Disjoint Routing Algorithms: A Systematic Literature Review

Adoum Youssouf[1], Daouda Ahmat[1,2](✉), and Mahamat Borgou[3]

[1] Virtual University of Chad, N'Djamena BP: 5711, Chad
{adoum.youssouf,daouda.ahmat}@uvt.td
[2] Univerty of N'Djamena, 1117 N'Djamena, Chad
[3] National School of Information and Communication Technologies, N'Djamena 5363, Chad
m.borgou@enastic.td

Abstract. The expansion of the Internet and technological innovations have revolutionized the world. This digital effervescence has fostered in its path an increased connectivity of services and applications. Optimal use of these requires support for quality of service (QoS), fault resilience, reduced transmission delay, reliable packet delivery, network security, and fair sharing of data. Resources available in the network as needed. In order to satisfy these requirements, disjoint routing algorithms have been developed to improve network performance. These algorithms distribute the load evenly over several paths between the different nodes of the network. The objective of this article is to provide a comprehensive literature review on disjoint routing algorithms as a whole, unlike several research works in the literature which focus only on specific network architectures including MANET, SDN, WSN, ... First, we review the advantages and disadvantages of disjoint routing algorithms, which will allow us to identify future research work. Then, we will present a detailed study of disjoint routing algorithms. Finally, we will also describe disjoint routing algorithms based on some specific network architectures.

Keywords: Multipath routing · Vertex-disjoint paths · Edge-disjoint paths

1 Introduction

Nowadays, the Internet and technological innovations continue to advance at an exciting and impressive rate in various fields, including communication networks, multimedia applications, energy industry, high-speed circuit integration scale (VLSI) brings in its wake an increased community of services and applications. In order to ensure optimal connectivity and efficient data sharing in the network, new disjoint routing techniques have been developed to improve the quality of service (QoS) in the network.

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On the other hand, multipath routing allows data to be sent over a set of paths leading from a source to a destination. Disjoint routing algorithms seem to be efficient solutions in networks allowing to ensure the continuity of traffic in case of failure of a route between source and destination [1]. They also provide certain benefits, such as improved package delivery reliability [2], reducing network congestion, increasing network security [3–5] and higher aggregate bandwidth [6]. These allow to improve the performance of the communications and to aggregate the resources available in the network.

However, disjoint routing algorithms also have many drawbacks, including special message control, duplicate packet handling, longer path, and large route demand. Overall, this paper contributes to a holistic investigation of disjoint routing algorithms as a whole, unlike several works in the literature that focus only on specific network architectures including MANET, SDN, WSNs, etc. The study attempts to encompass almost all relevant scientific publications. The specific contributions of the study are as follows:

- Exhaustive analysis on specific disjointed architectures, evaluating on different metrics.
- Comparative study of the advantages and disadvantages of disjoint routing algorithms.
- Taxonomy of applications of the multipath routing
- Relevant aspects of disjoint routing approaches are rational load distribution, resilience to ensure service continuity in case of failures, packet delivery reliability, etc.

The rest of the review is organized as follows: Sect. 2 presents the body of related work on surveys of disjoint routing algorithms. Section 3 introduces the notion of disjoint path types. Section 4 describes the advantages and disadvantages of disjoint routing algorithms. Section 5 presents the notion of disjoint routing algorithms based on specific network architectures. Section 6 presents analyses and approaches to disjoint routing. Finally, Sect. 7 concludes this paper by presenting future work.

For the understanding of this document, the acronyms used are presented in the Table 1

Table 1. Notations used

Name	**Description**
CandidateSet	all candidates
TraceSet	the trace set
Failprobability	the probability of end-to-end failure of the paths
m_{max}	upper limit of
P_u	end-to-end reliability requirement
$\pi^0_{S,D}(t)$	the path reliability set
ETX_j	link cost function at node j
Route_path	route of the itinerary
Route_reply	a set of route response messages
Route_request	route requests from origin to receiver
RPT	received packets throughput
S's bucket	out of the bucket
BL	length of the bucket outlet port
PN	number of ports in the bucket
SW	OpenFlow switch
tmp_bucket	temporary bucket
f^0	a zero value stream contains no paths
nextHop	next jump
stack.pop	stack jump
$S_{neighbors}$	list of unsorted neighbouring nodes
$S_{sorted\_neighbors}$	list of sorted neighbouring nodes
ResBatt	residual battery
$w_{uv} = \frac{b-1}{\delta_{uv}}$	the capacity assigned to the links
P_L	set that contains the disjoint paths in the original graph.
P_N	set that contains the node-joined paths in the original graph
TCP	transmission control protocol
UDP	user datagram protocol

1.1 Research Sources

This method aims at listing and collecting reliable data related to the theme during research. We conducted an exhaustive search on several electronic databases, the list of which is as follows

- IEEE Xplorelatex math symbols amsmath amssymb example
- Google scholar
- ACM
- ScienceDirect
- ResearhGate

- Springer
- Wiley

The information retrieval procedure is performed on the above mentioned electronic databases. These databases include the most important journals and conferences in the field of computer networking; specifically, on the disjoint routing approach based on specific network architectures, which are listed in the Table 2.

Table 2. Fundamental journals and conferences

Classification	Abbreviation	Description
Journal	-	IEEE Access
	-	IEEE Transactions On Wireless Communications
	-	International Journal of Distributed Sensor Networks
	JISE	Journal of Information Science and Engineering
	IACC	IEEE International Advance Computing Conference
	IJCAT	International Journal of Computer Applications Technology and Research
	JNCA	Journal of Network and Computer Applications
	I-SPAN	International Symposium on Pervasive Systems, Algorithms and Networks
	IEICE	Institute of Electronics, Information and Communication Engineers
	FOCS	IEEE Symposium on Foundations of Computer Science
	SIAM	Society for Industrial and Applied Mathematics
	JTCB	Journal of Combinatorial Theory, Series B
	CIT	Journal of Computing and Information Technology
	-	International Journal of Communication Systems
Conference	-	International Conference on Ubiquitous Intelligence and Computing
	ICRAIE	IEEE International Conference on Recent Advances and Innovations in Engineering
	ICECS	International Conference on Electronics and Communication System
	-	International Conference on Informatics, Electronics
	ICNP	International Conference on Network Protocols
	-	International Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery
	CMCE	International Conference on Computer, Mechatronics, Control and Electronic Engineering
	JCSSE	International Joint Conference on Computer Science and Software Engineering
	-	International Conference on Information and Telecommunication Technologies and Radio Electronics
	LCN	IEEE Conference on Local Computer Networks

1.2 Search Strategy

This section mainly elaborates the search steps, which are used to identify articles deemed relevant (journal quality, number of citations, impact factor, etc.) in accordance with the theme. The search strategy adopted is based on four principles:

- Principle 1: Select articles published in English in the indexed journals.
- Principle 2: Read the title and abstract of the selected articles.
- Principle 3: List only articles dealing with disjoint routing algorithms.
- Principle 4: Categorize and reference items using disjoint routing approaches.

