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Reliable and scalable tactical networks: A systematic literature review on routing protocols in mobile ad hoc networks (MANET)

Communication and Cyber Security Engineering
Master's Degree Programme in Information and Communication Technology
Department of Computing, Faculty of Technology
Master of Science in Technology Thesis

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Tactical environments are challenging for wireless communication. The area of operation lacks infrastructure while the operations require reliable communications and scalable networks. Mobile ad hoc networks (MANET) is a solution to infrastructure-less networking. MANETs are used by units from the military, the police, and the border security, along with search and rescue teams and other similar government agencies. There is overlapping terminology in infrastructure-less networking but this thesis focuses on general MANETs.

There is a deficiency of review articles about general MANETs applicable to tactical communications in recent years. In this thesis we conducted a systematic literature review on general MANETs. 226 papers were reviewed from 2017 to 2024. We aimed to find research trends and focused on novel networking protocols

In this thesis we found that the scientific community is moving away from MANETs in favour of other ad hoc technologies such as wireless sensor networks and vehicle born MANETs. Reactive routing has seen especially drastic decrease during the observation period. Similarly traditional algorithms have lost interest to machine learning algorithms and meta-heuristic algorithms which have shown increase in the observation period. We found that protocols increasingly use additional metrics in routing decisions. These metrics include energy, delay, congestion, quality of service, and physical location.

The future correlation of ad hoc networks to tactical networks needs to be studied further. This thesis does not describe the effectiveness of the found routing methods, and they need to be studied further.

Keywords: tactical MANET, general MANET, routing protocol, SLR, systematic literature review

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1 Introduction

Military, police, and border security units, along with Search And Rescue (SAR) teams and other government agencies rely on wireless communication during their operations. The nature of these operations may lead the teams to operate in areas without any established infrastructure. Mobile Ad hoc NETwork (MANET) is a widely used type of wireless communication built to function in infrastructure-less environments. MANETs had initially been developed for military purposes but were quickly adopted by other agencies and civilian networking. Tactical networks have special limitations and capability requirements over the general MANETs, but they can be used to generalize the research on tactical networks.

In the 1970s the United States's Defense Advanced Research Projects Agency (DARPA) began developing a solution to reliably use packet based information routing in networks made of mobile nodes. The term node describes a collection of devices consisting of transmission, processing and user input capabilities e.g. a computer attached to a handheld radio. DARPA developed solution where the nodes were wireless and functioned independently of central control. The solution was named Packet Radio Networks (PRNET), and it provided store-and-forward capability to dynamic nodes with broadcast antennas. The network topology was dynamic, and each node had enough information about the network to allow independent routing decisions. PRNET's description is closely related to that of MANETs', and it is widely considered a development base for them e.g. [1]. DARPA initially developed PRNET for military purposes, which is still the most mentioned application for MANETs in research. It was however acknowledged early on that this technology has civilian applications as well. [2]

One of the first mentions of the term MANET is from 1997 when Internet Engineering Task Force (IETF) started a new working group (WG) named *Mobile Ad-hoc Networks* whose acronym is *manet*. The first IETF Request for Comments (RFC) describing MANETs was RFC 2501 published in 1999 by the manet WG. In the RFC, MANET was described as having: "dynamic, sometimes rapidly-changing, random, multihop topologies which are likely composed of relatively bandwidth-constrained wireless links". In addition, the nodes in the network act as both routers and end-devices. The dual purpose nodes allowed autonomous construction of the network. [1] The premise of MANETs was well thought out and the current solutions still adheres to this description.

Currently MANETs and their derivatives are widely used in civilian applications along with military ones. For example, MANETs are employed in emergency rescue communications, smart-city cellular networks, vehicle and arial vehicle communications, sensor networks in factories and logistics, and maritime communications. [3]

1.1 Tactical communication network requirements and description

Tactical operations refer to coordinated small scale and local actions for achieving a specified outcome. In this thesis, tactical operations are conducted by units from the military, the police, the border security, and other similar government agencies. SAR teams, when coordinated by a government agency, are also considered tactical units.

Communication in tactical setting is integral for the effectiveness of the operation when there are large number of personnel involved. While there are specialised unit which might not require constant communication with higher echelon, we consider tactical operations to be medium to large scale. In this scale tactical units require reliable wireless communication between the members of the teams and to higher echelon. The communication is essential for keeping personnel safe and effective, especially when the number units increases. [4], [5]

Reliability is a challenging requirement for the network in environments where tactical operations are conducted. Tactical operations are unpredictable, dynamic, and fast paced at times. They may be conducted at unexpected locations without existing electrical or network infrastructure. The radio links are unpredictable as personnel move geographically in and out of radio transmission range. Personnel may be attached and detached during the operation making the maximum supported node count unpredictable as well. These limitations and requirements need to be considered when deploying communication network. [6], [7]

Tactical networks need to be self-forming and -functioning to account for the lack of network infrastructure and central host. Self-healing network is required to allow reliable data transmission in constantly changing network topology. [8] The nodes are typically battery powered to account for the lack of electrical grid and to not limit the personnel’s movement to vehicles or other electrical sources. The requirements for functional size batteries and extended use time constricts the computation and radio transmission powers. The nodes need to support both real-time transmissions, i.e. voice or video, and reliable data transmissions. Tactical networks compared to traditional wireless networks typically have lower data rates and longer transmission ranges. Data rates are typically well below 1 Mbps and radio ranges are in the tens of kilometres. The devices transmit in VHF or UHF bands and require up to multiple watts of transmission power to achieve these distances. [5], [7] Förster et al. in their paper list the differences between infrastructure-less and wireless networks. From the paper it can be seen that general MANETs adheres to the requirements of tactical networks. [3]

Extending the transmission range of tactical networks is under research with vehicles and unmanned arial vehicles functioning as relay nodes. While this thesis focuses on man-portable nodes, it is important to acknowledge the possibility of using nodes with lower transmission power when the network is extended with higher powered device. Satellite communications are also widely used especially in the military setting, but they are usually not used en masse due to the high cost of the devices and the network and do not fit the scope of this thesis.

Tactical networks may be segregated from the Internet and are limitedly connected to a central network. The nodes are provided and monitored by central administrator creating a possibility to trust all the devices in the network. The homogeneity of the nodes reduces the complexity of trust-building compared to heterogeneous networks. Other network security problems are prominent in MANETs, but outside of the scope of this thesis. [6], [9]

1.2 Motivation and related work

In the past five years several survey and review papers have been published on MANETs. The five most relevant papers for this study are described below. The papers and seven other papers found regarding MANETs are presented on Table 1.

Wijonarko et al. [10] in their paper from 2025 presented systematic literature review of 4685 papers from a four year period from 2021 to 2024. There wasn't any additional filtering criteria applied to the dataset beyond the search query. The authors used general search term in Scopus to gather their data. AI-based tools Scopus-AI and Consensus.app were used to summarize the papers and evaluate the extracted bibliometric data. Several keywords and topics were identified including network security, vehicular MANETs, and use of 5G and machine learning.

Dalal et al. [11] presented a systematic literature review on opportunistic networks (OppNet). Released in 2022 the review included 65 papers from 2003 to 2021. The authors used keyword based manual search as opposed to single formatted search query. While OppNets do not have the same use case as MANETs, the research gives indication on ad hoc network trends. The main contribution of the analysis was to highlight different categories of OppNets and their opportunities and challenges.

Kafetzis et al. [12] reviewed research on Software Defined Networking (SDN) and Software Defined Radios (SDR) in their paper from 2022. SDN-SDR is a type of MANET where a central network controller is present. The authors analysed 100 articles from the 1980s to the 2020s. The paper highlighted literature contributions and challenges for the SDN-SDR. The authors concluded that the importance of considering SDNs and SDRs as a combined capability is increasing.

Arjun and Kaur [13] reviewed 10 novel general MANET protocols. Released in 2023 the paper describes papers from 2020 to 2022. The authors presented the findings of the 10 paper which ranged from energy efficiency to Packet Delivery Ratio (PDR). The authors did not make further discussion, comparisons, or conclusions about the findings.

Safari et al. [14] in their paper from 2023 reviewed 23 routing protocols with AI-based forwarding strategies. Even though the reviewed papers were from 2005 to 2022 the paper did not present any trends considering publication years. The authors presented categories for bio-inspired and Machine Learning (ML) -based routing algorithms. The paper concluded with open problems and praises for AI-solutions.

The relevant articles excluding Wijonarko et al. emphasise narrow scopes on specific types of MANETs for their reviews. Most of the articles have limited findings about trends on the topic. Neither general MANETs nor tactical MANETs have seen a systematic literature review in recent years. There are also no articles discussing the trends in routing approaches in these technologies. This lack of systematic literature reviews on general MANETs applicable to tactical networks forms the primary motivation for this thesis.

Table 1 Surveys made in the past five years in general MANETs

REF.	Y.	Notes
[10]	2025	Systematic literature review on MANET using only bibliometric analysis of 4685 papers from 2021-2024. Authors present trends on MANET research.
[11]	2022	Systematic literature review about OppNet routing. 65 papers from 2003 to 2021. Authors resent categories for OppNet, and opportunities and challenges.
[12]	2022	Comprehensive and systematic review of SDN-SDR based routing protocols. The authors review 100 papers from the 80s to the 2020s. The authors conclude with the importance of SDN-SDR and opportunities and challenges.

[13]	2023	The authors reviews 10 papers from 2018 to 2022 about MANET routing. Authors do not use systematic review method or make conclusions or comparisons.
[14]	2023	The authors review 23 AI based routing protocols from 2005 to 2022. No systematic method mentioned. The authors present several bio-inspired and ML-based routing algorithms and conclude with opportunities and challenges.
[15]	2021	The authors review 14 Zone Routing Protocol based routing protocols from 2003 to 2020. The authors conclude that MANET protocols and their improvements are of research interest.
[16]	2021	In this overview the authors describe MANET terminology. The authors conclude that hybrids protocols are better than other protocols due to lower power consumption and more efficient bandwidth use.
[17]	2020	In the survey the authors review 18 papers from 1997 to 2013. The authors discuss clustering in MANETs and VANETs. The authors present opportunities and challenges with different clustering algorithms.
[18]	2020	The authors review 17 papers from 2001 to 2018. The main contribution of the paper is the conclusion that congestion is best avoided by taking multiple criteria into account by blending multiple algorithms.
[19]	2020	The authors review 20 papers about energy efficiency and load balancing. The papers are from 2009 to 2019. The authors conclude that multipath protocols are more energy efficient than single path ones.
[20]	2020	In the paper authors review over 50 papers considering forwarding strategies in Named Data Networking (NDN) in the context of MANETs and VANETs. The papers are from 2010 to 2019. The authors conclude that the research area is still young.
[21]	2025	Pages 238 to 242. The paper is closed access.

1.3 Research objective and structure of thesis

The purpose of this thesis is to carry out quantitative research on routing trends in wireless and infrastructure-less networks based on bibliometric data. The technological focus of this thesis is about general MANETs in tactical environments. We use general bibliometric data (e.g. publication year, citations, author affiliations) and routing protocol descriptions from the reviewed papers in the analysis. The research objective is divided into three research questions (RQ) which are formulated in chapter 2.1 as part of the Systematic Literature Review (SLR) planning process. The RQs are as follows:

RQ1: What techniques are used to enhance the reliability and scalability of routing in general MANETs?

RQ2: Which individuals and institutions participate most in routing research on general MANETs and what is their impact on the field?

RQ3: How can the resulting trends guide the development of future tactical networks?

The rest of the thesis is divided into six parts. In chapter 2 the methodology for the systematic literature review is described. In chapter 3 background information important for understanding the findings is presented. Chapter 4 presents the findings of the systematic literature review. In chapter 5 discussion and future research is presented. Chapter 6 concludes the thesis.

1.4 Statement of use of AI

As directed by UTU code of conduct 2024 the use of Artificial Intelligence (AI) in making of this thesis is opened here. ChatGPT (several versions), a Large Language Model was used in the making of this thesis. The LLM was used to solely give feedback on writing style and spot grammatical errors. The LLM was not used to analyse, select or otherwise work with the dataset.

2 Methodology

We chose Systematic Literature Review (SLR) as the research methodology for this thesis. SLR is a quantitative research method used to find trends in large number of publications. This fits the research objective of this thesis. The SLR framework chosen for this thesis was described in an article by A. Carrera-Rivera et al. in [22]. This framework was chosen for its description of SLR in computer science. The article was considered novel and impactful since being released in 2022 it has been cited over 300 times as of spring 2025. Carrera-Rivera et al. describe six steps in the SLR process first used in planning the study and then conducting it. These steps are (1) keyword definition using PICOC criteria, (2) research question formulation based on the PICOC criteria, (3) database selection based on the research topic and objective, (4) inclusion and exclusion criteria definition, (5) Quality Assessment (QA) criteria definition, and (6) data extraction using an extraction form. [22] The SLR process of this thesis conforms to these six steps, and the process is presented in Figure 1. The rest of this chapter presents each step in detail.

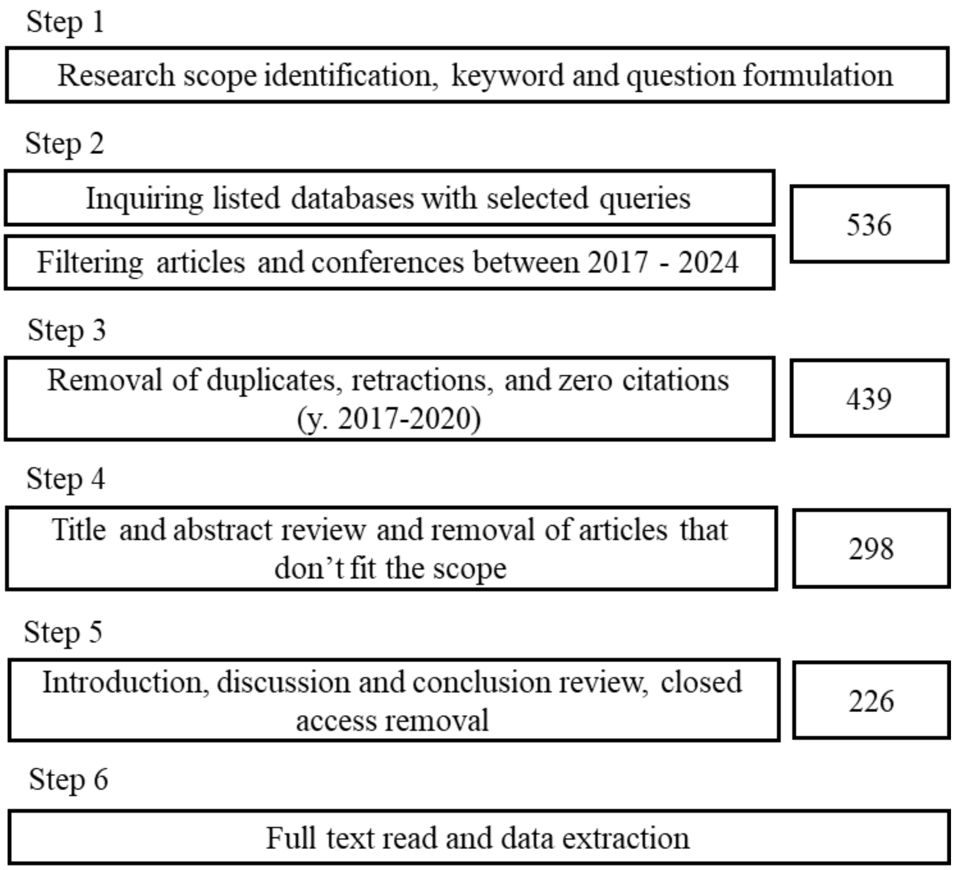

Figure 1 Systematic literature review process used in this thesis. Numbers on the right represent number of papers left after each step.

2.1 Research design

The objective of this thesis described in chapter 1.3 was split into keywords using PICOC criteria described in [22]. PICOC is made to aid the researcher to consider wider scope for the search query. PICOC is especially prominent in sociology and medical studies but has been successfully adapted to computer science research. The criterion in PICOC are Population, Intervention, Comparison, Outcome, and Context. The PICOC criteria and the keywords considered in this thesis are presented in Table 2.

