Machine Learning (TinyML) [6]. The engineering challenge consists of integrating complex deep learning algorithms into a hardware

environment with limited memory and computational resources. To ensure successful software deployment, the development workflow is divided between two main environments: the Arduino IDE for low-level programming and the web-based Edge Impulse platform for building and optimizing the artificial neural network.

In order to overcome the complexity of the direct low-level camera driver programming, the software architecture uses the specialized C/C++ library EloquentEsp32Camera. This library enables configuration of capture resolution and pixel format, and frame buffer management. As a result, the captured video stream can be immediately converted into a digital matrix suitable for further processing.

The design, training, and optimization of the artificial neural network are performed using the Edge Impulse software platform. Edge Impulse [7] is a leading development environment for embedded ML models, as it provides automated software tools for compressing mathematical models through the Edge Impulse EON Compiler. This tool enables computationally expensive software models to be converted into highly optimized pure C++ code by applying three main software optimization techniques integrated into the Edge Impulse: quantization, pruning, and the use of specialized convolutional networks designed for microcontrollers. The Edge Impulse “Faster Objects, More Objects” (FOMO) model requires up to 30 times less Random Access Memory (RAM) than standard computer vision algorithms.

Initially, during the machine-learning stage, the images of the objects that have to be recognized are collected in the form of a dataset. For the software implementation, the EloquentESP32Cam library [8] is used. This enables the ESP32-CAM to connect to a local Wi-Fi network and start a local streaming server, through which the images are sent directly to a computer.

Below are given the steps for collecting the data:

- the code is compiled and uploaded to the ESP32-CAM board;
- the device IP address is obtained via the Serial Monitor. When this address is opened in a web browser, the web interface is shown and it allows images to be captured and downloaded easily as a ZIP archive;

- once the initial set of images has been captured, the software implementation proceeds entirely within the Edge Impulse cloud platform, where data management, neural network architecture definition, and model training for computer vision are performed;

- the next important step is performed in the platform. This step requires correct import and structuring of the captured image archive. Through the Data Acquisition tool, all captured files are uploaded to the system. During the import process, the software automatically divides the dataset into 80% (Training set) for training and 20% (Test set) for subsequent testing. A total of 69 images of aluminium cans and plastic bottles were used for model training of the current development;

- the next step is Labeling: each image is labelled manually, placed into a template, and assigned an appropriate label. In this development, there are two labels that are used: `aluminium_can` for aluminium cans and `plastic_bottle` for plastic bottles. The platform groups the images into these two classes, which enables rapid assessment of data balance and helps ensure that the model does not develop statistical bias toward either object class.

After the data has been prepared, an impulse is created. The impulse represents the architectural skeleton defining how data flows from a raw input to a classified output.

In the input block (Image data), image resizing parameters are specified. All images are scaled to a fixed resolution of 96×96 pixels, and a gray-scale colour scheme is selected. Converting images from RGB to grayscale reduces the input data size by a factor of three - from three channels to one, which substantially optimizes RAM usage and accelerates processing by the microcontroller, without significantly affecting the recognition of the geometric contours of bottles and cans.

In the processing block, the specialized Image block is selected. Its function is to normalize the data and transform the matrix of each image into a flat vector of features.

In the learning block, a specialized object detection block (Images) is added. Unlike a standard classification, this block is designed to predict both the object class and its spatial coordinates within the frame.

Then, a Feature Generation process has to be performed. It is done on a training set consisting of 55 items, since 80% of the image material is used for training and is distributed between the two target classes: aluminium_can and plastic_bottle.

After the software processing is completed, Edge Impulse activates the Feature Explorer tool. This tool visualizes the extracted mathematical features in two- or three-dimensional space, where each image is represented as a point coloured according to its class: blue for aluminium cans and orange for plastic bottles (Fig. 2).

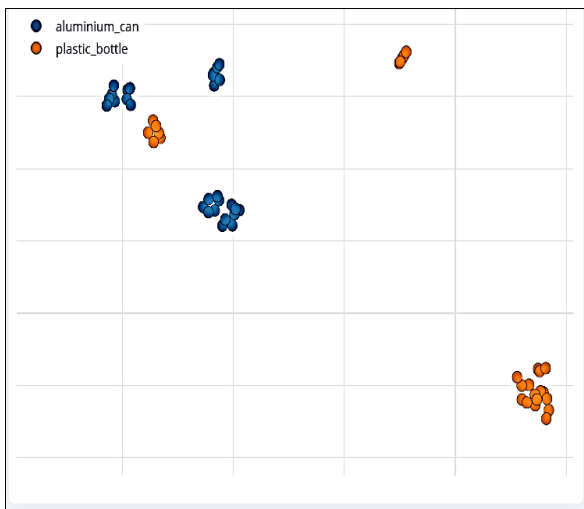


Fig. 2 Feature explorer

Fig. 2 demonstrates the excellent visual separation of the points into distinct and widely separated clusters. The absence of significant overlap or mixing between the blue and orange points confirms that the convolutional features have been extracted correctly and that the two types of waste are fully distinguishable based on their geometric contours in grayscale mode. This ensures high model accuracy and stability during subsequent training.

