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Contextual information aware optimal communication in radio networks in considering the pervasive computing -A literature review

Shuraia Khan*, Adam Wilson, Farookh Khadeer Hussain

School of Computer Science, 15 Broadway, Ultimo NSW 2007, Australia
Insitec Pty Ltd, Wollongong Street, Fyshwick, ACT 2609, Australia

Abstract

The modern tactical network demands a highly dynamic communications environment that involves autonomous platforms and systems. In order to achieve the full potential of modern technologies, it is critical to ensure the critical data finds the optimum path at the right time in a highly aggressive environment employing secure and best possible available communication path or network resources. Moreover, Contextual information aware optimal communication, such as the power of the radios, battery level, distance among the radios, and maximum and minimum data rates of the radio aware optimal path selection, remains an unresolvable research area. The mentioned limitation engenders various complex challenges in mission-critical networks. Therefore, contextual information-aware optimal communication in radio networks is a priority demand raised as a primary objective for military communication research. In this paper, we have performed a comprehensive review of various proposed methodologies to achieve the objective, followed by a critical comparative analysis to anticipate the state of the mentioned research area that leads to a future research direction for military researchers.

Keywords: Context-aware communication; Optimal path selection; Heterogeneous radio network;

* Corresponding author. Tel.: 61 2 9514 9681.
E-mail address: Shuraia.khan@student.uts.edu.au

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1. Introduction

The highly contested modern military network demands very efficient and secure communication, which leads to a high dependency on the communication infrastructure and facilitates the highly controlling of network traffic. On the other hand, highly controlling traffic refers to identifying, managing, and controlling the best possible link for certain data flows at a particular time. Besides, the highly controlling transmission increases the demand for interconnecting autonomous systems in a tactical operations environment. The expectation raises the question, "is the current tactical network capable and efficient enough to support high-performing communication demands?" for example, transmitting mission-critical information should be using a robust anti-jam path. In contrast, a less secure path offers a higher throughput automatically considered for complementary data. From this realization, military researchers and industry are working to advance the research and find various potential solutions to address the above question. (1) Research identifies the need to integrate various communication technologies to provide coherent communication infrastructure to achieve the above objective. On the other hand, many best-path selections or best route selection algorithms are proposed to achieve the same objective.

Furthermore, integrating the multiple heterogeneous radio access technologies (RATs) requires more intelligent algorithms to get the best performance from these integrated wireless technologies. Introducing Software-Defined Networking (SDN) offers a powerful mechanism in the network architecture that enables the network to be intelligently and dynamically select an optimal path for a certain flow. On the other hand, Heterogeneous Networks (HetNets) based integration is one of the popular options considered. Such as RAN-based 3GPP/WLAN integration architecture is proposed to achieve the optimal result.

We have reviewed broad areas of existing research, including the architecture-based solution and various optimal path selection-based algorithms. Moreover, this research introduces various radio network-based architecture or techniques considered and eventually incorporated into the mission-critical network. Therefore, in this research, we discuss several emerging networking equipment and architecture-based research for the military network and have performed a comprehensive review of the existing studies in section 2 and critical comparative analysis in section 3, followed by a conclusion and future research recommendations.

2. Existing research

Optimal path selection in the radio access network (RAT) is an ongoing research challenge. Several military communication researchers are trying to find a suitable and efficient solution for the current demand for intelligent battlefield networks that enable to delivery of agile and resilient C2 functionality to meet the flexible, scalable, and interoperable network needs of the battle group (BG) operating independently or with partners. Existing research on best path selection can be classified according to the approaches used in their research are discussed in the following

2.1. SDN based architecture for optimal path selection

Software-Defined Network (SDN) is an emerging revolutionary technology in the current IT industry due to its capability for centralized control of the overall network from a single location, scalability, and lots of advanced features that enable dynamic network management with limited human interaction. Since the future network demands various intelligent applications to support, academics, network professionals, the IT industries, and military researchers are exploring and employing SDN-based communication networks.

An SDN-based heterogeneous radio access network (RAN) is proposed, and evidence that an SDN-based variety of RAN networks can interoperate and enable to achieve the objective of selecting the best path while the messages are floating in a RAN (2). The researchers identify that every RAT is controlled and managed by RAT-specific elements such as Mobility Management Entity (MME) and Evolved Node B (eNodeB) to control and manage the LTE. Similarly, WLAN is controlled by WLAN controllers. Using these findings, the researchers decoupled the control plane functionalities of different RATs using SDN principles from the network elements of various RATs and accumulated them in the control plane. The user sent the control-related messages through RRM (Radio Resource Management) to the LTE and LTE base station (BS) and forwarded the control signals to the SDN controller. The Packet Data Convergence Protocol (PDCP) layer of LTE has an incredible functionality named Deep Packet

Inspection (DPI) that filters the control packets and routes them toward the SDN controller. In addition, An SDN-based application is introduced to transmit the encapsulated control messages for RAN with suitable headers.

