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CONTENTS

COMPUTER SCIENCE

Akhmetova S.T., Yunussova A.A., Alisheva S.S., Olzhataeva B.T., Mussirepova E.B.
Social network data mining for automated offensive language detection.....13

Amanov A.N., Kazbekova G.N., Zhunissov N.M., Abibullayeva A.A., Aben A.B.
Artificial intelligence-based intrusion detection for DDOS attacks in Software Defined Networking.....30

Amanzholova S.T., Ussatova O.A., Mutanov G.M., Mukhanov S.B., Aitmukash D.
Backend architecture of a hybrid blockchain-based academic credential verification system.....52

Amirkhanova G.A., Nurgazy T.N., Amirkhanov B.S., Tokhtassyn M.M., Nurgazy N.N.
Developing a predictive digital twin for a food product based on Edge ML and IoT sensors.....73

Bekarystankyzy A., Ussen D., Kassenkhan A., Chinibayev Y.
Cold-start in educational recommender systems: classical and LLM-Era strategies.....91

Bimoldina Zh., Mussiraliyeva Sh., Bagitova K., Tereikovska L.
Detection of cyber-propaganda content using machine learning and semantic models....106

Chezhimbayeva K.S.
Forecasting key 5G network KPIs using MLP and LSTM neural network models.....129

Dauitbayeva A.O., Konyrbaev N.B., Abildayeva Zh.T., Yessirkepova A.U., Karim N.A.
Development of an application to optimize the process of employment of graduates.....148

Dzhsupbekova G., Othman M., Ordabayeva G.
Comparative analysis of artificial intelligence algorithms to detect network attacks.....167

Issakhov A., Orazmoldayev N., Zharkynbek Y., Abylkassymova A.
Numerical modeling of the spread of viral infection by airborne droplets in confined spaces.....182

Kantureeva M., Omarova G.S., Duisen Z.D., Shekerbek A.A., Tulebayev Y.B.
Application of machine learning methods in forecasting and optimizing the processes of evacuation of people in high-rise buildings.....202

Khusain B., Telmanov M., Khusain A.B., Brodskiy A.R., Sass A.S.
Digital twin of an integrated emission purification and decarbonization system for thermal units.....218

Kulakayeva A., Ashurov A., Zhumazhanov B., Daineko Ye., Zylgara A.
Algorithm for determining the initial orbital parameters of KazeEOSat-1 for deorbiting.....236

Mimenbayeva A.B., Turebayeva R.D., Ospanova T.T., Aruova A.B., Naizagarayeva A.A.
Development and comparative analysis of machine learning models for urban traffic prediction.....253

Naumenko V.V., Mukanova Zh.A., Kiseleva O.V., Maintser D.A., Nerezov A.K.
The use of real-time polling to improve student academic performance.....271

Nazyrova A.E., Kaderkeyeva Z.K., Bekmanova G.T., Milosz M., Lamasheva Zh.
Transformation of education through digital technologies: advancing student academic performance across learning stages.....287

Oralbekova D., Mamyrbayev O., Akhmediyarova A., Kassymova D., Alibiyeva Z.
Development of a multi-level model for text summarization based on pretrained models.....316

Orazbayev B.B., Zhumadillayeva A.K., Kurbangalieva N.B., Yessirkessinov R.Zh., Orazbayeva K.N.
Synthesis of linguistic models for assessing sulfur quality and fuzzy modeling of the sulfur production process.....337

Sarsenbayeva A.K., Rakhimova D.R., Shormakova A.N., Mansurova M.E., Adali E.
Application of semantic methods in the field of legislation: an intellectual system for analysis of agglutinative texts.....354

Serek A., Shoiynbek A., Sharipov K., Kuanyshbay D., Mukhametzhanov A.
Analysis and classification of telephone fraud based on lexical features of speech transcriptions.....373

Shynzhigit B.B., Balabekova M.O., Amangeldy T.T.
Analysis and forecasting of brick product sales using machine learning models.....393

Tokhayeva A.O., Alzhanov A.K., Nezih Önal, Ziyatbekova G.Z., Begalieva K.B.
Formation of students virtualization competencies in higher education based on Proxmox VE.....412

Tukenova L.M., Auyelbekov O.A., Sapakova S.Z., Sametova A.A., Bostanov E.L.
Modelling and optimisation of hybrid power plant operating modes for unmanned aerial vehicles.....430

Yerimbetova A., Berzhanova U., Daiyrbayeva E., Sakenov B., Sambetbayeva M.
Sign language recognition using temporal convolutional network and MediaPipe.....443

Zhukabayeva T.K., Benkhelifa E., Mardenov Y.M., Baumuratova D., Karabayev N.
Decision support for responding to attacks in cyber-physical industrial internet-of-things systems.....461

МАЗМҰНЫ

ИНФОРМАТИКА

Ахметова С.Т., Юнусова А.А., Алишева С.С., Олжатаева Б.Т., Мүсірепова Э.Б.
Әлеуметтік желідегі бейәдеп пікірлерді автоматты анықтауда деректерді интеллектуалды талдау.....13

Аманов А.Н., Казбекова Г.Н., Жунисов Н.М., Абибуллаева А.А., Абен А.Б.
Бағдарламалық жасақтамамен анықталған желідегі DDOS шабуылдары үшін жасанды интеллектке негізделген шабуылдарды анықтау.....30

Аманжолова С.Т., Усатова О.А., Мутанов Г.М., Муханов С.Б., Айтмукаш Д.
Гибридтік блокчейнге негізделген академиялық сенімдік деректерді тексеру жүйесінің бекендік архитектурасы.....52

Амирханова Г.А., Нұрғазы Т.Н., Амирханов Б.С., Нұрғазы Н. Н.
EDGE ML және IOT сенсорлары негізінде азық-түлік өнімінің предиктивті цифрлық егізін әзірлеу.....73