On a wider scope the topic in this study is wireless networking in infrastructure-less environments where nodes are geographically dynamic. We chose this as the *population* criterion. This formulates to keywords *wireless and infrastructure-less networking* and *dynamic nodes*. While these do describe the intended network, these keywords were found in preliminary searches to be too vague to meaningfully limit the search. Förster et al. [3] described the field of wireless and infrastructure-less networking. The paper presented several promising keywords including (general) MANET, Vehicle and Flying MANET (VANET and FANET respectively), Wireless Sensor Network (WSN), Delay Tolerant Network (DTN), and Opportunistic Network (OppNet). The differences and similarities between these techniques are described further in chapter 3.2. We chose *MANET* as the *intervention* criterion since it has similar characteristics to tactical networks described in chapter 1.1. The term *MANET* is used in several different context in research. The term is used to describe an ad hoc -style network or specifically to adhere to the description in RFC 2501 [1] which we also use. To distinguish our use case from the universal term, we adopt the term *general MANET* from [3] to be used in this thesis. The term is used to describe the type of network and to differentiate it from other ad hoc networks e.g. VANET or WSN.

During preliminary searches the term *wireless ad hoc network* was also found to be prominent in the literature. The term is older than the term MANET and it is phasing out of literature. Traditionally the term wireless ad hoc network describes networks with static nodes while general MANETs describes networks consisting of mobile nodes. Some authors prefer to use the term wireless ad hoc network instead of MANET while still describing similar networks. We chose to include the term in the intervention criterion for a more complete search query.

The *comparison* criterion wasn't applicable in this study, since we did not aim to find suitable techniques for tactical networks but rather find trends in the research. Reliability and scalability were found in chapter 1.1 to be pivotal aspects of tactical network development and therefore they were chosen as the *outcome* criterion. These two keywords were used in the research question formulation. While comparison between technologies wasn't a focus in this study, the *context* criterion was fundamentally identified as tactical operations. These criteria helped in the formulation of the inclusion and the exclusion criteria described in the next chapter.

The resulting PICOC criteria was used to formulate the Research Questions (QR) presented below:

RQ1: What techniques are used to enhance the reliability and scalability of routing in general MANETs?

RQ2: Which individuals and institutions participate most in routing research on general MANETs and what is their impact on the field?

RQ3: How can the resulting trends guide the development of future tactical networks?

Table 2 PICOC criteria and keywords used in this thesis

Criterion	Description based on Carrera-Rivera et al. [22]	Keywords
Population	Can be a specific role, an application area, or an industry domain.	Wireless and infrastructure-less networking, dynamic nodes
Intervention	The methodology, tool, or technology that addresses a specific issue.	MANET, wireless ad hoc network
Comparison	The methodology, tool, or technology in which the Intervention is being compared (if appropriate).	- Not applicable -
Outcome	Factors of importance to practitioners and/or the results that Intervention could produce.	Improved reliability and scalability
Context	The context in which the comparison takes place. Some systematic reviews might choose to exclude this element.	Communication in tactical operations

2.2 Data selection

Formulation of the search query was based on the keywords found with PICOC criteria on the previous chapter. In the preliminary searches network security was found to be a prominent topic in the MANET research. This was also found in [10]. We decided to focus solely on the trends in the routing solutions and disregard their possible vulnerabilities in this study. Hence, network security and cybersecurity were chosen to be beyond the scope of this thesis and were excluded in the search query and Quality Assessment (QA). The preliminary searches also found that the term *tactical MANET* was too rarely used to show significant trends. We chose to search for general MANETs and impose the tactical environment in the modified QA step.

We chose observation period of eight years from 2017 to the end of 2024. This was deemed long enough timeframe for random yearly variations to diminish. The observation period also considered the Covid19 pandemic and mitigated its possible effect on the number of publications.

Numerous papers about ad hoc networks mention the term MANET making the distinction between relevant articles cumbersome. Additionally, the term MANET is not used reliably as a document keyword. The Document title search operator was used to aid in selecting papers that only describe general MANETs. This also aided in the second round of reviews where document titles and abstracts were reviewed. The disadvantage of the document title operator is that it excluded papers which replaced the term MANET in the title with a well-known general MANET protocol e.g. AODV. We deemed this to be negligible in terms of the trends in the research.

The exclusion operators of the search queries were used to exclude most papers about cybersecurity or protocol comparison analyses. We chose to exclude these comparisons as they do not fit the thesis objective of finding trends in novel protocols.

Table 3 Publication query and results

Database	Query	No. results
IEEE Xplore	(("Document Title":"MANET*") OR ("Document Title":"mobile ad hoc network*") OR ("Document Title":"wireless ad hoc network*") OR ("Document Title":"mobile ad-hoc network*")) AND ("Document Title":"Routing") AND NOT ("Document Title":"attack*") AND NOT ("Document Title":"Secur*") AND NOT (("Document Title":"survey") OR ("Document Title":"comparative") OR ("Document Title":"a review") OR ("Document Title":"overview"))	340
ACM Digital Library	((Title: manet) OR ((Title: "mobile ad hoc") AND (Title: network*)) OR ((Title: "mobile ad-hoc") AND (Title: network*)) OR ((Title: "wireless ad hoc") AND (Title: network*))) AND (Title: "routing") AND NOT ((Title: attack*) OR (Title: secur*) OR (Title: "comparative") OR (Title: "survey") OR (Title: "a review") OR (Title: "overview")) AND (E-Publication Date: (01/01/2017 TO 12/31/2024))	196

The search was limited to two databases focused on engineering: IEEE Xplore and ACM Digital Library. The extended ACM Guide to Computing Literature was chosen due to its wider reach compared to the ACM Full – Text Collection. The search queries were modified to accommodate the different search rules on both databases. Publication types were chosen to be the one with most representation to limit duplications. From the IEEE Xplore *conference papers* were chosen and from the ACM Digital Library *other periodicals*. The queried papers and their abstracts were exported to Zotero reference management software in BibTeX format. The search queries resulted in total of 536 papers.

In the first round of reviews papers without citations from 2017 to 2020 were excluded. This imposes recency in the resulting trends. We deemed that papers without citations are more likely to be of inadequate quality or describe a niche solution both of which do not contribute to any trends. Newer paper might not attract any citations for several years, which is why the exclusion was limited to the first half of the observation period. Retracted and duplicated papers were also removed in the first review. Total of 97 papers were removed in the first round, of which 83 were no-citations with one duplicate, 10 redacted with one duplicate, and 4 other duplicates. The remaining 439 papers were further reviewed which is described in the next chapter.

2.3 Data coding

The modified QA used inclusion and exclusion criteria derived from the keywords found with the PICOC criteria and the description of tactical networks from chapter 1.1. The inclusion and exclusion criteria are presented in Table 4.

Table 4 Inclusion and exclusion criteria in quality assessment

Inclusion criteria	Exclusion criteria
- Papers that provide novel implementations. - The implementations are evaluated in simulations or real-world applications.	- WSN or other IoT with low transmission power and little to no mobility. - High powered and energy reliable implementations e.g. VANET. - Network security focus including attacks, authentication, and trust building.

Similarly to the search queries, papers concerned about cybersecurity and papers which only analysed or compared existing protocols and did not present novel routing solutions were excluded. The novelty was limited to those applications that were complete protocols i.e. they were evaluated in simulations or real world testbeds. This excluded e.g. theoretical frameworks. Papers where nodes had either excessive or too limited transmission power or mobility were excluded as they did not fit the tactical network characteristics. These criteria excluded e.g. IoT devices and vehicle born MANETs. The papers which remained after the two QA rounds described functional protocols for general MANETs where nodes conformed to the tactical network characteristics.

The remaining 439 papers from the first review underwent two rounds of modified QA. In the first QA round, document titles and abstracts were reviewed. In the second round, introductions and conclusions were reviewed in addition to the titles and abstracts. The paper were ranked from 0 to 2 on each round. The rank 0 consisted of papers which met one or more exclusion criteria. Papers ranked 1 were unclear whether they met both the inclusion criteria and none of the exclusion criteria. Papers ranked 2 met both inclusion criteria and none of the exclusion criteria. In the first round of the QA total of 141 papers were ranked 0 and removed. 78 papers were ranked 1 and 220 were ranked 2. In the second round total of 72 papers were ranked 0 and the rest were ranked 2. About three quarters of the papers ranked 1 on the previous round were ranked 0 in this round. The rest of the papers ranked 0 this round were papers already ranked 2 which were inaccessible through University of Turku online credentials or met an exclusion criterion. After the QA, 226 papers were left for the review and data extraction described in the next chapter.

2.4 Data extraction

In the last step the papers were fully reviewed, and bibliometric data was extracted. Bibliometric data was chosen for this review due to the difficulty of empirical evaluation of the proposed protocols. The following fields were used in the data extraction: article title, names of the authors, 1^{st} author's institution, publication year, countries the authors are affiliated with, number of citations, the name of the introduced method, algorithm(s) or protocol(s) the introduced method is based or build upon, protocol class (i.e. proactive, reactive, or hybrid), primary objective keyword, algorithm category (i.e. traditional or modern), and maximum number of nodes used in simulations.

The number of citations were extracted on the 1st of July 2025 from the Google Scholar database. This was done to consider duplicate publications in other databases not queried in the data selection. Chapter 4 presents the graphical representation of the extracted data, and chapter 5 describes the approaches each paper took to achieve their objectives.

3 Background

This chapter describes the fundamental concepts that are needed for understanding the importance of the extracted and analysed data presented in this thesis. This chapter also describes the limitations of the results of the analysed data based on the tactical environments description.

3.1 Different wireless and infrastructure-less network technologies

There are several overlapping technologies in wireless and infrastructure-less networking. Förster et al. summarize the most prominent technologies in [3]. The differences these routing technologies and their suitability to tactical networks are discussed in this chapter. The discussion is summarized in Table 5. Colour of the cell represents the scale where lowest (red) and highest (green) are highlighted. The rest of this chapter describes the differences between solutions and their applicability tactical communication.

Table 5 Maximums for relevant metrics to compare wireless infrastructure-less networks [3] to tactical networks

Technology	Node mobility	Tolerable delay	Connectivity	Nodes leaving and joining	Network size	Number of direct links
DTN	Satellite	Months	Intermittent	Static	Dozen	Tens
OppNet	Flying	Hours	Intermittent	Groups	Thousands	Hundreds
MANET	Cycling	Minutes	Direct	Individuals	Hundreds	Hundreds
VANET	Driving	Hours	Both	Groups	Thousands	Hundreds
FANET	Flying	Hours	Both	Groups	Hundreds	Tens
AANET	Flying	Hours	Both	Individuals	Tens	Tens
WSN	Walking	Months	Direct	individuals	Hundreds	Hundreds
Tactical networks	Cycling	Minutes	Direct	Groups	Hundreds	Hundreds

Delay-Tolerant Networks (DTNs) are communication architectures designed to function in environments where network connectivity is intermittent or unreliable. DTNs use the Store-Carry-Forward routing concept where relaying nodes cache received messages until a valid next-hop comes into transmission range. DTNs aim for extremely reliable end-to-end connection with the disadvantage of large delays. The main use case for DTNs is space communications where communication between satellites or interplanetary nodes are irregular. The node count of DTNs is minimal, usually consisting of only under ten nodes. The networks usually use the traditional Internet Protocol (IP), but face challenges due to the low connectivity between nodes. DTNs represent foundational model for highly constrained networks. The DTN model is further developed into ground based delay tolerant and infrastructure-less networks called Wireless Sensor Networks (WSN) and Opportunistic Networks (OppNet). [3], [11] DTNs do not present networking solution to tactical communications in themselves. DTNs are important to recognise as the base for WSNs and OppNets which fit better to the characteristics of tactical networks.

Similarly to DTNs Opportunistic Networks (OppNet) apply the store-carry-forward routing concept but to a more dynamic network. While relaying nodes in DTN usually have a selected path for the data transmission, OppNets rely on the mobility and larger number of nodes to disseminate the packets. OppNets often contain variation of off-the-shelf devices carried by people or vehicles creating a heterogenous networks. The main use case of OppNets are smart-cities and emergency communication. Similarly to DTNs, OppNets have reliable but delay-prone data transmission. [3], [11] While both DTNs and OppNets aim for data reliability, the unpredictable delay discourage their use in tactical MANETs.

Wireless Sensor Networks (WSN) also utilise the store-carry-forward methodology but usually only at the source node. WSNs contain performance constrained devices that have variation of mobility and connectivity. The nodes in WSNs usually have low device memory, low processing and transmission power, and small batteries. Due to the constraints of the nodes, the gathered data is only simple telemetry data that can be stored memory efficiently and transmitted in small packets. Nodes in WSNs utilize duty cycles where nodes switch between sleep and active states to conserve energy, often leading to intermittent communication and dynamic topology changes. The sensor nodes may be near stationary with constant connectivity (e.g. industrial automation) or very dynamic and intermittently connected (e.g. cold-chain logistics). Prominent application for WSNs are Body Area Networks (BSN) where the nodes gather health information. [3], [23] While the restricted nature of the nodes makes WSNs unsuitable for most tactical applications, BSNs may be used in tactical environments to monitor personnel.

When data rates do not make the store-carry-forward a suitable network methodology, a direct connectivity is considered. Device-to-Device (D2D) communication refers to direct data exchange between mobile devices within a cellular network, where a base station uses them as relaying nodes. In crowded environments like densely populated cities, the number and type of antennas along the spectrum usage limit the performance of data delivery in 4G and 5G networks. D2D enables efficient spectrum reuse, localized data sharing, and offloading of traffic from the cellular core network. Unlike most other ad hoc networks, D2D is tightly coupled with the existing cellular infrastructure. This method allows for low latency and energy-efficient short-range communication, making it well-suited for typical cellular content distribution. The infrastructure-less and ad hoc subclasses of D2D networks include Train-to-Train (T2T) and Ship-to-Ship (S2S) networks, where mobility is predictable. These networks typically prioritize safety, coordination, and control messaging in environments with limited external connectivity. [3] While D2D and its subclasses overlaps with general ad hoc networking they are distinguished by their tight integration with domain-specific constraints and control architectures. These factors do not adhere to the needs of most tactical environments.

Tactical environments often contain ground vehicles and increasingly Unmanned Arial Vehicles (UAV). These can be used as network nodes to extend the tactical networks especially in areas with unfavourable terrain for handheld nodes. Vehicular and Flying Ad Hoc Networks (VANET and FANET respectively) have increased mobility and are less constrained compared to nodes in general MANETs. VANETs communicate through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). The network is often used to relay emergency information in smart-cities similar to D2D. FANETs consist of cooperative UAVs that coordinate missions through ground stations and links between the UAVs. These UAVs can be used as relaying nodes for other networks e.g. MANETs, WSNs or VANETs. The three dimensional nature of airborne communication drives routing and dissemination in FANETs into geographics rather than topological considerations. This is especially true for Aircraft-to-Aircraft NETworks (AANET) where node devices are airborne in fast moving aircrafts. Due to the high relative speed of the nodes in these networks, links are unreliable causing unpredictable latency. Collectively, these networks enable high-mobility, infrastructure-less communication across air and vehicular domains, though they remain subject to frequent disconnections and protocol design challenges. [3], [17] The other ad hoc networking technologies have potential in various tactical scenarios, but do not enable the general use case. General MANETs were initially made for military use and describe a network with moderate node mobility, low latency, direct connectivity, low topology volatility, and moderate network size. General MANET research has traditionally focused on network-layer routing protocols, Quality of Service (QoS), and transport-layer optimizations, positioning it as a foundational model in the field of wireless ad hoc communication. With the increased interest in WSNs the research on energy efficiency has also seen increase in general MANETs. A major research limitation in general MANETs is its practical deployments in large-scale applications due to scalability and stability limitations under high mobility conditions. [3], [10] General MANETs best describe the characteristics of tactical networks with limitations in scalability and reliability.

3.2 General MANET categorisations

MANET routing protocols can be divided multiple ways, but the commonly accepted way is to divide them by path formation method between nodes. The three classes in this category are proactive or table driven routing, reactive or on-demand routing, and hybrid routing which utilizes both proactive and reactive methods. These three classes are distinct and can be meaningfully studied in the context of tactical networks. The path forming can also divided into flat and hierarchical protocols which emphasizes the relation between nodes over the topology information knowledge. Another way of dividing the protocols is into topology based and geographic based protocols. The three mentioned protocol classes are all topology based. Geographic protocols can be divided into distance, direction, and progress based protocols. [24] The routing protocols can also be divided based on the number of paths used in transmission i.e. unicast or multicast, or whether the protocol maintains back-up paths i.e. single-path or multipath [25].

Additional information may be used regardless of the protocol category. Routing decisions can be affected by other information e.g. node’s physical location, received signal strength, delay, congestion, or a central controller may control the network. The standardised protocols do not use additional metrics, while novel approaches utilize numerous algorithms to best optimize the use of the metric data. The rest of this sub-chapter describes the MANET categories that are essential for understanding the analysis of this thesis.

