# A Novel Wi-Fi Mesh Network Framework for Efficient Mobile Data Transmission

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Abstract: The current trend involves the use of robots and various IoT devices to assist in production and development. In the future, with the integration of AI technology, related applications will become even more widespread. Within this context, whether it is command transmission, equipment status reporting, or equipment condition monitoring, a stable network environment is essential. Presently, the technology can be mainly categorized into wired networks, wireless networks (Wi-Fi), and mobile networks. While wired networks are fast and stable, they are constrained by physical lines and cannot be used in environments requiring interlaced movement. Wireless networks face disconnection issues when crossing different APs. While mobile networks, particularly those using 5G, offer excellent real-time performance, the establishment of private networks is expensive and the signal sources are relatively singular. This study proposes the use of Wi-Fi technology combined with the UDP (User Datagram Protocol) and QUIC (Quick UDP Internet Connections) protocols to create a new type of multipath network system. This system aims to reduce the adverse effects of physical environmental changes and wireless access point (AP) device transitions, achieving a low-cost, high-speed, highly mobile, and secure network environment in specific settings. The proposed scheme leverages the encryption and security features of the QUIC protocol to protect data privacy while supporting the needs of high-mobility applications.



## 1 INTRODUCTION

In contemporary industrial production and warehouse management, efficient communication systems are crucial for maintaining operational efficiency. Particularly in large warehouses, manufacturing environments, and other locations that require high mobility and flexibility, the network environment needs to support high-speed data transmission while being able to cope with the impacts of environmental interference and equipment transitions. This study proposes the use of Wi-Fi technology combined with the UDP (User Datagram Protocol) and QUIC (Quick UDP Internet Connections) protocols to create a new type of multipath network system. This system aims to reduce the adverse effects of physical environmental changes and wireless access point (AP) device transitions, achieving a low-cost, high-speed, highly mobile, and secure network environment in specific settings.

The main research motivation of this study is to address the wireless network communication needs of mobile autonomous devices in future unmanned factories (such as unmanned warehouses) by designing a Wi-Fi mobile network data transmission system with data privacy protection and high reliability using the QUIC network protocol. Based on data security (for example, ensuring that data is stored locally rather than uploaded to third-party ISPs for storage or processing), we believe that establishing a dedicated network system is necessary.

Table 1 lists the possible network solutions currently available. After comprehensive evaluation, it can be found that WiFi is a good choice. The popularity and technological maturity of Wi-Fi networks make them an ideal basis for implementing such network systems. However, traditional Wi-Fi systems often perform poorly in the face of environmental interference and switching between APs. In addition, with the improvement of network security requirements and the increase of data transmission volume, existing Wi-Fi systems face many challenges in ensuring data integrity and communication efficiency. Therefore, this study



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explores the use of UDP's low latency characteristics and QUIC's encryption and security features to optimize the performance of Wi-Fi networks. The main objectives of the study include:

- Enhance reliability of Wi-Fi transmission: Explore technical solutions to mitigate the effects of packet loss due to error-prone wireless transmission.
- Improve AP handoff performance: Develop seamless AP handoff technology to improve network stability and reliability in dynamic environments.
- Achieve high transmission speed and low cost: By combining efficient protocols and cost-effective wireless technology, an affordable and efficient communication solution is provided.
- Enhance security and mobility: Leverage the encryption and security features of the QUIC protocol to protect data transmission from threats while supporting the needs of high-mobility applications.

We hope to develop an innovative network architecture that is applicable to a variety of commercial and industrial scenarios, which will not only improve the efficiency of on-site operations, but also enhance the security and reliability of data transmission. These achievements will help promote the development of wireless communication technology in the future, especially in the growing fields of smart manufacturing and smart warehouses.

