Enhancing E-Commerce Security through Metaheuristic Optimization: A Migrating Birds Optimization Approach to Cyber Attack Mitigation

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Abstract. E-commerce platforms are becoming increasingly vulnerable to sophisticated cyber threats, such as distributed denial of service (DDoS) attacks, phishing schemes and SQL injection attempts. Traditional cybersecurity frameworks are known as effective in static environments however they often lack the adaptability required to respond to dynamic and evolving attack vectors. This study introduces a novel application of the Migrating Birds Optimization (MBO) algorithm — a nature-inspired metaheuristic — to dynamically optimize security strategies for e-commerce systems. By modelling the adaptive and cooperative behavior of migratory birds, the proposed model allows for the continuous adjustment of intrusion prevention policies in response to changing threat landscapes. Comprehensive simulation studies demonstrate that the MBO-based approach significantly outperforms conventional static approaches in discovering improved security settings, resulting in enhanced detection accuracy and improved mitigation efficiency. The results specify the potential of MBO as an extensible and robust framework for improving cyber-security for commercial cyberspaces.

Keywords: E-commerce security, Cyber attacks, Metaheuristic optimization, Migrating Birds Optimization, Intrusion prevention.

1 Introduction

E-commerce systems are important infrastructures that have become attractive targets for cybercriminals. The increasing number of digital transactions has brought along cyber threats such as Distributed Denial of Service (DDoS), phishing, SQL injection, and botnet attacks [1]. Traditional security solutions like firewalls and antivirus software are static and often ineffective to respond to evolving attack strategies [2]. Researchers have proposed adaptive security systems that use artificial intelligence (AI) and optimization algorithms to address these challenges. Among these, metaheuristic optimization provides a problem-independent, flexible solution to dynamically reconfigure defenses in real time [3-4].

Research Paper
DOI: https://doi.org/10.46793/BISEC25.066U
Part of ISBN: 978-86-89755-40-4

2 Metaheuristic Optimization and MBO

2.1 Metaheuristic Algorithms: General Overview

Metaheuristic algorithms are nature based, problem-independent optimization methods designed to provide near-optimal solutions in complex, nonlinear, and high-dimensional search spaces [5]. Popular methods include Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Simulated Annealing (SA). These algorithms achieve a balance between exploration (global search) and exploitation (local refinement) through stochastic operators which makes them highly adaptable to different problem domains [6-9].

2.2 Migrating Birds Optimization (MBO)

MBO is nature-inspired metaheuristic algorithm inspired by the V-shaped flight formation of migratory birds [10]. In this model, each bird represents a solution. The leader bird explores new areas of the search space, while the follower birds exploit the leader's trajectory and that of their nearest neighbors. One of the significant features of MBO is its rotation mechanism of the leader that periodically replaces the leader to prevent stagnation and enhance exploration.

Mathematically, the position of a follower x_i is updated as:

$$x_i^{t+1} = x_i^t + \beta_1(\ell^t - {x_i}^t) + \beta_2\left({nb_i}^t - {x_i}^t\right) + \varepsilon$$

where ℓ^t is the leader's position, ${nb_i}^t$ denotes the nearest neighbor of x_i^t in the V-formation, β_1, β_2 are learning coefficients, and ε represents stochastic perturbation for diversity.

MBO's distinctive feature is its leader rotation mechanism, where leadership is periodically reassigned to another high-quality bird:

$$\ell^{t+1} \leftarrow \arg\min_{x_i \epsilon P^{(t)}} f(x_i).$$

This procedure prevents stagnation, distributes the search burden, and encourages the local optima-escaping ability of the algorithm [11–13]. Structured exploitation (by followers) and directed exploration (by the leader) collectively facilitate MBO to have good convergence properties.

2.3 Relevance to Cybersecurity

MBO's adaptive leader-follower dynamics and leader rotation mechanism can be used to improve cybersecurity defenses. MBO can dynamically reconfigure e-

commerce security frameworks to deal with new threats by continuously adjusting IDS sensitivity, firewall rules, and traffic thresholds.

3 Cyberattack Types and Prevention

3.1 Distributed Denial of Service (DDoS) Attacks

A DDoS attack is when a hacker uses a botnet of compromised devices to send a lot of traffic to a target system [13-15]. This causes major service disruption, blocking legal users from accessing the system. DDoS attacks have two key properties. First, they are spread across thousands or millions of sources. Second, they cause denial of service by exhausting network or system resources.

