# From Mission-Critical to Smart Homes:

## A Decentralized Software-Defined MANETs and Fault-Tolerant Architecture for IoT and Smart Environments

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## ABSTRACT

Mobile ad hoc networks (MANETs) are dynamic, infrastructure-less systems where nodes self-organize to communicate. They are vital for mission-critical domains—military operations, disaster relief, and rescue—and increasingly support Internet of Things in smart homes, smart environments, and Industry 4.0. Despite flexibility, MANETs face frequent topology changes, packet loss, and quality of service degradation. Software-defined networking offers centralized visibility and control, but current software-defined MANETs (SD-MANETs) suffer scalability limits and single points of failure. The authors implemented a decentralized SD-MANET that distributes control across clustered Ryu controllers, coordinated by Apache ZooKeeper for leader election and Redis for synchronized state. In Mininet-Wi-Fi, the framework delivers higher throughput, better scalability, and improved fault tolerance with lower control overhead than centralized SD-MANETs. Replacing a single controller with a cluster strengthens deployments and provides a resilient backbone for Internet of Things-driven smart environments where high reliability and mobility are essential.

## KEYWORDS

Software-Defined Networking (SDN), Mobile Ad-hoc Networks (MANETs), Software-Defined Mobile Ad-hoc Networks (SD-MANETs), Smart Environment, Wireless Sensors, IoT

## INTRODUCTION

A mobile ad hoc network (MANET) requires an adaptive scheduling mechanism to cater to the dynamic nature of such networks (Chlamtac et al., 2003). MANET performance and quality of services (QoSs) can be improved if it has a centralized view of the entire network. Supporting a dynamic topology in MANET is an essential requirement in routing information between the nodes connected in a network (Goyal et al., 2011). State-of-the-art research aims to mitigate significant

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weaknesses related to limited transmission capacity, security, and power consumption by using a single controller (Chlamtac et al., 2003). Therefore, software-defined networking (SDN) has been introduced into MANETs to provide centralized control, global visibility, and adaptive scheduling capabilities.

Software-defined MANETs (SD-MANETs) consist of a centralized controller to manage MANET nodes seamlessly. However, a completely centralized SD-MANET control plane hinders scalability and security of the deployment (Dusia & Sethi, 2021). In particular, reliance on a single controller introduces a critical single point of failure and creates scalability bottlenecks as network size and control-plane traffic increase.

A MANET is a group of mobile nodes that communicate or are connected in a network. MANET is one of the prominent frameworks to address radio frequency issues in wireless networks. MANETs support many applications, such as entertainment, tactical networks, wireless sensor networks, data networks, device networks, and emergency services (S. K. Singh & Prakash, 2020). Beyond mission-critical deployments, MANETs are increasingly relevant to emerging Internet of Things (IoT) domains, such as smart homes and smart environments, where heterogeneous devices frequently join and leave the network. Such environments benefit from fault tolerance, scalability, and adaptive scheduling to ensure seamless operation of smart appliances, sensors, and actuators.

In wide geographical areas, users can communicate with multiple users without radio frequency coverage limitations by using multi-hop, store-and-forward techniques. Each node adapts to network topology variations in a MANET. MANETs, wireless mesh networks, and cellular networks are primarily used for wireless communication. Due to this dynamic nature, MANETs require efficient scheduling, scalability, and control.

SDN introduces a centralized control plane by decoupling the control plane from the data plane (Shalimov et al., 2013). The SDN controller has a global view of the network and enables informed routing decisions, dynamically adjusting paths between senders and receivers. The southbound interface uses protocols, such as OpenFlow, to communicate with the forwarding plane (J. Singh & Behal, 2020). Higher-level components communicate with the controller through northbound application programming interfaces, and software-defined systems have been developed leveraging these interfaces (Jararweh et al., 2016).

SD-MANET aims to bring the control and flexibility of SDN to MANETs, with enhanced communication management capabilities through a logically centralized controller (Mishra et al., 2018). Traditional multicasting protocols do not support the needs of MANETs, such as robustness, scalability, and low control overhead. Although MANETs exhibit features, such as dynamic topology, multi-hop routing, fluctuating link capacity, and partitioned operation, they face significant challenges related to energy efficiency, load balancing, and frequent topology changes.

While SDN-based control improves visibility and adaptability, current SD-MANET designs predominantly rely on a single controller, limiting applicability in large-scale or highly dynamic environments. SD-MANET aims to improve performance and reliability and address MANET management challenges through SDN principles. However, most implementations still use a single controller, leading to congestion, processing bottlenecks, and a single point of failure. As the number of MANET nodes grows, reliance on a single controller becomes infeasible; simultaneous control requests can overwhelm the controller, resulting in delayed responses or service disruption. Consequently, scalability and fault tolerance remain inadequately addressed in classic centralized SD-MANET deployments.

Adopting SDN for MANETs solves flexibility, management, and control challenges; however, centralized SD-MANET implementations continue to suffer from limited scalability and controller dependency. In this paper, we investigate whether a decentralized SDN control plane can preserve the benefits of SDN while overcoming these limitations.

Unlike existing SD-MANET approaches that rely on a single centralized controller or loosely coupled hybrid control mechanisms, this work introduces a fully decentralized SD-MANET control plane that preserves a logically centralized network view while eliminating single-controller

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