26ING ARTIFICIAL INTELLIGENCE AND SOFTWARE-DEFINED NETWORKING (SDN) TO IMPROVE PASSENGER FLOW AND NETWORK EFFICIENCY IN AIRPORT LANDSIDE AREAS

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Rezumat. *Congestiile provocate de numărul mare de pasageri în zonele aeroportuare critice, cum ar fi zonele de lanside, creează provocări semnificative pentru stabilitatea operațională și furnizarea serviciilor. Lucrarea prezintă o interpretare nouă a unui sistem cu o abordare sistematică pentru a îmbunătății astfel de medii aglomerate prin sinergia Inteligenței Artficiale (IA) și a Rețelelor Definite de Software (SDN) pentru a crea un sistem inteligent care execută analize în timp real ale fluxului de pasageri, niveluri de ocupare și timpilor de staționare prin intermediul prelucrării digitale a imaginilor. Contribuția principală a autorilor este reprezentată de transformarea acestor analize în politici de rețea acționabile pe care un controler de tip SDN le efectuează, permițând asfel o direcționare dinamică a traficului, bazată pe politici, pentru a se asigura că aplicațiile critice pentru sarcina în execuție, orientate către pasageri (automate de auto-check-in, ecrane de informații) și conectivitatea necesară (acces point) primesc o alocare de lățime de bandă deprioritizată în perioadele de congestie excesivă. Lucrarea prezintă, așadar, arhitectura sistemului, algoritmi aplicați și componente tehnologice de suport. De asemenea validează performanța soluției prin scenarii de utilizare din realitate, demonstrându-se, astfel, creșterea eficienței operaționale prin reducerea conflictelor de resurse și îmbunătățește experiența pasagerilor prin menținerea unui acces stabil la serviciile digitale necesare.*

Abstract. *Congestion caused by high passenger numbers in critical airport areas, such as lanside areas, creates significant challenges to operational stability and service delivery. The paper presents a new interpretation of a system with a systematic approach to improve such congested environments through the synergy of Artificial Intelligence (AI) and Software Defined Networks (SDN) to create an intelligent system that performs real-time analyses of passenger flow, occupancy levels and dwell times through digital image processing. The authors' main contribution is represented by the transformation of these analyses into actionable network policies that an SDN controller performs, thus enabling dynamic, policy-based traffic routing to ensure that mission-critical, passenger-oriented applications (self-check-in machines, information screens) and the necessary*

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connectivity (access points) receive a deprioritized bandwidth allocation during periods of excessive congestion. The paper therefore presents the system architecture, applied algorithms and supporting technological components. It also validates the solution's performance through real-world usage scenarios, thus demonstrating increased operational efficiency by reducing resource conflicts and improving the passenger experience by maintaining stable access to necessary digital services.

Keywords: SDN, airport management, landside operations, passenger flow simulation.

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1. Introduction

The operational context of modern airports is defined by an exponential increase in passenger numbers, a trend that was confirmed at a global scale, before the pandemic outbreak in 2020, an is now resuming its upward course. [1] This evolution puts preasure on all componets of the airport infrastructure, with a particular impact on landside areas, which include check-in terminals, security control areas, commercial spaces and boarding gates. Digital communication systems play an important role in these dynamic environments, supporting a wide range of essential services: from self-check-in kiosks and baggage handling systems to passenger Wi-Fi networks, digital information displays, and PoS terminals.

Regarding managing the challenges in passenger density and fluctuating digital services, traditional network infrastructures are no longer up to the task. Based on fixed architectures and manual configuration, these networks are unable to adapt and fine-tune resource allocation in real time, and cannot react to the massive fluctuations that arise in passenger density and digital service demands. The result, is network congestion degradation of quality of service and a general decrease in the quality experience of service passengers enjoy.

When it comes to the design and operation of airport networks, a reactive and rigid approach is no longer efficient, a modern adaptive system is what we need. A system that's going to work in harmony with the physical surroundings. Well-known technologies like Artificial Intelligence (AI) can be used to give us a much more sophisticated understanding of the physical world, and Software-Defined Networking (SDN) brings the speed and agility we need to control the digital side of things. Coming together, AI and SDN form a closed-loop system that can see the condition of the physical airport. How crowds are moving, where they're concentrated, and so on, automatically adjust the network in response.