3.2.1 Proactive routing protocols

Proactive or table driven routing protocols rely on every node having enough information about the network to form routing paths at any time. The routing tables of each node have to contain enough network topology information to calculate a path for the protocol to function. For optimal paths, the topology information is larger. This mechanism requires periodic control messages between nodes. The topology information sharing is the key research area in proactive routing protocols. Two most commonly referred proactive routing protocols found in this study were Destination-Sequenced Distance Vector (DSDV) and Optimized Link State Routing (OLSR).

The Destination-Sequenced Distance-Vector (DSDV) protocol incorporates destination sequence numbers to ensure loop-free and distinct routes. Each mobile node using the protocol maintains a routing table with the next hop information and the number of hops to every possible destination. The routing table is updated periodically by nodes broadcasting their neighbour information throughout the network. Sequence numbers serve as a mechanism to determine the freshness of routing information, allowing nodes to select the most recent and reliable path. To mitigate the issues caused by frequent topology changes, the protocol classifies updates as either full dumps or incremental updates, reducing unnecessary overhead. DSDV’s proactive nature ensures that routes are always available when needed, leading to lower delays in data delivery. However, this constant maintenance of routes results in increased overhead, particularly in highly dynamic or dense networks. Thus, DSDV is best suited for networks with moderate mobility and where timely route availability is critical. [26] The protocol laid a foundational framework for future mobile routing protocols and introduced key ideas, such as sequence numbers, which have been adopted and refined in later reactive protocols like AODV.

Optimized Link State Routing (OLSR) protocol is the other prominent table driven link-state routing protocol. Similarly to DSDV, nodes using OLSR continuously maintains topology information about the network by exchanging control messages. Its core innovation is the use of MultiPoint Relays (MPRs), a selected subset of one-hop neighbours responsible for retransmitting control messages. This mechanism significantly reduces redundant flooding and improves bandwidth efficiency, particularly in dense networks. [27]

OLSR employs two key message types: HELLO messages and Topology Control (TC) messages. HELLO messages are exchanged locally for neighbour discovery and MPR selection while Topology Control (TC) messages are disseminated via MPRs to convey link-state information. The protocol assumes symmetric links and a relatively stable MAC layer for accurate link sensing. While OLSR is well-suited for scenarios requiring low-latency communication, such as tactical or conferencing environments, it is less efficient in sparse or highly mobile topologies due to its constant control traffic and limited adaptability to rapid topology changes. Additionally, OLSR's performance depends on the quality of MPR selection, which the protocol does not standardize. [27] The improved OLSRv2 standardized the MPR selection making the protocol more reliable and allowed native support for IPv4 and IPv6. [28]

Overall proactive routing protocols have low route acquisition time due to the routing tables but filling them causes high initial control overhead. Proactive networks require wide bandwidth to accommodate the periodic control information. The network requirements increase when the network size or node mobility increases. Larger routing tables require increased internal storage and path calculation and control data processing require more power. [29]

3.2.2 Reactive routing protocols

Reactive or on-demand routing protocols construct the path from the source to the destination only when the node has a message to send. Most reactive protocols establish a connection from the source to the destination, but blind routing is also possible. Depending on the protocol, nodes can cache paths for a limited time. When no existing connection is established, the source node initiates a path discovery process. In the process the source inquires the network for the destination. When the inquiry reaches the destination, it answers with a message containing the path or paths to it. The paths have traditionally been the shortest possible but optimizing paths with energy efficiency or Quality of Service (QoS) are widely researched. The path discovery process was found in this study to be the most researched area in reactive routing protocols. Especially energy efficiency is researched in AODV and reactive protocols in general [30], [31].

The most researched reactive routing protocols found in this study were Ad-hoc On-demand Distance Vector (AODV) and its multipath version AOMDV. Other frequently researched protocols were Dynamic Source Routing (DSR) and Temporary Ordered Routing Algorithm (TORA).

The Ad hoc On-Demand Distance Vector (AODV) routing protocol, unlike proactive protocols establishes routes only when required by source nodes, significantly reducing control message overhead. AODV introduces three key control messages: Route Request (RREQ), Route Reply (RREP), and Route Error (RERR), and employs destination sequence numbers to maintain loop-free and up-to-date routes. When a source needs a path to a destination, it initiates a route discovery process by broadcasting RREQs, which propagate until either the destination or an intermediate node with a cached route is found. RREPs are unicast back to the source, and route maintenance is performed via periodic "hello" messages or link-layer feedback. Despite added delays during route discovery and occasional control message flooding, AODV excels in rapidly changing topologies and situations where bandwidth conservation is critical. Its modular design supports unicast and multicast routing and offers extensions for IPv6. Overall, AODV represents a robust and flexible routing solution for MANETs, balancing route discovery latency with minimal overhead. [32], [33]

The multipath and node-disjoint extension to AODV was named AOMDV. The protocol was designed to address the frequent route failures in dynamic networks, AOMDV enables the discovery and maintenance of multiple loop-free, link-disjoint paths in a single route discovery. The term *node-disjoint* describes paths with only source and destination nodes in common while *link-disjoint* paths do not share any links but may share link nodes. Unlike AODV, which drops duplicate route requests (RREQs), AOMDV selectively retains them to build disjoint alternate routes. The protocol supports a bounded number of replies to control overhead and achieves fault tolerance by switching to alternate paths upon route breakage without initiating new path discoveries. [34]

Overall reactive protocols have low control message traffic and are less affected by node mobility than in proactive protocols. The path discovery process however causes delays for the initial data delivery. The performance of reactive networks are more related to the throughput than the size of the network. Increasing the network size does not inherently result in congestion if the data rate is same throughout the network and relatively low.

3.2.3 Hybrid routing protocols

Hybrid routing protocols typically describe protocols that utilize both reactive and proactive techniques in the data delivery. All hybrid routing protocols divide the network so that single nodes do not broadcast path discoveries to the whole network nor have the whole network topology information available. The most common solution to this is to use hierarchical networking. Compared to flat networks, nodes in hierarchical networks have parent nodes who have some coordinative functionalities over the child nodes. Hierarchical hybrid networks divide the nodes into sub-networks called clusters. [16] The clusters have a default gateway called Cluster Head (CH) which coordinates inter cluster networking. Nodes within a cluster know which node is their assigned CH. Depending on the protocol the nodes might also have topology information about their own cluster. When the destination is not within the cluster, the source node sends the messages to the CH which then completes the inter cluster routing. Not all hierarchical protocols use both reactive and proactive approaches. For example, they might use proactive approach for both inter and intra cluster routing. [35] [36] To streamline the definition of hybrid protocol, all hierarchical protocols are categorized as hybrids in this thesis. [37, pp. 6–22] The most common hybrid protocol found in this thesis was Zone Routing Protocol.

Zone Routing Protocol (ZRP) was proposed as a scalable and adaptive solution for highly dynamic ad hoc networks. ZRP uses proactive routing within the cluster and reactive outside of it. Unlike traditional hierarchical routing protocols, ZRP does not have CHs. Rather every node has a hop-limited topology information about a zone. If the destination is outside of the zone, the node initiates a reactive path discovery. Unlike global flooding in AODV, ZRP limits route queries to peripheral nodes at the edge of the zone, greatly reducing control message overhead. The protocol uses sequence numbers similar to DSDV and AODV in the path discovery message. The hop-limit of the zone is configurable. This allows tuning the network to mobility and performance requirements. Its modularity, robustness to frequent topology changes, and ability to discover multiple paths make it particularly well-suited for military, emergency, and sensor network applications. ZRP represents a balanced and efficient routing framework for large-scale, mobile wireless networks where traditional protocols struggle. [15] [38]

3.2.4 Other routing protocol categories

The division into proactive, reactive, and hybrid protocols is commonly accepted way of categorizing protocols. All of these protocols can be divided into either multipath or single-path protocols. The division is sometimes important since single-path routing can place lower load on the network compared to multipath protocols. Multipath protocols have the benefit of more reliable links especially in high mobility networks. [39] The protocols can also be divided into unicast and multicast protocols. unicast protocols send traffic along only one path regardless of how many paths they have cached. Multicast protocols balance the load along multiple paths or send traffic to multiple destinations simultaneously. This helps avoid one central node being used disproportionately and e.g. draining its battery or increasing congestion. [25] An example of multicast protocol is the Multicast AODV (MAODV). [40]

The protocols increasingly use cross-layer approaches in routing. Cross-layer routing refers to routing technique where other layers along transport and network layers are used in the path discovery or message forwarding decision making. This usually involves physical or application layers. Physical layer can be used to gather information about the physical properties of the network. Two most prominent metrics are the physical location of nodes and the strength of the signals in the network. A protocol using the physical location of the neighbouring nodes is Location Aided Routing (LAR). The location data can be shared proactively or attached to path discovery messages and can be gathered from GPS or signal analysis. [41] Other prominent physical layer metric is Received Signal Strength Indicator (RSSI). RSSI can be used to estimate or analyse the neighbouring nodes congestion or physical distance, which can be used to optimize transmissions. Software Defined Networking (SDN) is an example of cross-layer routing utilising the application layer. SDNs utilize a central controller in the network with varying roles. The controller can aid in routing by sending topology information, or it may monitor the network to increase efficiency or security. In hybrid protocols, the controller may assign clusters and CHs. [12]

3.3 Path finding algorithms

Routing protocols use path finding algorithms to determine either the shortest path or an optimal path from the source to the destination. Optimal paths are based on network metrics e.g. remaining energy level, congestion level, delay, jitter, or RSSI. Network metrics are easy to apply to existing routing algorithms but create complexity in the network. The algorithms covered in this study are divided into two categories: traditional and modern.

Traditional algorithms consists of deterministic and heuristic algorithms. Deterministic algorithms are general algorithms that provide the same answer every time for a given primer. These algorithms guarantee the best solution as a result. AODV and DSR are examples of deterministic algorithms as is the Dijkstra’s algorithm used in OLSR. Heuristic algorithms are more general and usually provide an approximate non-deterministic answer. Heuristic algorithms optimise for speed with the cost of accuracy. Heuristic algorithms are usually purpose made for a specific problem.

Modern algorithms include Machine Learning (ML) based solutions and Meta-heuristic or nature inspired algorithms. ML-based algorithms in this study include Neural Networks (NN), Deep and Double Deep NN (DNN and DDNN), Reinforcement Learning (RL), Q-learning and Deep Q-learning, and fuzzy logic based algorithms. Meta-heuristic algorithms include bio-inspired algorithms and other nature inspired algorithms. Bio-inspired algorithms covered in present in this study include Genetic Algorithm (GA), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Cuckoo Search Optimization (CSO), and other animal behaviour based algorithms. Physics inspired algorithms include simulated annealing, lightning strike, and hill climbing.

Modern algorithms typically utilise metrics in search optimization. There are many benefits to modern algorithms over traditional ones. For example, bio-inspired algorithms have been found to be more scalable and flexible [42]. Especially swarm intelligence like PSO and ACO have shown high topology volatility capacity. [43], [44] The disadvantage of modern algorithms is increased complexity and higher resource requirement due to the poor problem optimization compared to traditional algorithms. This inefficiency causes decrease in energy efficiency and requires an increase in processing power. [45]

3.4 Limitations of simulations

We set a requirement that all the papers reviewed in this study include simulations or physical experiments for the proposed protocols. While the simulations provide objective and comparative data on the proposed protocols, the evaluations, and comparisons of the simulations from different papers is difficult.

One pivotal metric used in simulating the proposed new or modified protocols is the mobility of the nodes. This is modelled using a mobility model in the simulation environments. The most common mobility models found in this study were the Random Waypoint (RWP) mobility model and Random Walk (RW). RWP and RW model the movements of individual nodes and do not take the relations of them into account. Nodes can also be modelled with dependencies for each other. These group mobility models consider the movement of the whole node group while allowing some independent movement. In tactical operations personnel rarely move completely independently from others. Both individual and group mobility models have limitations when considering them in a tactical environment.

Individual mobility models RWP and RW function as general models for simulating node movement. Both of these models are widely used in MANET performance simulations. While these models can be used in multiple spatial dimensions, the 2-dimensional model is typically used when simulating MANETs. In other applications 3-dimensional model might be needed e.g. FANETs. RWP and RW both move nodes in straight lines with a random velocity and direction. The models are memoryless meaning previous values do not affect the next values for velocity or direction. This creates unnatural changes of direction in the resulting simulations. RWP has a pause time at the end of a leg, while RW does not. This makes the movement in RWP more natural. [37, pp. 33–124] The benefits of RWP and RW are the wide availability of these models. As an example, the widely used simulator NS-2 has supported both RWP and RW from at least the beginning of the 2000s.

RWP and RW simulate random movement in spatially confined spaces. The movement of personnel in tactical operations is rarely this random, nor do the nodes move in straight lines in an un-obstructed plane. Tactical operations might seem chaotic and random, but the movement of the nodes is always at least semi-coordinated, be that in the battlefield, in search and rescue, or a police operation. The coordination of the tactical operations also leads to co-operation between the personnel carrying the nodes. This causes the distances between the nodes within a group to stay near static while the distance between groups may have large fluctuations. This movement enhances the performance of the network since nodes do not lose connection with each other as randomly. When nodes or group of nodes do lose connection the reconnection process is difficult to model with individual mobility models. [37, pp. 33–124, 635–670]

Group mobility models model movement of nodes that function as a part of a coordinated system. The group of nodes co-operate towards a common result, and their movement reflect that. Roy in their book [37] highlights military units as a prime example of group of nodes working together and being modelled with group mobility. Other applications for group mobility are vehicles in crowded cities or emergency rescue personnel. Roy describes numerous group mobility models that all benefit different use cases. One example for tactical movement is Reference Point Group Mobility (RPGM) model. In RPGM a group centre is determined and all nodes in the group generally follow the movement of the centre while allowing random individual movement. [37] This movement closely resembles a military or a police unit conducting offensive operations. RPGM can also be applied for Search And Rescue (SAR). [37, pp. 635–670]

Ray in their thesis conclude that neither RWP nor RW are sufficient at modelling military movement. In the thesis a Universal Mobility Model Framework (UMMF) is proposed and evaluated in order to model military movements better. The proposed method was found to be more accurate in modelling military movement than RWP or RW. [46] Military Group Mobility (MGM) model has also been introduced. The model was built on observed data from various military operations. [47] While group mobility models are more accurate at modelling real world movements, they are also more complex. The ease of use in the individual movement models and the ability to compare them accurately discourages researchers from using group mobility models.

The mobility models used in the simulations of the reviewed papers make it difficult to assess the performance in tactical environment. There are also several different simulating environments and tools used to simulate the proposed protocols. The tools behave differently to each other depending on the computing resources used in the simulations. The different versions and models of the simulation software also effects the results. For example, 60 of the reviewed papers utilized AODV in their solutions and compared their protocols to it in the simulations. Despite the seemingly uniform testing premise, the resulting performance for AODV was vastly different in the different simulations. For these reasons, the proposed protocols and their effectiveness weren't able to be compared. The only metric used in this study is the size of the node pool in the simulations.

We used the maximum size of the node pools to assess the scalability and maturity of the reviewed protocols. The number of nodes used indicates the focus application and the maximum scale for performance in the proposed protocols. The large size of the simulations also indicates more mature algorithms as they prosper in more demanding tests. Authors typically do not include simulation sizes where diminishing returns are found. Using the maximum size does however undermine the most efficient network size for the protocols. The algorithms with low node count in simulations are mostly proof-of-concept research, while the large simulations are linked to comprehensive applications.

4 Findings

This chapter makes graphical representation of the findings from the SLR. Due to Covid19, most conferences were either cancelled or moved to later date delaying publications. We believe that this led to the significant reduction of publications in 2020 and an increase in 2021 we see in the data. To make the data more readable, some figures have been normalized by taking the average value for the years 2020 and 2021 to represent both years. This normalisation is explicitly mentioned in the figures it affects. The findings are further discussed and methodologies described in the chapter 5.

4.1 Number of publications and the topics of interest

There were 226 papers reviewed in this SLR. Of these 62.4% were reactive protocols, 17.3% were proactive protocols and 20.4% were hybrid protocols. In Figure 2 the yearly number of publications for each protocol class is presented. From the figure it is observed that proactive and hybrid protocols have insignificant variations in the number of yearly publications compared to reactive protocols. The linear regression analysis indicates significant decrease for reactive routing protocols (-2.49, $p = 0.0047$, $R^2 = 0{,}76$). The analysis does not indicate significant results for proactive (0.083, $p = 0.83$, $R^2 = 0.0084$) or hybrid (0.15, $p = 0.75$, $R^2 = 0.018$) protocols. Overall, the number of publications has seen a 46% decrease from 2017 to 2024. While the reduction of publications considering reactive protocols is partially responsible for it, the algorithm type also plays into it.