The four-pronged research strategy is shown in Fig. 1.

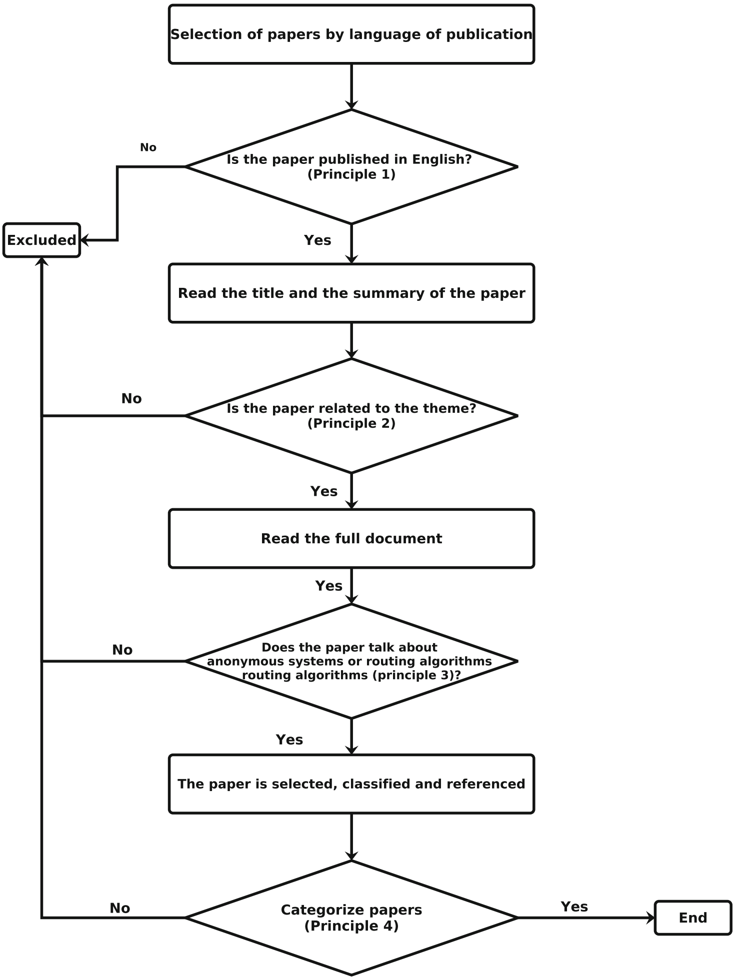

Fig. 1. Research strategy

1.3 Contributions of this Study

Unlike existing studies, this study focuses on disjoint routing algorithms in their entirety, unlike several works in the literature that focus only on specific network architectures including MANET, SDN, WSNs, etc. We conduct a comprehensive review of various related works on disjoint routing algorithms based on specific network architectures. We will also highlight their advantages and limitations while indicating some challenges in terms of security related to the protection of information and the scheduling of the and packet scheduling.

In addition, we discuss the technical notions of disjoint routing and compare the effectiveness of these approaches at the end of their complexity. Finally, we conclude on the basis of our analysis that disjoint routing algorithms can improve the performance of communications and aggregate the resources available in the network. resources available in the network.

2 Related Work

The search for disjoint paths has received attention from several researchers in the literature review because of its interest in many applications, such as very large scale integrated circuit technology [7], communication protocols [8], secure data transmission protocols [9], robust design and optimization of telecommunication networks [10] and the reliability of network communications [11]. Several works have been widely studied for decades in various contexts in the literature concerning disjoint routing algorithms.

Tsai et al. [12] presented a study on a disjoint routing approach based on wireless ad hoc and mesh networks. In the case of wireless ad hoc networks, the proposed approach traverses properties such as mobility, disturbance and architecture to increase routing efficiencies. The path selection protocol for the IEEE 802.11s mesh standard handles both on-demand and proactive tree-based routing. Selvam et al. [13] proposed a survey on disjoint routing algorithms related to data security in wireless sensor networks. Standard security protection mechanisms cannot be implemented directly in the network due to low energy and low computational power. Some research work has shown that the security of sensor networks can be enhanced by applying new cryptographic algorithms [9].

Hassan et al. [14] conducted a survey on disjoint routing approaches oriented to wireless multimedia sensor networks. These protocols ensure network performance by providing quality of service. Fu et al. [15] have studied a survey on the disjoint multi-path routing algorithm inherent to software-defined network (SDN). The authors compared the disjoint approaches to the classical one-way path routing approach to achieve load balancing.

Tarique et al. [16] proposed a review on disjoint routing techniques for mobile ad hoc networks. The primary objective of this review is to increase the reliability of mobile ad hoc networks based on delay and transmission rate. In Hodroj et al. [17], the authors reviewed the literature on methods, mechanisms, and latest standards for video streaming in multipath overlay networks and multihoming.

In addition, the autors shown that the using of multi-homing enables increase reliability, resiliency and performance. Finally, different studies have been conducted on mathematical and statistical approaches to generate adaptive algorithms.

Afzal et al. [18] presented a comprehensive review of the literature on wireless video streaming over disjoint paths by evaluating each approach at the protocol stack level from the beginning to the end of a time period. The autors presented a taxonomy of the different schemes. Myoung Lee et al. [19] proposed a study on the different mechanisms of disjoint routing algorithms. These mechanisms can be used in the MPLS/GMPLS network, to enhance the performance of the network by the technique of information carrying capacity. In addition, the discussed algorithms provide efficient solutions for computing multiple paths, reducing delay and increasing throughput.