For the implementation of the detector on the end device, the Faster Objects, More Objects (FOMO) MobileNetV2 0.35 architecture was selected. FOMO is a highly optimized convolutional neural network that replaces conventional heavy regression layers with a cell-based structure, making it suitable for microcontrollers with the ESP32-CAM architecture. The input layer accepts a total of 9,216 features, corresponding to a single-channel 96 × 96-pixel grayscale image.

The network was trained using the following parameters:

- 60 training cycles (epochs);
- learning rate of 0.01;
- data augmentation enabled.

By applying real-time software modifications to the images such as rotation, brightness variation, and cropping, the model's ability to generalize and correctly detect objects under variable lighting conditions in a real environment was improved. After the completion of the final, sixtieth epoch, Edge Impulse generated the following report:

- F1 Score: the model achieved a stable overall F1 Score of 90.9%, demonstrating high reliability in waste detection and classification. The precision and recall metrics also showed high values of 0.91;
- Confusion Matrix: the detailed analysis showed that the aluminium_can class was recognized with an accuracy of 100%. For the plastic_bottle class, successful detection was achieved in 83.3% of cases, while the remaining 16.7% were classified as background noise;
- On-device performance: the software simulation using the optimized EON Compiler (RAM optimized) showed that the model requires 114.7 KB peak RAM usage and 81.0 KB flash usage. The processing time required to analyze one frame and locate the object within it (inferencing time) is 1003 ms.

4. DEPLOYMENT, EXPERIMENTS AND RESULTS

After the successful training of the model in Edge Impulse, the Deployment tool is used to export the programming code required for object classification in ZIP format as an Arduino library [9]. This archive contains the C++ source code of the neural network and is imported directly into the Arduino IDE, making the model fully compatible with the ESP32-CAM architecture.

During the configuration, the EON Compiler is selected. This Edge Impulse technology optimizes the network architecture [10] by eliminating the heavy software dependencies of the standard TensorFlow Lite model. As a result, the model preserves its full accuracy while requiring 17% less RAM and 36% less ROM (flash memory).

Open source libraries from the Arduino IDE are used for the control of the servo motor and the LCD display. The first library that is used is ESP32Servo [11], intended for the precise generation of PWM signals that are needed for controlling the SG90 servo motor, while the second library is LiquidCrystal_I2C [12], which implements serial communication with the liquid-crystal display over the I2C bus.

This section presents the experiments conducted with the developed prototype of the intelligent bin. The purpose of the experiments is to verify the real-time accuracy of the convolutional neural network, as well as its robustness in the presence of external disturbances and objects outside the target classes.

Due to limited volume of the current paper, only the results of the experiment for recognizing trained objects are presented here, including crushed bottles (Bottle 2 in Table 1).

The results show that the model recognition accuracy for objects for which the model has been trained is above 90%. The pictures of the objects with which the experiment has been conducted is supplied as a real-time video stream through the ESP32-CAM camera.

Table 1. Experimental results

Test Object	Expected Result	Actual Result	Accuracy, %
Bottle 1	Plastic	Plastic	90.2 %
Can 1	Can	Can	90.6 %
Can 2	Can	Can	94.5 %
Bottle 2	Plastic	Plastic	98.5 %

Performance data are displayed in the Serial Monitor. The total time for software processing and system response is below one second, with an average measured value of 687 ms. The results indicate that the DSP stage, which includes preparation and resizing of the frame to 96×96 pixels, requires only 7 ms, while the classification stage, in which the neural network recognizes the object, requires 680 ms. This is expected for constrained hardware such as the ESP32-CAM. The source code is available in [9].

5. CONCLUSION

A functional intelligent recycle bin for automated separation of municipal solid waste – more specifically PET plastic bottles and aluminium cans has been developed. The developed IoT system is based on an ESP32-CAM microcontroller and successfully recognizes and sorts plastic bottles and aluminium cans using edge artificial intelligence technologies (Edge AI).

The developed system has the following main advantages:

- Affordable hardware components (ESP32-CAM, Arduino UNO, SG90 servo motor, LCD 1602 display) are used, which makes the system cheap, energy efficient and easy to reproduce;
- Open source software (Arduino IDE) and the Edge Impulse platform are used, which allows for rapid development, easy modification and upgrading of the programming code and computer vision algorithms;
- The system demonstrates successful implementation of the peripheral AI model, with 100% accuracy for the classified target objects and over 90% accuracy for deformed (crushed) plastic bottles;
- Local computation of the convolutional neural network provides a total software processing and decision-making time of less than 1 second (exactly 687 ms), without the need for Internet connectivity or cloud infrastructure;
- The system can be used both for educational purposes and as a real basis for more complex environmental or industrial waste management devices.