Table 1: Comparisons between different wireless technologies.

| | Wi-Fi | LoRa | HaLow | BT | 5G |
|---|---|---|---|---|---|
| Bandwidth | ++ | - | + | - | ++ |
| Easy to use | + | - | - | + | + |
| maintainability | + | + | + | + | - |
| robustness | - | - | - | - | + |
| Low cost | ++ | ++ | + | ++ | - |
| Coverage | + | ++ | ++ | - | ++ |

# 2 PROPOSED SYSTEM FRAMEWORK: DWM

## 2.1 DWM System Overview

The main motivation for this research topic is to meet the wireless network communication needs of mobile autonomous devices in future unmanned factories (such as unmanned warehouses). From Table 1, we can find that Wi-Fi is a relatively good choice. In order to provide Wi-Fi coverage and improve the reliability of data transmission, we propose a DWM (Dual-connected Wi-Fi Mesh) network architecture (Figure 1). In the proposed DWM network system architecture, each autonomous mobile device such as an AGV (Automated Guided Vehicle) or an AMR (Autonomous Mobile Robots) is equipped with two Wi-Fi NICs, which are connected to two different SSID APs (SSID-A and SSID-B). In the AP layout of the mesh network, we use a grid structure, with an AP placed at each grid point.

The SSIDs of adjacent APs are set to SSID-A and SSID-B as in the example shown in Figure 1. Under this architecture, we allow the mobile clients (AGV/AMR) move in the network with maintaining the possibility of connecting to two APs in most cases. Each mobile client is given an IP address (for ***Tun*** interface), and its IP gateway is designated to the IP address of the server gateway. At the same time, two IP addresses are assigned to the two underlying Wi-Fi wireless network interfaces. Basically, these three interfaces (***TUN*** x1 + ***Wi-Fi*** x2) belong to different IP subnets.

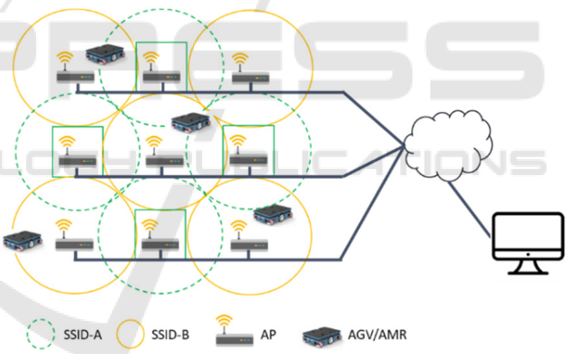


Figure 1: A 3x3 DWM network architecture.

## 2.2 DWM Software Architecture

Figure 2 shows the software architecture of DWM. The communication requirements of AGV/AMR in unmanned factories are mainly the communication between each AGV/AMR and the remote central control server gateway (communication between AGV/AMR needs to go through the server gateway). Therefore, we mainly focus on the communication between individual AGV/AMR and server gateway. The idea of the architecture is basically borrowed from the IPsec tunnel architecture. From the perspective of the AGV/AMR Client App programmer, it can be regarded as a virtual link directly connecting the AGV/AMR and the remote server gateway without having to care about the actual underlying network architecture. Therefore, the burden on upper-level application developers can be greatly reduced. They only need to focus on the messages that need to be reported to the server gateway or how to process the messages sent by the server gateway.

In addition, because we use the QUIC API, all data will be encrypted by QUIC, thus ensuring the risk of information leakage during data transmission. At the same time, QUIC provides a TCP-like network packet resending mechanism, thus ensuring that transient packet loss would not impair the integrity of the data. The underlying software architecture basically adopts the proposed Implicit Multi-Path QUIC (iMP-QUIC) software architecture introduced in the next subsection.

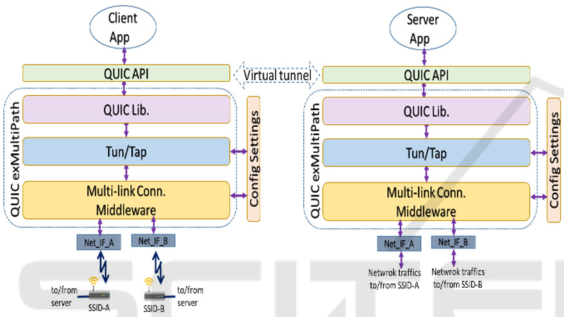


Figure 2: DWM software architecture.