This proposed solution is able to fulfill a fair number of criteria that modern military networks demand. Moreover, the mentioned approach can determine the priority-based path between end devices and the controller; however, it does not have enough clarification on end-to-end user communication. In addition, there is no clear indication about whether this approach can work with Low bandwidth and low frequency-based devices.

(3) proposed a Software-Defined network-based Multi-Path TCP (MPTCP) for Mobile Wireless Tactical Networks intends the conventional Single path TCP by leveraging multiple data paths across multiple interfaces between a pair of hosts. The approach combines the SDN and MPTCP in a heterogeneous SATCOM and UAV network and achieves optimized communication. The research scenario comprises an SDN switch for managing traffic, SATCOM systems as data service providers, UAVs (Unmanned Aerial vehicles), GCEs (Ground Combat Element) as data customers, and global SDN controller to serve as a bandwidth broker. Moreover, the Flow Deviation Method (FDM) algorithm is introduced to enable handling dynamic traffic flow allocation and minimizing the impact of flow reallocation.

The MPTCP achieves a smoother reaction to network changes due to UAV node migration. On the other hand, SDN in this approach improves the optimal flow computation for each MPTCP sub-flow and trades throughput for reasonable flow allocation, and guides the choice of links. The approach can partially fulfill the modern military communication demand with C2 functionalities. However, there is no clear indication about whether this approach can communicate with Low bandwidth and low frequency-based devices and choose the best path in terms of the contextual network information, including the affable services of the networks such as the power of the radios, battery level, distance among the radios, Maximum and minimum data rates of the radios as input.

An SDN-enabled wireless fog architecture is proposed that combines OpenFlow and distributed wireless protocols (4). The architecture enables a programmable fog router to lower the latency and efficient load balancing. This novel architecture uses a hybrid SDN control plane to manage wireless fog infrastructure in terms of flexible deployment and management. Besides, a hybrid SDN routing protocol combines the OLSR data forwarding and OpenFlow to perform global and optimal path selection and monitor the entire network. In addition, the SDN testbed emulation shows that transmitting the Signal-to-noise Ratio (SNR) to the controller performs the best path selection. However, contextual information-aware path selection is still undiscovered in the research.

2.2. Heterogeneous network-based architecture

Characterizing routing with Radio-to-Router information in a Heterogeneous Airborne Network (5) is proposed by employing the proxy in PPPoE architecture. The approach evaluates the metrics such as network reachability, link, path latency, reported vs. measured latency per link, link up/down percentage, and routing protocol overhead, under varying conditions of OSPF hello/dead interval, flight orbits and time, and several heterogeneous technologies. Naval Research Laboratory and Boeing developed OSPF-MDR to extend the base OSPF to MANET environments; however, there is minimal evidence that the proposed approach can achieve this research's objective.

(6) proposed research for Optimizing Content Distribution in Vehicular Networks with Radio Heterogeneity enables formulation and solves an optimization problem to maximize content dissemination from the infrastructure to vehicles within a predetermined deadline while minimizing the cost of communicating over the cellular connection. Moreover, the research numerically examines the trade-offs between cost, delay, and system utility in the optimum regime. Furthermore, the research developed a polynomial-time algorithm to acquire the optimal discrete solution and experiment using real GPS traces of 632 taxis in Beijing, China [5]. This research determines the optimal communication for low-bandwidth, long-range radios, and high-bandwidth short-range radios; however, there is no clear indication of how the research contributes to the optimal path selection of a heterogeneous radio network.

(7) proposes a mechanism to assess the multi-homing concept and offers a system model for increasing the applicability of multi-homing and multi-radio access technologies (multi-RAT). The evaluation demonstrates that:

a) traffic offloading is used to gain more capacity, b) higher data rates and real-time services. This work undertakes the data classifications, evaluations, and ranking of the available connections and utilizes them in an unequal load balance scheme. Three used choices for multiple attributes decision-making (MADM) methods, analytical hierarchy process (AHP), and a utility equation is applied to analyze the system performance and propose an energy-efficient based mechanism. Therefore, resulting in a better quality of service, traffic management, and availability of solutions.

However, the research has a minimal discussion about the success rate of the critical objective of finding the optimal path.