Бекарыстанқызы А., Үсен Д., Қасенхан А., Чинибаев Е.
Білім беру саласындағы ұсынымдық жүйелеріндегі «Cold-start» мәселесі: классикалық әдістер және LLM дәуірінің стратегиялары.....91

Бимолдина Ж.А., Мусиралиева Ш.Ж., Багитова К.Б., Терейковская Л.З
Кибернасихаттық контентті анықтау үшін машиналық оқыту және семантикалық модельдер қолдану.....106

Чежимбаева К.С.
MLP және LSTM нейрондық желі модельдерін қолдана отырып, 5G желісінің негізгі KPI-лерін болжау.....129

Дәуітбаева А.О., Қоңырбаев Н.Б., Әбілдаева Ж.Т., Есіркепова А.У., Кәрім Н.Ә.
Бітіруші түлектердің жұмысқа орналастыру процесін оңтайландыру үшін қосымша әзірлеу.....148

Джусупбекова Г., Othman M., Ордабаева Г.
Жасанды интеллект алгоритмдерін желілік шабуылдарды анықтау үшін салыстырмалы талдау.....167

Исахов А.А., Оразмолдаев Н., Жаркынбек Е., Абылкасымова А.
Ауа тамшылары арқылы вирустық инфекцияның шектеулі кеңістікте таралуын сандық модельдеу.....182

Кантуреева М.А., Омарова Г.С., Дүйсен Ж.Д., Шекербек А.Ә., Тулебаев Е.Б.
Биік ғимараттардағы адамдарды эвакуациялау процестерін болжау және оңтайландыруда машиналық оқыту әдістерін қолдану.....202

Хусаин Б., Тельманов М.М., Хусаин А.Б., Бродский А.Р., Сасс А.С.
Жылу қондырғыларының шығарындыларын кешенді тазалау және
декарбонизациялау жүйесінің цифрлық егізі.....218

Кулакаева А.Е., Ашуров А.Е., Жумажанов Б.Р., Дайнеко Е.А., Зылғара А.Е.
KAZEOSAT-1 ғарыш аппаратының деорбитациясын жүзеге асыру үшін
бастапқы орбиталық параметрлерін анықтау алгоритмі.....236

Мименбаева А.Б., Туребаева А.Д., Оспанова Т.Т., Аруова А.Б.,
Найзағараева А.А.
Қалалық көлік ағынын болжауға арналған машиналық оқыту модельдерін
әзірлеу және салыстырмалы талдау.....253

Науменко В.В., Муканова Ж.А., Киселева О.В., Майнцер Д.А., Нерезов А.К.
Білім алушылардың үлгерімін арттыру үшін real-time
сауалнамаларын қолдану.....271

Назырова А.Е., Кадеркеева З.К., Бекманова Г.Т., Милош М., Ламашева Ж.Б.
Цифрлық білім және студенттердің академиялық жетістіктері:
деңгейлер бойынша білім беруді дамыту.....287

Оралбекова Д., Мамырбаев О., Ахмедиярова А., Қасымова Д.З, Алибиева Ж.,
Алдын ала оқытылған модельдер негізінде мәтінді резюмелеуге
арналған көпдеңгейлі модельді әзірлеу.....316

Оразбаев Б.Б., Жумадиллаева А.К., Курбангалиева Н.Б., Оразбаева К.Н.
Күкірт сапасын бағалаудың лингвистикалық модельдерін синтездеу
және күкіртті өндіру процесін бұлыңғыр модельдеу.....337

Сарсенбаева А.К., Рахимова Д.Р., Шормакова А.Н., Мансурова М.Е., Адали Э.
Семантикалық әдістерді заңнама саласында қолдану: агглютинативті
мәтіндерді талдауға арналған интеллектуалды жүйе.....354

Серек А., Шойынбек А., Шарипов К., Қуанышбай Д., Мухаметжанов А.
Сөйлеу транскрипцияларының лексикалық белгілеріне негізделген телефон
алаяқтықтарын талдау және жіктеу.....373

Шынжігіт Б.Б., Балабекова М.О., Амангелді Т.Т.
Кірпіш өнімдерін сату көлемдерін машиналық оқытуда талдау
және болжамдау.....393

Тохаева А.О., Альжанов А.К., Nezih Ö., Зиятбекова Г.З., Бегалиева К.Б.
PROXMOX VE негізінде жоғары оқу орындарында білім алушыларды
виртуалдандыру құзыреттерін қалыптастыру.....412

Төкенова Л.М., Әуелбеков О.А., Сапақова С., Саметова А.А., Бостанов Е.Л.
Пилотсыз ұшу аппараттарына арналған гибридті электр станцияларының жұмыс режимдерін модельдеу және оңтайландыру.....430

Еримбетова А.С., Бержанова У.Г., Дайырбаева Э.Н., Сәкенов Б.Е., Самбетбаева М.А.
Уақытша конволюциялық желі мен mediapipe көмегімен ым тілін тану.....443

Жукабаева Т.К., Бенхелифа Э., Марденов Е.М., Баумуратова Д., Карабаев Н.
Киберфизикалық өнеркәсіптік интернет заттары жүйелеріндегі шабуылдарға әрекет ету кезінде шешім қабылдауды қолдау.....461

СОДЕРЖАНИЕ

ИНФОРМАТИКА

Ахметова С.Т., Юнусова А.А., Алишева С.С., Олжатаева Б.Т., Мүсірепова Э.Б.
Интеллектуальный анализ данных для автоматического выявления языка ненависти в социальных сетях.....13

Аманов А.Н., Казбекова Г.Н., Жунисов Н.М., Абибуллаева А.А., Абен А.Б.
Обнаружение вторжений на основе искусственного интеллекта для DDoS-атак в программно-определяемых сетях.....30

Аманжолова С.Т., Усатова О.А., Мутанов Г.М., Муханов С.Б., Айтмукаш Д.
Бэкенд-архитектура гибридной системы проверки академических достижений на основе блокчейна.....52

