

EO-ZT: Economically Informed Zero-trust for Secure Spectrum Trading in Open Radio Access Networks (O-RAN)

Guhan Zheng^a, Qiang Ni^b, Wenjuan Yu^b

^aSchool of Communication and Information Engineering, Shanghai University, Shanghai, 200444, China

^bSchool of Computing and Communications, Lancaster University, Lancaster, LA1 4WA, U.K.

Abstract

The adoption of Zero-Trust Architecture (ZTA) in 6G O-RAN spectrum trading introduces additional energy overhead from continuous authentication and encryption, along with economic-security challenges such as moral hazard and reduced security investment. To address these challenges, we propose the EO-ZT framework, a novel ZTA tailored for the O-RAN. Our framework includes a novel deposit-refund system (DRS)-based trust evaluation component and adaptive policy components designed for O-RAN spectrum trading. The DRS-based trust evaluation component aims to suppress moral hazard, drawing inspiration from the sharing economy. Within the adaptive policy component, security, energy, zero-trust policy and spectrum trading policy are jointly formulated as coupled decision-making problems. Hence, we propose a game-theoretical spectrum trading scheme (GSTS) to enable fair spectrum trading between subscribers and cell sites, mitigating moral hazard and incentivizing dynamic security investment by RAN intelligent controllers (RICs). Building on this, the presented spectrum market competition scheme (SMCS), based on a winner-take-all model, employs cell zooming strategies to reduce energy consumption while promoting security investment among cell sites. Simulations demonstrate the superiority of EO-ZT over existing potential application algorithms for ZTA in O-RAN, effectively balancing energy efficiency, economic viability, and security requirements in spectrum trading markets.

Keywords: Zero-trust architecture (ZTA), open radio access networks

(O-RAN), moral hazard, Peltzman Effect, spectrum trading, energy consumption.

1. Introduction

To fulfill the high-performance aspirations of 6G, Open Radio Access Networks (O-RAN), an architecture focused on decomposing RAN components and opening interfaces, is one of the main proposals [1]. It converts the RAN into open and fully interoperable [2]. Within this framework, different mobile network operators (MNOs) have the flexibility to employ different spectrum strategies tailored to various types of subscribers [3]. These strategies are developed via a RAN Intelligent Controller (RIC). O-RAN, therefore, opens the doors to openness for MNOs' core business, spectrum trading. Subscribers enable rent and access spectrum resources from various MNOs' cell sites according to their economic utilities. MNOs' cell sites allow for the flexible change of the scope of cell site service by performing cell zooming, enhancing spectrum market competition among cell sites, and developing rental strategies based on economic utilities.

O-RAN, as an emerging and promising next-generation wireless network, requires counterpart security measures. Nevertheless, conventional network security frameworks exhibit notable weaknesses in provisioning security in O-RAN spectrum trading environments [4]. This is primarily because they set up a trust zone within the network boundary, in which devices operating over the authentication protocols are assumed strongly trusted [5]. The delineating of the network boundary, however, is extremely challenging due to the complexity and dynamics of O-RAN. Furthermore, a malicious subscriber with access to the spectrum enjoys the unfettered ability to manipulate all the contents contained within the O-RAN network.

Zero-trust architecture (ZTA) [6] is an emerging security paradigm. It follows the philosophy of not trusting any device. Under this philosophy, the devices accessing the network resources remain untrusted after the initial authentication and authorization. Each device seeking access to each network resource must undergo dynamic authentication and continuous monitoring. It effectively addresses the challenges associated with defining network boundaries as well as potential lateral movement in the classical frameworks [7]. ZTA is thus viewed as a promising security solution for O-RAN and was incorporated in the O-RAN security requirements specification of the

O-RAN ALLIANCE Security Work Group [8]. The integration of ZTA in O-RAN for spectrum trading is deemed imperative.

1.1. Challenges

The integration of ZTA, while imperative for security, fundamentally alters the economic calculus of O-RAN spectrum trading. Information security, however, inherently demands both technical and economic considerations [9]. The effectiveness of technological solutions in ensuring network security cannot be guaranteed without an economically grounded assessment [10], and these economically driven security challenges are equally relevant to the new economic paradigm in the O-RAN with ZTA.

Firstly, during spectrum trading, if O-RAN equipment fails to serve subscribers as expected, compensation is required for subscribers. The subscriber, however, is normally unable to compensate equivalently for O-RAN loss if the subscriber defaults, e.g., excessive resource utilization. This nourishes the moral hazard issue. Moral hazard [11] is an economic principle that explains subscribers engage in high risk-taking behavior if their consequences are negligible. For instance, subscribers may purchase additional spectrum resources at low prices without utilizing them fully, thus maximizing their utility but disrupting the spectrum market. Developing preventive and suppression mechanisms for moral hazard in ZTA tailored for O-RAN, therefore, is crucial.

Secondly, for O-RAN employing ZTA, devices in O-RAN may inadvertently relax device vigilance against risks, as ZTA improves security protection and increases the economic expenditure of O-RAN. Devices thus diminish the inclination towards investing in security measures (e.g., insurance, and information exchange of collaborative intrusion detection) for self-protection, even if it should be a parallel protection measure to zero trust. This is called the Peltzman Effect [12]. It is also an economic principle. It points out the inherent reflexive tendency of individuals towards regulation. This principle argues that safety regulation can be counterproductive. For example, increasing safety technologies for cars causes drivers to be less alert to risks and accelerate, thus cancelling out the effects of safety enhancement [13]. Hence, it is essential to design schemes to incentivize the decrease in security investments due to the Peltzman Effect.

Moreover, the network energy consumption is deemed a crucial component of the network's economic cost [14, 15, 16]. Therefore, several additional unique challenges for spectrum trading emerge alongside the aforementioned

challenges. Because ZTA raises the energy cost of selling spectrum resources and alters the security investments due to the Peltzman Effect, it changes the O-RAN economic paradigm for spectrum trading. Optimizing spectrum trading strategies among cell sites and subscribers to maximize their economic utilities, subject to security, poses a significant challenge. In particular, considering the open nature of O-RAN, in case spectrum trading triggers changes in market supply and demand, cells also need to dynamically adjust the cell zooming strategy via intelligent controllers, i.e., adjust the cell coverage and transmit power in real time according to the service demand, to match the new energy cost-revenue balance point. This multi-dimensional coupling between security requirements, economic benefits, and resource allocation fully reflects the complexity of spectrum trading challenges in the O-RAN.

Building upon the above discussions, the primary challenges entwined with ZTA in O-RAN involve the moral hazard, the Peltzman Effect, as well as coupled decision-making challenges in terms of spectrum trading.

1.2. Related works

Several but limited studies have explored the deployment of ZTA on O-RAN. K. Ramezanpour and J. Jagannath [4] introduced an intelligent ZTA and discussed the suitability of this framework integrated into the O-RAN architecture. Similarly, [17] and [18] explored the design of the ZTA adapted for O-RAN. They, however, focused on architectural design and did not consider the joint security and economically informed challenges specifically confronting O-RAN. H. Moudoud et. al [19] further considered real-time detection and prevention of cyber threats of O-RAN. They introduced deep reinforcement learning in ZTA for O-RAN to effectively enforce access control rules. Nevertheless, these ZTA frameworks neglect to analyze the security issues of ZTA in O-RAN from an economic viewpoint. The impact of ZTA presence on O-RAN strategies, i.e., spectrum allocation and cell zooming, is also overlooked.

To the best of our knowledge, all other proposed general ZTAs have not considered the security challenges from economic perspectives. To ensure ZTA security, economically informed discussion is, however, essential.

Nevertheless, simply applying generic economic models is insufficient. Generic economically informed models, for instance, Zhang et. al[20] propose a bi-Level game approach for attack-aware cyber insurance. Moreover, in [21], a framework for cyber risk management is introduced. These existing

economic models, while promising, are not readily applicable to spectrum allocation and trading in O-RAN. A primary shortcoming is that these models often prioritize securing energy efficiency and insurance, but they fall short of incorporating the mechanisms of transactions. This misalignment makes them difficult to apply directly to developing jointly optimized security and economic strategies.