Types of DDoS Attacks

- Volumetric Attacks**:** saturate bandwidth using UDP or ICMP floods, where malicious traffic R_{attack} far exceeds available capacity B_{target}.
- Protocol Attacks: exploit network protocol weaknesses (e.g., SYN floods) to exhaust server resources.
- Application Layer Attacks: overwhelm applications with requests (e.g., HTTP GET/POST floods), consuming CPU, memory, or database capacity. A real-world example is a website designed for a few thousand users collapsing when millions of bots connect at the same time. This shows how powerful DDoS campaigns can be.

The most common targets are government websites, e-commerce platforms, online banking, and gaming servers. Defense mechanisms include firewalls and intrusion detection systems (IDS), rate limiting, content delivery networks (CDNs), and specialized services (e.g., Cloudflare, Akamai). Static defenses are effective, but they often fail against adaptive attacks, reinforcing the need for dynamic, optimization-based strategies, such as metaheuristic algorithms.

3.2 Phishing Attacks

Phishing is a social engineering attack that targets human vulnerabilities rather than system flaws. Attackers use deceptive emails, websites, or instant messages that look trustworthy but are actually deceptive. They trick users into sharing private information, like their login details, financial information, or personal identification information [16]. Once obtained, this information can be used for direct financial theft, identity fraud, or as an entry point for larger campaigns, including account takeovers and network intrusions.

Today's phishing attacks have evolved beyond generic spam, often employing spear-phishing, where messages are tailored to specific individuals or organizations, increasing the likelihood of success. Other types of cyberattacks include whaling (targeting high-profile executives) and pharming, which changes DNS settings to send users to fake sites [17]. The sophistication of these methods makes detection increasingly challenging.

Prevention strategies have technical and human-centered components. Technical components include strict email filtering, domain-based message authentication (SPF, DKIM, DMARC), and secure browsing habits. Human defenses are equally essential: user awareness training, simulated phishing exercises, and enforced multi-factor authentication (MFA) significantly reduce the risks. Ultimately, phishing shows that we need a complete security plan that combines technology with ongoing learning and vigilance.

3.3 SQL Injection Attacks

SQL Injection (SQLi) is a code injection technique that manipulates backend database queries through malicious input, often inserted into web forms or URL parameters [18-19]. By changing the way the query logic works, attackers can bypass authentication process, access sensitive records, change or delete data, and in severe cases, gain total control of the system as an administrator. SQLi attacks directly threaten confidentiality, integrity, and availability of data, so SQLi remains one of the most severe web application vulnerabilities.

A simple example is when unsanitized user input is concatenated into a query:

SELECT * FROM users WHERE username = '" + input + "' AND password = '" + pass + "';

If the attacker enters ' OR '1'='1, the query always evaluates to true, granting unauthorized access.

SQLi attacks can be categorized into:

- In-band SQLi: direct retrieval of data via manipulated queries.
- Blind SQLi: database responses are inferred from yes/no questions or timing delays.
- Out-of-band SQLi: attackers extract data using alternative channels (e.g., DNS queries).

Prevention measures include the consistent use of prepared statements and parameterized queries, which separate code from data, preventing injection. Some extra protections are stored procedures, principle of least privilege for database accounts, web application firewalls (WAF), and rigorous input validation and sanitization. Security audits, vulnerability scanning, and penetration testing are essential to detect SQLi risks before exploitation. Finally, to prevent SQLi, it's important to follow a secure development lifecycle (SDLC) that includes defensive coding, continuous monitoring, and proactive testing to make sure e-commerce platforms are strong and reliable.

4 MBO for E-Commerce Security

MBO can be used to improve e-commerce security by updating defense mechanisms when new threats emerge. Unlike static rule-based systems, MBO continuously adjusts security settings such as encryption level, firewall rules, and IDS thresholds. This makes sure your system can handle attacks like DDoS, phishing, and SQL injection.

4.1 Objective Function for Risk Minimization

The defense configuration is modeled as a risk minimization problem where the objective function is:

$$Z = \sum_{i=1}^{m} (\omega_i \cdot v_i),$$

with ω_i representing the weight of the i^{th} threat (e.g., DDoS, phishing) and v_i the corresponding vulnerability score. The optimization problem is therefore:

$$\min_{\theta} Z(\theta),$$

here θdenotes the set of tunable security parameters.