Амирханова Г.А., Нургазы Т.Н., Амирханов Б.С., Нургазы Н.Н.
Разработка предиктивного цифрового двойника пищевого продукта на основе Edge ML и IoT-сенсоров.....73

Бекарыстанқызы А., Үсен Д., Қасенхан А., Чинибаев Е.
Холодный старт в системах рекомендаций в области образования: классические подходы и стратегии эпохи LLM.....91

Бимолдина Ж.А., Мусиралиева Ш.Ж., Багитова К.Б., Терейковская Л.
Использование машинного обучения и семантических моделей для обнаружения киберпропагандистского контента.....106

Чежимбаева К.С.
Прогнозирование ключевых KPI сетей 5G на основе нейросетевых моделей MLP и LSTM.....129

Даутбаева А.О., Конырбаев Н.Б., Абильдаева Ж.Т., Есиркепова А.У., Карим Н.А.
Разработка приложения для оптимизации процесса трудоустройства выпускников.....148

Джусупбекова Г., Othman M., Ордабаева Г.
Сравнительный анализ алгоритмов искусственного интеллекта для обнаружения сетевых атак.....167

Исахов А.А., Оразмолдаев Н., Жаркынбек Е., Абылкасымова А.
Численное моделирование распространения вирусной инфекции воздушно-капельным путём в замкнутых помещениях.....182

Кантуреева М.А., Омарова Г.С., Дүйсен Ж.Д., Шекербек А.Ә., Тулебаев Е.Б.
Использование методов машинного обучения для прогнозирования
и оптимизации процессов эвакуации людей в высотных зданиях.....202

Хусаин Б., Тельманов М.М., Хусаин А.Б., Бродский А.Р., Сасс А.С.
Цифровой двойник комплексной системы очистки и декарбонизации
выбросов тепловых установок.....218

Кулакаева А.Е., Ашуров А.Е., Жумажанов Б.Р., Дайнеко Е.А., Зылғара А.Е.
Алгоритм определения начальных орбитальных параметров KazEOSat-1
для деорбитации.....236

**Мименбаева А.Б., Туребаева А.Д., Оспанова Т.Т., Аруова А.Б.,
Найзағараева А.А.**
Разработка и сравнительный анализ моделей машинного обучения
для прогнозирования городского трафика.....253

Науменко В.В., Муканова Ж.А., Киселёва О.В., Майнцер Д.А., Нерезов А.К.
Применение опросов в режиме реального времени для повышения
успеваемости обучающихся.....271

Назырова А.Е., Кадеркеева З.К., Бекманова Г.Т., Милош М., Ламашева Ж.Б.
Цифровое образование и академическая успеваемость учащихся:
межуровневый анализ.....287

Оралбекова Д., Мамырбаев О., Ахмедиярова А., Касымова Д., Алибиева Ж.
Разработка многоуровневой модели для абстрактивного резюмирования текста
на основе предварительно обученных моделей.....316

**Оразбаев Б.Б., Жумадиллаева А.К., Курбангалиева Н.Б., Есиркесинов Р.Ж.,
Оразбаева К.Н.**
Синтез лингвистических моделей оценки качества серы и нечёткое
моделирование процесса её производства.....337

Сарсенбаева А.К., Рахимова Д.Р., Шормакова А.Н., Мансурова М.Е., Адали Э.
Применение семантических методов в юридическом анализе: интеллектуальная
система для обработки агглютинативных текстов.....354

Серек А., Шойынбек А., Шарипов К., Куанышбай Д., Мухаметжанов А.
Анализ и классификация телефонного мошенничества на основе
лексических признаков речевых транскрипций.....373

Шынжігіт Б.Б., Балабекова М.О., Амангелді Т.Т.
Анализ и прогнозирование объёмов продаж кирпичной продукции
с использованием машинного обучения.....393

Тохаева А.О., Альжанов А.К., Nezih Ö., Зиятбекова Г.З., Бегалиева К.Б.
Формирование компетенций в области виртуализации у обучающихся
в высшем образовании на основе платформы Proxmox VE.....412

Тукенова Л.М., Ауелбеков О.А., Сапакова С.З., Саметова А.А., Бостанов Е.Л.
Моделирование и оптимизация режимов работы гибридных силовых установок
для беспилотных летательных аппаратов.....430

Еримбетова А.С., Бержанова У.Г., Дайырбаева Э.Н., Сакенов Б.Е., Самбетбаева М.А.
Распознавание языка жестов с использованием временных свёрточных
сетей и MediaPipe4.....43

Жукабаева Т.К., Бенхелифа Э., Марденов Е.М., Баумуратова Д., Карабаев Н.
Поддержка принятия решений при реагировании на атаки в киберфизических
промышленных системах интернета вещей.....461

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DECISION SUPPORT FOR RESPONDING TO ATTACKS IN CYBER-PHYSICAL INDUSTRIAL INTERNET-OF-THINGS SYSTEMS

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Abstract. Industrial Internet-of-Things (IIoT) systems have emerged as a foundational technology underpinning a wide range of modern applications, including environmental monitoring, healthcare systems, industrial automation, and smart infrastructures. Their inherent advantages incorporate scalability, low energy consumption, intelligence and programmability, rapid data acquisition, reliability, low cost, and the absence of maintenance requirements. At the same time, they attract the attention of attackers, making the task of ensuring the security of such networks crucial. This study introduces a comprehensive decision support methodology for responding to cyberattacks in IIoT systems, including systems using edge computing principles, based on analytical modeling for the analysis of networks, attacks, and countermeasures. The methodology also employs machine learning, rules, and multi-criteria optimization for attack detection and countermeasure selection. It consists of three stages: data collection

on events occurring in the system, detection of attacks and anomalies, and selection of countermeasures for the identified attacks. Within the framework of the methodology, models of networks, attacks, and countermeasures, specific for IIoT systems, are presented. The main components and topology of IIoT systems are considered within the network model. The main types of attacks and possible countermeasures for IIoT systems are identified to specify the models of attacks and countermeasures. The algorithm for countermeasure selection within the proposed methodology based on rules and multi-criteria optimization and using the specified models is described. The application of the methodology is demonstrated through an example. The advantages and limitations of the proposed methodology are analyzed, and directions for future research are outlined.