The obtained experimental results demonstrate that the proposed prototype can perform local recognition and mechanical sorting with accuracy exceeding 90%, while maintaining good response times on low-cost embedded hardware.

6. ACKNOWLEDGMENTS

This research is realized and funded under the scientific-research project № КП-06-ПН97/47 “Exploring the possibilities of using artificial intelligence and simulation models to increase energy efficiency” by the contract КП-06-Н97/11 with Bulgarian National Science Fund.

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ACTIVE COMMUNICATION FOR DISTRIBUTED POWER GENERATORS

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Abstract

This paper outlines various options for communication between energy storage systems and power generation sources that are designed for self-consumption. Goal is to minimize energy consumption from the power grid to create more predictable load schedules. It explores various methods for sharing generated electricity by one consumer with other consumers or a group of consumers. The group can be viewed as an energy society that meets its electricity demands during outages of the main power supply, periods of increased consumption from its own source, or in the event of a power failure. The energy society is designed to share electricity among individual consumers/producers without disrupting the grid by introducing harmonic distortions or active power beyond the geographical boundaries of the isolated system. In the event of uncontrolled injection of active power into the grid and in the absence of consumption, the active power will flow from the low-voltage (LV) grid through the transformer substations to the medium-voltage (MV) grid. This transfer can cause grid parameters to exceed their limit values, posing a risk to human health and household equipment, and resulting in property damage. Communication between the individual systems is of key importance, and the speed of processing and executing commands is crucial to avoiding problems in the LV and MV distribution networks. This paper discusses the use of smart devices to control power converters and energy storage systems, utilizing various communication technologies — a total of three types will be investigated.

1. COMMUNICATION METHODOLOGY TO ACHIEVE ELECTRICITY DEMANDS OF AN ENERGY COMMUNITY WITHIN AN URBANIZED AREA

In recent years European directives aimed at promoting the production and consumption of renewable energy, that have a low carbon footprint, regulations governing the transmission, access, and consumption of such energy have been eased. As a result, the possibility of utilizing the technical infrastructure managed by distribution network operator can be investigated. Therefore, installation of power generation capacity in a single household has been made more accessible and sharing electricity generated among consumers connected to a single distribution network can be further investigated. In this case a medium-sized village has been taken in consideration. Using the existing low-voltage distribution network can enable the transmission of electrical power to individual consumers to meet individual demands, as well as communication options necessary to communicate each demand.

A. Power Line Communication

This type of communication is achieved by transmitting high-frequency signals over the power line at frequencies between 2 and 28 MHz, without altering the network parameters by introducing interference at the fundamental frequency. This type of technology is the most technically and economically efficient as it utilizes the existing power infrastructure and does not require additional system connectivity, as in the case with Ethernet communication. The range is approximately 400 meters, depending on the network topology, and does not require signal amplifiers.

B. Radio band communication

This type of communication, there is no demand to use additional physical lines on existing electrical poles to establish communication between devices. It uses a radio frequency of 433 MHz—radio frequency communication. The network's broadband depends on external conditions, such as buildings, signal reflectors, the amount of data being transmitted, and other external factors; to determine it precisely, mathematical modeling is

required that considers all of the listed potential sources of interference.

C. Ethernet communication

Using Ethernet as a method for communication a local network between the devices needs to be considered allowing data to be transmitted over electrical (LAN) cable or fiber-optic cable. The modules can be connected directly to a standard connector to ensure active communication.

Each of the listed communication methods can be configured with different topology – either individually or all in a single device – depending on household demands. In addition, each module supports Modbus communication, enabling connection to the power converter via RS485 or RS232 using a twisted-pair copper cable. The power converters in question are hybrid, allowing both a power generation source (photovoltaic or wind generator) and an energy storage system to be connected to them. The energy storage system allows the stored energy to be used at times when solar or wind energy is not available. The installation of the communication devices is a so-called plug-and-play system that implements master/slave connectivity via a SCADA system. These devices are connected to existing renewable energy generation systems, with an algorithm implemented to automatically manage the flow of energy to or from other energy production systems or consumers in that area. Firewall protection against cyberattacks is also required when accessing the system from outside the urbanized area to prevent malicious attacks disrupting normal operation.

2. PHYSICAL INFRASTRUCTURE CONSIDERED FOR THE TRANSMISSION OF POWER AND COMMUNICATIONS LINES

Connection of different household systems or already existing power plants is carried out using each power plant's connection point and utilizes the low-voltage distribution network consisting of overhead power lines. Additionally external power is supplied by two independent medium-voltage feeders supplying two 20/0.4 kV step-down transformer stations. There is no physical connection between the two transformer stations, which means that the two transformers operate in isolated mode. For the energy demands of the energy society, to ensure full connectivity between individual consumers, an electrical connection between

the two transformers is necessary; that is, they must operate in parallel. To this end, a sectional connection must be constructed. Due to the doubled power from this sectional connection, the equipment must be calculated to withstand higher thermal and dynamic effects from faults, as the short-circuit currents are consequently twice as high.