AI-SDN integration is a major part of the larger trend of developing intelligent infrastructures, as seen in the fields of Smart Cities[2], Vehicular Ad-hoc Networks (VANETs)[3] and the Industrial Internet of Things (IIoT)[4], and an airport can be thought of as a “smart micro-city” that's perfectly contained and controlled. Because an airport has a centralised coordination system, a uniform network and very clear objectives, it's the ideal place to test the ideas and methods that will shape the future of urban technologies. This framework gives the paper a relevance that goes beyond the simple optimization of an airport network, presenting it as a case study with broad implications for the implementation of technology on a large scale.

The specific contributions in this paper are laying out a customised architecture that integrates AI and SDN, an exhaustive analysis of the cyber threats and personal data problems that come with it, along with practical, real-world fixes and a financial framework for calculating return on investment.

2. Current State of Research

When it comes to the management of passengers in airports, the theoretical and empirical foundations of the proposed system are rooted in the literature of passenger flow management, machine learning, dynamic network management and the relationship between AI and SDN technology.

2.1 Intelligent passenger flow management

The history of passenger management in airports has marked a shift from manual processes to advanced technologies that can handle the increasing volumes [1]. Optimization initially involved the deployment of self-service technologies such as check-in kiosks, and the automation of border processes with the aid of biometric systems, Automated Border Control – ABC [1]. These features have efficiently streamlined several stages of the journey. More recent research, which employs the use of AI, is now providing more profound insights into the passenger mindset enabling analysis of crowd movement, so that supply chain efficiency.

2.2 Machine learning techniques for crowd analysis

For counting the number of people in images captured by video sensors, Convolutional Neural Networks, or CNNs, are now the standard go-to solution[5]. However, problems such as people obstructing each other, cluttered backgrounds and the way objects appear larger when they’re closer to the camera can throw a wrench into the works [6].Well-known architectures such as multi-column CNNs, or MCNNs, have been developed to address these problems. They split the input image into parallel streams that zoom in on people counting at a specific level, each using a different sized filter, and then combine the results to generate a detailed density map that takes into account the effects of perspective[6]. Another more recently developed architecture is CSRNet, which employs a different strategy called dilated convolutions in order to increase the range of the network, and crush through the clutter and occlusions found in scenes[6].

Crowd flow prediction

Temporal dependencies need to be taken into account, and recurrent neural networks, especially Long Short-Term Memory (LSTM) architectures, are capable of doing just that, when predicting the evolution of passenger flows[7]. Coming hotfooting off the heels of CNNs, these RNNs can take the sequences of density maps that the CNNs produce and get to the heart of movement patterns, and accurately predict what's going to happen next. Such as the formation of queues at security checkpoints or the rapid movement of people that could signal a major incident [8]. It's no coincidence that LSTMs have shown to be effective in similar applications, monitoring passenger flow in subway stations [7].

2.3 Dynamic network management with SDN

When it comes to the future of networking, SDN or Software Defined Networking represents a seismic shift in how we think about network architecture. It is essentially based on two concepts, separating the control plane and the data plane and pooling the brain power of the network in a programmable controller[9]. Well-known studies in the field show that SDN is capable of carrying out very sophisticated traffic engineering and QoS techniques. The SDN controller can dynamically parcel out bandwidth to applications in real time, rank mission-critical traffic over less pressing traffic[10], such as video streaming[11], and cleverly distribute the load across various access points or network links[12].The OpenFlow protocol has, in practice, become the default for the southbound interface, enabling the controller to send custom instructions to network switches, and tell them exactly what to do[10].

2.4 IA-SDN association in complex management systems

And have shown a clear precedent for the proposed solution, when combining AI and Software-Defined Networking (SDN) the results have been promising in various complex systems. In the field of Industrial Internet of Things, AI-driven anomaly detection systems are able to sniff out strange activity on the network and tell the SDN controller to quarantine the problem area [4]. Coming hotfooting into the world of 5G networks, the technique of “network slicing”. A fundamental part of SDN lets us create seamless, end-to-end virtual networks that can be fine-tuned to suit different types of applications, from ultra-reliable low-latency communications to the sort of massive connectivity that's required for IoT devices [13]. Now, the literature doesn't have a complete framework or detailed breakdown of what's needed to make AI-SDN systems fly in the landside area of airports, which is precisely what this paper aims to address.