Key words: IIoT systems, cyberattacks, countermeasures, decision support, response

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КИБЕРФИЗИКАЛЫҚ ӨНЕРКӘСІПТІК ИНТЕРНЕТ ЗАТТАРЫ ЖҮЙЕЛЕРІНДЕГІ ШАБУЫЛДАРҒА ӘРЕКЕТ ЕТУ КЕЗІНДЕ ШЕШІМ ҚАБЫЛДАУДЫ ҚОЛДАУ

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Аннотация. Өнеркәсіптік интернет заттары жүйелері (Industrial Internet of Things, IIoT) қоршаған ортаны мониторингтеу, денсаулық сақтау жүйелері, өнеркәсіптік автоматтандыру және ақылды инфрақұрылымдар сияқты заманауи қолданбалардың кең ауқымының негізін құрайтын базалық технологияға айналды. Олардың негізгі артықшылықтарына масштабталуы, төмен энергия тұтынуы, интеллектуалдылығы мен бағдарламалануы, деректерді жинаудың жоғары жылдамдығы, сенімділігі, төмен құны, сондай-ақ техникалық қызмет көрсетуді қажет етпеуі жатады. Сонымен қатар, мұндай жүйелер қаскөйлердің назарын өзіне аударады, бұл олардың қауіпсіздігін қамтамасыз ету мәселесінің өзектілігін арттырады. Осы зерттеуде IIoT жүйелеріндегі кибершабуылдарға әрекет ету кезінде шешім қабылдауды қолдауға арналған кешенді әдістеме ұсынылады, оның ішінде шеткі есептеу (edge computing) қағидаттарын қолданатын жүйелер де қамтылған. Әдістеме желілерді, шабуылдарды және қарсы шараларды талдауға арналған аналитикалық модельдеуге негізделген, сондай-ақ шабуылдарды анықтау және қарсы шараларды таңдау үшін машиналық оқыту әдістерін, ережелерді және көпкритерийлі оңтайландыруды пайдаланады. Ұсынылған әдістеме үш кезеңнен тұрады: жүйеде орын алатын оқиғалар туралы деректерді жинау; шабуылдар мен аномалияларды анықтау; анықталған шабуылдар үшін қарсы шараларды таңдау. Әдістеме аясында IIoT жүйелеріне тән желілердің, шабуылдардың және қарсы шаралардың модельдері ұсынылған. Желілік модельде IIoT жүйелерінің негізгі компоненттері мен топологиясы қарастырылады. Шабуылдар мен қарсы шаралар модельдерін нақтылау үшін IIoT ортасына тән негізгі шабуыл түрлері мен ықтимал қарсы әрекеттер айқындалған. Әзірленген модельдерді қолдана отырып, ережелер мен көпкритерийлі оңтайландыруға негізделген қарсы шараларды таңдау алгоритмі сипатталған. Әдістеменің қолданылуы практикалық мысал арқылы көрсетілген. Ұсынылған тәсілдің артықшылықтары мен шектеулері талданып, болашақ зерттеулердің негізгі бағыттары айқындалған.

Түйін сөздер: IIoT жүйелері, кибершабуылдар, қарсы шаралар, шешім қабылдауды қолдау, әрекет ету

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ПОДДЕРЖКА ПРИНЯТИЯ РЕШЕНИЙ ПРИ РЕАГИРОВАНИИ НА АТАКИ В КИБЕРФИЗИЧЕСКИХ ПРОМЫШЛЕННЫХ СИСТЕМАХ ИНТЕРНЕТА ВЕЩЕЙ

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Аннотация. Промышленные системы интернета вещей (Industrial Internet of Things, IIoT) являются базовой технологией, лежащей в основе широкого спектра современных приложений, включая промышленную автоматизацию, системы мониторинга, здравоохранение и интеллектуальную инфраструктуру. Ключевыми преимуществами IIoT являются масштабируемость, энергоэффективность, высокая скорость обработки данных, программируемость и надёжность. Вместе с тем такие системы представляют собой привлекательную цель для кибератак, что обусловливает необходимость разработки эффективных методов обеспечения их безопасности. В исследовании предложена комплексная методология поддержки принятия решений при реагировании на кибератаки в системах IIoT, включая среды с использованием пограничных вычислений (edge computing). Методология основана на аналитическом моделировании сетей, атак и контрмер, а также включает методы машинного обучения, экспертные правила и подходы многокритериальной оптимизации для обнаружения атак и выбора оптимальных мер реагирования. Предложенная методология включает три основных этапа: сбор и анализ данных о событиях в системе, обнаружение атак и аномалий, а также выбор контрмер для нейтрализации выявленных угроз. В рамках исследования разработаны модели сетевой

архитектуры, типов атак и соответствующих контрмер, характерных для IIoT-среды. Описан алгоритм выбора контрмер, основанный на правилах и многокритериальной оптимизации с использованием предложенных моделей. Практическое применение методологии продемонстрировано на прикладном примере. Проведён анализ преимуществ и ограничений предложенного подхода, а также определены направления для дальнейших исследований.

Ключевые слова: системы IIoT, кибератаки, контрмеры, поддержка принятия решений, реагирование

Introduction and Related Work. IIoT systems are spatially distributed sensor nodes capable of collecting data, processing it, and interacting via wireless channels (Tossa et al., 2025). At present, they are applied in smart home management, transportation and logistics, industry, agriculture, environmental monitoring, urban surveillance, entertainment, healthcare, and energy, as well as in security and battlefield monitoring (Kardi et al., 2019).

