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中控式Wi-Fi三鏈路冗餘傳輸之無縫漫遊策略

A Controller-Based Tri-Interface Redundancy Framework for Seamless Roaming in Industrial Wi-Fi Networks



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研究領域

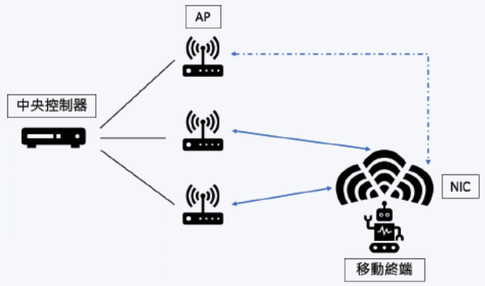
智慧聯網技術、無線資源管理及智慧製造。

作品摘要

隨著工業物聯網發展，打造無人化製造場域成為企業轉型目標，自主移動機器人(AMR)與自動導引車(AGV)不可或缺。現有行動網路具高可靠度，但建置維運成本高昂。相較之下，Wi-Fi具成本優勢，但傳統漫遊採「先斷後連」機制，移動終端切換AP時需經歷掃描與認證，即使搭配IEEE 802.11k/v/r標準，仍有數十毫秒延遲，易導致斷線與封包遺失。且工業環境金屬設施遍布，易引發訊號波動與乒乓效應。為解決上述痛點，本作品提出「中控式Wi-Fi三鏈路冗餘傳輸之無縫漫遊策略」。

本作品整合三大核心創新設計，突破現有工業Wi-Fi的技術限制：第一，集中式管理網路架構：有別於市面上Wi-Fi系統多採側重終端自主決策的分散式架構，本作品將漫遊決策「上收」至中央控制器。透過RYU控制器統籌全域連線狀態與資源調度，徹底避免移動終端因局部訊號波動自主切換所引發的決策衝突，確保網路具備高度可預測性。第二，多通訊介面下之循環式調度策略：捨棄傳統單一介面需兼顧傳輸與掃描的作法，改由多介面協同運作，將「管理鏈路」與「資料鏈路」功能解耦。系統能在維持既有通訊的同時，預先完成目標節點的關聯，達成「先連後斷」的無縫機制。第三，三鏈路協同冗餘傳輸：移動終端配置三組獨立通訊介面。系統預設兩組介面進行雙路冗餘傳輸，透過於資料平面自動複製封包並分流，確保單一路徑受阻時資料仍可送達。第三組介面則專職背景環境掃描。當掃描到更佳AP並連線後，系統即進入「三路併發」狀態，隨後主動斷開品質最差的鏈路使其回歸掃描任務。此「汰弱留強」的角色輪替機制，從物理層面消除漫遊斷線風險。

經由實作與效能驗證，相較於傳統單鏈路漫遊無可避免的封包遺失，本系統能維持穩定連續的資料傳輸。數據顯示，本系統傳輸延遲小於22.7毫秒的機率達100%，遠優於單鏈路機制的73.3%，達成較佳的傳輸確定性。整體而言，本作品成功將Wi-Fi通訊品質提升至近零中斷、近零封包遺失的水準，未來可廣泛應用於高可靠智慧物流、自動化控制工安系統及廣域遠端協作。



圖一 系統架構圖。由中央控制器統籌全域資源調度。移動終端則透過三組獨立通訊介面（NIC 1~3）執行角色動態輪替，完美奠定「三路併發、汰弱留強」的無縫漫遊基礎。

Abstract

With the rapid development of the Industrial Internet of Things (IIoT), building unmanned manufacturing environments has become a key objective for corporate transformation, making Autonomous Mobile Robots (AMRs) and Automated Guided Vehicles (AGVs) indispensable. While existing mobile networks offer high reliability, their deployment and maintenance costs are prohibitively high. Wi-Fi presents a cost-effective alternative; however, traditional roaming relies on a “break-before-make" mechanism. When a mobile terminal switches Access Points (APs), it must undergo scanning and authentication. Even with IEEE 802.11k/v/r standards, tens of milliseconds of latency persist, easily causing disconnections and packet loss. Furthermore, industrial environments are filled with metal structures that trigger severe signal fluctuations and ping-pong effects. To address these pain points, this project proposes a “Centralized Wi-Fi Triple-Link Redundant Transmission Strategy for Seamless Roaming”.

Our design integrates three core innovations to break through the technical limitations of current industrial Wi-Fi:

1. Centralized Network Management Architecture: Unlike high-end industrial Wi-Fi solutions on the market that typically rely on decentralized architectures emphasizing terminal-driven decisions, we centralize roaming decisions at a central controller. By leveraging an RYU controller to orchestrate global connection states and resource scheduling, this architecture completely eliminates decision conflicts caused by terminals reacting to local signal fluctuations, ensuring highly predictable network performance.

2. Cyclic Scheduling Strategy with Multiple Interfaces: Moving away from the traditional single-interface approach that must juggle both data transmission and environmental scanning, we employ coordinated multiple interfaces to decouple the “management link” from the “data link”. This allows the system to pre-associate with the target node while maintaining ongoing communications, achieving a true "make-before-break" seamless transition.

3. Triple-Link Coordinated Redundant Transmission: Mobile terminals are equipped with three independent network interfaces. By default, the system uses two interfaces for dual-path redundant transmission, automatically duplicating and splitting packets at the data plane to guarantee delivery even if one path fails.

The third interface is dedicated to background environmental scanning. Upon detecting and connecting to a superior AP, the system temporarily enters a “triple-concurrent” state before actively disconnecting the lowest-quality link, returning it to scanning duties. This dynamic role-rotation mechanism structurally eliminates the risk of roaming disconnections at the physical layer.

Through practical implementation and performance validation, our system demonstrates stable and continuous data transmission, in stark contrast to the unavoidable packet loss seen in traditional single-link roaming. Experimental data shows that our system achieves a 100% probability of maintaining transmission latency below 22.7 milliseconds—far outperforming the 73.3% rate of single-link mechanisms—thereby delivering superior transmission determinism. Overall, this project successfully elevates Wi-Fi communication quality to a level of near-zero interruption and near-zero packet loss, showing tremendous application potential for high-reliability smart logistics, automated industrial safety control systems, and wide-area remote collaboration.

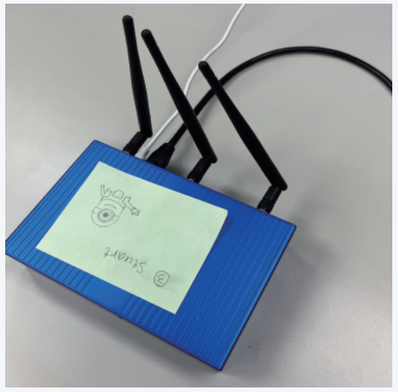


Fig. 2 Openwrt one, the primary equipment for this experiment.