Satav et al. [20] proposed a robust and less energy consuming disjoint routing technique for mobile ad hoc networks. The proposed techniques mainly select the best path among the available paths between the nodes at the end of the network. In the work of Adibi et al. [21], the authors proposed a study on various disjoint routing approaches for mobile ad hoc networks. These approaches are sensitive to security and computational power. Nazila et Raziyeh [22] investigated existing energy-efficient routing mechanisms in MANETs. The proposed approaches allow for efficient energy use and increased network performance.

Qadir et al. [23] proposed a comprehensive survey of the literature on multipath routing based on network layer. This paper focuses on the problems related to multipath propagation, namely the control plane problem, which consists in computing and selecting routes; and the data plane problem, which consists in dividing the traffic flow over the computed paths. Gulati et al. [24] presented a survey on some multipath routing protocols for mobile ad hoc networks. The approaches presented in this survey provide optimal quality of service.

Radi et al. [25] presented a comprehensive analysis of multipath routing protocols for wireless sensor networks. The proposed approach improves the network performance by efficiently using the available resources. Dua et al. [26] proposed a systematic literature review on various routing schemes for vehicular ad hoc networks. The purpose of the proposed approach is to select a particular strategy based on its applicability in a particular application.

There are also related works discussed on other disjoint categories, for example, in the work of Daouda et al. [27], The authors have applied Dijkstra's algorithm for searching disjoint paths. The approach is based on graph traversal to determine the shortest path in a positive weighted graph. Then, the same procedure is applied on the residual graph determined previously, until P are determined, with $P \leq k$ disjoint paths and k being the minimum number of disjoint paths required. The disjoint paths thus determined are used in the routing of anonymous subpackets.

Chekuri et Khanna [28] have proposed a greedy non-combinatorial algorithm using a subroutine called the V- separable from the problem. The algorithm [29] first finds the shortest paths and removes them from the graph; then, when there are more than all pairs of information to route, v is considered a node and uses the paths disjointed by V as a strategy to find all disjoint paths in the residual graph G' that pass through v.

Most of the above work in this paper focuses on specific architectures. The summaries of related work from this survey are summarized in the Table 3 and illustrated in the form of a taxonomy (See Fig. 2).

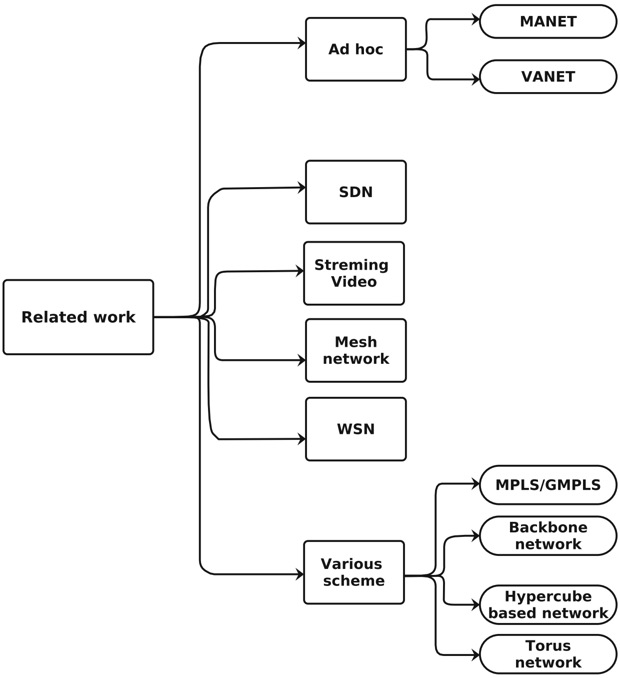

Fig. 2. Taxonomy of applications of the multipath routing

3 Kinds of Disjoint Paths

This section presents finding disjoint paths approaches in the given graphs. As shown in the Figs. 3 and 4, vertex-disjoint and edge-disjoint cases can be considered to determine the disjoint paths in the graphs.

The Table 4 summarizes the different problems of finding disjoint paths in graphs and their features. Disjoint routing algorithms improve in particular load balancing and reliability of packet delivery with low collision probability and ensure fault tolerance in case of equipment failure.

Table 3. Summary table of related work

Network architecture based on disjoint routing	Reference
Mobile Ad hoc Network (MANET)	Majdkhyavi et al. [22], Tsai et al. [12] Adibi et al. [21], Tarique et al. [16]
Vehicular Ad hoc Network (VANET)	Dua et al. [26]
Wireless Mesh Network	Tsai et al. [12]
Wireless Sensor Network (WSN)	Selvam et al. [13]
Software Defined Network (SDN)	Fu et al. [15]
Streaming Video	Hodroj et al. [17], Afzal et al. [18]
MPLS/GMPLS	Myoung Lee et al. [19]

Table 4. Features of disjoint path routing

Properties	Paths		Reference
	Vertex-disjoint	Edge-disjoint	
Hypotheses	- Have no common vertex	- Have no common edges	Tsai et al. [12] Smail et al. [30], Daouda et al. [31]
	- Except source and destination vertices $\bigcap_{i=0}^{n} P_i \setminus \{s,d\} = \emptyset$	- Can have common vertices $\bigcap_{i=0}^{n} P_j \{s,d\} = \emptyset$ -$G = (E,V)/\{E = V \times V\}$ -$P_j = \{(x,y)/x, y \in E\}$ -$\Longrightarrow P_j \subset E$	
Fault tolerance	Robust	Low	Tsai et al. [12]
Reliability	Best	Average	Xie et al. [32]
Probability of collision	Weaker	Strong	Xie et al. [32]
Applications	More used	Less used	Hassan et al. [14]

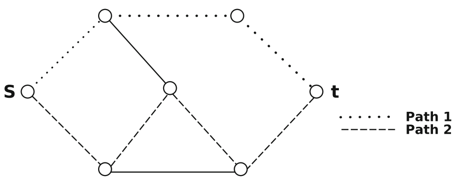

Fig. 3. Vertex-disjoint paths

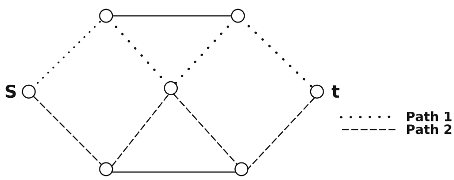

Fig. 4. Edge-disjoint paths

4 Advantages and Disadvantages of Disjoint Routing

Using multiple paths to route packets through the network has many advantages. Disjoint routing algorithms offer better features such as transmission delay, failure resistance, bandwidth efficiency, aggregation of available resources in the network and continuity of services. They also present some challenges in terms of security such as information protection and packet scheduling. The Table 5 describes avantages inherent to disjoint routing.