Various subscriber-cell spectrum trading (spectrum allocation) and cell-cell spectrum market competition (cell zooming) may have the potential to address these security challenges while developing spectrum trading strategies for O-RAN employing ZTA. For instance, Bonati et. al [22] proposed a flexible and demand-driven approach to resource trading for O-RAN with neutral host techniques. Cui et. al [23] introduced a multi-service spectrum resource trading strategy for vehicle-to-everything applications supported by O-RAN. Moreover, [24] developed several algorithms to tackle the spectral efficiency maximization problems. However, these spectrum trading schemes assume fixed numbers of users in the cell and fixed ranges of cell services, without accounting for economically informed security challenges.

Cell-cell spectrum market competition studies, e.g., in [25], Xu et. al investigated adaptive cell zooming schemes and proposed a cell zooming factor (CZF) to improve the network utility. Liu et. al [26] proposed a cell zooming strategy to balance user benefits and communication system operating costs. Zhou et. al [27] further proposed a cell zooming algorithm for visible light and radio frequency networks. However, they are all based on the assumption that subscribers are allocated the same or a fixed amount of spectrum. Economically informed security challenges are also not considered.

As a result, existing studies inherently lack an approach that simultaneously considers subscriber-cell spectrum trading and cell-cell spectrum market competition, while also overlooking moral hazard and the Peltzman Effect. This is due to the change in cell service range leading to the alteration of energy costs, spectrum pricing, and the number of subscribers served. It increases the complexity of joint consideration. However, with the inclusion of the new ZTA energy paradigm, these two strategies for spectrum trading necessitate change and be considered jointly. Therefore, the development of a novel zero-trust framework to tackle these challenges jointly is imperative.

1.3. Contributions

Given the abovementioned existing literature and challenges, we contend that there is an urgent need for a novel zero-trust framework and supporting

mechanisms for O-RAN to jointly counteract moral hazard, Peltzman Effect with a specific focus on spectrum trading. Consequently, the primary aim of this paper is to design a new ZTA tailored for O-RAN, i.e., EO-ZT, aimed at jointly addressing these challenges.

Taking inspiration from the sharing economy, our novel EO-ZT includes a novel deposit refund system (DRS)-based trust evaluation components tailored to enhance O-RAN’s resilience to moral hazard. The evaluation outputs are then incorporated into the proposed new adaptive policy component. [In this policy, security, and economically informed challenges are jointly considered and formulated as mathematical problems.](#) In response to these challenges, we propose two new schemes grounded in distinct economic relations and theories to collectively address.

The main contributions of this paper are summarized as follows:

- [We propose a novel and effective EO-ZT framework that is able to jointly address the security and economically informed challenges of O-RAN ZTA.](#) The EO-ZT comprises two innovative and mutually reinforcing components, DRS-based trust evaluation and adaptive policy components. The DRS-based trust evaluation component is designed to monitor and prevent instances of moral hazard behavior, based on the sharing economy. Their outputs are then incorporated into the adaptive policy component for the dynamic policy development of O-RAN. Economic risk prevention and strategic decision-making problems are mathematically formulated in this component.
- Our subsequent proposition proposes a game-theoretical spectrum trading scheme (GSTS) for the EO-ZT adaptive policy component, grounded in the economic relations between subscribers and cells. It is designed to trade spectrum and prevent the moral hazard posed by subscribers. In this scheme, the cell site assumes the role of the leader in determining the spectrum price fairly, and subscribers function as followers who engage in spectrum purchases. Moreover, the GSTS also introduces modest incentives to encourage RICs to increase dynamic security investments. This aligns with the overarching objective against the Peltzman Effect.
- We propose a spectrum market competition scheme (SMCS) within the EO-ZT adaptive policy component, building upon the proposed GSTS. It is predicated on energy-based economic relations between cells in

the O-RAN. The purpose of this mechanism is to incentivize O-RAN to counteract the decline in security investments due to the Peltzman Effect while improving the system's economic utility via cell zooming. To derive optimal market strategies, we present an approach based on the winner-take-all (WTA) market. The scheme is meticulously crafted to transform into a constrained quadratic programming (QP) problem, facilitating its resolution.

1.4. Organization of the paper

The rest of the paper is organized as follows: Section II presents the O-RAN system model, and Section III provides an overview of the proposed EO-ZT. [The joint security and economically informed challenges are discussed and formulated in Section IV.](#) In Section V, the GSTS design is proposed, and SMCS is presented in Section VI. Section VII presents the simulation results showing that our proposed EO-ZT scheme achieves better performance than existing schemes. Finally, the paper is concluded in Section VIII.

2. O-RAN System Model

The O-RAN is in control of multiple mobile network operators (MNOs). The core control component is RIC and can be split into two levels, i.e., the near-real-time (RT) RIC and the non-RT RIC. Near-RT RICs are located at the edge of the network and enable rapid reaction and processing of real-time tasks, e.g., spectrum allocation and cell zooming [3, 22]. Non-RT RIC is located at service management and orchestration (SMO), i.e., the core of the network. It is an RIC for tasks that do not require an immediate response, e.g., cell activation [22].

For a given near-RT RIC A at the edge connected to a non-RT RIC S at SMO, it controls a set of various MNOs' cell sites, $\mathcal{B} = \{1, 2, \dots, b, \dots, B\}$. A set of subscribers, $\mathcal{C}_b = \{1, 2, \dots, c_b, \dots, C_b\}$, connected to the cell site b . In cell site b , there is N_b number of the spectrum resource blocks that can be allocated to C_b subscribers. Moreover, the time-sharing technique is considered in spectrum resource blocks [28], [29].

In this paper, we model the subscriber association strategy based on previous cell zooming strategies, i.e., [25] and [26]. We have the access condition before cell zooming as:

$$p'_{c_b} + \varrho > \delta_{c_b}, \quad (1)$$

where δ_{c_b} is the subscriber c_b 's satisfactory accessible threshold, $\varrho > 0$ is the deviation value and p'_{c_b} is the subscriber c_b 's receiving power unit in Watt (W). After cell zooming, we have the receiving power of subscriber c_b as:

$$p_{c_b}^u x_{c_b} = p'_{c_b} + \varrho = p_b^u x_{c_b} \left(\frac{d_{c_b}}{Z_b}\right)^{-\alpha_b}, \quad (2)$$

where d_{c_b} is the distance between cell site b unit in meter (m) and subscriber c_b , and α_b denotes the path loss factor of cell site b . Further, $p_{c_b}^u$ is the subscriber c_b ' received power per unit spectrum, $x_{c_b} > 0$ is the allocated spectrum resources number for subscriber c_b and p_b^u is the transmission power of cell site b per unit spectrum. Moreover, Z_b is the cell zooming factor and $Z_b^{min} \leq Z_b \leq Z_b^{max}$, where Z_b^{min} and Z_b^{max} are the minimum zooming value and the maximum zooming value, respectively. The deviation value $\varrho = 0$ in case $Z_b = 1$ (i.e., no zooming). Similarly, $\varrho > 0$ in case $Z_b > 1$ and $\varrho < 0$ in case $Z_b < 1$. In this paper, to guarantee the quality of service (QoS), we assume the Z_b^{min} can ensure full coverage of the O-RAN service range, i.e., satisfying the minimum reference signal receive power (RSRP) for subscribers.

The average area transmission power of cell site b thus can be denoted by

$$\overline{P}_b = \frac{\sum_{C_b} p_b^u x_{c_b}}{A_b}, \quad (3)$$

where A_b is the coverage area of cell site b . It can be expressed as:

$$A_b = \pi(R_b Z_b)^2, \quad (4)$$

where R_b is the cell radius in case $Z_b = 1$.

3. EO-ZT: Framework Design

In this section, we present the design of the EO-ZT framework. We also introduce the novel components in the proposed framework, including DRS-based trust evaluation and adaptive policy components. This is followed by a detailed description of the EO-ZT.