Optimized Radio Access Technology (RAT) selection and ensuring CRRM (Common Radio Resource Management) functionality, a hybrid decision-making framework with satisfaction-based Multi-Criteria Decision-Making (MCDM) method proposes that dynamically integrates operator objectives and user preferences (8). The research uses two heuristic methods, namely the staircase and the slope tuning policies, to dynamically obtain network information and enhance resource utilization. Moreover, a comparison of the proposed hybrid approach with six different RAT selection schemes (8). The research performs the RAT selection process according to the cost and QoS parameters rather than considering the status of the radio and the surrounding contextual information.

(9) proposes an intelligent network selection method in congregated multi-radio heterogeneous networks. The paper examines various options to integrate Wi-Fi with the 3GPP LTE network. Possibilities include application layer Integration, Core network-based Integration, and RAN-based Integration. Besides, a user-centric approach and the RAN-assisted approach are proposed that primarily aim for a Radio resource management algorithm. The alternative network selection algorithm flows are discussed and performed an emulation based on throughput. The research primarily portrays the controlling of the Ran rather than selecting an optimal path in RAN.

(10) research from NATO nominal researchers describes a scenario and architecture in a heterogeneous tactical network to improve connectivity and efficiency. This report provides detailed guidelines for deploying an efficient well-connected heterogeneous tactical radio network that significantly impedes information sharing at the lower tactical level [9]. IST-124 has conducted studies to enhance the understanding and recommendation to build interoperable heterogeneous mobile radio networks at the tactical edge. The research objective is to discover and utilize a method for the best mobile networks that can be carried to an operation by different coalition partners. The report covers three broad objectives: a) evaluate different technological solutions related to the scenario. b) provide end-to-end connections across different mobile networks, and c) prioritize and utilize scarce network resources. Guidelines and monitoring mechanisms) is proposed to Improve Resource Management (RM) and Quality of Service (QoS) in the network.

This research aims to understand better the challenges involved when establishing mobile heterogeneous coalition networks at the tactical edge that will help NATO nations evolve/procure network equipment that can be interoperable. However, the solution details of the identified challenges are still not publicly available.

(11) the research proposes an approach considering associations of users and access points (AP) in heterogeneous wireless networks with multiple radio access technology. Optimizing AP selection on the concept of minimal utility and sustainability is the motivation of this research. The System Model consists of a) Access Point Selection Strategy using a developed algorithm by considering minimal utility. B) Another algorithm is developed named mutual concession-based selection algorithm Simulation results suggest that the proposed selection i) enhances the total minimal utility in sustainable and fair manners, ii) indicates a distinctive trend in load balancing, and iii) requires a comparable computational time and handover frequency in contrast with the other selection.

2.3. Algorithm-based solution for optimal path selection

A new routing protocol for a heterogeneous metropolitan area network (MAN) architecture is suggested that combines an IEEE 802.11 wireless mesh network (WMN) with long-term evolution (LTE) network (12) by employing metrics to determine the best path by dynamically switching transmission technologies within the heterogeneous MAN. The proposed routing protocol's two essential components (A heterogeneous Routing table and a routing algorithm) address the challenges of long paths packet transmission, island nodes, and interference in WMNs. Moreover, it optimizes the cost of the combined network by employing unlicensed frequency bands and increases the overall capacity instead of buying additional licensed frequency bands for LTE. The routing algorithm is developed based on reinforcement learning called heterogeneous cognitive routing (CHR algorithm), is proposed to select the appropriate transmission technology based on parameters and is responsible for selecting the best radio access network. In contrast, CHR adopted a multi-rate medium access control (MAC) protocol for 802.11 called RARE was developed for a WMN-only environment in considering the collision and interference with the neighboring nodes and employed the transmission rate as a metric to quantify the quality of the Wi-Fi channel. In addition, the OLSR routing protocol employs the hop count as a metric.

Since the SDN-based solutions are critical for modern military networks, there is no clear indication that this approach is implemented in the SDN-based network. Moreover, though the CHR algorithm is designed for RAT, the simulation shows minimal evidence of implementing the protocol in the domain of RAT. There are many potentialities in this algorithm to achieve the objective of optimal path selection by knowing the surrounding information; however, to achieve the best benefit, Further research and development are required.