Table 5. Advantages of disjoint routing algorithms

Parameters	**Description**	**Reference**
Fault tolerance	Possibility of using alternative paths in case of failure of the main path.	Tsai et al. [12]
Load balancing	Possibility of using multiple routes to transmit packets from the source to the destination. This mechanism ensures bandwidth optimisation and also load balancing in order to prevent link congestion.	Tsai et al. [12]
Bandwidth aggregation	Using multiple paths allows for load balancing between network nodes to achieve better bandwidth using	Tsai et al. [12]
Reduction in transmission time	Reduced delay in disjoint routing because backup routes are identified during route discovery.	Tsai et al. [12]
Application support	High bandwidth multimedia applications can benefit from the resilience offered by the techniques of disjoint routing algorithms	Qadir et al. [23]
Secure key/information exchange	A key exchange mechanism that explores disjoint transmission paths based on both the Diffie Hellman protocol and the Shamir threshold.	Daouda et al. [31]

Disjoint routing algorithms have not only many advantages as mentioned in the Table 5, but also theses routing schemes have also several disadvantages which are listed in the Table 6 [12, 21].

Table 6. Disadvantages of disjoint routing algorithms

Parameters	Description	Reference
Longer paths	Packets generally travel over more hops, which will increase the end-to-end delay and waste more bandwidth.	Tarique et al. [16] Wu et al. [33], Satav et al. [20]
Message control mechanism	Special messages used in multipath routing can overload the network, especially when the network is large.	Satav et al. [20] Tarique et al. [16]
Route request storm	Multipath routing causes intermediate nodes to transmit a duplicate request message which can cause a large amount of redundant overhead packets in the network.	Satav et al. [20] Tarique et al. [16]
Duplicate packet processing	Duplicate packets create redundant packets and thus take up useful bandwidth	Satav et al. [20] Tarique et al. [16], Tsirigos et al. [34]
Dynamic environment	It is hard to keep paths disjoint in a dynamic environment (the cost of the Dijkstra algorithm is $O(n^2)$).	Daouda et al. [27]

5 Disjoint Routing Applied on Network Architectures

Multimedia applications require increased transmission to have good quality of services, reduction of energy consumption and securing traffic on networks. To meet these requirements, disjoint paths can be the solution to address bandwith management, packet loss and data security.

Many researchers have been interested in disjoint routing algorithms, especially in the areas of ad hoc networks, wireless sensor networks, software-defined networking, video streaming and wireless mesh networks, as well as other specific types of network architectures (cf. Table 7).

5.1 Disjoint Routing Applied on Mobile Ad Hoc Networks

Routing algorithms play an important role in MANETs. In these networks, all nodes act as routers, access points and servers (see Fig. 5). Some research works have focused on disjoint routing algorithms for mobile ad hoc networks [35–37].

Velusamy et al. [38] proposed a new multi-path routing algorithm based on multi-objective and node-disjoint functions for mobile ad hoc networks. The approach aims at finding multi-node disjoint paths that satisfy the multi-objective optimization problem in terms of minimizing energy consumption and reducing information transmission delays.

Robinson et al. [39] presented a disjoint multi-path routing algorithm to solve the optimization problem in a real-time network environment. The proposed method selects the best possible path using the dynamic control technique in MANETs. It also provides better performance compared to other related methods in terms of energy efficiency, reliability, load balance and works well in the dynamic network environment.

Leung et al. presented a dynamic disjoint routing approach to guarantee data delivery in wireless ad hoc networks. The proposed approach transmits outgoing packets along several paths that are subject to particular end-to-end reliability. The pseudo-code that formally illustrates the selection of disjoint paths is presented in the Algorithm 1.

Several research works on ad hoc networks addressed disjoint routing schemes [39–47].

The results of various works have shown that disjoint routing algorithms based on mobile wireless networks offer the best performance in terms of minimization of energy consumption, reliability, load balancing, reduced packet delivery time, considerable resiliency and operates very well in a dynamic network environment.

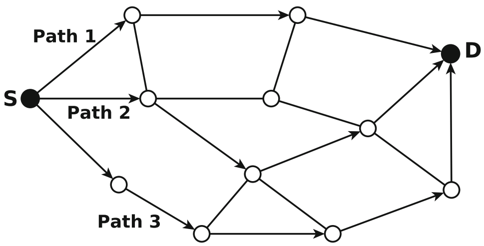

Fig. 5. Ad hoc architecture using disjointed paths

Algorithm 1: Disjoint path selection [48]

$set\ CandidateSet \in \{P_0, P_1, ..., P_{n-1}\}$
$set\ PathReliabilitySet \in \{\pi^0_{S,D}(t), \pi^0_{S,D}(t), ..., \pi^0_{S,D}(t)\}$
$set\ TraceSet \in \{\}$
int $DisjointPathSelection(si, failProbability)$
if $(1 - failProbability \geq P_u)$ **then**
  return $Success$;
for $(each\ feasible\ path\ P_i\ in\ subset\ \{P_{si}, ..., P_{n-1})\}$ **do**
  if $(P_i\ does\ not\ contains\ node\ in\ any\ paths\ of\ TraceSet)$ **then**
    $TraceSet = TraceSet \bigcup P_i$
    if $((DisjointPathSelection\ (i+1), failProbability * (1 - \pi^i_{S,D}(t)) = 1)$
    $and(|TraceSet| < m_{max}))$ **then**
      return $success$;
    $Remove\ P_i\ from\ TraceSet$
  $return\ failure$;

5.2 Disjoint Routing Applied on Wireless Sensor Networks

Several research works have proposed disjoint routing algorithms on wireless sensor networks. Indeed, Junho et al. [49] presented a disjoint routing scheme for real-time data transmission in multimedia sensor systems. The approach relies on combined routing based on both Bluetooth and Zigbee to overcome the restriction of bandwidth deficit in sensor networks and on non-overlapping disjoint path parameterization methods based on concurrency to address the overhead produced by the disjoint path control mechanism. In the work of Sun et al. [50], The authors presented a disjoint routing algorithm based on the lowest hop count metric with a congestion control mechanism combined with time slice load balancing. This algorithm allows for a higher proportion of data to be received and a longer latency. This method is more efficient than the normal disjoint paths without the throttling mechanism. Huang et al. propose a method for key sharing in WSN using disjoint routing and Reed-Solomon code [51].