«Ideal» IIoT systems are scalable, consume little energy, are intelligent and programmable, provide rapid data acquisition, are reliable, low-cost, and require no maintenance. However, they also attract the attention of attackers. In particular, passive attacks those aimed at stealing information on IIoT systems are discussed in (Keerthika et al., 2021) (eavesdropping and traffic analysis). Active attacks those aimed at damaging the network by altering or replacing data are considered in (Verma et al., 2022) (denial of service), (Sánchez et al., 2021) (masquerade attack), (Hu et al., 2022) (replay attack), (Hu et al., 2014) (selective forwarding attack), (Sujihelen et al., 2022) (node replication), (Al-Ahmadi et al., 2022) (wormhole attack), (Faris et al., 2023) (Sybil attack), (Teng et al., 2023) (sinkhole attack), (Allimuthu et al., 2022) (rushing attack), and (Beddoe et al., 2013) (message modification). The types of attacks on IIoT systems are further classified in (Keerthika et al., 2021) and (Verma et al., 2020).

One of the key challenges in deploying IIoT systems is ensuring cybersecurity (Jadhav et al., 2017). Possible countermeasures are outlined in (Turakulovich et al., 2019) and (Mamdouh et al., 2018). Among them are security measures that should be incorporated during the system design stage, such as the use of secure data transmission protocols (Turakulovich et al., 2019) (such measures for all identified attacks are discussed in (Keerthika et al., 2021)). However, these alone cannot completely eliminate the possibility of a successful attack. Therefore, it is also necessary to integrate protection mechanisms into the system that enable the detection of cyberattacks and the implementation of countermeasures, for example, through the use of machine learning (Mamdouh et al., 2018). This study focuses on decision support issues based on such protection mechanisms.

This paper proposes a decision support methodology for responding to cyberattacks in IIoT systems, based on analytical modeling for simulating the system, attacks, and countermeasures; machine learning for attack detection; rules

and multi-criteria optimization for countermeasure selection. The application of the methodology is demonstrated through an example. The advantages and limitations of the proposed methodology are analyzed, and directions for future research are outlined. Thus, the main contributions of this research are as follows: (1) a decision support methodology for responding to cyberattacks in IIoT systems, based on analytical modeling, machine learning, and rules and multi-criteria optimization; (2) analytical models of system, attacks, and countermeasures considering specificity of IIoT systems, and considering the types of attacks and appropriate countermeasures; (3) algorithm for countermeasure selection based on rules and multi-criteria optimization and using the specified models; (4) demonstration of applicability of the proposed methodology on the toy example.

The paper is organized as follows. Relevant studies are briefly reviewed in the introduction. Section 2 presents the key definitions and problem statement. Section 3 describes the proposed decision support methodology for responding to cyberattacks in IIoT systems. Section 4 provides an example of the methodology's application and a discussion.

Materials and Methods

IIoT systems. A IIoT system can be formalized as follows:

$$IS = <N, C>, \quad (1)$$

where

N – nodes,

C – wireless links between them.

A node consists of core and additional components (Tossa et al., 2025). The core components include:

Data acquisition component (consisting of a physical sensing device that collects data from the local environment and an Analog-to-Digital Converter, ADC) collects analog data from the local environment and converts it into a digital format understandable by the processor,

Data processing component, including ones using edge computing (a processor complemented with Random Access Memory) manages the operation of other components and analyzes/processes the data obtained from the data acquisition component,

Communication component (which can be optical or radio-frequency) transmits and receives data in the wireless medium,

Power supply component (a small, limited-capacity battery).

The additional components may include GPS (Global Positioning System), a mobility system, and an energy generator.

According to (Tossa et al., 2025), depending on the application domain and architecture, the following types of nodes are distinguished:

Standard node includes a data transmission component and a data processing component;

Sensor node (source) a standard node with a data acquisition or detection component;

Actuator node a standard node with a component for performing specific mechanical tasks;

Gateway a standard node that relays traffic into the network;

Base station a standard node with a serial converter connected to a second communication component for relaying data from nodes to users or other networks

Various architectures of IIoT systems are distinguished, including:

Flat architecture all nodes have equal energy, computing resources, and memory, perform identical roles, and each node can interact with any other,

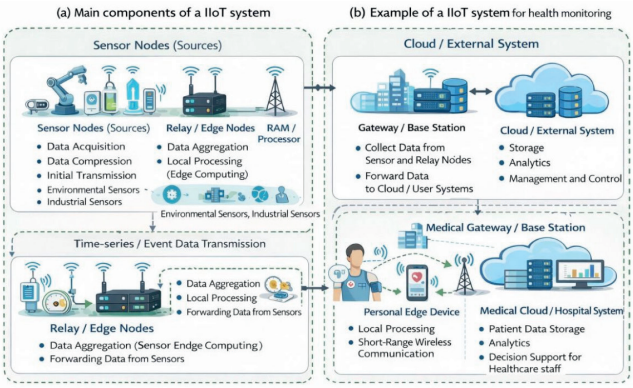
Hierarchical architecture nodes possess different resources and perform different roles, and Multitier architecture a hierarchical architecture in which nodes are grouped into clusters according to their functionality.

Depending on the architecture, the role of each network node is defined: source, relay, or data collection node. Typically, a IIoT system consists of a base station (data collection node) interacting with multiple sensors (sources and relays) (hierarchical architecture). A sensor (source) collects data, compresses it, and transmits it to the base station (data collection node) either directly or through other sensors (relays). The base station forwards the data to the system. An example of such an architecture is shown in Figure 1 (a - main components of a IIoT system and the connections between them, b - an example of a IIoT system for health monitoring).

The following features of IIoT systems are significant for developing a decision support methodology for responding to cyberattacks in such systems:

Heterogeneity in terms of energy sources, data processing capabilities, communication ranges, and sensing modalities, which complicates the deployment process of IIoT systems;

Constraints related to network lifetime, coverage, energy/memory/ computational resources, and data transmission time.