Electrical conductors considered are three different cross-sections: ACSR-70, ACSR-50, and ACSR-35. The allowable voltage drop must not exceed 5% under the most critical conditions. The overhead power line is connected by means of a circuit breaker on one side and a disconnect switch on the other at poles No. 5 and No. 32, along with a 240 mm² cable line with an aluminum conductor.

Most consumers are connected to the distribution network via overhead power lines (OPLs), but some consumers who are more difficult to access are connected via underground power lines (UPLs). Installation of a communication module for each consumer and replacement of electricity meters from two-quadrant single directional to bidirectional four quadrant meters is considered. In chapter IV the technical and economic aspects of investments in new equipment will be addressed.



Fig. 1. Topology of an urbanized area for energy society

Two photovoltaic power plants have been considered in the immediate vicinity of the transformer substations, and either support residential consumers' installations or operate as power plants for consumers who are unable to build their own generation and use shared one. The total installed capacity of the generating facilities is 500 kW AC

and 745 kWp, which provide approximately 900 MWh of electricity annually. There are 100 households, each with an allocated capacity of 5 kW AC. Average household consumption is approximately 1,080 W/h during the heating season and approximately 490 W/h during the summer season. The generating capacity has been adjusted to account for the renewable energy system's inability to produce power—estimated at 3% per year or 3.65 days – and the degradation of the photovoltaic modules, which is approximately 9% over a 25-year period.

3. MATHEMATICAL MODELING OF COMMUNICATION OPTIONS BETWEEN INDIVIDUAL PRODUCERS AND CONSUMERS

3.1. Power Line Communication

When using existing power infrastructure via PLC, the main problems are noise in the electrical networks – generated primarily by the equipment – and the fact that line length is a determining factor in communication capability. The wavelength can be determined by the following equation (1):

$$\gamma = \sqrt{((R + j\omega L)(G + j\omega C))} \quad (1)$$

Where:

R – the active resistance of the power line in Ω/m ,

L – the inductance of the line in H/m;

G – the conductivity in S/m;

C – the capacitance of the power line in F/m;

ω – the angular frequency in rad/s.

This equation (1) can be simplified to:

$$\gamma = \alpha + j\beta \quad (2)$$

Where:

α – the damping coefficient;

β – the phase constant.

$$A = \alpha L \quad (3)$$

A – signal attenuation, dB;

α – attenuation coefficient;

L – line length, m.

3.2. Radio band communication

The Longley-Rice model (Irregular Terrain Model—ITM) calculates the total attenuation of radio wave propagation (A) as the sum of free-space attenua-

tion (A_0) and additional losses caused by terrain, the atmosphere, and the environment (A_d):

$$A = A_0 + A_d \quad (4)$$

Calculating a Radio Link (Link Budget) can be expressed as:

$$R_x = T_x + G_t + G_r - L_t - L_r - A \quad (5)$$

T_x – Power output of the transmitter;

G_t, G_r – Gain of the transmitting and receiving antennas, dBi;

L_t, L_r – internal losses for the radio communication devices;

A – signal attenuation, dB.

To ensure a reliable connection and line of sight (LOS), the first Fresnel zone must be free of obstacles (a maximum of 20% of the zone may be occupied by objects; that is, 80% of the radius must be completely clear). The radius R of the first Fresnel zone at any point along the route is calculated using the formula:

$$R = 17,32 \sqrt{((d_1 d_2)/(f d))} \quad (6)$$

d_1 and d_2 – the distance between transmitter and receiver, km;

d – the overall distance between transmitter and receiver, km;

f – the frequency, Hz.

3.3. Ethernet communication

Third option discussed in this paper is communication via an optical link. This method offers very high speeds and the ability to transmit large volumes of data.

The wavelength in optical cables can be expressed as (3):

$$\lambda = c/f \quad (7)$$

λ – wavelength in m;

c – the speed of light in a vacuum, m/s;

f – frequency in Hz.

The speed in the fiber is given by the following expression:

$$v = c/n \quad (8)$$

n – the refractive index of light in a fiber (~1.46)

To determine the maximum length of the line, it is necessary to determine the attenuation in the fiber using Equation (3) or by:

$$A_{dB} = \log_{10}(P_{in}/P_{out}) \quad (9)$$

P_{out} – the power output of the signal;

P_{in} – the power input of the signal.

The dispersion of the optical connection is of critical importance in optical links. There are standardized optical cables known as non-dispersion-mode fibers or those conforming to the G655 standard. The dispersion loss $[\Delta t]$ can be calculated using the following equation:

$$\Delta t = D \cdot L \cdot \Delta \lambda \quad (10)$$

D – coefficient of dispersion (ps/nm·km);

L – optical path length;

$\Delta \lambda$ – spectral width (for G655, this is typically 1550 nm).