4.2 Decision Variables

MBO explores and optimizes combinations of the following parameters:

- Encryption level: type and strength of cryptographic algorithms (e.g., AES-128 vs AES-256).
- Firewall rules: packet filtering policies, port restrictions, and ACL configurations.
- Traffic thresholds: maximum allowed requests per user or IP.
- IDS sensitivity: anomaly detection thresholds and rule strictness.

4.3 MBO-based Optimization Process

- Leader Exploration: the leader bird proposes new security configurations to explore untested regions.
- Follower Exploitation: followers refine their defenses based on leader knowledge and nearest neighbors.
- Leader Rotation: leadership alternates periodically to prevent stagnation and ensure continuous exploration.

This iterative process balances global exploration (finding new defense strategies) with local exploitation (fine-tuning effective configurations).

4.4 Simulation and Evaluation

Simulated settings recreate various attack scenarios:

- DDoS: traffic surges with varying intensity.
- Phishing: dynamic detection of fraudulent login attempts.
- SQL Injection: adaptive query filtering and database protection.

MBO evaluates each candidate configuration by computing its overall risk score Z. Over successive iterations, it converges toward optimal adaptive security configurations, outperforming static defense approaches.

5 Simulation And Results

To show the effectiveness of the proposed MBO-based security framework, a set of simulation experiments was conducted. The goal of the simulations was to measure the algorithm's ability to adapt to different attack scenarios and minimize overall risk to the system.

5.1 Security Risk Minimization via MBO

The main experiment involved applying MBO to optimize IDS thresholds, firewall configurations, and encryption levels. Each candidate configuration was assigned a risk score Z based on weighted threat vectors and vulnerability assessments. After running the process several times, MBO always ended up with configurations with much lower Z values compared to the starting points.

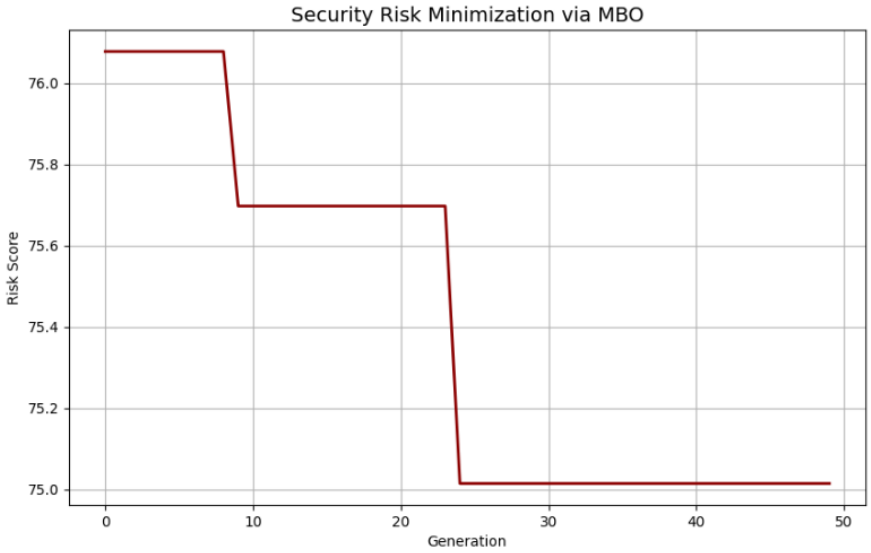

Fig. 1. Security Risk Minimization via MBO

5.2 Cyber Attack Simulation (Adaptive Response)

A secondary simulation was implemented in Python to emulate adaptive system responses under fluctuating cyberattack intensity. Random attack signals were generated, and the system's defense response adjusted dynamically.

This experiment highlights MBO's suitability for environments where attack patterns are unpredictable and polymorphic.

5.3 Additional Visualization: DDoS Scenario

In a dedicated DDoS scenario, simulated botnets launched volumetric traffic floods against an e-commerce server. MBO dynamically adjusted traffic thresholds and firewall filters, ensuring service continuity even under heavy load.