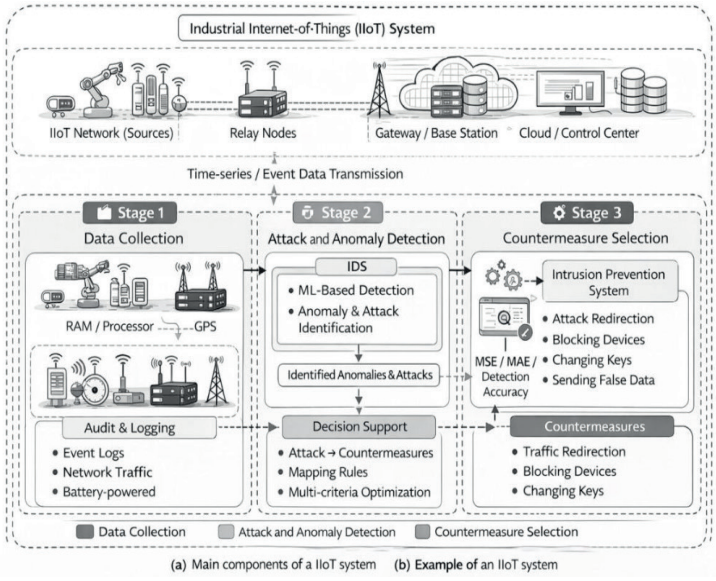


a) Main components of a IIoT system b) Example of a IIoT system for health monitoring

Figure 1 – Hierarchical architecture of a IIoT system.

Problem Statement of the Study. Given: a IIoT system (IS), a set of events – E, a set of attacks on the IS – A, a set of security mechanisms – SMP, and a set of countermeasures – CM. It is necessary to develop a decision support methodology for responding to cyberattacks in IIoT systems that enables the mapping of the set of attacks A onto the set of countermeasures CM: F: A → CM, taking into account resource and privilege constraints.

Decision Support for Responding to Cyberattacks in IIoT systems. The proposed decision support methodology for responding to cyberattacks in IIoT systems is based on analytical modeling for simulating the system, attacks, and countermeasures; machine learning for attack detection; rules; and multi-criteria optimization for countermeasure selection. The methodology consists of three stages: data collection on events occurring in the system, detection of attacks and anomalies, and selection of countermeasures for the identified attacks (Figure 2).



a) Main components of a IIoT system b) Example of an IIoT system

Figure 2 – Decision support methodology for responding to cyberattacks.

For data collection, it is proposed to implement auditing and logging; for detecting attacks and anomalies an intrusion detection system based on machine learning; and for countermeasure selection an intrusion prevention system based on rules and multi-criteria optimization.

Models. First, we define a set of models based on the relationships between the objects and subjects involved in the decision-making process, including network objects (nodes and links between them), their vulnerabilities and weaknesses, known exploits and attacks, incidents, as well as countermeasures (Figure 3). In the event of a security incident, protection mechanisms which may be network objects

or components of such objects are employed to implement countermeasures (for example, a firewall can be used to block a connection).

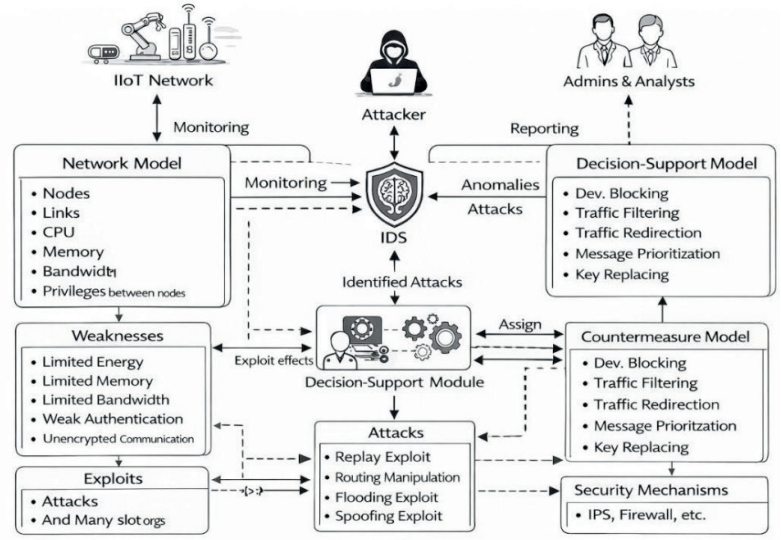


Figure 3 – Relationships between objects and subjects involved in the decision-making process for response.

Thus, it is necessary to extend the set of possible node roles in the network with security mechanisms, such as intrusion detection and prevention systems (Figure 4).

To account for the possible roles of network nodes as well as embedded security mechanisms, we define the elements of the network model from Equation 1 ($IS = <N, C>$) as follows:

N – network nodes, $N = \{\cup_i n_i\}$, where i – number of system node, $n_i = <name, role, SM>$, where name is the node identifier, role is the node's role determining available resources (energy, memory, computing capacity) and privileges (user/administrator/owner), and SM denotes the security mechanisms available for this node, $SM = \{\cup_i sm_i\}$, where i – number of security mechanism, $sm_i = <name, CM>$, where CM – the set of countermeasures related to the security mechanism sm_i;

C – wireless and wired links between them, $C = <prot, trCh>$, where *prot* is the transmission protocol, and *trCh* is the bandwidth.