The propagation constant is analogous to that of a PLC; according to (2), the propagation constant, where β , can be expressed as:

$$\beta = 2\pi n/\lambda \quad (11)$$

4. CONCLUSION

This paper aims to analyze different communication options.

Choosing power line communication means there is no need to further improve existing power lines. Reliability is to be further analyzed as while there are no internal faults in the urbanized area this type of communication will not be disrupted.

Regarding the radio band frequency, the radio channel is owned by the customer, external operation can be included. Reliability in case of power loss may be improved by having additional uninterrupted power supply. Fresnel zones should be considered as urbanized areas are of different types where tall buildings may be in the way for the line of sight.

Regarding ethernet communication a new set of cables should be put either underground or on the power line poles. This communication may be owned by the customer. Additional firewalls must be installed to prevent malicious external attacks.

To have a steady data transmission between each producer or consumer best suited is to use two types of above-mentioned types of communications. One type being the main data transmission and the other to be used as a reserve in the case of a failure.

In a subsequent paper data transmission is to be further analyzed with a mathematical modelling program. Aimed at providing communication network load of an urbanized area.

5. APPENDIX AND ACKNOWLEDGMENTS

The authors of the current work would like to thank the Research And Development Sector at the Technical University of Sofia for the financial support for publish this article

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METHODS FOR ACTIVE AND PASSIVE RECONNAISSANCE IN GRID SUBSTATION CONTROL SYSTEMS

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Abstract

With the rapid development of digitalization in all spheres in the world, the electric power industry has also taken a step towards digital management and monitoring. The development of digital and remote management has led to several advantages but also significant disadvantages, such as interference of unauthorized access into digital access networks with the purpose of changing data. This unauthorized access could lead to wrong manipulation of main electrical equipment, could additionally slow down any data rate of transmission, influencing different digital regulators which could lead to financial and economic losses. As a result of this access and control over objects from the EU is taken. This article will describe the main methods for active and passive reconnaissance and testing of the digital network to find vulnerabilities and their removal to ensure high data protection.

1. MAIN PRINCIPLES OF CYBER SECURITY

Primary goal of cybersecurity is to protect database servers, computers, electronic devices, networks, mobile devices, and data from malicious attacks. Cybersecurity can be divided into several main categories:

- Network security – providing security from loss of data or malicious changes to data on a computer network from a breach;
- Software security – provides protection from threats from outsiders on a piece of software or devices connected to it;
- Information security – protects data exchanged on a network from being altered in the process of transmitting data or saving data;
- Operational security – the primary purpose is to define how an organization can respond to malicious external influences or in the event of data loss.

This paper investigates an existing power plant connected in SCADA.

2. PASSIVE RECONNAISSANCE IN EXISTING NETWORK

Passive reconnaissance is the first activity to gather information about an object without being detected by the object itself. It is the scanning of open resources that are accessible in a network. It

allows the construction of a virtual map for a given object (domains, DNS map of connected devices, available files, codes and others).



Fig. 1. Cybersecurity areas

The main activity is to scan the Domain Network server and create a map through:

- Scanning the DNS devices included in a network is the first step to successfully create a virtual map of the devices in a network;
- The main purpose is to access personal data of operators by extracting data from their emails, tied appliances to a server;
- Scan software tied to the network, available files, access copied data, credentials, SSH keys.