Marjan et al. [52] have developed a disjoint routing algorithm for wireless sensor networks with reduced disruption and lower power consumption. The proposed approach was designed primarily to ensure reliable data transmission, and reduce packet latency by discovering multiple disjoint paths between the originating and destination nodes. Therefore, when a group of sensor nodes detects an event, and the proposed method attempts to define multiple node-joined routes and minimize the disturbance between the originating node and the receiving node as illustrated in Fig. 6. After the definition of each route and some aggregation of data, resulting in a decrease in the proportion of information received at the receiving node. In this case, it disables the newly created path, stops the setup process, and distributes traffic on the previously created paths. To start the route definition mechanism, a packet of type (Route_request) is routed from the origin to the receiver. On each node, the neighbor with the best cost metric is chosen as the next hop:

$$Cost_{i,j} = (ETX_j + \frac{1}{p_{i,j}q_{i,j}}).\frac{1}{ResBatt_j}(1 + Interference\_Level_j) \quad (1)$$

Other research works on multipath sensor networks is not listed in this paper have been also proposed [53–56]. Research results have shown that disjoint routing algorithms that address wireless sensor networks improve network performance by effectively using available resources, efficient on the overhead problem generated by the routing path configuration and robust in terms of security. The respective descriptions of the above mentioned mechanisms are presented in the Algorithms 2, 3 and 4.

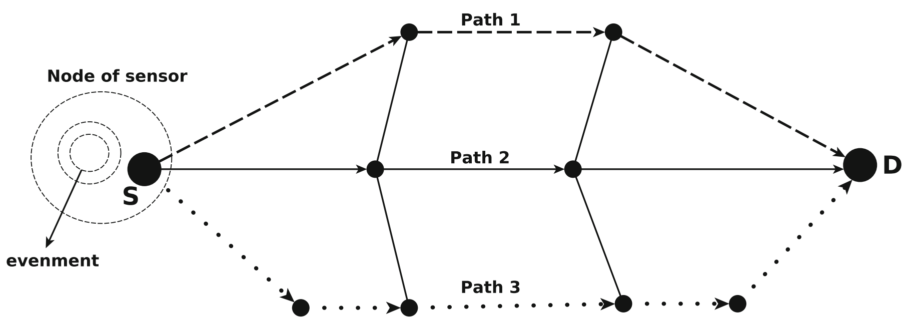

Fig. 6. Structure of multiple paths in sensor network

Algorithm 2: Source node's algorithm [52]

```
if (no Route_request packet is sent before) then
    for (all of this node's neighbors) do
        if (Route_path_i == 0) then
            Calculate cost_i for neighbor i;
            Send Route_request to the node which has minimum cost_i;
if (Route_reply for nth path is received) then
    Transmit data packets over the n created paths, using
    load balancing algorithm;
if (a positive feedback is received for nth path) then
    Continue data packet transmission over the n created
    paths, using load balancing algorithm;
    for (all of this node's neighbors) do
        if (Route_path i == 0) then
            Calculate cost_i for neighbor i;
            Send Route_request to the node which has minimum cost_i;
if (a negative feedback is received for nth path) then
    Disable the nth path;
    Transmit data packets over the n − 1 previously created
    paths, using load balancing algorithm;
```

Algorithm 3: Intermediate nodes' algorithm[52]

```
if (Route_request packet is received) then
    for (all of this node's neighbors) do
        if (Route_path_i == 0) then
            Calculate cost_i for neighbor i;
            Send Route_request to the node which has minimum cost_i;
            Route_path = 1;
if (Route_reply packet is received) then
    Send this packet in the reverse path to the source node;
    Route_path = 2;
if (Route_reply packet is overheard from node i) then
    Refer to neighbor table and extract backward packet reception rate to node i;
    Add the extracted value to Interference_Level;
```

Algorithm 4: Sink node's algorithm [52]

if (*the first Route_request packet is received*) **then**
  Send Route_reply packet in reverse path;
if (*the nth Route_request packet is received*) **then**
  Calculate RPT of using $n-1$ *paths*;
  if ((*RPT of* $n-2$ *paths*) <= (*RPT of* $n-1$ *paths*)) **then**
    Send positive feedback;
  else
    Send negative feedback;

5.3 Disjoint Routing Applied on Defined Network Software

Recently, efficient algorithms related to disjoint routing have been developed for software defined network (SDN).

Liao et Tsai [57] presented a new technique based on the process of disjointed path reorientations. This technique uses OpenFlow switches for deep distributed search to determine secondary paths, without controller intervention. After the configuration of flows and group grid buckets, the presented system aims to largely decrease the exchange between the switch and the SDN controller. In the proposed paper by Abe et al. [58], the authors provided an algorithm to find a solution that relies on disjoint paths to increase the capacity of distribution traffic with the maximum $k - disjointpaths$ in SDN networks.

Note that other work on software defined networks based on disjoint routing is not considered [59–63]. Research results have shown that disjoint routing algorithms increase survivability or resiliency in the event of a main path failure and distribute available resources across all entities in the network by applying forking and expansion functionality.

In the paper [57], the authors also proposed an algorithm for hierarchical disjoint paths by using locally separated routes as a secondary path, which constitute the disjoint paths by accepting a subpath of a separated route. This procedure is repeated by moving the end of the two nodes toward each other along the route and eliminating the edges that occur in the discoveries of new separate routes. As shown in figure, if the [F-D] link fails, then from node C, the split route (3) will be used to send packets, instead of returning to node A. The formal description of the proposed approach is described in the Algorithm 5.