## 2.3 Implicit Multi-Path QUIC

The key idea of iMP-QUIC (Implicit Multi-Path QUIC) is to separate QUIC from the underlying multi-path transmission network, and to separate the client/server program data communication (data plane) from the underlying multi-path packet manipulation (control plane). Through the underlying TUN/TAP virtual network interface, iMP-QUIC provides a communication tunnel between Client-Server programs. The application program (data plane) only needs to focus on application data exchange/handling between the client and server. The underlying multi-path packet manipulation (control plane) is handled by the Tun/Tap process daemon in the iMP-QUIC architecture. Since the Tun/Tap process daemon program is a user process (not a kernel module), it can be easily developed by the application program developer. The QUIC lib in iMP-QUIC can be any third-party QUIC protocol stack without special support for QUIC-MP (multipath QUIC). From the QUIC perspective, its underlying layer is a single network interface (TUN/TAP virtual interface), so it is a standard single network interface and does not need to run the QUIC-MP function.

As shown in Figure 3, when the upper layer application data is sent out through the QUIC socket interface, QUIC encapsulates the data into a QUIC packet and sends it out. The QUIC packet is routed through the kernel network protocol stack and sent to the Tun/Tap virtual interface. The Tun/Tap process daemon receives the data from the upper layer. When QUIC packets are sent, they are processed according to the daemon program settings and then handed over to the multi-link connection middleware below for processing. The multi-link connection middleware provides a (UDP) transport service between client/server hosts, with one UDP connection for each path. When data is sent to the other party through the multi-link connection middleware, the Tun/Tap process daemon collects the packets from different UDP connections, processes the packets according to the settings of the daemon program, and then sends the processed packets (that is, the packets sent by the client to the client) to the client. The QUIC packet sent out by the client is written into the TUN/TAP virtual interface, and the QUIC packet sent out by the client is sent to the QUIC socket buffer on the server side through the system routing, and then handed over to the server program for processing. And, the packet transmission process from the server side to the client side is similar to the above procedure.

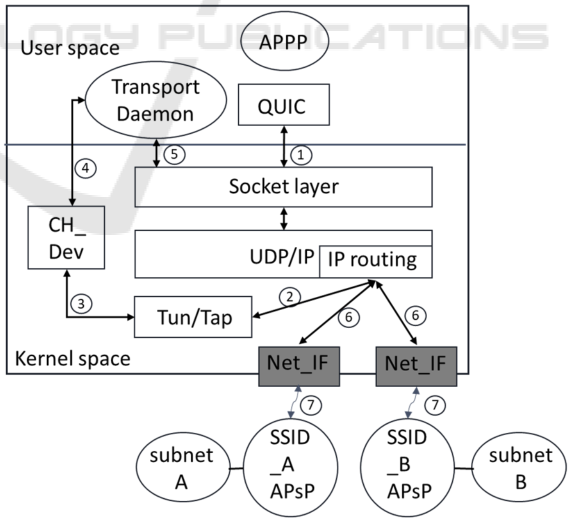


Figure 3: Packet transmission flow of iMP-QUIC.

# 3 EXPERIMENTS

## 3.1 Experiment Settings

We developed a small prototype system. Due to limited experimental space, we were unable to conduct large-scale complete system experiments. We set up three APs along the corridor in our department. The positions of the three APs are set according to their signal coverage areas, to make sure the signal coverage areas of two immediately adjacent APs are overlap with each other, as shown in Figure 4. The yellow circles, in Figure 4, refer to coverage are of the first and third APs with the same SSID (SSID-A); the red circle refers to the coverage of the second AP with another SSID (SSID-B). In addition, we made an Arduino robot car to simulate AGV/AMR. A laptop was placed on the robot car, which executed the software for AGV/AMR to communicate with the server gateway, as shown in Figure 5. This laptop is equipped with two Wi-Fi network cards. The equipment for other experiments is shown in Table 2.