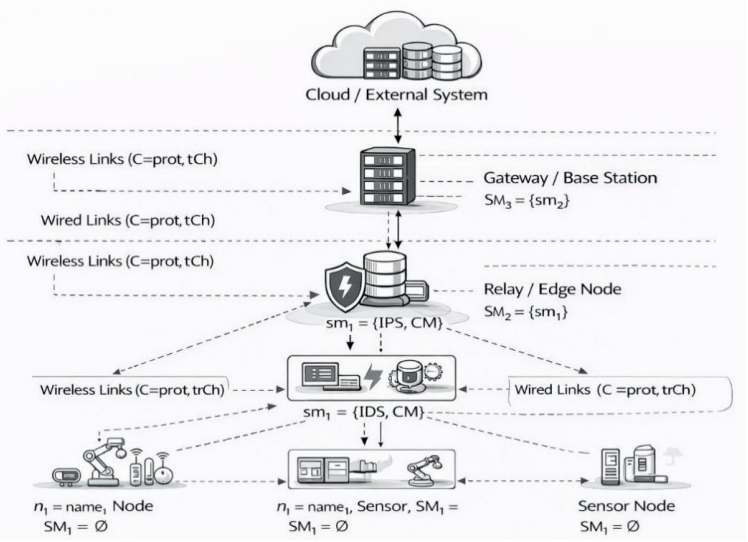


Figure 4 – Hierarchical architecture of a IIoT system with security mechanisms.

To identify possible security mechanisms and countermeasures, it is necessary to define the potential attacks. In (Shahzad et al., 2017), the authors highlight the following threats to IIoT systems and their corresponding attacks:

Confidentiality threat (unauthorized access to information; in IIoT system terms a message transmitted over the wireless network can be read and understood by an attacker): Eavesdropping (information gathering from carriers, wiretapping, interception of electromagnetic/radio frequency signals, traffic analysis, staff negligence), Interaction (data theft, replay attack, masquerade attack, integrity violation, man-in-the-middle attack, bypassing security mechanisms, physical intrusion, authorization violation), System compromise (trapdoor attack, Trojan attack, service spoofing, viruses/worms).

Integrity threat (unauthorized modification or theft of information; in IIoT system terms a message transmitted over the network is altered or forged): Modification (denial, interception/modification), Interaction (see above), System compromise (see above).

Availability threat (denial of service or prevention of authorized access; in IIoT system terms – inability to transmit a message or for a node to use resources): Denial of Service (integrity violation, resource exhaustion), Interaction (see above), System compromise (see above).

Non-repudiation threat (denial of an action that has occurred or claiming that an action has not occurred; in IIoT system terms providing information to an unauthorized/unauthenticated or fake sensor): Reposting, Theft/modification, Interaction (see above), System compromise (see above).

In (Shahzad et al., 2017), the authors highlight the following possible security measures and countermeasures according to the types of threats:

Confidentiality (counteracting unauthorized access to information): passwords and certificates (key and certificate management must be ensured), firewalls with access control lists, auditing and logging, intrusion detection systems, antivirus/spyware software.

Integrity (counteracting unauthorized modification or theft of information): passwords and certificates (key and certificate management must be ensured; compared to confidentiality measures, digital signatures and checksums are additionally introduced), firewalls with access control lists, auditing and logging, intrusion detection systems, antivirus/spyware software.

Availability (counteracting denial of service or prevention of authorized access): backup during and recovery after an attack, security and vulnerability incident reporting, bandwidth limitation, access management, firewalls with access control lists, auditing and logging, backups and recovery, intrusion detection systems, antivirus/spyware software, network and system management.

Non-repudiation (counteracting denial that an action took place or claims that it did not): passwords and certificates (key and certificate management must be ensured), auditing and logging (for legal proceedings).

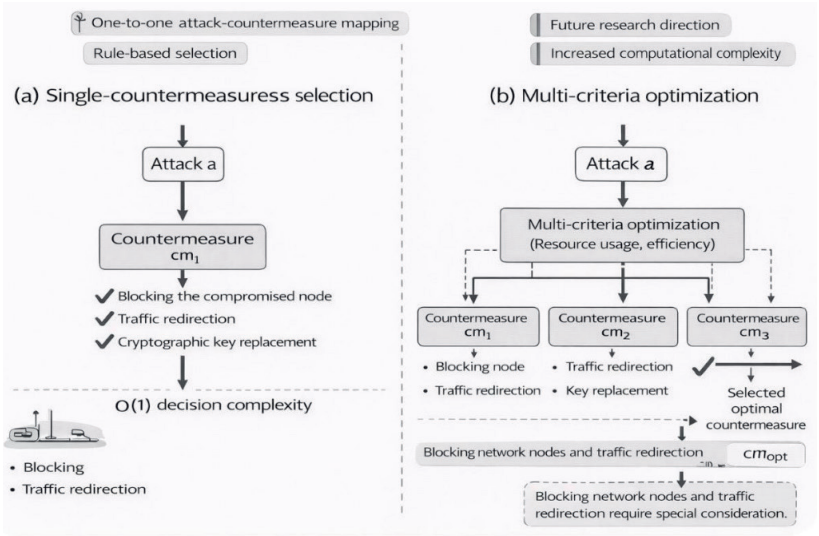


Figure 5 – Comparison of single-countermeasure selection and multi-criteria optimization in the proposed decision-support methodology.

The security mechanisms applied during the operational phase include:

• Firewalls with access control lists (measures: blocking access to a specific node, blacklisting, message prioritization, bandwidth limitation, and traffic redirection),

• Audit and logging (a passive measure, i.e., used for data collection but not involved in supporting response decision-making),

• Intrusion detection systems (a passive measure, i.e., used for detecting attacks but not involved in supporting response decision-making, performing monitoring to identify attacks and anomalies),

• Antivirus/anti-spyware software (blocking malicious software),

• Network and system management (access control, bandwidth limitation).

Within the intrusion prevention subsystem of the security system (Figure 4), it is proposed to implement the selection of countermeasures for different types of attacks based on rules, using Table 1 (Keerthika et al., 2021).