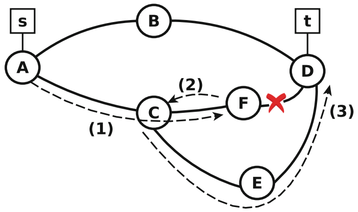

Fig. 7. Case of hierarchical divided roads with a partial divided road [C-E-D], and two divided roads: [A-C-F-D], [A-B-D]. [57].

Algorithm 5: Find Hierarchical Disjoint Paths (G, pathlist)[57]

$Result = \emptyset$
forall *path in pathlist* **do**
  $G' = G \setminus \{e : link\ e\ appears\ in\ pathlist\}$
  for $start = 1st\ node\ of\ path\ tolast\ node\ of\ path$ **do**
    for $end = last\ node\ of\ path\ to\ start\ local\_disjoint\_paths =$ ***Find_Disjoint_Paths***$(G', start, end)$ **do**
      $Result = Result \cup local\_disjoint\_paths$
      $G' = G' \setminus \{e : edge\ e\ \in\ local\_disjoint\_paths\}$
return *Result*

5.4 Disjoint Routing Applied on Video Streaming

Streaming is an application where reliability is important for transmission. The use of disjointed paths reduces data transmission delay and packet loss.

Xie et al. [6] have provided a disjoint algorithm to reduce interference and contention, leading to a higher transmission rate and acceptable delay. The proposed protocol provides superior video quality with reasonable transmission delay. Seo et al. [63] have developed disjoint routing algorithms, which customize routing for each streaming application as a key component of the streaming program orchestration. These algorithms aim at minimizing link contention and improving both the bandwidth available for streaming communication and the throughput of applications. Xie et al. [32] presented a disjoint routing approach to reduce the disruption and restriction of the video streaming solution system, enabling maximum transmission with reasonable delay. As shown in Fig. 8, TCP is applied for the transfer of primary path data to ensure reliable delivery, and UDP is used for intermediate data routing as a secondary path to reduce transmission delay. The decision step to define a route occurs at the network layer. This data is routed through disjoint paths using node-disjoint and link-disjoint methods. As such, the route discovery method primarily chooses node-disjoint paths as a backup path. In the absence of a node-disjoint route, the disjoint link route will be chosen. The pseudo-code that illustrates the formal description is listed in the Algorithm 6.

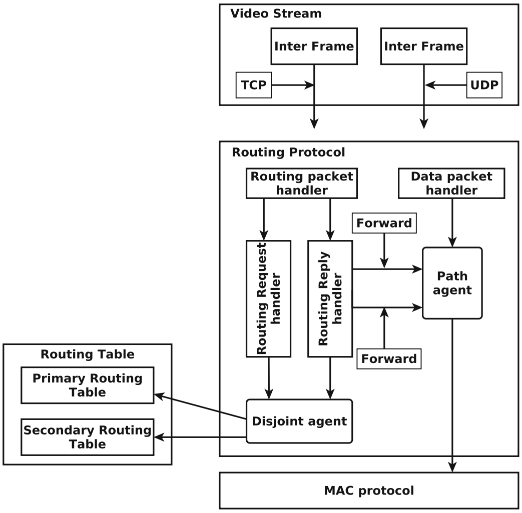

Fig. 8. Anatomical illustration of multipath video streaming. [32]

It should be noted that many of the works on video streaming focused on multi-path routing are not included [64–72]. The results of the various works have shown that disjoint routing algorithms based on video streaming aim to reduce interference and link contention. They improve both the bandwidth available for streaming communication with reasonable transmission delay.

Algorithm 6: for node disjoint [32]

$Input : path1.length > 0$
$Input : path2.length > 0$
$sort(path1)$
$sort(path2)$
$i, j = 0$
while $i < path1.length \ \ or\ j < path2.length$ **do**
  if $path1[i] = path2[j]$ **then**
    return $(false)$
  else
    if $path1[i] < path2[j]$ **then**
      $i++$
  else
    if $path1[i] > path2[j]$ **then**
      $j++$
return $(true)$

5.5 Disjoint Routing Applied on Wireless Mesh Networks

Wireless mesh network (WMN) technology has gained momentum in recent times due to its advantage in certain application areas such as community networks and enterprise backbones [73].

In the work by Kushwaha et al. [74], the authors applied an AOMDV protocol that relies on local repair to define the best metrics in terms of the proportion of packet loss, overhead, and the proportion of packet transmission in high-speed networks with mobile nodes.

Zhang et al. [75] presented a route discovery method to find the shortest and second shortest disjoint paths in a wireless mesh network. This approach achieves the result at a reduced delay, which leads to better communication in a unit path mesh network. Experimental results have shown that this method is applied to find the shortest path and the second shortest path disjoint from the shortest in wireless mesh networks. In the work of Ikenaga et al. [76], the authors proposed a new disjoint routing technique to prevent disturbance variations and enhance the transmission speed in the mesh system. For example, in Fig. 7, the source vertex first detects the disjoint routes P_1 and P_2, then it records P_1 in its routing structure so that the vertex identifier s is less than t. Conversely, vertex t finds paths P_1 and P_2, so it stores P_2 in its data structure so that the vertex identifier t is larger than s. However, the authors described an algorithm using flow to find disjoint paths. The flow f is determined by the man defined below (Fig. 9):

$$|f| = \sum_{v:(s,v)\in E} f_{(s,v)} \qquad (1)$$

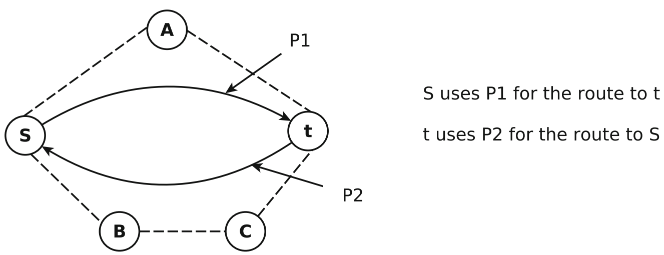

Fig. 9. Example of path selection [76].