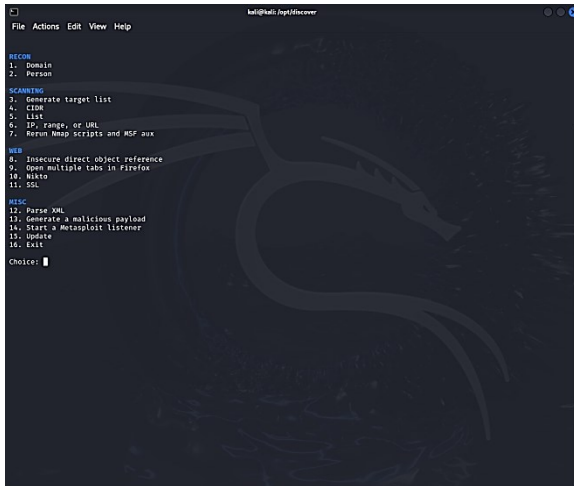


Fig. 2. Discover tool homepage

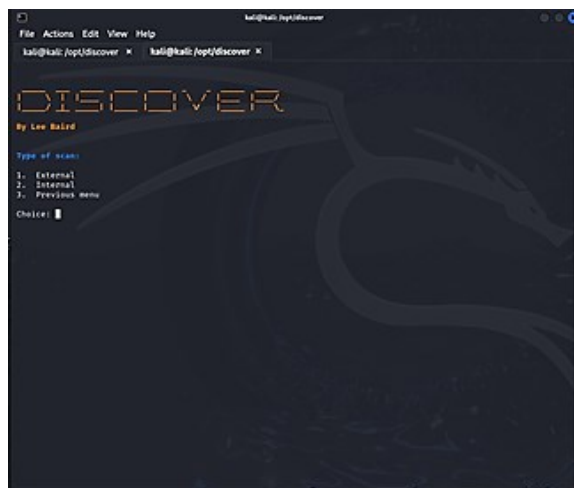


Fig. 3. Direct IP address reconnaissance

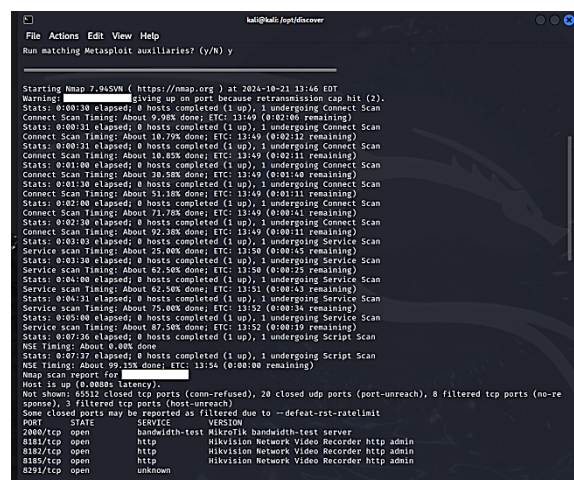


Fig. 4. Network analysis and data acquisition from reconnaissance

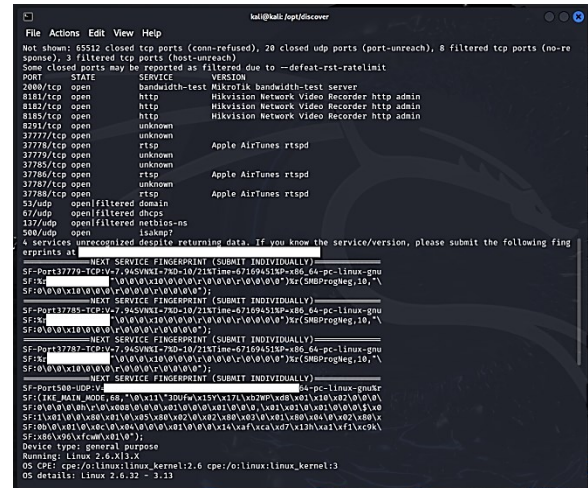


Fig. 5. Data for specific port usage

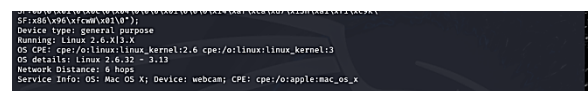


Fig. 6. Data for operational system version

3. Active reconnaissance in existing network

This activity is a follow-up after passive reconnaissance. Information is actively scanned for ports, server access and others.

Port scanning allows:

- Active monitoring through virtual capture of a free port;
- Active manipulation of electrical equipment over free ports and monitoring of received and sent data packets.

One tool commonly used for active scanning is "nmap". This tool (short for network mapper) scans a network and performs analysis on it. It is primarily used by network administrators, security professionals, and pentesters to detect active devices on the network, scan ports, and identify running services on those devices.

Main purposes of Nmap:

1. Port Scan - Nmap can check for open and closed ports on a device on the network, which helps to understand available services.
2. Detecting devices on the network - Through various scanning techniques, Nmap can identify active devices and their IP addresses on the network.

3. Operating system detection - Nmap can determine what operating system a device is using based on the characteristics of network responses (called fingerprinting).
4. Service Fingerprinting - In addition to detecting whether a port is open, Nmap can determine what service is behind that port (e.g. HTTP, FTP, SSH) and even the version of software being used.
5. Vulnerability Scanning - Through add-ons such as the Nmap Scripting Engine (NSE), Nmap can execute specific scripts to detect vulnerabilities in systems, services or applications.
6. Create a network map - Nmap can provide a complete view of the network structure, which is useful for network analysis, maintenance, and planning.
7. Stealth scanning - Nmap offers various ways to "silently" scan to avoid detection by security systems such as firewalls or intrusion detection systems (IDS).

It can be used successfully due to the fact that when data packets pass through, a virtual port can be created as a duplicate of a used one.

Nmap Application:

- Detect unauthorized devices on the network.
- Evaluate network security status.
- Prepare for penetration tests.
- Network inventories and configuration control.
- Detection of potential vulnerabilities and security holes.

Nmap is a powerful tool that can be very useful for advanced analytics and network monitoring, but it should also be used with caution because it can be perceived as hostile activity if used on unauthorized networks.