3.Strategic and operational impact analysis

The proposed architecture is designed as an integrated cyber-physical system consisting of two main modules operating in a continuous control loop: an AI-based crowd analysis module and an SDN-based network management module. This section transforms high-level concepts into a specific technical design based on specialized research.

3.1 AI-based crowd analysis module

This module manages the perception and interpretation of the physical environment. Its operation is based on a data processing flow, from acquisition to the generation of structured alerts.

In the data acquisition stage, the system collects data from heterogeneous sources to obtain a complete picture of airport's status. These include video streams from surveillance cameras (CCTV), connectivity data from Wi-Fi access points (AP), and data from electronic access gates or ticket scanning systems.

To process this data, a data flow with two specialized components is proposed:

●Density Estimation: A Multi-Column Convolutional Neural Network (MCNN) is used. Its architecture, composed of parallel columns of CNNs with filters of different sizes, is ideal for handling the scale variation caused by the perspective of images obtained from video surveillance systems. Each column is dedicated to detecting objects at a specific scale, allowing the model to be equally accurate for both foreground and background people.[6] The output of this model is a real-time density map for each monitored area, indicating the spatial distribution of the crowd.

●Flow Prediction: A Recurrent Neural Network based on LSTM is used. This model receives as input a sequence of density maps generated by MCNN. By processing this temporal sequence, the LSTM learns the dynamics of flows and can predict future events, such as queue formation, estimated average waiting time, or detection of abnormal crowd movements.[14]

●Output: The AI module does not just produce raw data, but generates structured and semantic alerts for the SDN module. An alert can have the format: {zone: "Check-In A", density: "High", predicted_wait_time: "15_mins", event: "Congestion"}. This level of abstraction is essential for the network control logic to make informed decisions.

The elements of acquisition, processing, flow generation, and alert generation for the SDN module contain elements found in most AI models used for crowd monitoring in transportation hubs, as shown in the comparative table below. (Table 1)

Table 1: Comparative Analysis of AI Models for Crowd Monitoring in Airports

Model Architecture	**Main Task**	**Strengths**	**Airport-Specific Challenges Addressed**
MCNN	Estimated Density	Excellent handling of scale variation; robust at different perspectives.	Perspective distortion in long corridors; accurate counting in areas with mixed densities (queues vs. open areas).
CSRNet	Density Estimation	Uses dilated convolutions to capture broad context; top performance on standard datasets.	Severe occlusion in very dense crowds (e.g., at boarding gates); background clutter.
LSTM	Flow Prediction	Models long-term temporal dependencies; capable of learning movement dynamics.	Prediction of queue formation at security/check-in; estimation of waiting times; detection of abnormal behavior (panic).
CNN + LSTM	Density Estimation and Flow Prediction	Combines spatial feature extraction with temporal analysis (LSTM) for a comprehensive understanding.	Correlate current density with future flow prediction for proactive resource allocation.

3.2 SDN-based Network Management Module

This module acts as the "nervous system" of the infrastructure, translating logical decisions into concrete actions at the network level.

- **Basic Architecture:** The standard SDN architecture with three planes is adopted: Application, Control, and Infrastructure (Data). The Infrastructure plane consists of switches and Wi-Fi access points compatible with the OpenFlow protocol.[10] The Control plane is orchestrated by a centralized SDN controller (open-source platforms such as Ryu or OpenDaylight are suitable candidates).[10]

- **Advanced Resource Management - Network Slicing:** To provide granular and accurate control, the proposed system considers traffic prioritization and implements the concept of **Network Slicing**, borrowed from 5G architecture.[13] The SDN controller has the ability to create and manage multiple logically isolated virtual networks running on the same physical infrastructure. Each slice can have its own QoS, security, and topology policies. Examples of slices considered in the proposed model in an airport are:
  - **Critical Operations Slice:** Maximum priority, guaranteed bandwidth, and low latency for airline check-in systems, payment terminals, baggage handling systems, and operational communications.
  - **Passenger Services Slice:** High bandwidth, but with a "best-effort" model, for the public Wi-Fi network.
  - **Security and Emergency Slice:** An on-demand slice with absolute priority for public alert systems, emergency team communications, and digital display updates in the event of an incident.
  - **IoT slice:** A slice optimized for a large number of connections but with low bandwidth, dedicated to environmental sensors, asset tracking (luggage, ground equipment), etc.