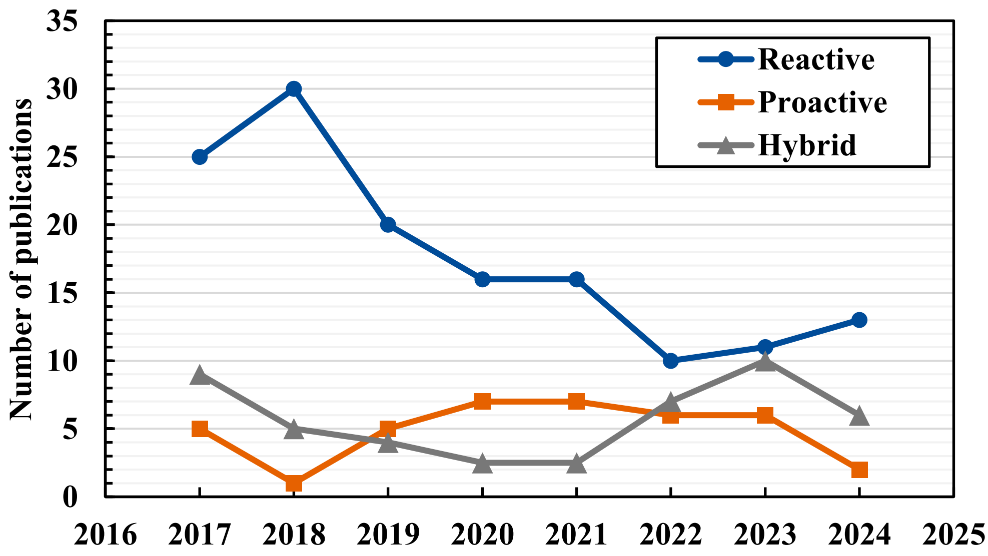

Figure 2 Yearly number of published papers for each type of protocol. Years 2020 and 2021 are normalised

The reduction in number of publications can also be seen when comparing traditional and modern routing algorithms as described in chapter 3.3. From Figure 3 we observed that traditional algorithms decrease over the observation period while modern routing algorithms fluctuates with an insignificant overall increase. The linear regression analysis on traditional routing algorithms shows a statistically significant negative slope (–2.46, $p = 0.00087$, $R^2 = 0.86$), suggesting a consistent downward trend over the observation period. The same analysis showed insignificant trend for the modern algorithms.

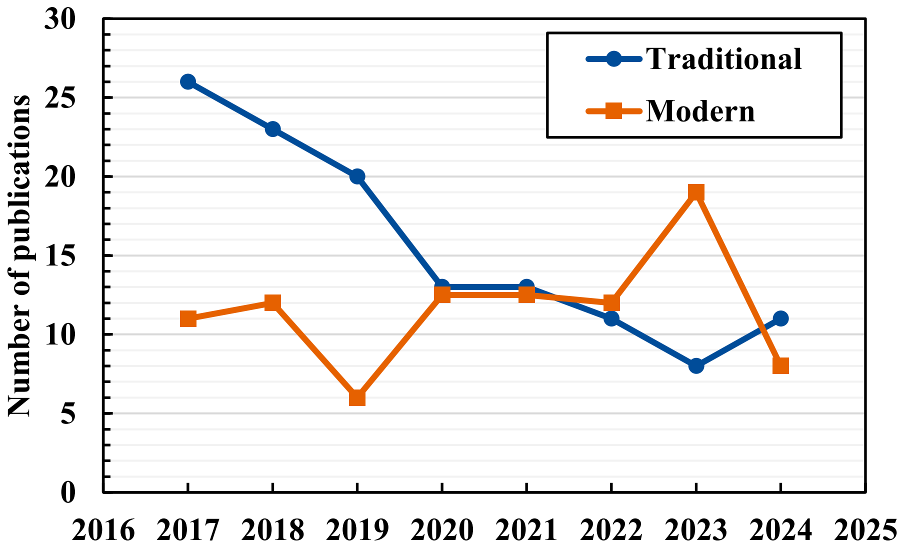

Figure 3 Number of protocols utilising traditional and modern algorithms. 2020 and 2021 are normalised

Comparing the significance of traditional algorithms to reactive routing it can be seen that they both describe the decrease in the number of overall publications with traditional algorithms being the stronger one. Reactive protocols using traditional algorithms do not however show significant correlation with only 56.3% of reactive protocols utilize them.

The primary objective of the reviewed papers were divided into keywords further discussed in chapter 4.3. There wasn't significant correlation between any single keywords to the number of papers.

The median and mean citations for reactive (median: 5, mean: 12.3), proactive (median: 4, mean: 11.0), and hybrid (median: 9, mean: 13.5) protocols indicate that the research on hybrid protocols has attracted quality papers. When we consider the top twenty cited papers, we notice that 11 of them are reactive, 4 are proactive, and 5 are hybrid protocols. Hybrid and proactive are slightly more represented than their portion of the whole dataset strengthening the observation.

The median and mean citations for modern algorithms were 6 and 11.17 respectively. The same values for modern algorithms were 5 and 14.01 respectively not indicating significant differences. This combined with the recent increase in the number of publications considering modern algorithms does however indicate increased interest, as older papers tend to have more citations. The analysis within modern algorithms yielded similar results. Of the twenty most citated papers 8 used traditional algorithms, 8 used machine learning algorithms and 5 used bio-inspired algorithms with one bio-inspired and ML combo. Das and Tripathi [48] has by far the most citated paper with 120 citations. The proposed energy efficient protocol is a reactive protocol utilising AODV and ML.

4.2 Scalable routing

Scalability was determined to be a significant requirement for tactical MANETs in chapter 1.1. The reviewed dataset does not confirm this significance as only one paper had scalability as the primary objective. We utilised the maximum number of nodes used in simulations as a metric to estimate the scalability of each proposed protocol.

The inclusion of simulations was one of the inclusion criteria in the SLR and hence all reviewed papers included simulations. However, eight of the papers included simulations but did not mention the size of the node pool in them. These papers are omitted from this data.

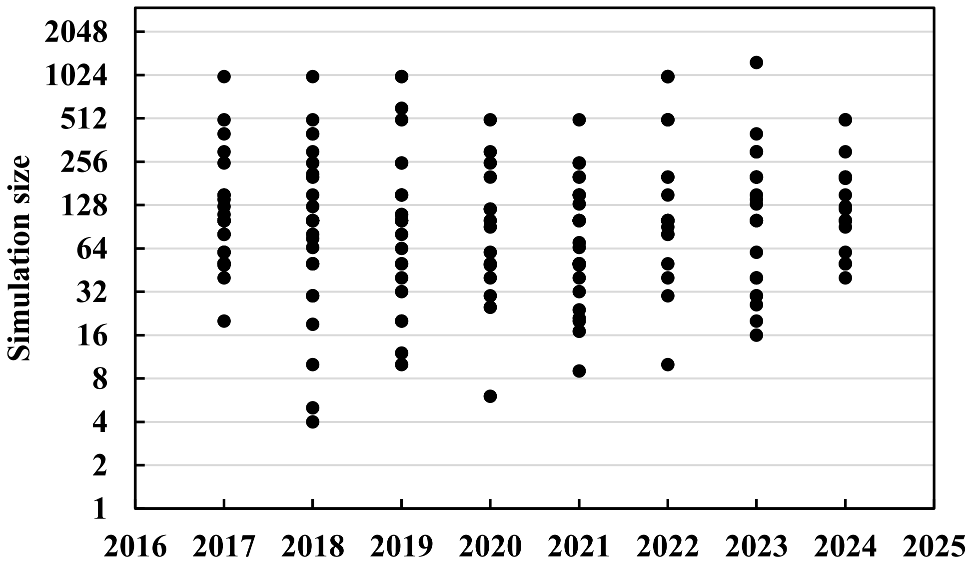

Figure 4 The simulation sizes in a logarithmic scale by year for the whole dataset

The whole dataset shows no significant increase in the simulation sizes over the observation period seen in Figure 4. Regression analysis shows that the whole dataset has a positive slope

(7.11, p = 0,24, R^2 = 0.0064). The large variation in simulation sizes within the dataset decreases the accuracy of the analysis and makes the positive slope non-significant ($p > 0.05$). Of the three protocol classes, non has significant slope and all have poor model fit. Hybrid protocols (23.95, p = 0.18, R^2 = 0.043) and proactive protocols (11.02, p = 0.45, R^2 = 0.017) have positive slope while reactive protocols (-2.31, p = 0.72, R^2 = 0.00095) has negative slope. Hybrid protocols has the least variation of the three but still enough to be non-significant. Significant slope wasn't found neither for the top 25% nor the bottom 25% of the simulation sizes for the whole dataset.

There were 23 papers with simulation size greater or equal to 400 nodes. 11 protocols were reactive, 9 were hybrid, and 3 were proactive. Hybrid protocols are represented more than their share of the whole dataset while proactive protocols are represented less. This indicates weak correlation between scalability and hybrid protocols and no correlation in the other two. One of the overall aims for hybrid protocols is scalability and this finding seems to support that.

In Figure 5 the simulation sizes for traditional and modern routing algorithms are compared. In the figure an increasing trend can be observed for modern algorithms. The regression analysis shows significant increase even though the model only explains 4.7% of the variation in the dataset (18.17, p = 0.036, R^2 = 0.047). The traditional algorithms has non-significant slope indistinguishable from random variation (-1.47, p = 0.87, R^2 = 0.00022). The increased simulation sizes indicate increased maturity for the modern algorithms leading to better scalability.

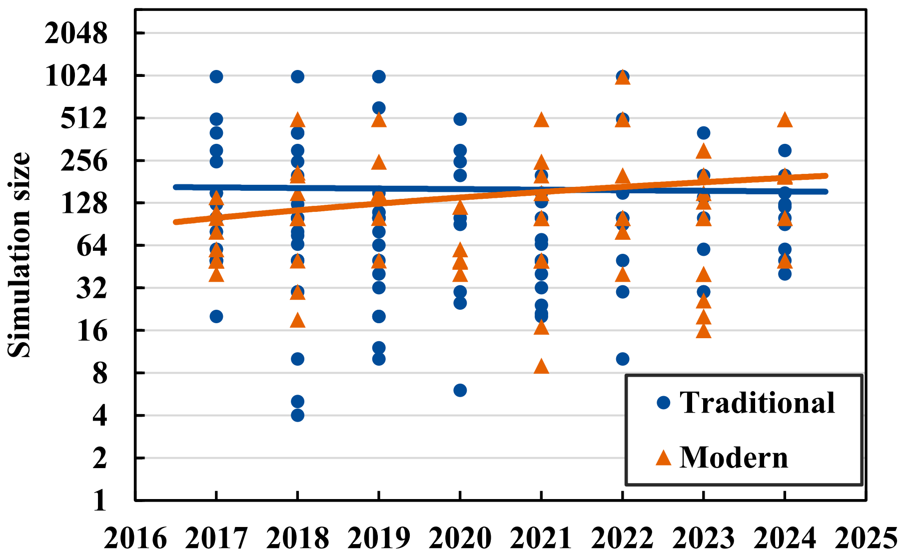

Figure 5 Simulation sizes for modern and traditional routing algorithms in logarithmic scale with linear trendlines

Of the 23 papers with highest simulation sizes 14 of the papers utilised traditional algorithms and 9 modern ones, of which 7 were bio-inspired and 2 were physics based. The first ML based protocol was a bio-inspired and ML combo with simulation size of 300. The first pure ML based protocol had simulation size of 210. The median node count in simulations for both routing algorithm types and all three protocol classes was 100 nodes. The same can be observed when considering the different sub-types of modern routing algorithms. This indicates that most of the interest in the research is on networks around 100 nodes. The comparatively small maximum simulation size for ML-based algorithms indicate that even though it is a research interest, the solutions are yet immature and more computationally heavy.

The size of the simulations does not show correlation to the number of citations as seen in Figure 6. Since the simulation sizes have not increased significantly in the observation period as seen in Figure 4, the newer publications with less citations does not skew the graph. A slight concentration of papers can be observer in Figure 6 at the 100 nodes size area compared to citations. This further strengthens the trend that the research interest is concentrated at about 100 nodes.

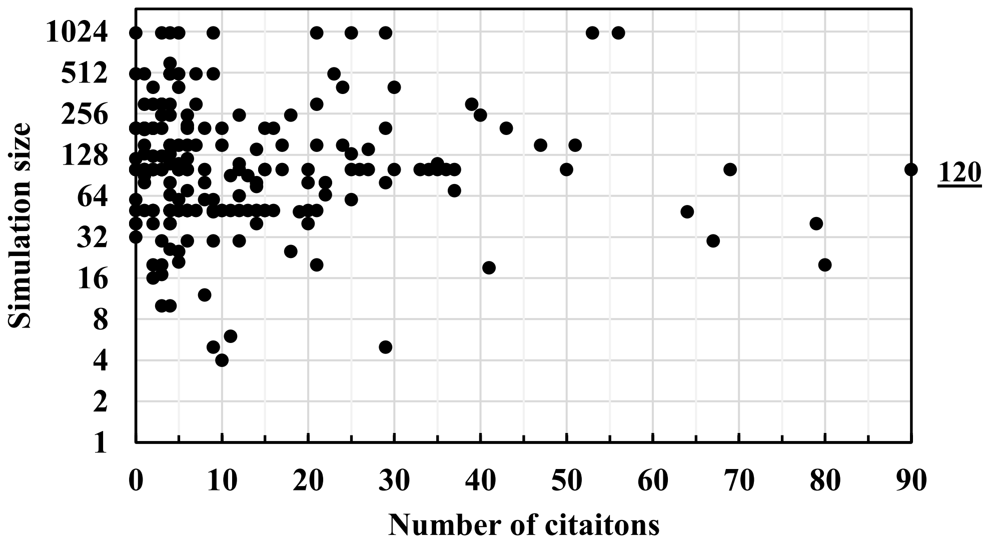

Figure 6 Size of simulations to number of citations in vertically logarithmic scale

4.3 Keywords on research

The research objectives of the reviewed papers were divided into keywords presented in Figure 7. There is overlap between the keywords, for example increasing energy efficiency usually ends up increasing network lifetime. However, network lifetime can also be increased by increasing the network size, making it distinct from pure energy efficiency objective. Similarly, Quality of Service (QoS) may be increased by avoiding congestion. This does not however inherently mean that different data has priority over others, which is a pivotal aspect of QoS routing. Distinguishing the keywords resulted in more detailed discussion in chapter 5. The keyword *other* includes papers with unique objectives from the rest deemed not to be part of any trends.

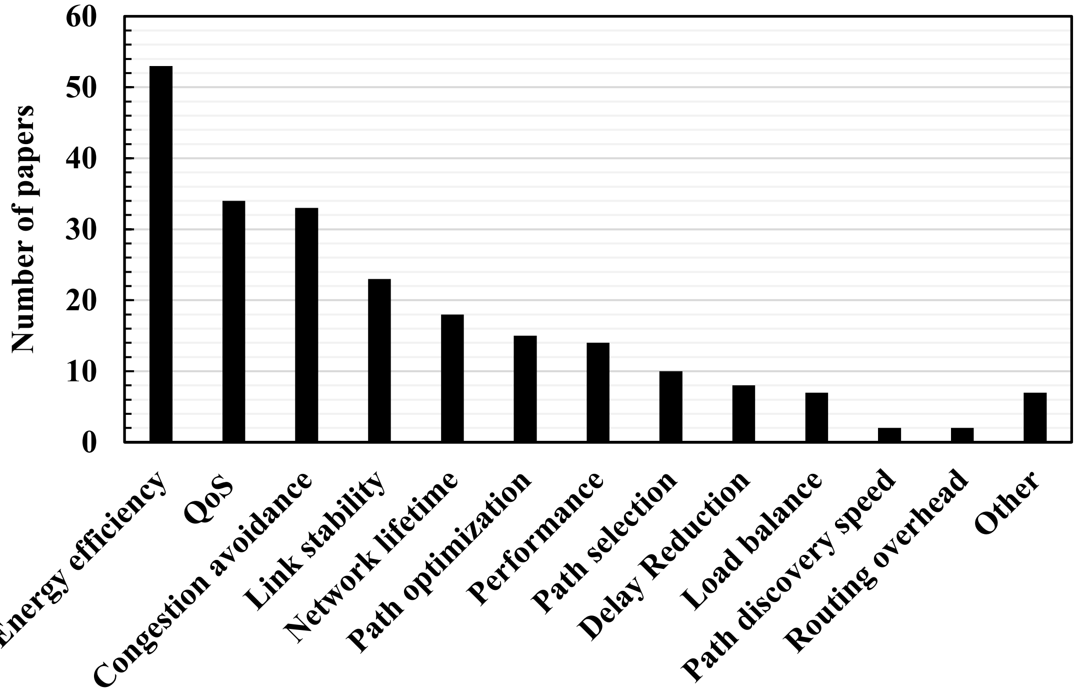

Figure 7 Number of papers for each primary objective keyword

Figure 7 shows that energy efficiency is the most attractive research objective followed by QoS, congestion avoidance, link stability and network lifetime. We analysed the five most common keywords further. The top 5 keywords make up 71.2% of the reviewed papers. The top five most common objective keywords conform to the common protocol limitations discussed in chapter 3.2.