Due to the risk of leaking sensitive data from the monitored site, no pictures are provided in this chapter for confidentiality purposes.

Third-order headings should be Arial 12-point bold-face, initially capitalized, flush left, with one blank line before, and one after.

The corresponding style name is "**Headings_3**".

4. FINDING WEAK POINTS

The combination of above mentioned methods are able to gather detailed information. Main parameters can be found on which there may be applied malicious influence and false information. After successfully scanning a given network, a methodology can be implemented to find the weak links, various devices can be controlled and the system can be monitored.

5. CONCLUSION

After reconnaissance, certain weak points are noticed, such as: free ports, unauthorized data acquisition of the transmitted information and others. Considered measures should be taken to ensure the safe transmission of data in these systems in a subsequent article.

6. APPENDIX AND ACKNOWLEDGMENTS

The authors of the current work would like to thank the Research And Development Sector at the Technical University of Sofia for the financial support for publish this article

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PARTICULATE MATTER RESUSPENSION AROUND AN IDLING VEHICLE AND ITS IMPLICATIONS FOR AIR QUALITY IN PUBLIC PARKING AREAS

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Abstract

This paper presents an experimental study of particulate matter resuspension around an idling passenger vehicle in an enclosed, parking-like hall. The experiment was conducted in Block 9 of the Technical University of Sofia using a Chery vehicle idling for approximately 50 minutes. External concentrations of PM_1 , $PM_{2.5}$, and PM_{10} were monitored as time-dependent signals. The results show a pronounced short-term increase in particulate matter concentration during the experiment, with the strongest response observed for the PM_{10} fraction. This peak is associated with activation of the engine cooling fan, which may generate airflow capable of resuspending deposited dust from the floor surface. The findings highlight that floor dust in enclosed public parking areas should be considered a potential source of airborne particles.

1. INTRODUCTION

Environmental quality directly impacts human health, comfort, and long-term social sustainability. In today's cities, air pollution continues to be a key concern for public health, particularly in crowded areas with heavy transportation, enclosed spaces, and poor natural airflow. The traffic congestion common on major urban routes highlights the need for effective monitoring methods to detect local pollution sources and short-term exposure risks [1].

In this context, smart cities are increasingly dependent on sensor-based monitoring, data collection, and signal processing to evaluate environmental and human-related parameters [2]. These measurement principles are already in use across various fields such as precision agriculture, infrared thermography for condition monitoring, biomedical signal analysis, and brain-computer interfaces [3]. While these domains have different specific goals, they all share a common approach: gathering time-dependent sensor data and interpreting it to support decision-making, assess risks, and enable preventive measures.

Air quality monitoring is a primary use of this sensor-based approach. Of various air pollutants, particulate matter is especially significant because it can be inhaled, potentially impacting respiratory and cardiovascular health. Different particulate fractions are typically distinguished based on particle size [4]. PM_{10} includes inhalable particles with an aerodynamic diameter under 10 μm , while

$PM_{2.5}$ and PM_1 are finer fractions capable of penetrating deeper into the respiratory tract. Therefore, measuring PM_1 , $PM_{2.5}$, and PM_{10} over time yields valuable insights into local pollution patterns and exposure risks [5,6].

Vehicle air pollution is often linked to exhaust gases and emissions. Yet, in enclosed or semi-enclosed areas like garages, service halls, and parking lots, another factor may be significant. Dust settled on the floor can be stirred into the air by airflow caused by vehicles. This can happen even when the vehicle is stationary and idling, as the engine cooling fan creates local air currents. If the floor isn't cleaned regularly, the accumulated dust can become a continuous source of airborne particles [7].

This issue is especially relevant in public parking areas, where numerous vehicles often operate for brief periods in confined or semi-confined spaces. Poor cleanliness of the floors can lead to temporary spikes in airborne particulate matter, particularly near vehicles. Consequently, routine floor cleaning should be viewed not just as maintenance, but also as an effective measure to enhance local air quality and minimize exposure risks [8,9,10].

This paper examines how particulate matter becomes resuspended around an idling passenger vehicle in a closed parking hall. Special focus was placed on the initial rise in particulate levels following the engine cooling fan activation.

2. THEORY

At a specific measurement point, particulate matter levels can be viewed as a time-dependent reaction of the local air environment to sources, transport, deposition, and removal of particles. For the three measured fractions, this reaction can be represented as

$$PM_i(t) = C_i(t), i \in \{1, 2.5, 10\}, \quad (1)$$

where $C_i(t)$ is the measured mass concentration of the corresponding particulate fraction.

Introducing an additional local disturbance can cause the measured concentration to differ from its original background level. As a result, the change in concentration can be expressed as

$$\Delta PM_i(t) = PM_i(t) - PM_{i,0}, \quad (2)$$

where $PM_{i,0}$ is the characteristic concentration before the disturbance. Positive values of $\Delta PM_i(t)$ indicate an increase relative to the initial local conditions, while the subsequent evolution reflects the combined effects of particle transport, deposition, dilution, and continued particle release.