The spectrum, energy, load, and link quality-aware Geographic routing protocol (GCM) for large-scale heterogeneous hybrid Cognitive radio Mesh networks are proposed (13). The explanation of the cognitive radio is

discussed in the section above. GCM is a multi-objective routing protocol to support spectrum dynamics and node mobility, scalability, low overheads, high packet delivery ratio, low end-to-end delay, high network throughput, and long lifespan of mobile nodes. The algorithm approach ensures GCM a high packet delivery ratio and a low end-to-end delay in the production network environment, defined as a problem of classical greedy forwarding algorithms. Moreover, GCM combines load and energy into the routing metric. In order to provision the network load balance, resource-abundant mesh routers are chosen as the next hop than resource-limited mesh clients. Thus, the approach reduces the end-to-end delay and increases the network throughput. In addition, the lifetime of mesh clients is long because the packets are routed via mesh routers. Furthermore, the proposed research reduces the per-node state and control overheads, resulting in GCM outrival in highly mobile and spectrum dynamic networks. The research is promising for optimal path selection in mission networks; therefore, further development is required to anticipate implementing SDN-based (future military network) architecture.

It is also identified that, In the CRN (cognitive radio network), an existing routing path may become unavailable for any link occupied by priority users (PU). To avoid this problem, (14) proposes a novel CRN routing protocol named 'Dynamic Path Switching (DPS)' by employing the high-quality link according to the capability though lots of PU activities are observed and improving the route repair cost to maintain the performance.

(15) describe the research's multiple attribute decision-making (MADM) problem. There are several methods explored in this paper for selecting the network or best path, and the methods are a) MADM methods, b) Game theory, c) Game Theory on network selection, d) Fuzzy logic e) utility functions. Researchers have also proposed SUTIL, a mechanism for network selection in next-generation networks.

(16) proposes a new metric for routing in multi-radio, multi-hop wireless networks to choose a high-throughput path between a source and a destination as a metric. The metric assigns weights to individual links based on the Expected Transmission Time (ETT) of a packet over the link. The studies anticipate the performance in the context of the used metric by implementing it in a wireless testbed consisting of 23 nodes, each equipped with two 802.11 wireless cards. Thus, the result shows that the proposed metric significantly outperforms by careful use of the second radio in a multi-radio environment.

(17) proposes a High Throughput Spectrum-aware Routing protocol (SPEAR), a robust and efficient distribution channel in Cognitive Radio Networks for dynamic spectrum networks based on integrated spectrum and route discovery for robust multi-hop path formation and distributed distribution path reservations to minimize inter and intra-flow interference. The protocol presumes that each device has one dedicated control radio and one data radio in SPEAR design. This concept generates a critical difference from the conventional multi-radio devices in mesh networks. The simulations and testbed experiment shows that SPEAR creates robust paths in diverse spectrum conditions and supports near-optimal throughput. Moreover, SPEAR performs high-speed flow setup and teardowns in end-to-end packet delivery and latency and can maintain interference-free flows for variance in channel availability.

3. Comparative analysis of the existing studies and discussions

This section demonstrates a comparative analysis of the existing studies that proposed various researched and developed approaches. The developed the comparative analysis (Table1) focused on five primary areas: a) Experimented research domain networks and their associated protocols, b) the experimented research validation approach or implementation approach, c) overall efficacy of the approach in terms of context-aware path selection, d) proposed solutions to achieve the research objective. The solution types involve architecture-based or algorithm-based, e) and finally, the primary contribution of the research. The comparative analysis assists in understanding the mission network in a summary form in terms of the five primary areas mentioned.

Table 1. A comparative analysis of the existing studies for context-aware path selection