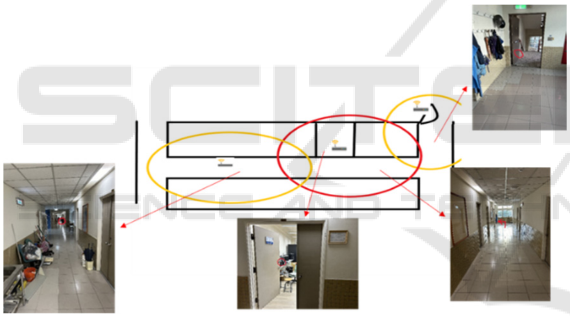

Figure 4: A small scale field try on the corridor.

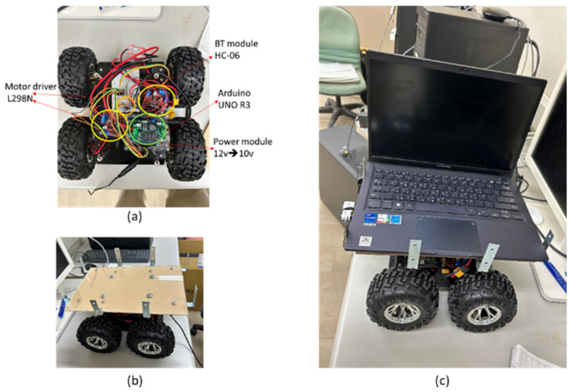


Figure 5: The Arduino robot car. (a) the control units, (b) the carrying platform on top of the control units. (c) the NB mounted on the carrying flatworm.

Table 2: HW/SW specifications of the experiment components.

| Devices | Spec. |
|---|---|
| Server gateway (PC) | CPU: CORE i7 $10^{TH}$<br>OS: Ubuntu 20.04.6 |
| Client (Notebook): | CPU: CORE i7 $11^{TH}$<br>OS: Ubuntu 20.04.6 |
| Wi-Fi adaptor 1&2 | ASUS USB-AC51 Wireless-AC600 |
| Wi-Fi AP x3 | ASUS RT-AX3000 |

## 3.2 Performance Evaluations

Since QUIC is a reliable transmission protocol similar to TCP, we use the existing QUIC package. In our implementation software, we cannot observe the actual QUIC packet loss situation directly (as the underlying QUIC packet is managed by the QUIC packet itself), so we use an indirect method to observe the UDP connection in the underlying multi-link connection middleware. At the same time, for our system design, we evaluated different system design options, especially the following points:

- Single link vs. dual link;
- Using the same SSID in dual link (AAA, all three APs are set to SSID_A) or alternative SSID (ABA, three APs are set to SSID_A/B/A in sequence);
- The impact of AGV/AMR moving speed on transmission performance;
- The impact of client transmission behaviour (transmission frequency and packet size) on transmission performance.

Since the client has two Wi-Fi interfaces, in order to record the client connection to the AP, we record the AP RSSI strength in each packet sent by the client. Experimental default parameters: client sends 1 packet per second; vehicle moving speed: Fast = 0.984 m/s (3.5 km/h), Slow = 0.328 m/s (1.18 km/h); data packet size It is 47 bytes.

## 3.3 Experimental Results

In this subsection we present the experimental results.

### 3.3.1 Constant Data Sending Rate (3pps Sending Rate)

First, we evaluate packet transmission efficiency regarding packet receiving rate and loss at receiving site (the server gateway), in which the mobile client transmits data at a fixed rate of 3pps (3 packets per second) to simulate sensor data transmission scenario.

The data size is 2KB (UDP or QUIC data payload size). The experimental results are shown in Table 3.