Figure 8 presents the ratio of papers concerned with each of the top five keywords for each protocol class. Hybrid protocols show significant priority for energy efficiency. This follows the finding from chapter 3.2 that hybrid protocols tend to be energy inefficient. Similarly, congestion avoidance was found to be a strength of hybrid protocols due to the clustering of networks which leads to lower interest in it compared to the other two protocol classes. Reactive protocols are more evenly distributed but favour energy efficiency with nearly a quarter of the papers. Proactive is similarly distributed to reactive with slight favour to congestion avoidance.

Proactive protocols have the highest native congestion levels due to the periodical control messages, and this shows in the interest of researching it.

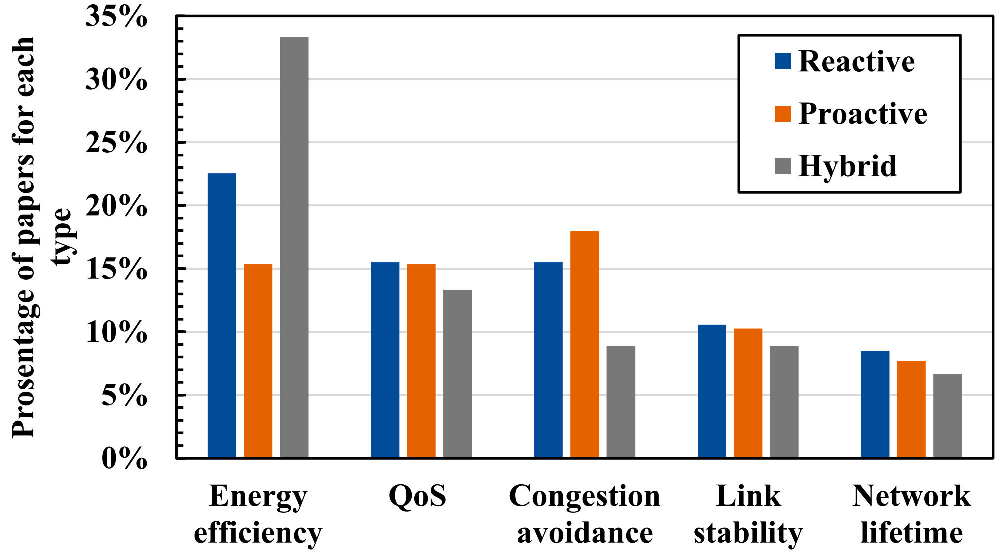

Figure 8 Percentage of papers focused on each keyword

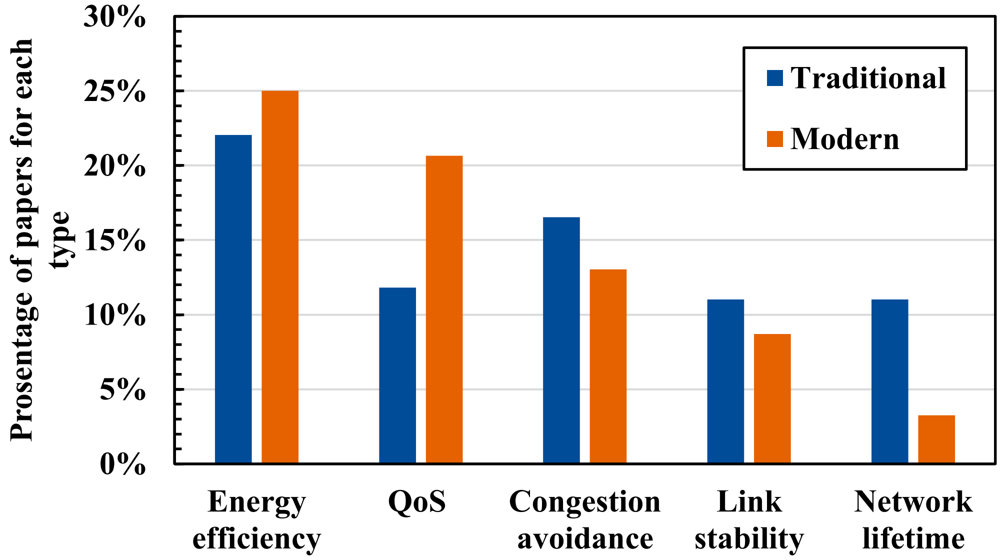

Figure 9 Percentage of papers with primary objective for traditional and modern algorithms

Figure 9 presents the percentage of publications with traditional and modern algorithms for each of the top five keywords. Protocols utilising traditional algorithms favour energy efficiency but greatly disfavour QoS. Modern algorithms also favour energy efficiency, but QoS is more prominent in them. Majority of the energy efficiency research was done on bio-inspired algorithms which were found to be energy inefficient in chapter 3.3. ML-based algorithms focused on QoS, and physics based on energy efficiency. Modern algorithms process network metrics used in QoS routing better than traditional algorithms. This is one of the reasons traditional algorithms are focused elsewhere from QoS. This is further discussed in chapter 5.

4.4 Research by publishers

General MANETs are an interesting research topic in Europe, Asia, the Middle East, Africa and North America. Figure 10 presents the number of publications where authors are affiliated with an organization in each country. Author(s) affiliated with Indian organisations dominates the dataset with 59.7% of publications having at least one author from India.

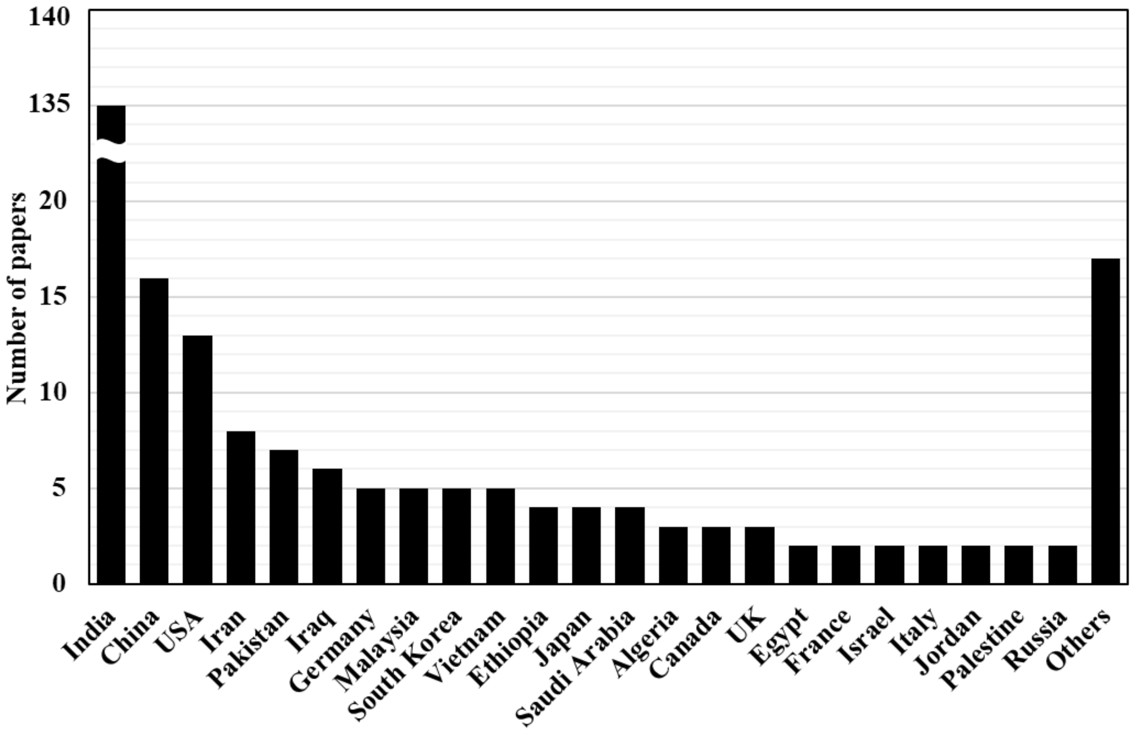

Figure 10 Total number of publications by country. The number of Indian publications are cut.

There were 122 publications with only Indian authors found in the dataset. There were also 13 publications where Indian authors are co-authored with authors from Iraq, Ethiopia, Jordan, Saudi Arabia, UK, Vietnam, Italy, Malaysia, Egypt, and Pakistan. Along with India, the other top five countries with authors affiliated with them are China, USA, Iran, and Pakistan. Together the top 5 countries are present in 178 papers (78.8%) with only one overlapping paper. The category *others* in Figure 10 include nations which were represented only once in the dataset. These include Bangladesh, Belgium, Brazil, Bulgaria, Ecuador, Finland, Mexico, Nigeria, Portugal, Slovakia, Spain, Sri Lanka, Switzerland, Syria, Taiwan, Thailand, and Turkey.

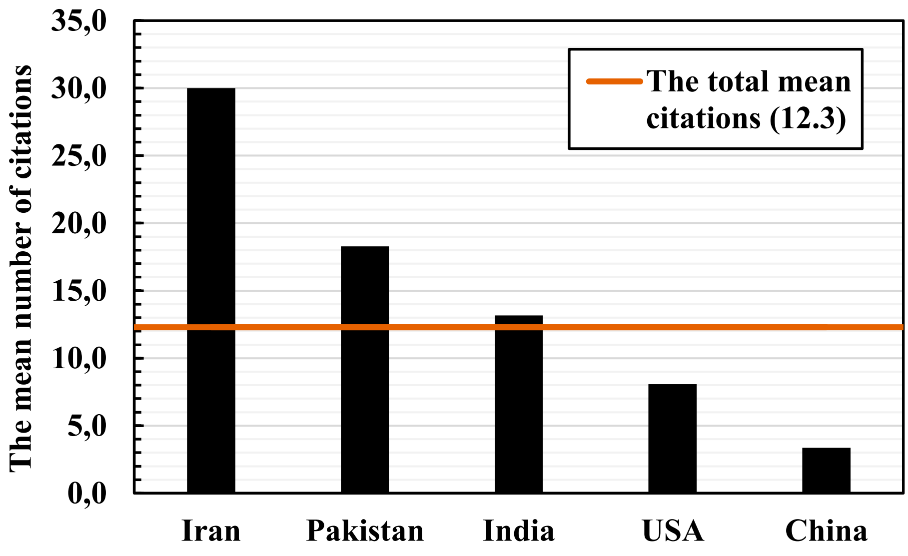

Figure 11 Mean number of citations per publications by country

Figure 11 presents the mean citations for the top five countries. The mean citations per paper for the whole dataset is 12.3. From the figure it can be observed that since India is represented in over half the paper, their mean citations steer the overall mean. Of the other four top5 countries, Iran and Pakistan have significantly higher mean citations while USA and China have significantly lower. Similar outcome can be obtained from Figure 12, where the ratio of papers which have over the mean number of citations are presented. Overall, 31.0% of papers were cited more than 12 times. Iran and Pakistan can be again observed to be more influential than USA and China. Especially Iran, with only 8 total papers published, can be seen as disproportionately influential on the field. The median citations also show influence of Iran and Pakistan. The mean citations for the top five are Iran (16.5, n = 8), Pakistan (22, n = 7), India (6, n = 135), USA(5, n = 13), and China (3, n = 16). The relatively low sample size of the other four countries in the top5 results in non-conclusive results.

Even though India was greatly represented in the dataset, there wasn't any single institution or author that had significant number of papers. Only seven authors were identified in the dataset having published more than two papers: Beongku An, E. Golden Julie, Ming Lei, S. Venkatasubramanian, Thong-Nhat Tran, Toan-Van Nguyen, Y. Harold Robinson. All authors have published three papers. These authors represent South Korea, China, and India. The Koreans, Beongku An, Thong-Nhat Tran, and Toan-Van Nguyen however author the same three papers. The approaches of the three papers are also similar, suggesting that the three authors worked as a research group on a project. Similarly, E. Golden Julie and Y. Harold

Robinson authored the same three papers although those have different approaches to routing. None of the institutions were mentioned more than three times.

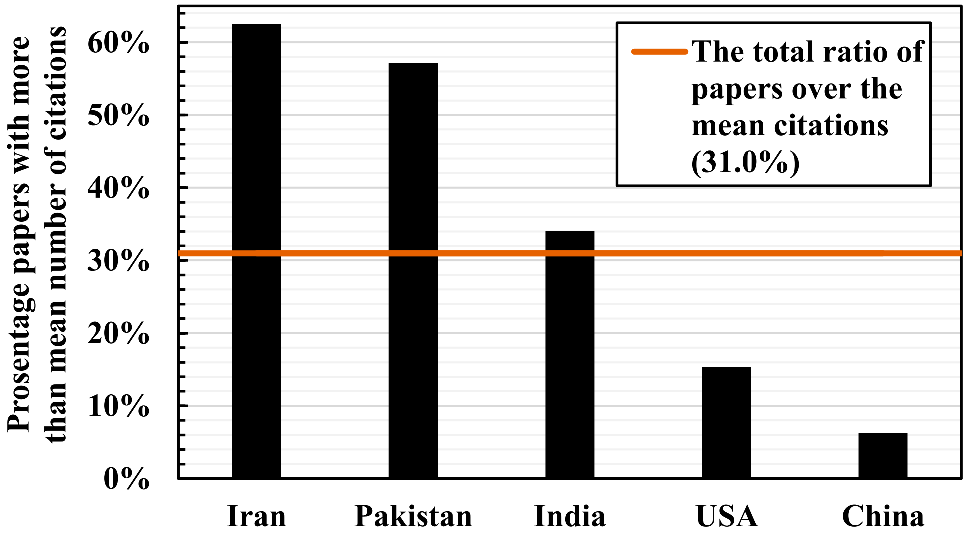

Figure 12 Ratio of publications with over the mean citations (12.3) to total number of publications by country

Along academic institutions, eleven of the first authors of papers represented a non-academic organization. The organization were state affiliated military or tech industries from the USA, Israel, Germany, China, and India. Two military institutions: German Bundeswehr University (n = 3) and Chinese National University of Defense Technology (n = 1) were identified. The non-academic institutions performed below the mean citations averaging only 4.9 citations per publication. The military institutions averaged 6 citations per publication also leaving below the mean citations for the whole dataset.

5 Results and discussion

The reviewed papers used numerous approaches to enhance several aspects of the routing protocols. The rest of this chapter summarizes the methods used and gives discussion on the trends found.

5.1 Trending research topics and their methods

This sub-chapter represents the methods to achieve the research objectives found in the reviewed papers. The driving force of all the solutions is to increase the reliability of the network which was found to be an important aspect of tactical networks in chapter 1.1. The rest of this chapter presents brief descriptions on how the papers achieved their objectives.

5.1.1 Energy efficiency

This sub-chapter presents the papers which primarily focus on energy efficiency. This chapter being the largest is divided into the three main protocol classes.

5.1.1.1 Proactive

Energy efficiency in proactive protocols was typically addressed by incorporating energy and mobility metrics, with OLSR most frequently serving as the base protocol.

Jain [49] proposed a modified OLSR protocol that integrates Ant Colony Optimization (ACO) into path selection. Here, node energy consumption and projected lifetime enhance the pheromone trails, and parameters are adjusted upon first path use to reduce repeated usage. Lavanya et al. [50] adapted OLSR to account for node mobility, employing Location-Aided Routing (LAR) to identify energy-efficient multipath routes. Yamini et al. [51] modified OLSRv2 by monitoring two-hop energy levels, using this information in MPR selection. If a change in neighbouring nodes is observed, the node recalculates its MPRs.