3.3 Integrated IA-SDN control loop

The interaction between the two modules forms a cyber-physical control loop. They form a cyber-physical control loop, turning the network from a passive into an active participant in the management of the airport, when the physical and digital modules of an airport's control system interact. The causal relationship between physical and digital events is direct and programmatic, which means that any changes in the physical state. Like the density of crowds can automatically be detected and then induce a logical and predictable reconfiguration of the digital infrastructure. This cyber-physical system can be exemplified and visualized through the scenario of a busy airport hub:

- **Perception (AI):** The AI module, through the CNN, detects a sudden increase in passenger density in the lounge area, correlated with an increase in the number of devices connected to local APs. Simultaneously, the LSTM model analyzes flight delay data and predicts that this congestion will persist for the next 45 minutes.

- **Analysis and Decision (SDN Application Plan):** The IA module sends an alert to a management application running on top of the SDN controller: {zone: "Lounge B", event: "Congestion_High", cause: "Flight_Delay", duration: "45_mins"}. The application interprets this alert and decides on the set of network policies needed to manage the situation.
- **Action (SDN Control Plan):** The application commands the SDN controller to implement the new policies. The controller translates these commands into OpenFlow messages that it sends to the relevant switches and APs:
    - **QoS Policy:** QoS rules are applied that prioritize traffic associated with critical applications (e.g., mobile boarding pass scanning, payment transactions) and throttle bandwidth for non-essential services, such as high-definition video streaming, within the passenger slice.
    - **Load Balancing:** The controller initiates "client steering" commands (per 802.11k/v standards) to transparently migrate some passenger devices from congested APs in the lounge to less-used APs in adjacent areas (e.g., corridors, other gates).
    - **Dynamic Bandwidth Allocation:** The controller dynamically reallocates bandwidth. For example, it can temporarily reduce the capacity allocated to the IoT slice in areas with low activity and increase the capacity of the slice for passenger services in the crowded lounge area, ensuring stable performance.
- **Result:** Despite physical congestion, network stability is restored within minutes. Critical services remain functional, and the passenger experience is maintained at an acceptable level, demonstrating the operational resilience of the system.

4.Conclusions and Future Directions

When discussing the highly dynamic environment of airports, the integration of artificial intelligence and software-defined networking has shown to be an efficient way to get the most out of traditional network infrastructures. Our proposed architecture builds an independent system that takes real-time readings of the physical state of the terminal through cutting-edge crowd analysis and then rearranges digital services to anticipate and respond to any operational needs.

This system's benefits are multi-faceted. First, we see a huge boost in operational efficiency as the system streamlines the flow of people and optimizes the use of network resources. Secondly, it ensures that passengers receive consistent top-notch service and that the digital services they need are always available, especially during peak periods. Thirdly, with a comprehensive security protocol in place, and features like federated learning that blur privacy lines and get right to the heart of the problem, we get a massive jump in the system's security posture and compliance to the highest data protection standards. Last but not least, the technical and economic analysis reveals the potential to transform the network from a cost center into a strategic revenue-generating asset through innovative business models such as Network-as-a-Service.

To advance this field, the following future research directions are identified:

●Advanced Predictive Models: Exploring more complex machine learning architectures, such as Graph Neural Networks (GNNs), to more accurately model the complex spatiotemporal interactions between different functional areas of an airport (e.g., how a queue at security influences the flow to the commercial area).

●Integration with a Digital Twin: Development of a complete digital twin of the airport, integrating the AI-SDN system. This would enable advanced simulation of "what-if" scenarios (e.g., the impact of closing a runway on terminal congestion), holistic optimization of operations, and training of AI models in realistic virtual environments[15].

●Resilience and Large-Scale Scalability: Investigating hierarchical or fully distributed control architectures to ensure system scalability and resilience in very large airports (international hubs), where a single cluster of controllers could become a bottleneck[12].

●Pilot Studies and Real-World Validation: The most important future direction is the implementation of pilot projects in real airports. Only through validation under operational conditions can performance gains and return on investment be accurately quantified and unforeseen practical challenges identified, thereby accelerating the widespread adoption of this transformative technology.

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