3.1. EO-ZT overview

According to the special publication 800-27 of the U.S. National Institute of Standards and Technology (NIST) [30], there are three core modules of the

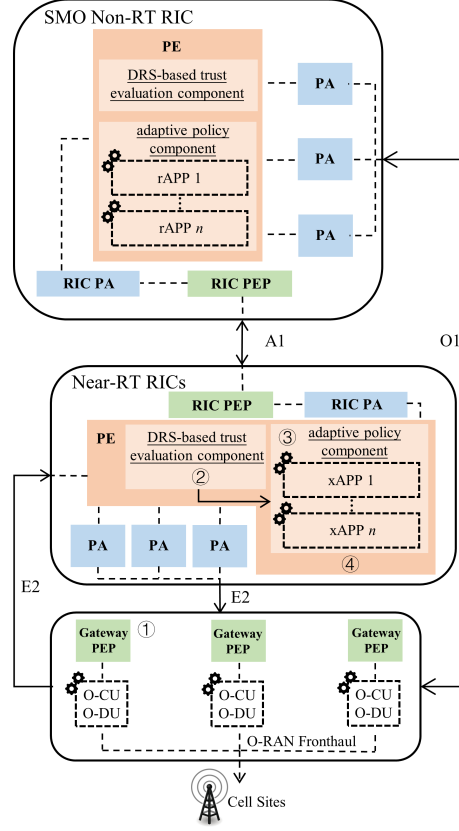


Figure 1: The schematic of the proposed EO-ZT in one authorization loop. The workflow contains the following 4 key steps: ① monitoring; ② risk/trust evaluation; ③ dynamic policy; ④ least privilege.

ZTA as follows: **Policy engine (PE)** is the brain of the ZTA. It performs risk/trust assessment and develops dynamic policies through collected data. Further, it develops decisions (i.e., approved, or denied) and provides the least privileged authorization. **Policy administrator (PA)** works with PE and communicates PE access decisions to the policy enforcement point. It may be incorporated into the PE [28]. **Policy enforcement point (PEP)** enables, monitors, and eventually terminates connections between a subject and an enterprise resource.

The key step of ZTA thus can be simply summarized in four steps: monitoring-risk/trust evaluation-dynamic policy-least privilege. These steps are a periodic cycle every certain time gap. Our proposed EO-ZT framework

(Fig. 1) adheres to the NIST reference and comprises these modules and steps while considering the O-RAN module.

First, authorizations in the spectrum market are divided into three segments: authorization of subscriber spectrum access, authorization of near-RT RIC strategies, and authorization of non-RT RIC strategies. This is due to such real-time decisions on spectrum trading being mainly in near-RT RIC at the edges. Their decision information is provided to SMO/non-RT RIC via the A1 interface for other non-real-time decision-making, e.g., cell activation. Moreover, it serves to prevent anomalies in the distributed center nodes (i.e., near-RT RIC). Adhering to the principle of mutual distrust, the near-RT RIC's decision-making authority needs to be authorized by the non-RT RIC from the core (i.e., SMO). To prevent SMO anomalies, the non-RT RIC's review authority also needs to be authorized by near-RT RICs. The non-RT RIC and near-RT RICs thus need to monitor each other.

Hence, the PEP module is categorized into three components, the subscriber PEP, gateway PEP, and RIC PEP. The subscriber PEP component is a lightweight component deployed on subscribers desiring access to the O-RAN. The gateway PEP is deployed on the O-RAN, connected to the O-CU (O-RAN central unit) and O-DU (O-RAN distributed unit) to execute the decisions given by the PA. RIC PEPs are deployed on near-RT RIC and non-RT RIC, respectively.

In addition, the PE is integrated with the PA and deployed in RICs as shown in Fig. 1. In the near-RT RIC, it is integrated with xAPPs. The monitoring information of subscribers purchasing spectrum services and non-RT RIC are received by the E2 interface and A1 interface, separately. It then makes spectrum allocation and cell zooming strategies, all while administering zero-trust authorizations, at a regular time interval t . This is mainly accomplished by the proposed novel components in PE, i.e., the DRS-based trust evaluation component and adaptive policy component. The decisions and environmental information are provided to the trustworthy SMO.

In the non-RT RIC, PE and PA integrated with rAPPs. It provides non-real-time decisions to trusted near-RT RICs via the A1 interface. Once the near-RT RIC is untrustworthy, it enables skipping the near-RT RIC and contact with the O-CU and O-DU directly via the O1 interface and makes spectrum trading decisions.

The design of EO-ZT is strictly aligned with the O-RAN Alliance specifications. The PE and PA are implemented as xApps and rApps, leveraging standard interfaces for integration. The PEP components communicate via

the O-RAN E2 interface and A1 interface, ensuring interoperability with commercial O-RAN components. This design allows EO-ZT to be deployed and tested within a standard O-RAN software ecosystem without requiring hardware modifications.

3.2. DRS-based trust evaluation component

The proposed DRS-based trust evaluation component is one of the core components of the EO-ZT framework and determines whether or not the authorization is delegated to a subscriber. It integrates the key steps of monitoring and risk/trust evaluation.

For first-time access subscribers, it goes directly to the risk/trust evaluation. The evaluation model is based on the previous ZTA study [32]. The risk/trust score T_{c_b} of subscriber c_b is defined as the probability that subscriber c_b is non-adversarial to the O-RAN, i.e., $\chi_{c_b} = 0$.

$$T_{c_b} = \Pr[\chi_{c_b} = 0]. \quad (5)$$

The determination of χ_{c_b} is based on a number of factors and can be utilized for RICs monitoring and trust evaluation directly, which we do not delve into that aspect here. Nevertheless, since the subscriber has not accessed the spectrum resource, the risk of spectrum utilization is ignored. It may lead to the emergence of moral hazard, i.e. subscribers applying for far more spectrum resources than they need to maximize their utilities.

To deal with this issue, we resort to the DRS-based trust evaluation. The DRS is a concept of circular economy to realize the recycling of resources [33]. A deposit is required at the time of purchase and refunded when the customer returns the used product. The money deposit is deducted if the customer decides not to return the used product. Establishing the appropriate deposit can achieve a 100% refund rate [34]. This is because the number of deposits lost far outweighs the utilities of non-refunds.

We thus introduce the DRS in the EO-ZT. Because moral hazard is where users maximize their utilities without having to bear the costs of incurring the risk [35], the deposit increases the cost of incurring the risk and thus decreases the probability of moral hazard. In EO-ZT, spectrum, as a product purchased, subscribers are required to pay the deposit. After proper utilization, i.e., satisfy minimum spectrum utilization, in time t , the deposit shall be refunded and proceed to the next loop of spectrum allocation and utilization.

Overcharging deposits, however, also dramatically discourage customers from purchasing products [34]. This, in turn, compromises the maximization of the sale utility of the cell site. The same problem arises in the sharing economy. High deposits discourage customers from sharing equipment [36]. Their solution is a deposit-free option for customers with a high enough credit [37].

Inspired by the sharing economy, we consider the trust value a part of the cost. The subscriber first pays a cost accumulation amount to reach the trust value for accessing the O-RAN spectrum. The subscriber suffers a trust cost loss of risk if it is denied future access to any O-RAN service due to trustworthiness. Hence, the trust value and the deposit are combined to ensure the cost loss outweighs the subscriber's utility of actions due to moral hazard. The new deposit of subscriber c_b needs to pay can be expressed as:

$$\varepsilon_{c_b} x_{c_b} = \varepsilon_b x_{c_b} - \iota T_{c_b}, \quad (6)$$

where ε_{c_b} is the unit spectrum deposit, ε_b is the actual unit spectrum deposit, where $\varepsilon_b > \varepsilon_{c_b}$, and ι is the monetary parameter. The deposit ε_{c_b} is not static but is dynamically adjusted in the adaptive policy component. This adjustment is based on real-time monitoring on current trust score fluctuation T_{c_b} .