Mehta [52] presented a modified DSDV with a cross-layer design, applying Huffman coding in the presentation layer to estimate packet success probability from link-layer signal data, which is then used for path selection. Kumar et al. [53] also proposed a cross-layer approach, selecting the optimal path based on node energy levels, communication cost, mobility, and data success rate. Goswami et al. [54] proposed the Mine Blast Algorithm (MBA), which optimizes link cost, path loss, and energy consumption by identifying an “initial blast zone” from which the search space is explored.

5.1.1.2 Hybrid

In hybrid protocols, using energy metrics is common way to enhance the energy efficiency. Physical locations of nodes are also used in multiple papers.

Hybrid protocols were often found to enhance energy efficiency by incorporating energy metrics, and many also make use of node physical location data. Several studies [25, 56-60] used node locations for clustering, cluster head (CH) selection, or improving path energy efficiency

Selvi and Ghanadhas [55] modified ZRP by forming clusters based on node locations and selecting CHs according to energy levels. They also used packet drop likelihood as a QoS metric, incorporating drop rates into path selection. Qabajeh et al. [56] likewise leveraged node location, sending directional RREQ messages toward the destination and defining borders outside which nodes discard RREQs. Gopalan [57] enhanced ZRP using the Dynamic Cuckoo Search (DCS) algorithm, where node locations form clusters and energy metrics guide path selection. Baseera et al. [24] divided the network into hexagonal zones using location data, selecting relay nodes closest to a straight line between source and destination.

Other location-based protocols used location data to control transmission power of nodes. Femila and Beno [58] created temporary clusters during path discovery using location data to adjust transmission power, while Malyadri and Ramakrishna [59] had nodes periodically exchange location information to adjust transmission power levels.

Jabbar et al. [60] modified Multi-Path OLSRv2 (MP-OLSRv2) using a cross-layer approach, computing multiple paths on demand while periodically exchanging routing information. This method incorporates network lifetime and queuing models to select MPRs for energy efficiency. Kumar et al. [61] and Bandani et al. [62] included energy levels in CH selection, with Bandani et al. also applying energy metrics in path selection. Pramodhini et al. [63] used energy levels, communication cost, network load, and hop count, applying Carpet Weaving Optimization (CWO) in CH and path selection. Tamizharasu and Kalpana [64] combined energy consumption and reserves, node location and density, and stability metrics in CH selection via Adaptive PSO (APSO). If a CH’s energy falls below a threshold in their approach, an alternative CH is selected, with AODV used within clusters. Chaudhari et al. [65] incorporated communication range, processing power, and energy level in clustering, CH selection, and path determination, updating routing tables both periodically and from CH initiative.

Devi et al. [66] used fuzzy logic to choose relay nodes, considering distance to destination, congestion, energy level, and number of neighbours, first selecting CHs, then the optimal path. Mehta et al. [67] improved ZRP through random CH selection, reducing control traffic and collisions, thereby improving energy efficiency. Preethi and Sughasiny [68] applied game theory to estimate energy consumption of nodes within a path, selecting the lowest-energy option after inter-cluster path discovery

Sreenivasu and Anil [69] used a Firefly-based approach where lower energy consumption produces “brighter” nodes, making them more favourable for routing; a central controller determines brightness, but nodes establish paths on demand.

5.1.1.3 Reactive

Reactive protocols frequently try to enhance energy efficiency by incorporating energy metrics to avoid low-energy nodes, reduce control messages, and balance power use. The most commonly adapted reactive protocols were AODV, AOMDV, and DSR.

AODV was modified in numerous works [71-80]. Rashid et al. [70] included node energy, estimated consumption, and mobility in RREP messages. Pariselvam et al. [71] added RSSI values from previous nodes into RREP messages. Ogawa et al. [72] introduced adding energy metrics in the RREQ messages. Destination node then initiates backtracking where nodes compare next-hop energy levels to neighbours and switch paths if a neighbour has higher energy, ensuring at least one viable path. Vanjale et al. [73] also appended energy levels to RREQ messages, allowing destinations to choose the highest total energy path. Bhattacharyya et al. [74] combined hop count with energy levels making an energy-to-hop ratio metric. Nabati et al. [75] added traffic rate, stability ratio, and energy rate to RREQ messages, applying a Genetic Algorithm (GA) when more than three paths were found. Tiwari and Kaur [76] introduced a threshold energy level, rejecting nodes below it during path discovery. Li et al. [77] accumulated path costs in RREQ messages. Comparing the different paths, higher-cost options could be discarded. Lane et al. [78] adapted EA-AODV where physical location is appended into RREQ messages. In the protocol energy levels and total path energy are also used. Roy and Chouhan [79] prioritized forwarding RREQs to nodes with higher neighbour density.

AOMDV was adapted in [81-84] for energy efficiency. Satav and Jawandhiya [80] added energy levels of all relay nodes to RREQ messages. The energy levels are recalculated every cycle to balance consumption. Shah et al. [81] used GA with node energy and hop count for path selection. Chen et al. [82] appended MAC-layer queue length, residual energy, and hop count in RREQ messages. Each relay node only forwards RREQ messages with lower cost than previously received for the same path. Benakappa and Kiran [83] added energy and RSSI-based distance to RREQ messages, enabling per-hop power adjustment.

Node-disjoint multipath discovery similar to AOMDV also appeared in [84] and [85]. Kumar and Kukunuru [84] applied simulated annealing with network load, energy drain rate, and link availability metrics. Bheemalingaiah et al. [85] modified Multipath DSR (MDSR) to incorporate residual energy metrics in node-disjoint path discovery.

Bio-inspired algorithms were used to enhance energy efficiency. Dsouza and Manjaiah [86], [87], added energy metrics to the pheromone cost function in Simple Ant Routing Algorithm (SARA). Shafi and Ratnam [88] combined energy levels, delay, stability, congestion, and hop count into ACO-based pheromone calculations, appending these metrics to RREQ messages. Li et al. [89] developed a greedy forwarding protocol with modified deflection and bypass forwarding, considering deflection angle, residual energy, link quality, and location. Kumar et al. [90] applied PSO-driven energy metric selection to TORA, while Garg et al. [91] applied cached RREQ messages in TORA where recurring and below energy threshold nodes are dropped from the path. Nallusamy and Sabari [92] applied PSO using location data to calculate distances and energy metrics. Karmel et al. [93] designed an ACO-based routing protocol that integrates delay, drain rate, link quality, and congestion into the pheromone trail updates. Saravanan et al. [94] combined Fire Hawk Optimization (FHO) and Osprey Optimization Algorithm (OOA), using energy, delay, and throughput metrics. Venkatasubramanian [95] enhanced DSR with the Fruit Fly Algorithm (FFA) and energy metric for energy-optimized path selection.

Maleki et al. [96] formulated energy-efficient routing as a Markov Decision Problem (MDP) and proposed a Reinforcement Learning (RL) model incorporating node mobility, link quality, and residual energy. The model combines local learning with shared neighbour observations to determine optimal paths. Das and Tripathi [48] introduced the Intelligent Energy-aware Efficient Routing (IE2R) protocol, applying Multi-Criteria Decision Making (MCDM) and Intuitionistic Fuzzy Soft Set (IFSS) to process energy, delay, hop count, and distance metrics for optimal route selection. Amiri-Doomari et al. [97] proposed the Stable and Reliable Link-aware Cognitive (SRLC) protocol for cognitive radio MANETs. The protocol selects stable paths and frequency-time slots using the cognitive radio and proactively considers node energy levels as metric. Shanmugham et al. [98] implemented fuzzy logic, incorporating residual energy, packet delivery ratio (PDR), and mobility; cross-layer functions estimate the metrics for a fitness function. Adhvaryu [99] adapted Expanding Ring Search (ESR) to alternate between broadcast and unicast when increasing TTL, reducing packet processing.

5.1.2 Quality of Service

Quality of Service (QoS) refers to the network's ability to prioritise traffic by some metric. Some proposed protocols used the traditional protocol for general traffic and the proposed novel approach for priority traffic. Most QoS-focused studies adapted AODV or AOMDV [100-110].

Singh et al. [100], Verma et al. [101], and Gawas et al. [102] took a cross-layer approach using RSSI as a QoS metric. Gawas et al. combined RSSI with energy levels, while Verma et al. added congestion and delay. In each case, nodes appended metric data to RREQ messages. Chaudhary et al, [103], Tamizharasi et al. [104], and Kumari and Sahana [105] incorporated bio-inspired algorithms into AODV. Chaudhary et al. appended energy and congestion levels to RREP messages, applying a seal-hunting–inspired algorithm for path selection. Kumari and Sahana combined ACO for initial path discovery with PSO for local recovery upon link breakage. Tamizharasi et al. used an Invasive Weed Optimization (IWO) algorithm in RREQ message propagation in AODV, and a Deep Residual Neural Network (DRNN) in optimal path selection.

Temesgen et al. [106] applied Q-learning to prioritise low-latency paths for critical data, adding queue length to RREQs and returning the path with the smallest total queue length. El Attar and El-Emary [107] monitored node energy during transmission, with nodes below 20% energy requesting to be removed from paths. Choudhury et al. [108] modified AOMDV with clustering. The network clustering was done via a Modified Bird Mating Optimization (MBMO) algorithm and CH selection via Mine Blast Optimization (MBO). Hierarchical Decision Tree–based DNN was used for inter-cluster routing. Lokare et al. [109] applied fuzzy logic with the TOPSIS method, using reliability, bandwidth, delay, and jitter as metrics on top of AOMDV. Kalpana and Karthik [110] modified AOMDV to enforce bandwidth thresholds based on data priority, with desired bandwidth specified in RREQs.

Zaghal et al. [111] introduced QoS into AOMDV at the data link layer using InfiniBand virtual links. Gurumoorthy and Kumar [112] created a GA-based hybrid protocol with clustering via Recommendation Preference Clustering (RPC), selecting CHs based on bandwidth, delay, and connectivity, and using the same metrics for GA-driven routing. Rao and Singh [113] combined K-means clustering with Firefly optimization for CH selection. Murugan and Anita [114] applied GA in a cross-layer DSDV approach, estimating link stability from signal data and factoring in node and neighbour energy levels.

Saritha et al. [115] differentiated between real-time and non-real-time traffic, adding XOR-coded redundancy packet to non-real-time messages. This allowed losing one packet in the transmission without need for retransmissions. Hendriks et al. [116] employed multi-agent reinforcement learning (Q-learning) in a hybrid protocol, where nodes learn optimal one-hop transmissions via both control and data traffic. Kohlstruck et al. [117] estimated link reliability statistically from global topology and link quality data, defining minimum required transmissions to achieve reliability. Jain and Kashyap [118] enhanced OLSR by factoring link stability into MPR willingness calculations, using node energy and consumption rate.

Streit et al. [119] proposed an SDN protocol where a central controller builds a tree topology with periodic control messages, while child nodes report neighbours; the reactive delivery method is not fully detailed. Karthick and Asokan [120] formed clusters using Improved Animal Migration Optimization (IAMO), selected CHs based on multiple metrics, and performed path discovery via Improved ACO (IACO). Suganya and David [121] used a Deep Convoluted Neural Network (DCNN) to optimise data transfer rate based on payload length, link quality, throughput, and other metrics at constant False Error Rate (FER). Kim et al. [122] proposed a proactive OLSRv2 and NeighbourHood Discovery Protocol (NHDP) based protocol using bandwidth utilisation and projected load for path selection, adjusting data rates via radio channel occupancy during transmission.

Sarangi and Panda [123] applied ACO to a reactive protocol, using bandwidth in pheromone calculations and adding path maintenance to mitigate link breakage effects. Baskaran and Karuppasamy [124] used bandwidth and delay as QoS metrics in reactive multipath routing. Jiang et al. [125] proposed a two-step SDN QoS protocol, first predicting link quality via Wavelet Neural Networks (WNN), then optimising paths with differential search. Nguyen et al. [126] introduced a deep RL (DRL)–based cognitive radio MANET protocol, where DRL evaluates link quality from physical-layer parameters and restricts RREQ forwarding to the lowest-cost neighbour. The same team proposed [127] with minor changes.

Prashanth and Senthil [128] modelled Dynamic Power Management as a Markov decision process, using a hidden Markov model with Lagrange relaxation to optimise resource allocation without degrading quality. Subbaiah et al. [129] factored mobility, neighbour count, and energy into CH selection. Revathi et al. [130] used cuckoo search and hill climbing for path discovery, optimising for CH congestion. Aruna et al. [131] evaluated jitter, PDR, execution time, and delay in SDN-based QoS. Li et al. [132] combined Time Division Multiple Access (TDMA) and DNN, using smart antennas to sense the network and dynamically alter routing strategies. Kamarunisha and Vimalanand [133] selected paths using delay and mobility metrics.

5.1.3 Congestion avoidance

Both proactive and reactive routing protocols were researched with congestion avoidance as the primary objective.

Glam et al. [134] proposed using modifying OLSR with neighbour information to determine the least congestion inducing paths. The MPRs are chosen such that the coverage does not hinder, but redundant control information is reduced. Vadivel and Bhaskaran [135] proposed proactive protocol that senses increased congestion and calculates multicast paths to distribute the traffic. The congestion indicator may also be sent by neighbouring nodes. The protocol uses cross-layer approach and RSSI to calculate the congestion. Maret et al. [136] used reinforcement learning to enhance the OLSR protocol. They used Q-learning to calculate rewards based on the current traffic queues of all nodes in the network. They also presented a modified version where Q-learning is used to predict the reward, making the learning process faster. The protocol is simulated in NATO IST-124 Anglova CP 1 scenario.

Glam et al. [137] also employed RL to impose congestion avoidance. The network was modelled as a MDP and the protocol used proactively shared cross-layer information to train the RL agent which chooses a forwarding policy based on those. The policy includes forwarding the message to one node, multiple nodes or withholding the messages. Shafigh et al. [138] proposed using fuzzy logic to make multicast routing selections. The protocol is independent of topology i.e. it can be deployed in either tree-based or mesh-based networks. The fuzzy logic uses PDR, and end-to-end delay gained through cross-layer techniques when choosing the least congested path. Tilwari et al. [139] proposed using node mobility, contention window size and link quality metrics with TOPSIS to optimise the path selection. Node mobility is calculated with location information and link quality with number of redundant messages.

Several papers modified AODV to account for congestion. Palmeri [140] used ring-search process in dense networks to regulate RREQ propagation by modelling acoustic sound waves. Probabilistic equations are used to calculate if the node relays the received RREQ based on the distance the message has travelled. Khayatbashi and Haghighat [141] modified AODV by broadcasting RREQ packets based on a probability function considering congestion, transmission overlap, connectivity, and survivability metrics. Ozen and Ozen [142] deployed a second routing table to be used only with emergency traffic. The emergency table includes nodes listed as emergency nodes which are less used and hence less congested. Akhtar et al. [143] avoided congestion proactively through HELLO messages by optimising bandwidth usage. Robinson et al. [144] also modified bandwidth usage but based on RSSI. By modifying the bandwidth usage, the network load can be balanced and congestion avoided. Deng and Tang [145] used node locations, congestion, and residual energy as path selection metrics. The nodes that do not meet the threshold values for these metrics silently drop the RREQs. Yadav and Firdaus [146] modified hierarchical AODV protocol which selects CHs based on the physical stability of the nodes. Sharma and Tharani [147] proposed modified AODV protocol that used ACO to make node-disjoint path discovery. Ullah et al. [148] proposed modified DSR where congestion and energy metrics are used. In the RREQ packets congestion and energy levels are appended. Relaying nodes use these to determine the quality of the path.

AOMDV was also modified in several papers. Jhajj et al. [149] proposed modifying multipath version of AODV (in paper called MAODV which is generally the abbreviation of multicast AODV [40]). The network has designated silent nodes that do not relay RREQ messages and are hence excluded from all paths they do not originate or are a destination of. Robinson et al. [150] increased AOMDV's path caching with buffers. The relaying nodes cache paths longer than in classic AOMDV and complete the path discovery by sending RREPs when they have the rest of the path cached. Prema and Divya [151] considered node mobility, RSSI, cooperative rate, and residual energy as metrics in two bio-inspired algorithms. Jain et al. [152] proposed using nodes' physical location and speed as metrics for AOMDV path selection. Bundela et al. [153] modified AOMDV with queue sensing algorithm. Packet drop rates for neighbouring nodes are estimated providing a queue model for the paths selection. Paths with heavily congested nodes are disregarded. Agrawal et al. [154] used Cuckoo Search (CS) to calculate link loads with delay, energy and hop count as metrics. The metric data is attached to the RREP messages of AOMDV path discovery process by the nodes selected in each path. Rathod and Gumaste [155] proposed using link queue length and residual energy metrics to dynamically switch between paths to avoid congestion. The protocol makes multipath routing decisions based on the metrics and may switch between paths if a node in the path becomes congested.