Existing Research	Network and Protocol	Implementation	Context-aware Path selection	Algorithm or architecture-based solution	Contribution
Cheng et al. (2013) (5)	PPPoE	Real-life (250 miles)	√(partially)	PPPoE with proxy	Airborne heterogeneous network,R2RI, dynamic routing, capacity 32.6Mbps
NATO (18)	Heterogeneous network (157nodes)	Emulated testbed. DAVC	√	Het-wireless mesh architecture	Architects-Guidelines to prioritize andutilize scarce network resources.
I.A. Shah et al. (2009)(2, 19)	Heterogeneous Mesh Network		√(partially)	Optimal path selection routing algorithm	(i) optimal path algorithm for efficientrouting(ii) Media independent handover.
F.Bendaoud et al. (2018)(15)	Wireless Heterogeneous Network	Simulation(partially)	×	Comparative discussion	Ranking, Ranking/Weighting Method,Game Theory, Fuzzy Logic, Utility Function.
A.L.Saadi et al.(2016)(12)	HeterogeneousWireless Mesh Network	NS-3 Simulator	×	Routing algorithm andtable	Compared with LTE networks with Wi-Fi and Random networks allocate
R.Draves et al. (2004)(16)	WirelessMesh Network	Wireless Testbed(23 nodes)	×	Multi-radio link quality source routing protocol	(WCETT) Matric - result shows metricsignificantly outperforms
A.Sampath et al.(17)	Cog-RadioNetwork	testbed	√(partially)	SPEAR protocol	Spectrum and Route Discovery -Distributed path reservations
M.Hung et al.(14)	Cog-Radio network	simulation	√(partially)	the dynamic path switching algorithm	utilize the good quality link. proactive path switching cost < passive path switching cost
J.Ahn et al.(2014)(6)	Heterogeneous network	with real equipment (632 taxies)	√(Partially)	Mathematical analysis for content dissemination issue.	A high-cost low-band, long-range and high-band, short-range radio, trade-offs between cost, delay, and utility
M.Naeem et al.(2019)(7)	Heterogeneous Wireless network	Simulation	√(Partially)	MADM and AHP methods	Energy-efficient transmission satisfy application needs.
S.Andreev et.al(2014)(9)	Heterogeneous network	Emulation	√(Partially)	Radio resource management algorithm	Wi-Fi and 3GPP LTE integration,Application layer, Core network-based, and RAN-based integration.
Zhao, Q., et al(3)	Heterogeneous Tactical-Network	Emulation	√(Partially)	File Deviation Algorithm for dynamic traffic allocation	SDN and MPTCP, optimized SATCOM and UAV communications minimize flow reallocation impact
Akram.H., et al(4)	SDN-Fog network	SDN testbed	√ (Partially)	Programmable Fog architecture	Lower latency, load balancing, hybrid SDN control, and path selection monitoring
Helou, ME, et al(8)	Radio Access Technology	simulation	√ (Partially)	Hybrid Decision-making framework in MADM	Dynamic resource allocation, six different RAT selections based on cost and QoS

Treaty, NA, (10)	Heterogeneous network	Emulated testbed(DAVC)	√ (Partially)	Het-wireless mesh architecture	prioritize and utilize scarce network resources.
Kobayashi, H., et al. (11)	Heterogeneous wireless network	simulation	√ (Partially)	Optimized Access Point selection algorithm	User and AP consideration with multiple radio access technology.

4. Discussion

The expectation raises the question, "is the current tactical network capable and efficient enough to support high-performing communication demands?" for example, transmitting mission-critical information should be using a robust anti-jam path. In contrast, a less secure path offers a higher throughput automatically considered for complementary data. Moreover, Contextual information aware optimal communication, such as the power of the radios, battery level, distance among the radios, and maximum and minimum data rates of the radio aware optimal path selection, is considered an intelligent network for the efficient mission-critical situations.

The above-detailed existing literature discussions and the critical comparative analysis demonstrate the following essential identification:

- The area of research is not new. The defense researchers are working to ascertain high-performing and efficient communication in tactical networks for battlefield communication.
- The existing research is performed not in one type of network but also in various possible networks such as heterogeneous wireless mash, RAT, SDN Fog network, Cognitive Radio network, PPPoE, and wireless mesh network.
- Most research experiments with simulation and emulation environments are very close to real-life ones.
- In terms of achieving the context-aware path selection, this research demonstrates that most of the research partially achieves the objective; however, the NATO researchers proposed some advanced technologies in the tactical network for battlefield communication that successfully achieve the objective.
- Each study has used various methods, where most of the methods proposed efficient and optimized path selection algorithms or protocols to achieve the objective. Limited research proposed architecture-based solutions.
- The proposed approaches are different from each other to achieve the objectives. However, each approach has its benchmarking matrix to measure the efficacy of the research. Hence, no standard matrix is used to evaluate the efficacy, and therefore no method to compare the efficacy rates of the existing studies in terms of achieving the objective.

5. Conclusion and Future Recommendation

This paper has performed a comprehensive literature review on context-aware optimal path selection in mission-critical networks. The research includes SDN architecture and heterogeneous network architecture-oriented solutions. Moreover, there is significant research on developing routing algorithm-based solutions to achieve the objective. The comparative analysis depicts the various methods and techniques proposed that can be employed in the tactical network to determine the best data path. However, no research can fully address the objective of contextual information such as the power of the radios, battery level, distance among the radios, maximum and minimum data rates of the radios aware optimal path selection, and remains an unresolvable research area

The research primarily focuses on finding the critical data path to the right user in a highly dynamic communication environment like a mission-critical network by employing secure control on the communication or network available resources. The mentioned objective can be able to address the challenges of a) network interoperability issues across heterogeneous communication systems, b) inadequate network capacity to support missions, and c) inability to autonomously configure and dynamically reconfigure networks to align with mission objectives. Addressing the mentioned challenges can be a future recommendation for this research.

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