For non-first-time access subscribers, trust/risk evaluation is still essential. The monitoring also needs to be employed. The presence of moral hazard can be checked using spectrum utilization. The predicted spectrum utilization can be expressed as the average transmission rate available per Hertz. We have

$$l_{c_b} = \frac{r_{c_b}}{x_{c_b}}, \quad (7)$$

where r_{c_b} is the transmission rate. The subscriber c_b is considered trustworthy in case actual spectrum utilization is greater than $l_{c_b} - \phi$, where ϕ is the range of acceptable fluctuation.

In addition, the security investments of the cell site are also monitored at the same time. Authorization, deposit, and investment information is then thrust into the adaptive policy component. The spectrum trading strategies associated with subscribers will be developed.

4. Problem Formulation

In this section, we elaborate on the problems that the integration of EO-ZT in O-RAN poses for secure spectrum strategic decision-making. Since the economic paradigm for both subscribers and sellers (cell sites) in the secure spectrum trading market is altered, we first discuss their economic utilities. We then introduce coupled decision-making problems arising under such a new security and economic paradigm.

4.1. Utility of subscribers

Firstly, we start from the subscribers' side. In wireless networks, subscribers rent some spectrum from a cell site for communications by payment of rental. Basically, the utility u_{c_b} of subscriber c_b channeled by this hire-purchase relationship can be expressed as:

$$u_{c_b}(x_{c_b}, y_b) = M_{c_b} - N_{c_b}, \quad (8)$$

where M_{c_b} is the benefit function of subscriber c_b gained from utilizing spectrum communications and N_{c_b} is the payment function. x_{c_b} is the allocated number of spectrum and $y_b > 0$ is the unit price of a unit spectrum in cell site b 's coverage.

First, based on the investigation in [38], the benefits gained from utilizing spectrum communications exhibit a logarithmic increase as the allocated spectrum number grows. We thus formulate M_{c_b} as:

$$M_{c_b} = \eta \ln(1 + \gamma_{c_b} x_{c_b}), \quad (9)$$

where $\eta > 0$ is the monetary parameter and γ_{c_b} is the spectrum requirement factor.

In addition, normally, N_{c_b} can be denoted by the unit price of goods multiplied by the quantity of goods. We have

$$N_{c_b} = y_b x_{c_b}. \quad (10)$$

Nevertheless, the deposit-refund system leads to a reduction in sales because of price perception, subscriber pressure, costs, etc [34]. This is due to the psychological pressure of the deposit given to the subscriber and should be considered in payment. We can regard this deposit pressure as a supply and demand function and formulate it by the linear function [39]. Hence, the N_{c_b} can rewrite as:

$$N_{c_b} = y_b x_{c_b} + \varsigma \varepsilon_{c_b} x_{c_b}, \quad (11)$$

where ς is the unit deposit-related monetary weight parameter.

Therefore, the utility of the subscriber c_b can be expressed as:

$$u_{c_b} = \eta \ln(1 + \gamma_{c_b} x_{c_b}) - y_b x_{c_b} - \varsigma \varepsilon_{c_b} x_{c_b}, \quad (12)$$

Therefore, in order to maximize the economic utility, the subscriber strategy selection problem can be denoted by

P1:

$$\max_{x_{c_b}, y_b} u_{c_b}, \quad (13a)$$

$$s.t. \quad p_{c_b}^u x_{c_b} > \delta_{c_b}. \quad (13b)$$

The constraint (13b) is to ensure the number of allocated spectrums meets the access condition presented in eq. (1).

The constraint in **P1** ensures the quality of service (QoS) by guaranteeing a minimum received power, which is a precursor for achieving low latency. Furthermore, the ZTA energy cost E_Z incorporated into the cell site's cost model (Eq. (16)) inherently accounts for the overhead of continuous authentication processes. A higher authentication frequency would be reflected by an increase in E_Z , thereby impacting the economic decisions of the cell site.

4.2. Utility of cell site

On the other hand, as mentioned earlier, the cell sites would want to achieve the maximization of economic utility for renting the spectrum. Without loss of generality, we define the utility U_b of the cell site b is the revenue R_b from the sale of spectrum minus costs Q_b , considering zooming factor Z_b , the number of subscribers C_b , and security investment ξ_b . We have

$$U_b(\mathbf{x}_b, y_b, \xi_b, C_b, Z_b) = R_b - Q_b - \xi_b, \quad (14)$$

where $\mathbf{x}_b = \{x_1, \dots, x_{c_b}, \dots, x_{C_b}\}$. We have $\sum \mathbf{x}_b \leq X_b$, where X_b is the total amount of assignable spectrum. The total revenue R_b thus can be denoted by

$$R_b = \begin{cases} (\frac{\xi_b}{\xi_R} y_b) \sum \mathbf{x}_b, & \text{when } \xi_b < \xi_R \\ y_b \sum \mathbf{x}_b, & \text{when } \xi_b \geq \xi_R \end{cases}. \quad (15)$$

where ξ_R is the security investment of the RIC. The security investment is dynamic, such as energy cost for collaborative intrusion detection during assessing time gap t .

Furthermore, spectrum rental costs Q_b are modeled as energy costs. As renting produces zero-trust execution energy as well as transmission energy, we have

$$Q_b = \rho(E_Z C_b + \overline{P}_b t), \quad (16)$$

where ρ is the monetary parameter, E_Z is the zero-trust performing energy cost per user and $\overline{P}_b t$ is transmission energy cost.

Therefore, the utility of the cell site can be expressed as:

$$U_b = \begin{cases} (\frac{\xi_b}{\xi_R} y_b) \sum \mathbf{x}_b - \rho(E_Z C_b + \overline{P}_b t) - \xi_b, & \text{when } \xi_b < \xi_R \\ y_b \sum \mathbf{x}_b - \rho(E_Z C_b + \overline{P}_b t) - \xi_b, & \text{when } \xi_b \geq \xi_R \end{cases}, \quad (17)$$

The cell site strategy decision (i.e., utility maximization) problem can be expressed as:

P2:

$$\max_{\mathbf{x}_b, y_b, \xi_b, C_b, Z_b} U_b, \quad (18a)$$

$$s.t. \quad \mathbf{x}_b \leq X_b, \quad (18b)$$

$$Z_b^{min} \leq Z_b \leq Z_b^{max}, \quad (18c)$$

The constraint (18b) is to ensure that the amount of allocated spectrum is within the range of availability and the constraint (18c) limits the range of cell zooming.

4.3. Coupled decision-making problems

Confronted with two such multivariable complicated problems, it can be observed that there are two types of variables in **P2**. Variables x_{c_b} and y_b are determined by the interaction between the subscriber c_b and the cell site b . Variables ξ_b , C_b and Z_b are determined by the cell site b , but affect the same strategies of other cell sites and the RIC. The two utility maximization problems are coupled decision-making problems and are not isolated. We thus still consider interactions and economic relations between subscribers, cell sites and the RIC from a microeconomics perspective. The **P1** and **P2** are further decomposed into a subscriber-cell coupled decision-making problem and a cell-cell coupled decision-making problem. These two coupled decision-making problems are also interrelated. We will provide the details in the following sections.

The formulated framework provides inherent economic resilience against spoofing and resource-based Denial-of-Service (DoS) attacks. The DRS mechanism increases the economic cost for malicious subscribers attempting to spoof or resource abuse. Simultaneously, the Peltzman Effect mitigation via ξ_b incentivizes continuous security investments, strengthening the system's overall defensive posture against evolving threats.