The approach consists in determining two disjoint paths using the link-disjoint, and on the other hand if the routes are not yet disjoint, then this approach builds node-disjoint paths from previously defined routes by applying the flow technique. The link-disjoint search determines an appropriate flow f with $|f| = 2$, decomposed into two separate routes $\hat{P}_1$ and $\hat{P}_2$ [77,78]. The technique using flow defines node-disjoint routes from link-disjoint routes. More precisely, it first constructs a new graph devoid of the original graph defined by f, and obtains a cycle that introduces the node and cross flows, applying Dijkstra's approach. The techniques used are formally described in the Algorithm 7.

Algorithm 7: for finding node disjoint paths(G, s, t) [76]

---

input : $G - the\ graph, s - source\ node, t - destination\ node$
output : $(\hat{P}_1, \hat{P}_2) - two\ node\ disjoint\ paths$
$(P_1, P_2) \leftarrow$ **FindLinkDisjointPaths** (G, s, t)
$f^0 \leftarrow \{P_1, P_2\}$
if $P1$ *and* $P2$ *are node disjoint* **then**
    return $P_1 and P_2$
    $f \leftarrow$ **ImproveFlow**(G, f^0)
    Decompose flow f *into two paths*, P_1 *and* P_2
    Jump *to* 3.
Procedure **FindLinkDisjointPaths** (G, s, t)
Identify path P_1 *in* G *by using Dijkstra's Algorithm*
$f \leftarrow \{P_1\}$
Construct the residual network $G(f)$ *of* G *imposed by* f :
Add to $G(f)$ *each link in* G *that doesn't belong to* P_1
foreach *link* $(u, v) \in P_1$ **do**
    Add a link (v, u) *to* $G(f)$ *with* $c_{(v,u)} = 0$
    Identify path P_2 *in* $G(f)$ *by using Dijkstra's Algorithm*
    Augment flow f *along path* P_2 :
foreach *link* $l_{(u,v)} \in P_2$ **do**
    if $f_{(v,u)} = 0$ **then**
        $f_{(u,v)} \leftarrow 1$
    else
        $f_{(u,v)} \leftarrow 0$
    Decompose flow f *into two paths*, $\hat{P}_1$ *and* $\hat{P}_2$
    return $\hat{P}_1$ *and* $\hat{P}_2$
Procedure **ImproveFlow** (G, f^0)
$f \leftarrow f^0$
Construct the residual network $G(f)$ *of* G *imposed by* f :
Add to $G(f)$ *each link* l *in* G *for which* $f_l = 0$
foreach *link*$_{(u,v)}$ *in* G *for which* $f_{(u,v)} = 1$ **do**
    Add a link$_{(v,u)}$ *to* $G(f)$ *with* $c_{(v,u)} = 0$
    Find the cycle W *including a node with crossed paths in* $G(f)$
    that minimizes $C(W)$
    Augment flow f *along* W
    return f

Many research works on wireless mesh networks that deal with the notion of disjoint routing are not taken into account [79–86]. The research results showed that the disjoint routing algorithms based on wireless mesh networks offer the best performance metrics in both packet loss rate, routing overhead and packet delivery rate in the networks and effectively increase the reliability of the communication. The work summary of some specific architectures are mentioned in the Table 7.

Table 7. Research works on disjoint routing according network architectures

Network architecture based on disjoint routing	Reference
Mobile Ad hoc Network (MANET)	[6, 35–39, 42–44]
Vehicular Ad hoc Network (VANET)	[87–95]
Wireless Sensor Network (WSN)	[49, 50]
Software Defined Network (SDN)	[57, 58]
Streaming Video	[6, 63]
Wireless Mesh Network	[73–75]
Backbone Network	[96]
Hypercube based Network	[97, 98]
Torus Network	[99]

6 Routing Approaches

In this section, various schemes of disjoint routing algorithms considered in this paper, as shown in Fig. 10.

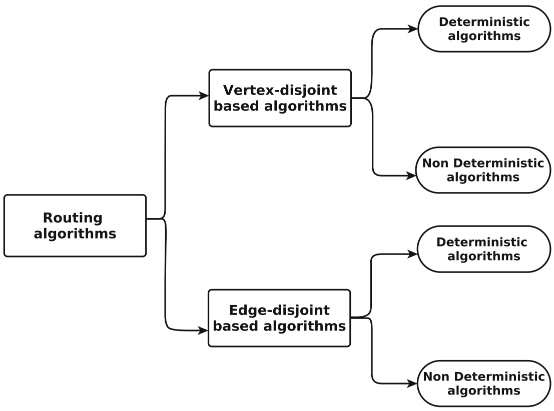

Fig. 10. Structure of disjoint routing algorithms

6.1 Conceptual Frame

In communication networks, a packet passes through one or more intermediate nodes on its way to its destination. [100]. The Fig. 11 describes the process of searching for disjoint paths connecting the source s and the destination t. The source node sends a first packet to determine the path P_1 (V and P_1 are initialized to $\emptyset$) ; the packet takes the most optimal path to t. Thus, the intermediate nodes $V_1, V_2, ..., V_n$ form P_1 ($P_1 = V_1, V_2, ..., V_n$) and are marked in the process: they are added to V ($V = V_1, V_2, ..., V_n$). Le nœud destinataire, en l'occurence t, acknowledges the receipt of the packet by sending back to the source node an acknowledgement packet containing the list V made up of the updated values, as well as a subkey that it has generated. The same process is executed for the determination of P_2 ($P_2 = V_1', V_2', ..., V_n'$), leads $V(V = V \cup P_2)$. Finally , $P_1 et P_2$ are disjoint($P_1 \cap P_2 = \emptyset$) [101].