Table 1 – Countermeasures in IIoT systems

Attack	**Threat to**	**Countermeasures**
Denial of Service (Verma et al., 2022)	availability	message prioritization
Jamming	availability	Spread spectrum, region mapping and traffic redirection
Physical Attack	availability	traffic redirection
Spoofing, Routing Information Forgery	availability, integrity, confidentiality, non-repudiation	Block compromised node and reconnect, change key
Selective Forwarding (Hu et al., 2014)	availability	traffic redirection
Sink Hole Attack (Teng et al., 2023)	availability	Block compromised node and redirect traffic
Black Hole Attack	availability, integrity, confidentiality, non-repudiation	traffic redirection
Sybil Attack (Faris et al., 2023)	availability, integrity, confidentiality, non-repudiation	Block nodes and redirect traffic
Wormhole Attack (Al-Ahmadi et al., 2022)	availability, integrity, confidentiality, non-repudiation	traffic redirection
HELLO Flood Attack	availability	message prioritization, traffic redirection
Acknowledgment Spoofing (Verma et al., 2020)	integrity, confidentiality, non-repudiation	Block fake node, reconnect with legitimate node, change key
Neglect and Greed Attack (Verma et al., 2020)	availability	Recover message transmission algorithm
Homing Attack (Verma et al., 2020)	confidentiality	Collect information, encryption
Node Takeover Attack	availability, integrity, confidentiality, non-repudiation	Block fake node, reconnect with legitimate node, change key
Node Failure Attack	availability	traffic redirection, restore node
Monitoring and Eavesdropping (Keerthika et al., 2021)	confidentiality	Collect information, encryption
Traffic Analysis (Keerthika et al., 2021)	confidentiality	Collect information, encryption
Attacker Masking	availability, integrity, confidentiality, non-repudiation	Collect information, encryption, restore message transmission algorithm

Node Replication (Sujihelen et al., 2022)	integrity	Block fake node, reconnect with legitimate node, change key
False Knot	availability	Block fake node, reconnect with legitimate node, change key
Replay Attack (Hu et al., 2022)	confidentiality, non-repudiation	Blocking fake node, reconnect with legitimate node, change key
Rushing Attack (Allimuthu et al., 2022)	availability	Blocking fake node, restoring message transfer algorithm, change key
Vampire Attack	Threat to	Replacing nodes, redirecting traffic

Considering Table 1, let us introduce two additional models: the attack model and the countermeasure model. The attack model is defined as:

$A = \{\cup_i a_i\}$, where i – number of attack, $a_i = <type, n_j>$, where type – type of attack, n_j – attacked network objects.

The countermeasure model is defined as:

$CM = \{\cup_i cm_i\}$, where i – number of countermeasure, $cm_i = <name, Pr, R>$, where *name* – name of the countermeasure, *Pr* – required privileges, *R* – required resources.

Algorithm. Since the number of countermeasure options for each type of attack is relatively small, the following rule-based algorithm is proposed for the countermeasure selection stage of the decision-support methodology:

Input data: *IS* system, attack *a*.

1. Map *a* to the *IS* using *n*.

2. Select all *cm* for *a* : *CM* <- *cm* #using rules defined on the basis of Table 1.

3. Map *CM* to countermeasures in *SM* : *CM_lim* #to define available countermeasures.

4. From *CM_lim*, select the optimal *CM_opt* considering *Pr* and *R*.

Output data: countermeasures *CM_opt*.

Results. Let us consider the application of the methodology using a simple example. Suppose that the network shown in Figure 1(b) is subjected to a spoofing attack or a routing information spoofing attack. A security system is deployed in the network (as shown in Figure 4). The implementation of the methodology proceeds as follows:

Stage 1. Based on the information collected by the auditing and logging component, the intrusion detection system uses machine learning to identify an attack or anomaly, namely, a routing information spoofing attack. It reveals that one of the sensor nodes *n* is malicious.

Stage 2. Using Algorithm 1 (*IIoT* system and attack *a* are input data). On the 1st step map *a* to the IIoT system using *n*. The output of this step is malicious node $n = <name, role, SM>$.

On the second step the countermeasures *cm* against *a* are determined using rules defined on the basis of Table 1: IF "a routing information spoofing attack" THEN action "Blocking the compromised node and redirecting traffic, key replacement.". There is only one response option *cm* "Blocking the compromised node and redirecting traffic, key replacement.". Step 3 of the algorithm consists in mapping *cm* to countermeasures in *SM* and obtaining *CM_lim = cm*. Step 4 is skipped as soon as there is only on countermeasure cm in the *CM lim* list. Implementation of this measure *cm* only requires administrator rights and user interaction for key replacement. Thus, final list of countermeasures *CM_opt* contains one countermeasure "Blocking the compromised node and redirecting traffic, key replacement." For implementation against the detected routing information spoofing attack.

Discussion. For the system to operate effectively, it is necessary to implement data collection and processing, as well as methodologies for detecting attacks and anomalies. Machine learning–based methods, such as those described in (Ahmad et al., 20122), have demonstrated good performance. This constitutes one of the directions for future research.

At present, most attacks in Table 1 have only one corresponding countermeasure, which does not require additional optimization in terms of resource usage and efficiency, and ensures low algorithmic complexity of O (1). It should be noted that the methodology can be easily extended with new countermeasures. In such cases, a multi-criteria optimization algorithm will be required to select the most suitable countermeasure, which also represents a future research direction.

In addition, algorithms for blocking network nodes and redirecting traffic deserve special attention.

Conclusion.

This study addressed the problem of decision support for responding to cyberattacks in IIoT systems. The architecture and key features of IIoT systems were analyzed. The main types of attacks and possible countermeasures were identified. A decision support methodology for responding to cyberattacks in IIoT systems was proposed, based on analytical modeling of the system, attacks, and countermeasures; machine learning for attack detection; rules; and multi-criteria optimization for countermeasure selection. Within the methodology, models of the system, attacks, and countermeasures, as well as an algorithm for countermeasure selection, were developed. The application of the methodology was demonstrated on a test example. Future work will focus on implementing attack and anomaly detection based on machine learning, analyzing the specifics of multi-criteria optimization in countermeasure selection, and examining in greater detail measures and algorithms related to traffic redirection.

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