5. EO-ZT: GTSP

Let us first consider the economic relation of subscribers and the cell sites, i.e., consider variables x_{c_b} and y_b and assume all ξ , C and Z of all cell sites are determined. The objective of subscriber c_b is to maximize its utilities by determining the number of spectrum applications x_{c_b} given the spectrum's unit price y_b^* . Meanwhile, cell site b aims to maximize revenue by developing the unit spectrum price y_b for a given number of spectrum applications $\mathbf{x}_b^*$. It can be formulated as a one-to-many game, i.e., Stackelberg game, based on economic studies. This game problem can be formulated as:

P3:

$$u_{c_b}(x_{c_b}^*, y_b^*) \geq u_{c_b}(x_{c_b}, y_b^*), \quad (19)$$

$$U_b(\mathbf{x}_b^*, y_b^*) \geq U_b(\mathbf{x}_b^*, y_b), \quad (20)$$

NE Existence:

It can be observed that the strategy set of a subscriber is convex and compact due to the time-sharing technique existence. According to Debreu-Glicksberg-Fan theorem [40], the pure strategy NE exists if the utility of the subscriber is also continuous and concave. We have the second-order partial derivative of u_{c_b} as:

$$\frac{\partial^2 u_{c_b}}{\partial x_{c_b}^2} = -\frac{\gamma_{c_b}^2 \eta}{(1 + \gamma_{c_b} x_{c_b})^2}. \quad (21)$$

As $\eta > 0$, $\frac{\partial^2 u_{c_b}}{\partial x_{c_b}^2} < 0$. A pure strategy NE exists.

To find the NE, based on game-theoretic studies, backward induction should be employed. The optimal strategies for the followers, i.e., subscribers, are achieved first, and then the leader, i.e., cell site, makes its optimal decision based on the subscribers' strategies. Therefore, we have the first-order partial derivative of u_{c_b} as:

$$\frac{\partial u_{c_b}}{\partial x_{c_b}} = \frac{\eta \gamma_{c_b}}{1 + \gamma_{c_b} x_{c_b}} - y_b - \varsigma \varepsilon_{c_b}. \quad (22)$$

Algorithm 1 GSTS

- 1: Initialization: set the search step s , initial iteration epoch $i=1$, $U_b^0 = 0$ and $y_b^0 = 0$.
 - 2: ξ_b , C_b and Z_b of cell site b .
 - 3: **while** $y_b^i \leq y_{b,max}$
 - 4: $y_b^i = y_b^{i-1} + s$
 - 5: **for** each subscriber c_b
 - 6: $x_{c_b}^i \leftarrow \text{eq. (23)}$
 - 7: **end for**
 - 8: $U_b^i \leftarrow \text{eq. (26)}$
 - 9: **if** $U_b^i \leq U_b^{i-1}$
 - 10: **if** $\sum \mathbf{x}_b^{i-1} \leq X_b$
 - 11: **end while**
 - 12: $y_b^* = y_b^{i-1}$ and $x_{c_b}^* = x_{c_b}^{i-1}$
-

By means of $\frac{\partial u_{c_b}}{\partial x_{c_b}} = 0$, the best response $x_{c_b}^*$ of subscriber c_b is

$$x_{c_b}^* = \frac{\eta}{\varsigma \varepsilon_{c_b} + y_b} - \frac{1}{\gamma_{c_b}}. \quad (23)$$

Considering the constraint (13b), i.e., $p_b^u x_{c_b}^* (\frac{d_{c_b}}{Z_b})^{-\alpha_b} > \delta_{c_b}$, we have

$$p_b^u (\frac{d_{c_b}}{Z_b})^{-\alpha_b} (\frac{\eta}{\varsigma \varepsilon_{c_b} + y_b} - \frac{1}{\gamma_{c_b}}) > \delta_{c_b}, \quad (24)$$

and thus,

$$0 < y_b < \eta \frac{\gamma_{c_b} p_b^u (\frac{d_{c_b}}{Z_b})^{-\alpha_b}}{\delta \gamma_{c_b} + p_b^u (\frac{d_{c_b}}{Z_b})^{-\alpha_b}} - \varsigma \varepsilon_{c_b}, \quad \forall c_b. \quad (25)$$

For simplicity, we set $y_{b,max} = \min\{\eta \frac{\gamma_{c_b} p_b^u (\frac{d_{c_b}}{Z_b})^{-\alpha_b}}{\delta \gamma_{c_b} + p_b^u (\frac{d_{c_b}}{Z_b})^{-\alpha_b}} - \varsigma \varepsilon_{c_b} | c_b \in \mathcal{C}_b\}$. We then can substitute $x_{c_b}^*$ in U_b and rewrite U_b as given in eq. (26) at the top of the page.

The optimal y_b and the corresponding $x_{c_b}^*$ are the NE point. However, it is mathematically intractable to directly find the optimal y_b , i.e., closed

$$U_b(y_b) = \begin{cases} (\frac{\xi_b}{\xi_R} y_b) \sum_{C_b} (\frac{\eta}{\varsigma \varepsilon_{c_b} + y_b} - \frac{1}{\gamma_{c_b}}) - \rho(E_Z C_b + \frac{\sum_{C_b} p_b^u}{A_b} (\frac{\eta}{\varsigma \varepsilon_{c_b} + y_b} - \frac{1}{\gamma_{c_b}}) t) - \xi_b, & \text{when } \xi_b < \xi_R \\ y_b \sum_{C_b} (\frac{\eta}{\varsigma \varepsilon_{c_b} + y_b} - \frac{1}{\gamma_{c_b}}) - \rho(E_Z C_b + \frac{\sum_{C_b} p_b^u}{A_b} (\frac{\eta}{\varsigma \varepsilon_{c_b} + y_b} - \frac{1}{\gamma_{c_b}}) t) - \xi_b, & \text{when } \xi_b \geq \xi_R \end{cases}, \quad (26)$$

form solution for multiple subscribers. Nevertheless, since y_b is bound, the optimal y_b can be obtained by performing a one-dimension grid search over y_b .

In addition, if a suitable y is not searched within the bound considering constraint (18b), the overloaded cell zooming (i.e., traffic steering) or cell barring needs to be performed. The details will be discussed in the next section.

The computational complexity of the proposed GSTS is primarily determined by the one-dimensional grid search over the price y_b . Let $\Delta = (y_{b,\max} - 0)/s$ denote the number of search steps. It is linear with respect to the search range and inversely proportional to the step size s . For each candidate price y_b^i , the algorithm calculates the best response $x_{c_b}^*$ for all C_b subscribers in the cell, an operation of complexity $\mathcal{O}(C_b)$. Therefore, the overall complexity of GSTS is $\mathcal{O}(\Delta \cdot C_b)$. This complexity is linear in the number of subscribers and the number of price steps, confirming the algorithm's low computational overhead and suitability for near-RT RIC deployment where timely decision-making is critical.

6. EO-ZT: DSII

After the subscriber-cell scheme, the retention sub-problem can be written as:

P4:

$$\max_{\xi_b, C_b, Z_b} U_b, \quad (27a)$$

$$s.t. \quad \mathbf{x}_b \leq X_b, \quad (27b)$$

$$Z_b^{\min} \leq Z_b \leq Z_b^{\max}, \quad (27c)$$

Here, C_b is decided by Z_b and Z_b is discrete, depending on the distance of the furthest served subscriber. **P4** is essentially a two-variable problem, i.e., how to find the maximum U_b via adjusting ξ_b and Z_b . Nevertheless, the

expansion of Z_b robbed customers (subscribers) who originally belonged to other cell services. This enables a competitive market relationship between the cells.

The WTA is a social phenomenon in market competition. It refers to the fact that the winner of a competitive market gains the lion's share of the market by serving slightly better than its competitors [41]. Because the person or business at the top of their field is the winner in their market sector.

We argue that the WTA is consistent with the trend of competitive markets between cells. The reason is that security investments concern the cell cost of service subscribers, and a more secure cell has a lower probability of failure, which reduces the probability of O-RAN and subscribers' risk. In addition, security should be the most important thing to be considered before providing services. Subscribers' bias in favor of accessing the most secure cell site.