Bagirathan and Palanisamy [156] proposed bio-inspired optimization algorithms enhancing a hybrid protocol. The protocol gathers location information to determine the shortest path. Message caching similarly to OppNets are used to make the network less congested. Mohsin et al. [157] proposed reactive two fold framework where location is used to determine optimal broadcast direction and signal strength to detect congestion. Cross-layer routing is employed to receive signal strength and location information from neighbouring nodes. Pham et al. [158] proposed using location information to enhance ZRP. The physical locations are used to divide the zones into two hemispheres where the destination is in the middle of one of them. In case of reactive path finding the hemisphere containing the destination is used. Yoshihiro et al. [159] proposed protocol similar to ZRP where link-state routing is used in k-hop area from the node and distance-vectors outside of it. In the proposed protocol the source node has the full topology information of the network unlike in the ZRP.

Haq et al. [160] proposed network coding approach in their protocol. The source node determines whether to code the packets or not based on observed data rates. Traffic load and link cost are used in probabilistic function to determine if path discovery process needs to be reinitiated. Mallapur et al. [161] measured the ratio of data arrival rate to outgoing data rate in order to determine congestion level. Upon detecting congestion, the node chooses another path discovered in a reactive multipath discovery process. The node distributes traffic in multicast manner into the distinct paths. Alzaben and Engels [162] considered topology information secondary to congestion levels in the network. Longer paths are used when they provide lower overall congestion. The protocol also adopted pausing the message propagation similar to [137]. Akshay and Apoorva [163] proposed using compression on messages to reduce the congestion on the network. The protocol uses tree topology with multicasting to further congest the network. Dusia et al. [164] did not use any control messages in their protocol. After the network is initialised all nodes send messages by flooding the network. When nodes receive these messages, they cache the 2-hop nodes from the path and general direction to all the other nodes. The nodes then start unicasting to the presumed direction of the destination. Tahir et al. [165] deployed Distributed Hash Tables (DHT)-routing in hierarchical protocol. The number of neighbours dictate the CHs, and all the nodes in a cluster use the identifier of their CH rather than having their own. Zhang and Liu [166] proposed routing protocol that adopts principles of quantum physics. This quantum ad hoc network used quantum bits (qubits) to enhance on-demand routing protocol by adopting quantum state transmission to the route reply phase of the path discovery process. The network requires specific node devices equipped with quantum computing capabilities to function.

5.1.4 Link stability

Link stability is especially important consideration in sparce MANETs where links break more frequently.

Similarly to the previously presented objectives, AODV and AOMDV are prominent in link stability research as well. Darabkh and Judeh [167] added mobility information to HELLO messages in AODV and it is used in the path discovery process. With the added information the protocol is able to predicts link breakages and avoid links having high probability of breaking. Prabhavat et al. [168] predicted link breakages with path usage information. The relaying nodes inform the source node during the path discovery about their availability and usability. Prasad et al. [169] used traffic load and energy consumption of nodes to make a link stability estimation. HELLO messages are modified to include energy level information and traffic load. The load is calculated using the arrival times and packet sizes to determine the processing queue a neighbour has. Periyasamy and Karthikeyan [170] proposed adding node disjoint method to AOMDV path discovery. This approach increases link stability by not allowing single node to disrupt multiple paths which is prominent in sparce networks. RSSI shared during path discovery and maintenance is used to measure link quality which is used along with residual energy in path selection. Prakasi and Varalakshmi [171] proposed using node mobility, traffic delay, and residual energy with a data mining approach to modify AOMDV. The approach aims for local optima by selecting the most stable next hop neighbour. Sruthy and Geetha [172] modified AODV by storing multiple paths similar to AOMDV. Mallapur et al. [173] proposed using cross-layer approach to enhance link stability in MAODV. MAC-layer is used to dynamically modify the transmission rate and network layer is used to multicast the traffic. GPS is used to gain mobility information, and a link up-time is also tracked. Sirmollo et al. [174] used node mobility to modify AODV in order to predict link breakages. Node speed, distance, and residual energy are considered in path discovery process to select the most stable nodes to paths. Node mobility is achieved by GPS. Lavadya et al. [175]

modified AODV with mobility metric. Mobility is found through GPS and is used in path discovery.

Ghasemnezhad and Gaffari [176] determined near optimal sable paths with fuzzy logic. The metrics used in the fuzzification were bandwidth, node mobility gained through GPS, residual energy, and hop count. Singal et al. [177] used node location to estimate stable paths. Movement based link breakage estimation and link up-time measurement are used to determine stable links. The proposal specifically does not use GPS for mobility estimation. Hu and Sosorburam [178] used nodes' physical locations to stabilise the links in sparce networks. The nodes share two-hop location information which is then used to select the most likely stable relay node. Lin and Sun [179] also used node mobility model to predict the link stability. The protocol used RW mobility model and node traffic queue to determine the link stability. Nodes aim to find the farthest away node that satisfies the link stability threshold to be selected as next hop node.

Tran et al. [180] employed deep Q-learning decision making for multicasting. The protocol core works similarly to MAODV with Q-values added to decision making to impose link stability and lower delay into the paths. Cai et al. [181] used Intelligent Reflecting Surfaces (IRS), a type of relay antennas, to avoid obstacles and keep links alive longer. The protocol uses deep Q-learning to instruct the IRS modules to make the optimized relays. Gaffari [182] used Q-learning to solve the predictions about the quality of the next hop. The protocol uses only information about the neighbouring nodes in the predictions. Anuradha and Mala [183] used fuzzy logic to determine network events. When a link is determined to be unstable or likely broken the protocol switches to another path found in a multipath path discovery.

Amagata et al. [184] proposed using top-k data retrieval method in cluster formation where only necessary nodes receive the top-k data. This allows better reliability in sparce networks. Sayad et al. [185] estimated link quality with RSSI in a hybrid protocol. The changes in RSSI are also used to predict link breakages. Malwe et al. [186] calculated neighbour stability using RSSI and location information. The information is shared during path discovery and maintenance. Wang et al. [187] proposed a modified multipath DSDV protocol. The protocol finds node-disjoint paths and switches paths when a failure occurs or is imminent during path maintenance. Robinson et al. [188] predicted link quality using PSO and fuzzy logic. Bandwidth and node mobility are used in the fuzzification to determine the status of the relaying nodes. The status is then used with PSO to make a multipath selection. Kumar [189] used OSPF protocol and a link failure detection algorithm to provide stable and short paths. The failure detection functions by using periodical HELLO messages with node information to their neighbours. The protocol also uses honey-potting to lure and detect malicious nodes.

5.1.5 Network lifetime

Papers [190-195] used energy level metrics in AODV to increase the network lifetime. Quy et al. [190] also used path length metric to discourage long paths. Patel and Patel [191] used link stability metric to lower the need to re-discover paths in case of link breakage. Pandey and Singh [192] used RSSI based link quality awareness metric to maintain neighbour information. Ilango and Kumar [193] also used path quality to decrease redundant traffic and route traffic through nodes with high energy levels. The proposed protocol used multicasting to discover new paths during message transmission. Ahammed et al. [194] used delay metric to avoid using congested paths which cause imbalanced energy usage and lower network lifetime. Singla et al. [195] also used delay along with mobility and hop count metrics. The metrics were analysed using TOPSIS method to determine the path which decreases the network lifetime the least. Preetha and Unnikrishnan [196] used only signal strength to estimate the most reliable path.

Carty and Jayaweera [197] began sending traffic through the path before the path discovery process was completed. This blind routing speeds up the delay caused by AODV path discovery process. Ahmadzadeh and Bokharaeian [198] modified AODV with a probabilistic density function. The density function considers node density based on share information. Cuckoo Optimization Algorithm (COA) is used calculate near-optimal solution to the density function. Firmino et al. [199] added multiple routing tables to default AODV allowing multiple simultaneous paths and seamless transition between them. The protocol isn’t proprietary and works with nodes running default AODV. This allows certain central nodes to function as gateways decreasing redundant messages using up energy in the network. Sahu et al. [200] modified AOMDV to use clustering in path discovery. The protocol uses RSSI and energy metrics to determine the best paths. CH is selected and cluster formed if a node with high enough residual energy is found.

Alappatt and Prathap [201] increased the network lifetime using ACO and Binary PSO (BPSO) algorithms. ACO is used to identifying energy efficient paths and BPSO makes duty cycle selection to optimize energy consumption in the network. Thebiga and Pramila [202] calculated the best path using Emperor Penguin Optimization Algorithm (EPOA). Congestion, residual energy, and link stability were used as metrics. The protocol requires location information gained from GPS. Alkhayyat [203] proposed using bio-inspired Escape Strategy with Golden

Jackal Optimization to select energy efficient CHs. The proposed protocol reduces link breakages and optimizes energy efficiency.

Nsaif et al. [204] proposed using two disjoint paths and sending packets through both. The packet faster to the destination is used and the subsequent packet is discarded. While this seemingly increases the redundant traffic, ultimately it decreases traffic in networks with frequent link breakages when smaller number of resends is required. Bharti et al. [205] decreased the number of dropped packets using larger buffers. Nodes are coupled with one other node creating node pairs who share routed packets. If one node drops the packet, the other may still send it. Dhiviya et al. [206] used tree based topology and energy metrics to increase network lifetime. The tree topology lowers the number of redundant path discovery messages and energy metrics balance the load in the network. Streit et al. [207] used SDN-approach to regulate the network traffic. The protocol uses Dijkstra's algorithm for path finding with recent mobility information having higher weight. The location information is gained through GPS.

5.1.6 Others

This sub-chapter describes briefly the papers whose objectives did not fit the five main objectives. Several of the protocols were concerned with the selected path in multipath discovery to generally increase the performance of the network.

Kunz [208] aimed to reduce the congestion at the CH in hierarchical networks. The solution was to flood the inter-cluster network which functioned as a backbone. They also compared using OLSR in both inter- and intra-cluster routing and using AODV in inter-cluster routing. Of these three solutions AODV reduced congestion at the CH the most, closely followed by OLSR. Flooding was the most inefficient by large margin. Pirzadi et al. [209] reduced delays in the network by incorporating simulated annealing and extended buffers. The network was described as DTN-MANET used in rescue operations. In the protocol, stationary relays with large buffers are used to act as CHs.

Several bio-inspired protocols were identified with varying objectives. Sathyaprakash et al. [210] reduced delays using bio-inspired protocol. The protocol is improved version of Petal Ant Routing (PAR) which uses similar pheromone trails as ACO. The solution confines path discovery and data transmissions to inside a petal region, a physical area where source and destination limit the area. Chaudhry et al. [211] used forwarding zones to narrow down the path from source to destination and PSO to find out the near optimal path. The forwarding zones are calculated on-demand using location information. Dholey and Sinha [212] proposed using ACO to balance the network traffic. ACO is used in multipath path discovery and to optimize the multipath usage. The protocol uses either bandwidth and distance or energy and stability metrics in the path selection to balance the network resources. Sumitra et al. [213] used Genetic Algorithm (GA) and ACO to select the path with the best performance in terms of delay and PDR. The protocol uses buffer availability, loss rate, and channel load as metrics. Satyam et al. [214] used ACO in grid-based routing. The network is divided into physical grid-cells and every ant going through the grid increases its likelihood of nodes in the cell being selected into the path. Mekkaoui et al. [215] used differential evolution algorithm to select the best path. The path considers energy and link stability. The proposed link-disjoint multipath protocol is modification of AOMDV. Vanarasan et al. [216] introduced bio-inspired protocol that uses energy, bandwidth, delay, reliability, and quality metrics in path selection. Kout et al. [217] modified AODV with Cuckoo Search Algorithm (CSA). AODV is used to make preliminary path discovery. The hop count is used as a metric for the CSA path selection. Trivedi et al. [218] used Genetic Algorithm (GA) in AODV path discovery process increasing performance. Omran [219] optimised path selection in AODV with Fruit Fly Optimization (FFO). Venkatasubramanian and Hariprasath [220] enhanced AOMDV with Coyote optimiser to make the multipath selection. The metrics used were residual energy, distance, delay, and congestion. Alotaibi [221] used physical location, delay, link lifetime, packet loss, and evaluated risk metrics in a bio-inspired protocol. Verma et al. [222] used PSO and neural networks to make path selections. Rajadurai et al. [223] used GA to select the best secondary path if the initial path fails. The protocol enhances MAODV with multipath path discovery using tree topology. The GA used residual battery energy, time lag and bandwidth as metrics for path selection. DeVoe et al. [224] proposed a bio-inspired modification to OLSR. The protocol uses mathematical model on a slime mold to estimate the node willingness to forward packets. The protocol uses PSO to optimise the neural network using node distances, energy levels, and statistical metrics. Kumaresan et al. [225] proposed bio-inspired protocol that utilizes fuzzy logic when designating clusters and CHs. The protocol uses location information to form the clusters. Energy consumption and residual energy along with location information and link stability are used to select the optimal CH.

Machine learning approaches were found standalone from bio-inspired algorithms as well. Zhou et al. [226] used Double Deep Q-Network (DDQN) to configure IRS antennas and reduce delays caused by the configuration similarly to [181]. The proposed Q-learning approach is trained with experience of on-transit packets and allows intelligent energy consumption modifications and blind beamforming on the IRSs. Pal et al. [227] used neural networks to predict neighbourhood stability. The proposed node-disjoint multipath protocol balances traffic using multicasting based on the path stability metric. Yang and Li [228] used neural networks to make near-optimal path selection based on the mobility of the nodes. Yu and Sun [229] used deep Q-network to make path selection. The RL model used number of neighbours, available bandwidth and relative speed between current and the next hop node to calculate the reward function. Wang and Tang [230] used reinforcement learning to make path selection based on residual energy and link quality. Link quality is calculated from the number of periodical HELLO messages are received and compared to how many were supposed to be received. Hemalatha et al. [231] used fuzzy logic to make the path selection based on available bandwidth, node mobility, and residual energy. Feng and Xu [232] used online Q-learning to learn the mission specific mobility plan. The protocol aims to maximise the PDR and minimise delay. Hrabcak et al. Cai et al. [233] used double deep Q-learning to optimise path selection. The protocol uses number of neighbouring nodes, latency, and SNR as metrics which are formulated into MDP. [234] proposed using cognitive radios in MANTEs. The protocol uses fuzzy logic based on RSSI, Signal-to-Interference Ratio (SIR), and traffic load to make the path selection. The cognitive radio then senses the network and used bandwidth and channels optimally.

Sagduyu et al. [235] used the concept of social-cognitive connected nodes to reduce delays in the transmission. The social-cognitive metric consider the movement of the nodes such that they encounter each other in a predictable manner. Lal et al. [236] aimed to reduce delay and jitter to increase the user experience by using stable paths with a delay threshold. Path stability is calculated with Signal-to-Interface and Noice Ratio (SINR) and delay with MAC layer queue length measurements. The relaying nodes are determined with delivery history, estimated delay, and location information. Pushpalatha et al. [237] used thresholds for delay and hop counts to decrease the delay caused by store-carry-forward methods found in OppNets. The proposed protocol estimated the delay probabilities of different paths to significantly decrease the delay.

Amouris [238] aimed for infinite scalability with a flat and gateway-less topology. The protocol uses Spatial-Dimensional Multiple Access technique and combines it with Barrage Relay Network (BRN) technique. The network is on-demand in nature, but no stateful connection is established between the source and the destination. Location information is used to guide the message to the destination. Goyal et al. [239] reduced delay with combining First-In First-Out

(FIFO) policy with SDN technique and M/M/1 queueing model further explained in the paper. The network is hierarchical in nature where SDN controller makes the clustering and CH selections. Selvan et al. [240] used congestion and path cost to move traffic to another path balancing the traffic load. Depending on location information, the protocol either makes traditional on-demand path discovery, or in long distances, the path minimizes cost and congestion. Tilwari et al. [241] used mobility and queue length to determine congested paths and balance load to them. The protocol uses multipath Dijkstra's algorithm in path finding. The initial path is selected using least mobility and shortest queue length. Yadav [242] modelled routing algorithm based on the Fibonacci sequence. The protocol uses multipath distribution to balance the load on the network. In the protocol *n*-th Fibonacci number of packets are send through the first path where *n* is the number of paths found. Then n-1 -th Fibonacci number of packets are send through the second path and so on. Mohammed et al. [243] extended the AOMDV with dynamic path selection to balance the traffic in the network. The protocol uses hop count to initially select the routing path. If the initial path breaks, the traffic moves to the secondary path. The secondary path is also used in unison with the initial path if the hop count is identical to the initial path. Ngo and Xuan [244] used probabilistic load balancing in AODV. The protocol modified AODV by saving multiple paths similar to AOMDV and choosing between them. The probability of being selected as the path for data transmission is weighted with shorter paths having greater probability of being selected.