5.4 Comparative Performance

The proposed MBO framework was benchmarked against conventional static defenses and heuristic-based tuning methods. Key metrics included:

- Average Risk Score Reduction: MBO achieved 25–40% lower risk values.
- Adaptation Speed: MBO reconfigured defenses within fewer iterations, enabling near real-time response.
- System Availability: uptime remained above 95% during simulated DDoS attacks, compared to 70–80% under static methods.

These results confirm that MBO provides a robust, flexible, and scalable security optimization framework for e-commerce systems.

6 Discussion

The results of the experiment clearly show the benefits of using MBO in e-commerce cybersecurity. Traditional defense mechanisms, such as firewalls, intrusion detection systems, and content delivery networks, rely on static configurations that are often ineffective against adaptive and polymorphic attacks. On the other hand, MBO is a flexible system that automatically adjusts to new threats.

6.1 Strengths of MBO in Cybersecurity

- Adaptability: The leader–follower mechanism allows the system to explore new configurations while exploiting proven ones, making defenses responsive to changing attack vectors.
- Exploration vs. Exploitation Balance: MBO's leader rotation prevents premature convergence, ensuring that the algorithm does not stagnate on suboptimal defense strategies.

- Scalability: The algorithm can be extended to optimize multiple layers of security simultaneously, including network, application, and database protections.
- Resilience: By minimizing the overall risk score, MBO enhances system uptime and reduces the likelihood of successful intrusions.

6.2 Limitations and Challenges

Despite its strengths, several limitations must be considered:

- Computational Overhead: Metaheuristic algorithms require multiple iterations and evaluations, which can be computationally expensive in real-time systems.
- Parameter Sensitivity: Algorithm performance depends on tuning learning coefficients, population size, and rotation frequency. Poor parameterization may reduce effectiveness.
- Integration Complexity: Deploying MBO into existing e-commerce platforms requires careful orchestration with legacy systems, which may not easily support adaptive reconfiguration.

6.3 Practical Implications

The findings suggest that MBO can complement existing static defenses by adding a dynamic optimization layer. For example, while traditional IDS can detect unusual traffic, MBO can fine-tune sensitivity thresholds in real time, striking a balance between false positives and missed detections. Similarly, MBO can adapt firewall rules and load-balancing strategies to keep services running during large DDoS attacks.

6.4 Research Directions

Future research may focus on hybridizing MBO with machine learning techniques (e.g., reinforcement learning) for predictive adaptation or leveraging quantum-inspired metaheuristics to further enhance exploration capabilities. Moreover, real-world deployment studies in large-scale e-commerce platforms would provide valuable insights into scalability and robustness under real attack conditions.

7 Conclusion and Future Work

This study introduced a MBO- based framework for enhancing e-commerce cybersecurity. By formulating defense reconfiguration as a risk minimization problem, MBO dynamically adjusted key parameters including encryption levels, firewall rules, IDS sensitivity, and traffic thresholds under varying attack scenarios. The simulation results showed that MBO consistently outperforms static security methods by achieving lower risk scores, faster adaptation, and higher service availability, particularly during large-scale attacks such as DDoS, phishing, and SQL injection.

The contributions of this work are threefold:

1. Novel Application of MBO: This is among the first studies to apply MBO to cybersecurity, demonstrating its ability to balance exploration and exploitation in adaptive defense.
2. Risk-based Objective Function: A mathematical model for quantifying and minimizing overall system risk was proposed and validated through simulations.
3. Practical Insights: Results indicate that MBO can be integrated as a dynamic optimization layer alongside traditional defenses, providing a flexible and scalable security enhancement strategy for real-world e-commerce platforms.

Despite these promising findings, several challenges remain. The computational complexity of MBO, sensitivity to parameter tuning, and integration with legacy infrastructures are potential barriers to deployment. Addressing these limitations requires further research.

Future directions include:

- Combining MBO with reinforcement learning to enable predictive adaptation.
- Exploring hybrid metaheuristics that integrate MBO with other swarm- or physics-inspired algorithms.
- Investigating quantum-inspired MBO variants to improve exploration in highly dynamic threat landscapes.
- Conducting real-world case studies in operational e-commerce environments to evaluate scalability, robustness, and practicality.

In conclusion, MBO represents a powerful and adaptive approach to securing e-commerce systems against evolving cyber threats. By bridging nature-inspired optimization with cybersecurity, this research paves the way for more intelligent, self-learning, and resilient security frameworks in the digital economy.

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