We thus convert **P4** as a k -WTA (k winners) problem. In each competitive quotation, the parameter Z_b is the range of markets occupied by cell site b , and has the corresponding subscriber number C_b . We have $\mathbf{Z}_b$ as the zooming strategy set according to different subscriber locations. If no cell in a winner's neighborhood can provide a more secure investment, this winner will implement the zooming strategy. For fairness, we formulated a fair linear relation of the zooming strategy with the security investment strategy for all cell sites controlled by the same RIC, i.e., $\xi_b \propto \psi \mathbf{Z}_b$, where ψ is the weight parameter. Mathematically, this k -WTA problem in each competitive quotation can be formulated as:

$$W_b = f(\xi_b) = \begin{cases} 1, & \text{if } \xi_b \text{ is one of the largest elements of } \boldsymbol{\xi} \\ 0, & \text{otherwise} \end{cases} \quad (28)$$

where $\boldsymbol{\xi} = \{\xi_1, \dots, \xi_b, \dots, \xi_B\}$. The determination of ξ_b is based on maximizing U_b , i.e., searching the optimal Z_b .

After one competition, we have $\mathbf{W} = \{W_1, \dots, W_b, \dots, W_B\}$. Based on [42], the k -WTA problem can be further formulated as a QP problem. We have

P5:

$$\min \quad v \mathbf{W}^T \mathbf{W} - \boldsymbol{\xi}^T \mathbf{W}, \quad (29a)$$

$$s.t. \quad \mathbf{e}^T \mathbf{W} = k. \quad (29b)$$

Algorithm 2 SMCS

```
1: Initialization: number of subscribers, iteration step  $i = 0$  and  $k$ .
2:  $\mathbf{Z}_b \leftarrow$  number of subscribers potentially served
3:  $\boldsymbol{\xi}_b \leftarrow \psi \mathbf{Z}_b$ 
4: while  $i < B$ 
5:    $\mathbf{W} \leftarrow$  eq.(31)
6:    $o = k -$  conflicting cell
7:    $i = i + o$ 
8:    $k = \lceil \frac{B-i}{2} \rceil$ 
9: end while
10: output  $\boldsymbol{\xi}_b$ 
```

where v is a positive constant, $e = [1, 1, \dots, 1]$ and $\cdot^T$ means transpose. By utilizing λ as a Lagrangian multiplier, the Karush-Kuhn-Tucker (KKT) condition of **P5** can be denoted by

$$\begin{cases} 2v\mathbf{W} - \boldsymbol{\xi} + \lambda e = 0 \\ e^T \mathbf{W} - k = 0 \end{cases}. \quad (30)$$

In the form of the matrix, we can rewrite it as:

$$\begin{bmatrix} 2v & e \\ e^T & 0 \end{bmatrix} \begin{bmatrix} \mathbf{W} \\ \lambda \end{bmatrix} = \begin{bmatrix} \boldsymbol{\xi} \\ k \end{bmatrix}. \quad (31)$$

We thus can get $\mathbf{W}$ via $\begin{bmatrix} \mathbf{W} \\ \lambda \end{bmatrix} = \begin{bmatrix} 2v & e \\ e^T & 0 \end{bmatrix}^{-1} \begin{bmatrix} \boldsymbol{\xi} \\ k \end{bmatrix}$.

The solution involves inverting a matrix of size $(B+1) \times (B+1)$, where B is the total number of cell sites involved in the competition. The complexity of this matrix inversion is generally $\mathcal{O}(B^3)$. Given that the number of cell sites B under a single near-RT RIC's control is typically manageable and does not scale to the level of subscribers, the $\mathcal{O}(B^3)$ complexity is considered tractable for non-real-time or moderate-frequency near-real-time operations.

Therefore, the adaptive policy component can output security and trading policies in this new security and economic paradigm. In summary, all devices' policies are intended to maximize economic utility while ensuring security. The economic utilities of subscribers and cell sites are formulated

considering the moral hazard and the Peltzman Effect. The utility maximization problems are then constructed as two interrelated coupled problems and solved by the GDSP and DSII schemes jointly.

7. Simulation Results

In this section, we present the simulation results to evaluate the performance of our proposed EO-ZT in jointly addressing moral hazard, Peltzman Effect, and spectrum trading-related challenges. Since no algorithm is specific for joint considered security spectrum trading scenario, we primarily compare it with available potential schemes for O-RAN spectrum trading, i.e., the general spectrum trading (spectrum allocation) approach for solving the subscriber-cell decision-making problem and the general spectrum market competition approach (cell zooming) for solving the cell-cell decision-making problem, drawing on the core ideas of spectrum allocation [23] and cell zooming [25, 27] approaches, respectively.

Based on cellular settings from these approaches, the simulation regards an O-RAN system-controlled 2-tier cellular network, i.e., 7 cells. For considering only the cell zooming usefulness and without the confounding effects of highly heterogeneous user behavior and dynamic power control, we assume all cell sites and subscribers have the same state. The transmission power of the cell site is 40 W, the cell site radius and its minimum radius are 500 m, and the number of resource blocks is 138 [22, 25]. In addition, we assume the $\varsigma = \varepsilon = 1$, ZTA energy cost for each subscriber is set to 0.1 J. This value is estimated by considering the additional computational overhead of continuous authentication and encryption on baseband processing units, which is analogous to the energy cost of running additional cryptographic protocols. The maximum zooming ratio of 1.3 is chosen to reflect power limitations on dynamic cell range expansion without causing significant interference. The initial ratio of security investment $\frac{\xi_b}{\xi_r} = 0.8$ is set to model a scenario where cell sites are under-investing relative to the RIC. Subscribers are randomly and uniformly distributed within the maximum service range of cell sites with $\eta = 500$ and $\gamma = 10$. Furthermore, the simulation results are averaged over 50 repetitive simulations. The details of the simulation parameters are shown in Table 1.

Fig. 2 depicts the effectiveness of various methodologies in resisting the Peltzman effect. At low subscriber numbers, “only the cell zooming” method drives more security investments at the cell site. This is due to the cell zoom-

Table 1: Simulation Parameters

Parameter	Value
Number of Cell Sites (B)	7
Cell Radius	500 m
Transmission Power (p_b^u)	40 W
Number of Resource Blocks (N_b)	138
ZTA Energy Cost per User (E_Z)	0.1 J
Maximum Zooming Ratio (Z_b^{max})	1.3
Security Investment Ratio (ξ_b/ξ_R)	0.8

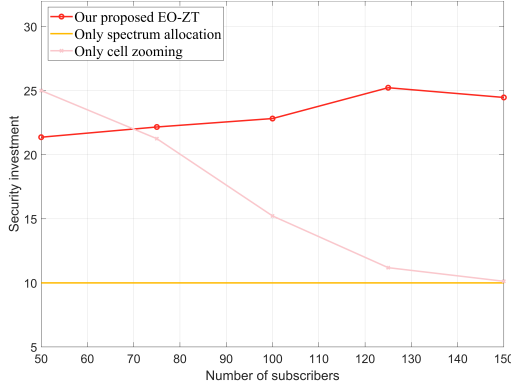


Figure 2: Security investment versus number of subscribers.

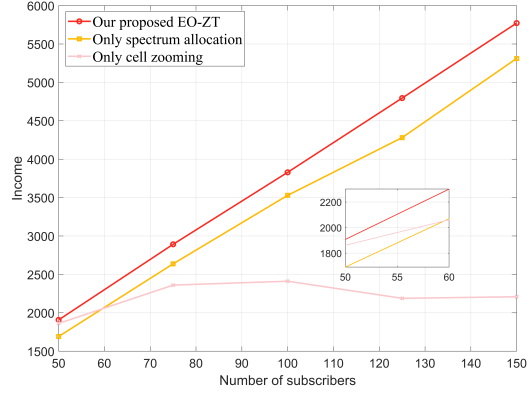


Figure 3: Cell site income versus number of subscribers.

ing requiring fixing the amount of spectrum for the subscribers, although it is not their optimal amount of spectrum to be purchased. In case of a low number of subscribers, the cell site can get a stable amount of spectrum to be sold at a high price. It is consistent with the revenue improvement of the cell site to carry out the service range expansion. Nevertheless, its investment gradually declines as expansion is no longer in the interest of the base station with subscribers growing, while our scheme achieves the highest volume of security investments. Because our proposed scheme always maximizes the utilities for both the subscribers and the cell sites fairly. The Peltzmann effect can thus be mitigated.