In Table 3, QUIC-ABA/AAA represents the proposed iMP-QUIC scheme is applied and the SSIDs of the three Wi-Fi APs are set to the same (SSID-A for AAA) or interleaving (SSID-A/SSID-B/SSID-A for ABA); The UDP-ABA represents a similar scheme as iMP-QUIC, in which we replace QUIC with UDP in the upper layer. Since QUIC packets are automatically resent if lost, the value of pkt_loss_rate is 0. From Table 3, we observe that when the mobile client moves at fast speed, the QUIC ABA/AAA suffers more packet lost and retransmission and thus a lower received packet rate is experienced in receiver side. This is mainly because the underlying Wi-Fi connection is interrupted when switching between APs. When the mobile client moves at slower speed, the impacts of the connection interruption is alleviated, and both QUIC-ABA and QUIC-AAA can achieve receiving packet rate of close to 3pps, the data generation rate at the sender side.

Table 3: packet receive rate and loss rate (sender rate=3 pps).

| | speed | QUIC - ABA | QUIC-AAA | UDP - ABA |
|---|---|---|---|---|
| PPS | fast | 2.57 | 2.08 | 3.02 |
| loss | | 0 | 0 | 0.104 |
| PPS | slow | 2.94 | 2.98 | 2.95 |
| loss | | 0 | 0 | 0.52 |

### 3.3.2 Unbounded Data Sending Rate

We, at the same time, simulated the situation of large file transmission. We had the mobile client transmit the data continuously without any break between two consecutive data transmissions. The size of each transmission is the same at 2KB (UDP or QUIC data payload size). The experimental results are shown in Table 4.

We analyse further the packet received at different layer of the proposed iMP-QUIC protocol (Figure 3): upper layer (QUIC for QUIC-ABA/-AAA, and UDP for UDP-ABA/-AAA) and lower layer (UDP for both protocols). The results are shown in Table 5.

Table 5 show that for the cases mobile client moving at high speed, the efficiency of QUIC-ABA is about 76% higher than that of QUIC-AAA and 17% higher than that of UDP-ABA; at slow speeds, the efficiency of QUIC-ABA is 17% higher than that of QUIC-AAA, and about 48% higher than UDP-ABA. Note that the data shown for UDP-ABA scheme in Table 5 is an upper bound pps, since we did not take those loss packets into account. So the actual packet received rate at receiver side for UDP-ABA should be lower than it. The results show that the proposed scheme QUIC-ABA out performs the others.

Table 4: packet receive rate (sender rate= unbounded).

| scheme | speed | pps@receiver |
|---|---|---|
| QUIC-ABA | fast | 181.82 |
| QUIC-AAA | | 101.91 |
| QUIC-ABA | slow | 176.45 |
| QUIC-AAA | | 134.35 |

Table 5: comparisons of packet receive rate at different layers (sender rate= unbounded).

| scheme | speed | pps@receiver | UDP |
|---|---|---|---|
| QUIC-ABA | fast | 181.82 | 389.48 |
| QUIC-AAA | | 101.91 | 220.77 |
| UDP-ABA | | 155.43 | 244.53 |
| QUIC-ABA | slow | 176.45 | 385.89 |
| QUIC-AAA | | 134.36 | 293.65 |
| UDP-ABA | | 119.43 | 313.54 |

## 4 CONCLUSIONS

In this study we propose a novel dual-connection Wi-Fi mesh system framework for efficient mobile data transmission, in which we combine multiple Wi-Fi transmission mechanism to QUIC protocol to create a new type of multipath network transmission system. This system aims to reduce the adverse effects of physical environmental changes and wireless access point (AP) device transitions, achieving a low-cost, high-speed, highly mobile, and secure network environment in specific settings. The proposed scheme leverages the encryption and security features of the QUIC protocol to protect data privacy while supporting the needs of high-mobility applications. We conduct experiments to evaluate the proposed scheme under different configurations including number of Wi-Fi interfaces, Wi-Fi SSID assignment, sender data generation rates, and client moving speeds. Experimental results show that the proposed scheme QUIC-ABA out performs the others.

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