Since PM_1 , $PM_{2.5}$, and PM_{10} are cumulative fractions, their relative temporal responses provide additional information about the size distribution of the disturbed particles [11,12].

A stronger increase in PM_{10} relative to the finer fractions is consistent with an increased contribution of coarse particles and may therefore indicate mobilization of deposited dust. In contrast, a comparable increase dominated by PM_1 and $PM_{2.5}$ would suggest a stronger contribution from fine-particle sources. These relationships are indicative rather than tied to specific sources, as multiple processes can occur at the same time.

The experimental response can thus be evaluated from the temporal profiles of $PM_1(t)$, $PM_{2.5}(t)$, and $PM_{10}(t)$, considering both short-duration concentration peaks and changes in the concentration level after the disturbance.

3. EXPERIMENT AND RESULTS

The experiment took place in an enclosed hall in Block 9 of the Technical University of Sofia (Fig.1).

A Chery passenger car served as the test object, idling for about 50 minutes. The vehicle stayed stationary during the experiment, so any particulate matter resuspension caused by tire movement

or vehicle displacement was not part of the scenario.



Figure 1. Experimental setup showing the stationary idling vehicle and the position of the particulate matter sensor in the enclosed hall

Particulate matter levels were measured outside the vehicle in its immediate vicinity. Continuous recordings were taken for three cumulative fractions PM_1 , $PM_{2.5}$, and PM_{10} which were analyzed as functions of time. Special focus was given to changes during the engine cooling fan activation, as this caused a local aerodynamic disturbance without the vehicle moving.

Fig. 2 illustrates how particulate matter concentrations change over time.

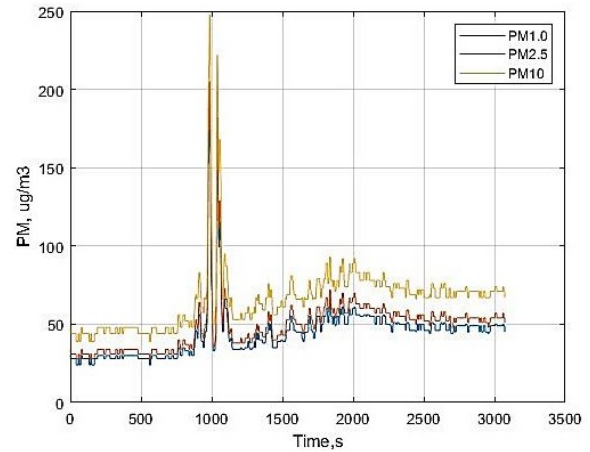


Figure 2. Temporal variation of PM_1 , $PM_{2.5}$, and PM_{10} concentrations around the idling vehicle, including the transient response associated with cooling-fan activation

At the start of the experiment, all three fractions are fairly stable, experiencing only moderate short-term fluctuations. PM_{10} exhibits the highest mass concentration, followed by $PM_{2.5}$ and PM_1 , which aligns with the cumulative characteristics of these particle fractions.

A significant transient event happens around 1000s. During this period, all three signals surge quickly, with PM_{10} showing the most pronounced response, peaking near $250\mu\text{g}/\text{m}^3$. $PM_{2.5}$ and PM_1 also display noticeable peaks, though their maximum levels are much lower.

The peak observed aligns with the engine cooling fan activation. Since the vehicle was stationary, this event is unlikely caused by tire dust resuspension or movement. Instead, the response supports the idea that fan-generated airflow disturbed settled material, aerosolizing some of it. Nonetheless, PM measurements alone don't specify the exact source, and other local or vehicle-related factors may still play a role [13,14].

After the sharp peak, concentrations decline quickly but don't instantly reach initial levels. There's a subsequent phase of higher and more fluctuating particulate matter, especially from about 1500 to 2200 seconds. Later in the experiment, the signals stabilize but stay above the original concentrations. This pattern indicates that the brief disturbance was succeeded by a longer process of redistribution and removal, involving particle transport, deposition, dilution, and local air circulation.

7. CONCLUSION

The particle-size response shows that airflow from a stationary idling vehicle can help resuspend floor dust, especially in the coarse particulate range. This indicates that particulate pollution in enclosed parking lots is affected not just by direct vehicle emissions but also by the condition of nearby surfaces and the amount of dust that can be resuspended.

Therefore, maintaining clean floors is an important aspect of air quality in enclosed and semi-enclosed parking areas. Routine dust removal, along with proper ventilation and localized monitoring, can help minimize short-term spikes in particulate levels and enhance overall environmental conditions where vehicles are often in use.

8. APPENDIX AND ACKNOWLEDGMENTS

This work is funded by the Research and Development Sector at the Technical University of Sofia.

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