In Fig. 3, the income of cell sites versus the number of subscribers is shown. It validates the previous statement that our scheme makes economic decisions in the context of maximizing benefits, and although higher costs due

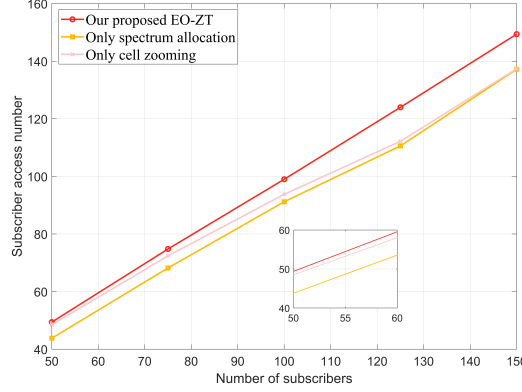


Figure 4: Subscriber access number versus number of subscribers.

to security investments (Fig. 2), our approach always achieves the highest income regardless of the number of subscribers. “Only spectrum allocation” also aims to maximize income, but by not performing cell zooming, a portion of subscribers are not served, resulting in a lack of income.

Fig. 4 illustrates the acceptance number of subscribers as a function of the number of subscribers for various approaches. EO-ZT also delivers outstanding performance. “Only spectrum allocation” enables access only to subscribers within the range at most, since it is unable to perform cell zooming. It has a minimal number of subscriber accesses. “Only cell zooming” is due to the increase in the number of subscribers, which makes the total income from performing cell zooming decrease. Moreover, the amount of spectrum of cell sites with this approach is also facing the issue of shortage. The ratio of access subscribers thus gradually drops. EO-ZT enables the largest number of subscribers to access the network in different scenarios of total subscribers. It increases the throughput of the O-RAN.

To verify the effectiveness of the scheme in dynamic environments, we neglect “only cell zooming” and adjust $\eta = 600 \pm 100$ and $\gamma = 20 \pm 10$. The performances of our proposed scheme and “only spectrum allocation” are illustrated in Fig. 5. It can be seen that as the number of subscribers grows, both in terms of total O-RAN income and the number of subscribers served, the proposed scheme consistently maintains superiority over “only spectrum allocation”. It demonstrates the adaptability of EO-ZT in various environments as well as its ability to optimize.

Fig. 6 investigates the effect of moral hazard measures as well as RIC

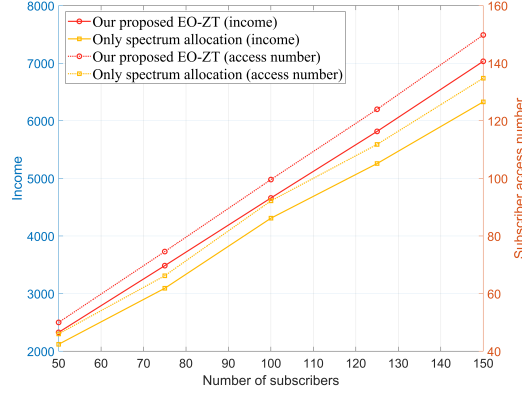


Figure 5: Comparison of EO-ZT with “only spectrum allocation” in dynamic scenario.

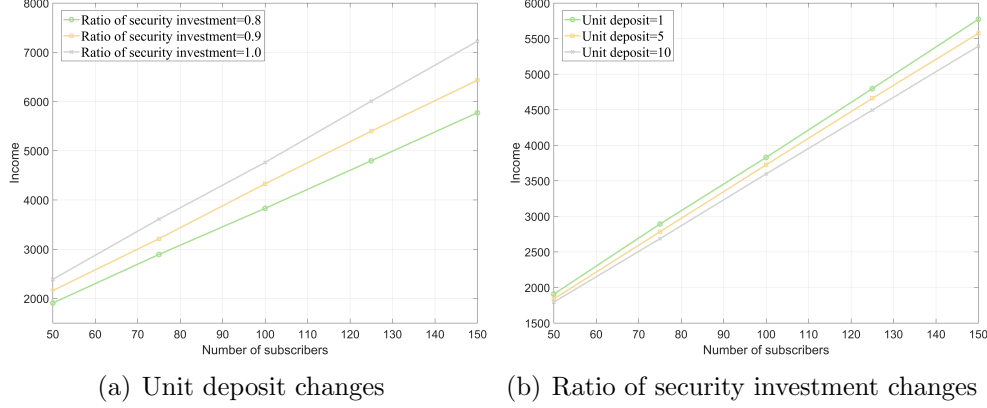


Figure 6: Influence of parameter changes on income.

security investment incentives on O-RAN income. In Fig. 6(a), it can be seen that the total income of O-RAN decreases as the number of deposits required to be submitted by subscribers increases. This is because subscribers reduce the amount of spectrum purchased. The increase in deposits reduces the purchase desire. In Fig. 6(b), it can be observed that cell sites with a higher ratio of security investment relative to RIC earn more income, which incentivizes RIC and cell sites to engage in mutual improvement of security investment.

8. Conclusions

In this paper, we explored the joint security and economically informed challenges associated with ZTA in O-RAN and proposed a novel framework called EO-ZT. Leveraging economy concepts such as the deposit-refund system and sharing economy, a DRS-based trust evaluation component was proposed to suppress moral hazard. Technical challenges within EO-ZT, including spectrum allocation, and cell zooming, were scrutinized. The economically informed challenge, the Peltzman Effect, was also included and delved into. To address these challenges, a GSTS and an SMCS were presented to enable subscribers and base stations to make optimal trading decisions in the spectrum market with security consciousness. Simulation results demonstrated the superiority of our proposed EO-ZT frameworks over the related approaches.

This work is limited by its simulated environment and simplified assumptions, and the framework has not been validated in a real O-RAN testbed. Future work will focus on hardware-in-the-loop validation and exploring the integration of machine learning with EO-ZT for enhanced adaptability in real-world deployments.

9. Acknowledgement

This work was supported in part by the Open Networks Ecosystem Competition Western Open Radio Access Network (O-RAN) Deployment (ONEWORD) Project.

References

- [1] V. -D. Nguyen et al., “Network-Aided Intelligent Traffic Steering in 6G O-RAN: A Multi-Layer Optimization Framework,” *IEEE Journal on Selected Areas in Communications*, vol. 42, no. 2, pp. 389-405, Feb. 2024.
- [2] J. Zhang et al., “Intent-Driven Closed-Loop Control and Management Framework for 6G Open RAN,” *IEEE Internet of Things Journal*, vol. 11, no. 4, pp. 6314-6327, 15 Feb.15, 2024.
- [3] M. Dryjański, “O-RAN Use Cases: Traffic Steering,” *RIMEDO Labs*, May 05, 2021. <https://rimedolabs.com/blog/o-ran-use-cases-traffic-steering/> (accessed Mar. 04, 2024).