Soomro et al. [245] proposed using OLSR's mechanism of making connections while the destination answers the using AOMDV RREP message. This hybrid protocol takes advantage of the efficient sides of both OLSR and AOMDV protocols lowering the path formation time. Dorathy and Chandrasekaran [246] discovered two paths in the path discovery process and selected the one based on physical distance. In this modified AODV the destination node compares the distance values accumulated by the nodes in the path as opposed to hop count in the traditional AODV. Yadav et al. [247] used location information and radio gain to select a path that always goes closer to the destination node with every hop. Path stability is considered by using delay threshold to select the next hop relays. The protocol works by maximizing the transmitted distance of single hop. Astudillo and Kadoch [248] proposed protocol that takes advantage of adaptive smart antennas. The antennas can dynamically increase their transmission range by limiting the transmission area. The neighbour discovery process aims to select nodes with minimum hop count using the smart antennas to extend the transmission range into the direction of the neighbour. Location information is used to aid in the neighbour selection.

Venkatasubramanian et al. [249] modelled the path discovery process as a ring toss game. Distance, load, cost, and delay are used as metrics in the path discovery process. Pestin and Novikov [250] used hop count, path stability, and delay to make multipath path discovery and multicast routing. Kohlstruck and Gotzhein [251] used both proactive information gathering and reactive path discovery in their protocol. In the protocol nodes share their topology and reliability in terms of packet delivery ratio proactively allowing preliminary path discovery. Reactive routing is then used to select the best path of them. Lokare and Jadhav [252] modelled OppNets' packet delivery uncertainty as a Markov Decision Problem. The multipath path discovery is done using Packet Delivery Ratio (PDR) as a metric. Gawas et al. [253] proposed a cross-layer protocol that takes congestion and delay into account. The node-disjoint multipath protocol uses these metrics in path discovery and path selection. The protocol dynamically modifies data rates to alleviate congestion in relaying nodes. Sufian et al. [254] used energy and node mobility in multipath selection. The multicast protocol ranks several paths with the metric data and send data through the best paths. Gunasekaran et al. [255] used node connectivity, relay hop-count, and bandwidth for path selection.

Roy and Chouhan [256] proposed density aware routing protocol. The protocol considers node density when flooding path discovery requests. Only some designated nodes in areas with high node density are allowed to forward RREQ messages. This decreases the number of redundant control messages. Sharma et al. [257] enhanced AODV with more rigorous hop count analysis. In the protocol, hop count is appended to RREQs and if a node receives a path that it has previously seen with lower hop count, the node updates the routing table to exclude the node making a shortcut. Quy et al. [258] used throughput and delay as metrics in path selection. Biswas and Dasgupta [259] introduced combined AODV and DSR protocol. In the network, most nodes route with AODV and some nodes with DSR. This solution increases the performance of the network. Venu and Rahman [260] modified AODV with restricted and probabilistic flooding of RREQ messages. The protocol added residual energy and destination details into the RREQ message. The destination then chooses the nodes with sufficient energy to forward the packets. Gao et al. [261] modified AODV RREQ header to include average link load, average link speed, average link Signal to Noice Ratio (SNR), link transmission delay and packet sending time fields. The fields are used at the destination to make the path selection. Shukla et al. [262] used simulated annealing to modify the path discovery process in AODV.

Simulated annealing considers both optimal and sub-optimal paths during the path discovery process to reduce the risk of local optima being selected over global optimum. Hop count, latency and packet loss metrics are considered.

Mast et al. [263] used channel contention to determine functional paths. Previously contended paths were more likely valuable paths. The protocol detects changes in contention and if contention increases amid the transit the relaying nodes inform the source to switch paths. Alshaikh and Morie [264] used Multi-Interface Multi-Channel (MIMC) technology to increase the network performance. The MIMC allows node to send multiple messages simultaneously to different channels. This requires special network card from the node. Margaryan et al. [265] proposed protocol selection protocol which decides between OLSRv2 and AODV. AODV is used when node mobility is over 20m/s and there are under 100 nodes in the network. Vivarekar et al. [266] proposed light weight protocol for networks with under 30 nodes. The protocol utilises one TDMA channel. Han et al. [267] modified TORA with election of clock synchronous nodes and through it synchronisation in the network. Jain et al. [268] proposed multipath protocol which uses RSSI in the path selection. Arumugham and Chenniappan [269] used energy and location information in path selection. Gupta et al. [270] proposed probabilistic routing protocol. The probability is primed with social ties, adjacency, distance, mobility, and location information. The protocol aims to increase the performance of the network. Pandey and Singh [271] used node lifetime and signal strength in path discovery. Hagenhoff et al. [272] used central network controller to cache up-to-date topology information and control the network traffic. The protocol aims to lower the time it takes to calculate paths and streamline the topology sharing process.

5.2 Discussion

The most significant trend found in this review was the reduction of yearly publications over the observation period. Overall, the number of publications has decreased 46%, reactive protocols have decreased 48%, and traditional algorithms 57.7%. None of the inspected categories showed significant increase over the observation period. Wijonarko et al. [10] also found that in the last four years there was a significant decrease in the number of publications.

The reduction in publications, especially protocols based on traditional algorithms can be linked to the decreased number of new standardised routing protocols. One such indication is that the IETF manet WG has not released an RFC in over four years, a longest time since the formation of the WG as seen in Figure 13. According to the publicly available meeting minutes from IETF meetings 121 and 122, the WG has trouble attracting authors for the projects on hand. One such project mentioned in the minutes was AODVv2, an improved version of AODV. As AODVv2 is reactive protocol, researchers might have shifted their interest into other fields in waiting for the new release. One such field is IoT and by extension WSNs.

Searching IEEE Xplore with the query "MANET*" gives 2073 results for 2000 to 2007. The same timeframe gives 1620 results for "WSN*". In the 2017 to 2024 range MANET yields 2264 results while WSN yields 11 102 results, a 585% increase compared to the first eight years of the 21st century. The interest in MANETs has clearly been outweighed by other applications such as WSN. The finding that no author or research group is frequent in the data confirms the results even more. The researchers, whose names were in three publications, all stated in their profiles that their research interests are broadly in wireless communication with IoT and WSN mentioned often. An exception to this makes S. Venkatasubramanian who is pursuing PhD in MANETs specifically. This author along with Beongku An were one the most mentioned authors found in [10].

Both Wijonarko et al. [10] and Förster et al. [3] conclude their articles stating that the research interest has moved away from general MANETs to more specified applications e.g. VANETs, FANETs, and WSNs increasing the reliability of this finding.

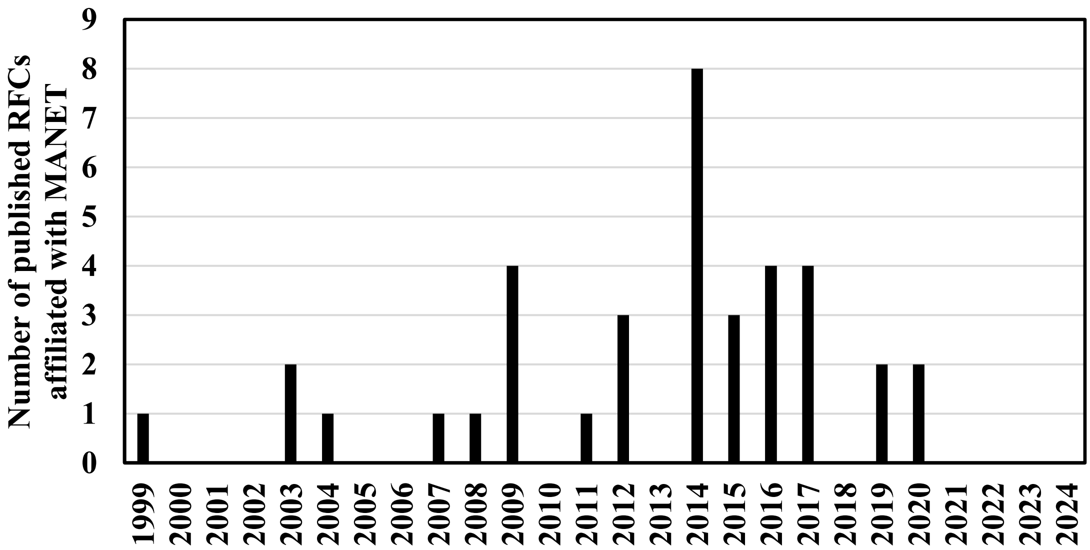

Figure 13 Number of released RFCs by IETF with keyword "MANET"

While the overall number of research has decreased, there are topics within MANET research that have gained interest over the observation period. With the global interest in AI and the increase in its funding, it is not surprising seeing AI-based protocols having gained interest.

Both ML-based and bio-inspired algorithms are an extension of the general AI research. While the number of publications about modern algorithms has not seen an increase, there isn't a similar decrease to them as with the whole dataset. The simulation sizes of modern algorithms have seen an increase over the observation period that might indicate maturity and efficiency in them.

The first research question of this thesis asked about the techniques used to increase the scalability and reliability of the general MANETs. While scalability was found to be only marginally interesting research area, reliability can be linked to all of the reviewed papers. The scalability was found to be slightly trending in hybrid protocols, which generally do aim for better scalability. Modern algorithms however showed great promise for scalability with the limitations of more complex networks.

The primary research objectives of the reviewed papers aimed for reliability. Energy efficiency was the most researched objective, and it was achieved mostly by modifying existing protocols. This can be observed from other objectives as well. The modifications included using energy metrics in the decision making process for path selection. There were several approaches to the energy metrics. Some papers used the current energy levels of the nodes to make paths or routing decisions others used the consumption speed. Of these two the consumption speed seems to be more reliable than the current energy levels as congested nodes drain their batteries faster. By using current energy level, the load is concentrated on few nodes whose energy levels deplete fast. The energy metrics as with other metric data were gathered by appending them to the path discovery messages or broadcasting them. Cross-layer approaches were also used where nodes estimate the factors based on e.g. signal strength and its change over time.

QoS was also achieved mostly my introducing network metrics into the routing. In traditional sense, QoS introduces priority messages into the network. For example, video conferencing requires less than 150ms of delay, while emails or instant messages may function with seconds to minutes of delay depending on the operation. Some of the papers considered QoS more like a performance metric considering only one type of data. This made it difficult to make clear trends. The most common metrics used to enhance QoS were congestion and by extension delay. Similarly to energy efficiency these metrics were from messages or observations.

Multipath protocols were most prominent in congestion avoidance. This was not surprising since their main purpose was balancing load and allowing transmission to continue if a link is broken. Several methods of making the path discovery maintenance were identified ranging from metric induced to novel node categorisations. Papers concerned with link stability saw similar approaches to congestion avoidance as the two are closely related.

The other protocols had similar approaches to the five main categories with objectives guiding e.g. the metrics used. Common with all of the categories was the use of cross-layer routing and especially physical location and RSSI. The location data was used to direct the packets to roughly the right direction or modify the transmission power. Few papers used location to minimize the transmission power and one to maximise the hop distance. RSSI was used in several different ways from locating neighbours to estimating their performance, delay, congestion and energy consumption. Modern radios used in tactical operations are equipped with GPS to aid in the tactical awareness. These could benefit from using the location data to also aid in the routing decisions. Especially in military environment, using only the minimum energy to transmit conceals the sender in the electromagnetic spectrum. Under jamming the ability to increase the transmission power is also valuable. These radios are also sufficiently powerful to analyse the RSSI metric to aid in routing decisions.

With the increase of processing power multipath protocols have been increasing as well. Especially several node- and link-disjoint multipath and multicast protocols were identified in this review. The increase in reliability with these protocols is a good indicator that they are good candidates for tactical communication.

The increased processing power has also made possible to use AI-based protocols. Bio-inspired protocols were identified to be computationally heavy but still prominent in this review. ACO and PSO were the most commonly used meta-heuristics with GA coming third. These algorithms were used in several very different protocols, but mostly for making fast near-optimal solutions based on some metric data. The metrics used in these were mostly simple data e.g. energy level, delay, and hop count. Other AI based approaches were Reinforcement Learning, Neural Networks and fuzzy logic. These mostly used similar metrics but also incorporated more advanced metrics e.g. energy consumption, path stability, congestion. Especially Q-learning with the ability to predict the reward were employed with advanced metrics.

Independently interesting protocol utilised quantum computing in routing. While this is relatively far from everyday usage, it is interesting to notice that quantum computing may be used to great effect in the field of MANETs as well as cryptography.

While there is great promise in these modern algorithms, a protocol based on them has not yet been standardized. The adoption of a bio-inspired routing method or a reinforcement learning method may be difficult without a primer standard. The increased requirements for computational capabilities of the nodes utilising modern algorithms might discourage the field currently. Especially since the focus seems to be shifting towards IoT devices, which currently do not support such computationally heavy algorithms.

The major limitation of this study is that the proposed protocols were not compared with each other. This was due to the numerous different simulation parameters and setups present in the papers. The comparison between few selected protocols offers an important topic for future research. Especially the preliminary finding that modern algorithms are more scalable than traditional ones needs to be confirmed with either controlled simulations or real world applications. This study also is limited in coverage of the disadvantages of the reviewed protocols. While general limitations of protocol classes and algorithms were discussed, the actual limitations of each reviewed protocol were limited. The primary objective found in this study give sufficient starting point for closer examination of reliability factors in general MANETs

As the global research community moves away from general MANETs, tactical communications loses a valuable source of research for development. It is important to identify which other area of research answers the needs of tactical communications. As this study found that general MANETs are the current best fit for tactical communications, this leaves open the question of which area of research is the future for tactical networks.

6 Conclusion

In this study we first determined what characteristics tactical environments impose on wireless communications. Tactical networks are used by units from the military, the police, the border security and SAR teams along with other similar government agencies. These units may need to operate in areas without electrical or network infrastructure. The communication network is required to be self-assembling, self-contained, and self-healing to accommodate the lack of infrastructure. Mobile Ad hoc NETworks were determined to be the best fit for the environment. The term general MANET was chosen to describe networks specifically as opposed to its universal use for any ad hoc network.

The objective of the thesis was to provide trends on the routing research on general MANETs. The objective was split into three research questions. These questions aimed to determine which techniques increase the reliability and scalability of MANETs, who and which institutions contribute to the research, and how future research might benefit from the trend found in this thesis.

To answer these research questions, we conducted a systematic literature review. We formulated the search queries and exclusion criteria to account for the tactical environment. We queried IEEE Xplore and ACM Digital Library resulting in total of 226 reviewed papers from 2017 to 2024.

The analysis of the papers showed that scalability was key interest in only one paper. We analysed the scalability by using the maximum number of nodes used in the simulations. The size of simulations were most researched and cited in and around the 100 nodes within all used categories. Only protocols based on bio-inspired algorithms such as ACO and PSO, showed significant increase in the size of simulations over the observation period. Hybrid class protocols also showed increase but was statistically non-significant finding.

The primary objective of the reviewed papers was determined to be most often about reliability. Energy efficiency, Quality of Service (QoS), congestion avoidance, link stability, and network lifetime were the five most common objectives accounting for 71.2% of all papers. The most common way of achieving all of these objectives was to add additional metric data to the routing process. This was either done by nodes themselves appending it into the packet header, or by gathering the information from the network. In the latter case the information was given to other nodes in proactive way or gained by observing the network. One prominent solution was to use cross-layer routing where physical information e.g. physical location, signal strength, or the time nodes use for packet processing to make routing decisions was used.

There weren’t any single author or organization which appeared in the dataset more than three times. The seven authors that did appear, all had other wireless communication interests over general MANETs, save one who is pursuing a doctorate in MANETs specifically. A major are of research in ad hoc networking is Vehicle based MANETs (VANET) or Wireless Sensor Networks (WSN). India was identified to be the centre of the research with 59.7% of authors being affiliated with it. China, the USA, Iran, and Pakistan were among the top five countries by number of publications.

The major trend found in this study was the decrease in number of publications over the observation period. The number of publications were reduced by 46% in eight years. Reactive class protocols showed the highest decrease compared to proactive and hybrid class protocols. Protocols based on traditional deterministic or heuristic algorithms also showed decrease. The finding of decreased interest in general MANETs was also found in other publications.

Since general MANETs were determined to be the best fit for tactical networks, this left open question about the future of the field. In the near future researchers about tactical networks need to decide whether to pursue MANETs or to change to other prominent technologies such as WSNs in tactical communications.

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