- [4] K. Ramezanpour and J. Jagannath, “Intelligent zero trust architecture for 5G/6G networks: Principles, challenges, and the role of machine learning in the context of O-RAN,” *Computer Networks*, p. 109358, Sep. 2022.
- [5] J. Cao et al., “A Survey on Security Aspects for 3GPP 5G Networks,” *IEEE Communications Surveys & Tutorials*, vol. 22, no. 1, pp. 170-195, First quarter 2020.
- [6] S. Rose et al., Zero trust architecture, Gaithersburg, MD, USA, 2020.
- [7] S. Teerakanok, T. Uehara, and A. Inomata, “Migrating to Zero Trust Architecture: Reviews and Challenges,” *Security and Communication Networks*, vol. 2021, pp. 1–10, May 2021.
- [8] “The O-RAN ALLIANCE Security Work Group Continues Defining O-RAN Security Solutions,” *www.o-ran.org*. <https://www.o-ran.org/blog/the-o-ran-alliance-security-work-group-continues-defining-o-ran-security-solutions> (accessed Mar. 06, 2024).
- [9] S. Walker, “Economics and the cyber challenge,” Information Security Technical Report, vol. 17, no. 1–2, pp. 9–18, Feb. 2012.
- [10] R. Anderson, “Why information security is hard - an economic perspective,” *Seventeenth Annual Computer Security Applications Conference*, New Orleans, LA, USA, 2001, pp. 358-365.
- [11] K. Arrow, “Uncertainty and the Welfare Economics of Medical Care”, *The American Economic Review*. American Economic Association, vol. 53, no. 5, pp. 941-73, 1963.
- [12] S. Peltzman, “The Effects of Automobile Safety Regulation”, *Journal of Political Economy*, vol. 83, no. 4, pp. 677-725, 1975.
- [13] P. M. Datta, T. Acton and N. Carroll, “Penny Wise, Pound Foolish: An Experimental Design of Technology Trust Amongst Organizational Users,” 2022 Cyber Research Conference - Ireland (Cyber-RCI), Galway, Ireland, 2022, pp. 1-4.
- [14] G. Zheng, Q. Ni, K. Navaie and H. Pervaiz, “Semantic Communication in Satellite-borne Edge Cloud Network for Computation Offloading,” *IEEE Journal on Selected Areas in Communications*.

- [15] Z. Song, Y. Hao, Y. Liu and X. Sun, "Energy-Efficient Multiaccess Edge Computing for Terrestrial-Satellite Internet of Things," *IEEE Internet of Things Journal*, vol. 8, no. 18, pp. 14202-14218, 15 Sept.15, 2021.
- [16] G. Zheng et al., "Mobility-Aware Split-Federated With Transfer Learning for Vehicular Semantic Communication Networks," *IEEE Internet of Things Journal*.
- [17] H. Jiang, H. Chang, S. Mukherjee and J. Van der Merwe, "OZTrust: An O-RAN Zero-Trust Security System," 2023 IEEE Conference on Network Function Virtualization and Software Defined Networks (NFV-SDN), Dresden, Germany, 2023, pp. 129-134.
- [18] A. S. Abdalla, J. Moore, N. Adhikari, and V. Marojevic, "ZTRAN: Prototyping Zero Trust Security xApps for Open Radio Access Network Deployments," *arXiv.org*, Mar. 06, 2024.
- [19] H. Moudoud, W. Hamhoum and S. Cherkaoui, "Strengthening Open Radio Access Networks: Advancing Safeguards Through ZTA and Deep Learning," *GLOBECOM 2023 - 2023 IEEE Global Communications Conference*, Kuala Lumpur, Malaysia, 2023, pp. 80-85.
- [20] R. Zhang, Q. Zhu and Y. Hayel, "A Bi-Level Game Approach to Attack-Aware Cyber Insurance of Computer Networks," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 3, pp. 779-794, March 2017.
- [21] R. Zhang and Q. Zhu, "FlipIn: A Game-Theoretic Cyber Insurance Framework for Incentive-Compatible Cyber Risk Management of Internet of Things," *IEEE Transactions on Information Forensics and Security*, vol. 15, pp. 2026-2041, 2020.
- [22] L. Bonati, M. Polese, S. D'Oro, S. Basagni and T. Melodia, "NeutRAN: An Open RAN Neutral Host Architecture for Zero-Touch RAN and Spectrum Sharing," *IEEE Transactions on Mobile Computing*, vol. 23, no. 5, pp. 5786-5798, May 2024.
- [23] Y. Cui, X. Yang, P. He, D. Wu and R. Wang, "O-RAN Slicing for Multi-Service Resource Allocation in Vehicular Networks," *IEEE Transactions on Vehicular Technology*.

- [24] Ö. T. Demir, M. Masoudi, E. Björnson and C. Cavdar, “Cell-Free Massive MIMO in O-RAN: Energy-Aware Joint Orchestration of Cloud, Fronthaul, and Radio Resources,” *IEEE Journal on Selected Areas in Communications*, vol. 42, no. 2, pp. 356-372, Feb. 2024.
- [25] X. Xu, C. Yuan, W. Chen, X. Tao and Y. Sun, “Adaptive Cell Zooming and Sleeping for Green Heterogeneous Ultradense Networks,” *IEEE Transactions on Vehicular Technology*, vol. 67, no. 2, pp. 1612-1621, Feb. 2018.
- [26] Z. Liu, X. Chen, Y. Yang, K. Y. Chan, and Y. Yuan, “Joint cell zooming and sleeping strategy in ultra dense heterogeneous networks,” *Computer Networks*, vol. 220, p. 109482, Jan. 2023.
- [27] F. Wang, F. Yang, J. Song, Z. Han, “Cell Zooming for Hybrid VLC-RF Cellular Networks With High Energy Efficiency”, *IEEE Wireless Communications Letters*, vol.12, no.5, pp.789-793, 2023.
- [28] C. Y. Wong, R. S. Cheng, K. B. Letaief and R. D. Murch, “Multiuser OFDM with Adaptive Subcarrier Bit and Power Allocation”, *IEEE J. Sel. Areas Commun.*, vol. 17, no. 10, pp. 1747-1758, Oct. 1999.
- [29] Q. Ni and C. C. Zarakovitis, “Nash Bargaining Game Theoretic Scheduling for Joint Channel and Power Allocation in Cognitive Radio Systems,” *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 1, pp. 70-81, January 2012.
- [30] S. Rose et al., Zero Trust Architecture (*NIST Special Publication 800-207*), 2020, [online] Available: <https://doi.org/10.6028/NIST.SP.800-207>.
- [31] N. F. Syed, S. W. Shah, A. Shaghaghi, A. Anwar, Z. Baig and R. Doss, “Zero Trust Architecture (ZTA): A Comprehensive Survey,” *IEEE Access*, vol. 10, pp. 57143-57179, 2022.
- [32] Y. Ge and Q. Zhu, “GAZETA: GAME-Theoretic ZERo-Trust Authentication for Defense Against Lateral Movement in 5G IoT Networks,” *IEEE Transactions on Information Forensics and Security*, vol. 19, pp. 540-554, 2024.

- [33] S. Millette, E. Williams, and C. E. Hull, “Materials Flow Analysis in Support of Circular Economy Development: Plastics in Trinidad and Tobago,” *SSRN Electronic Journal*, 2019.
- [34] G. Zhou et al., “A systematic review of the deposit-refund system for beverage packaging: Operating mode, key parameter and development trend,” *Journal of Cleaner Production*, vol. 251, p. 119660, Apr. 2020.
- [35] David Leo Weimer and A. R. Vining, *Policy analysis : concepts and practice*. New York: Routledge, 2017.
- [36] S. Si, H. Chen, W. Liu and Y. Yan, “Disruptive innovation business model and sharing economy: the bike-sharing cases in china”, *Management Decision*, 2020.
- [37] S. Hu et al., “Turbo: Fraud Detection in Deposit-free Leasing Service via Real-Time Behavior Network Mining,” *2021 IEEE 37th International Conference on Data Engineering (ICDE)*, Chania, Greece, 2021, pp. 2583-2594.
- [38] Z. Jiang, Y. Ge and Y. Li, “Max-utility wireless resource management for best-effort traffic,” *IEEE Transactions on Wireless Communications*, vol. 4, no. 1, pp. 100-111, Jan. 2005.
- [39] Q. Feng and J. G. Shanthikumar, “Supply and Demand Functions in Inventory Models,” *Operations Research*, vol. 66, no. 1, pp. 77–91, Feb. 2018.
- [40] D. Fudenberg and J. Tirole, *Game theory*. Cambridge, Mass.: Mit Press, 1991.
- [41] R. H. Frank and P. J. Cook, *The winner-take-all society: why the few at the top get so much more than the rest of us*. London], Virgin Books, 2010.
- [42] S. Liu and J. Wang, “A Simplified Dual Neural Network for Quadratic Programming With Its KWTa Application,” *IEEE Transactions on Neural Networks*, vol. 17, no. 6, pp. 1500-1510, Nov. 2006.