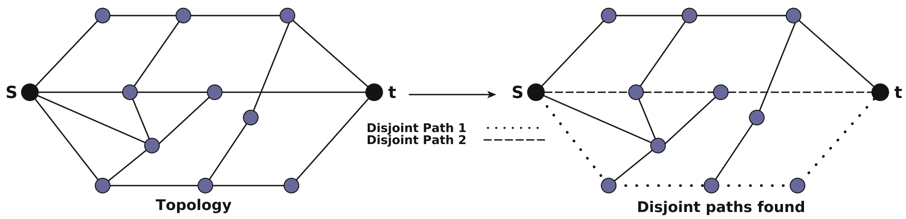

Fig. 11. Illustration of the case of two disjointed paths

6.2 Disjoint Routing Applications

Over the past few decades, the finding of disjoint paths has been widely studied in several contexts. The use of multiple paths has many advantages in various application areas mentioned in the Table 5. These applications are listed in the following items:

- Routing problems
- Load balancing and reliability in networks
- Very Large Scale Integration (VLSI)
- Multimedia applications
- Electrical or hydraulic circuits
- Parallel processing systems
- Transport modeling
- Secret exchange
- ...

6.3 Deterministic Routing Through Disjoint Paths

Deterministic routing consists of routing subpackets through predetermined disjoint paths. In the work of Daouda et al. [27], The authors proposed a disjoint deterministic routing algorithm. In this type of routing, the subpackets from the source node to the exit node rely on disjoint paths. In other words, the subpackets of the same packet do not use the same paths to be routed from the source node to the exit node, where all hops are determined in advance. In accordance with the Algorithm 8 which determines the shortest paths in the anonymous network. Initially, each subpacket has a stack of routers (see Fig. 12) containing routing information leading to the exit node. This mechanism is known as deterministic routing. Deterministic routing is not suitable for dynamic environments where topologies are constantly changing. The initially determined disjoint paths may no longer be valid by the time they are actually used for routing sub-packets.

Algorithm 8: Disjoint deterministic routing [27]

```
route(packet, destinationNode) return Success|Fail;
 stack ← packet.StackOfSubAddresses
begin
    do
        nextHop ← stack.pop()
        if nextHop ≠ null then
            node ← nextHop
            forwardto(packet,nextHop)
    while nextHop ≠ null
    return (node = destinationNode) ? Success : Fail
```

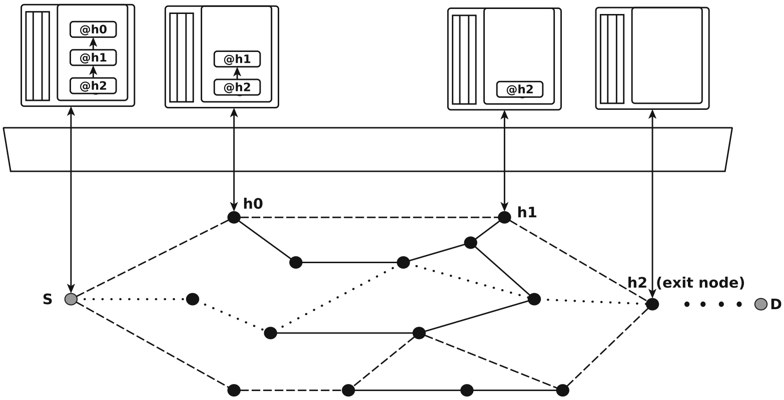

Fig. 12. Illustration of routing [27]

6.4 Non-deterministic Routing Through Disjoint Paths

Non-deterministic routing involves making a routing decision at each hop to redirect traffic to the next best hop. Unlike deterministic routing, it determines on the fly the hops that form each disjoint path as presented in the Algorithm 9.

Algorithm 9: Non-deterministic disjoint routing

```
route(packet, destinationNode) return Success|Fail;
 e ← packet.NeighborOfSubAddresses
begin
    do
        node ← s
        if neighbor ≠ null then
            node ← neighbor
            forwardto(e,node)
    while node ≠ t
    return (node = destinationNode) ? Success : Fail
```

6.5 Technical Comparison of Multi-path Routing Approaches

Table 8 presents a technical comparison related to the performance in terms of complexities provided by various disjoint routing algorithms.

Table 8. Comparison of some modes of multi-path routing

Finding disjoint paths	Complexity		Reference
	Time complexity	Spatial complexity	
Deterministic routing	$O(K(\lvert E\rvert + \lvert V\rvert log\lvert V\rvert))$	$O(K\lvert V\rvert)$	Daouda et al. [31]
Non-Deterministic routing	$O(K(\lvert E\rvert + \lvert V\rvert(1 + log\lvert V\rvert)))$	$O(K\lvert V\rvert)$	
Menger's theorem	NP	-	

Junho et al. [49] proposed a concurrency-based multi-path routing model to solve the excessive energy consumption on specific nodes due to the overlapping nodes on multiple paths in wireless multimedia sensor networks. As shown in Fig. 13, all nodes know their neighbors' location and traffic information. Using this information, the nodes receiving the packets select the closest node among their neighbors to forward the packets. This process is performed repeatedly until the packet has arrived at the destination. The Algorithm 10 presents the pseudocode of the disjoint multipath configuration based on concurrency (Fig. 14).

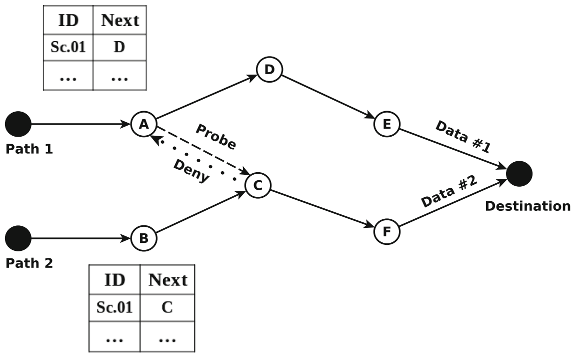

Fig. 13. Competition-based disjoint multipath configuration [49]

Algorithm 10: Competition-based disjoint multipath configuration [49]

$Input : Segment = Data\ Packet$
$S_{neighbors} = Unsorted\ Neighbor\ Nodes\ List$
$S_{sorted\_neighbors} = Sorted\ Neighbor\ Nodes\ List$
$destLoc = Information\ about\ the\ location\ of\ the\ sink$
$S_{neighbors} = [S_0, S_1, S_2, ..., S_n]$ $S_{sorted\_neighbors} = sort(S_{neighbors}, destLoc)$
foreach $S = S_{sorted\_neighbors}[i]$ **do**
    $sendProbMsg(s)$
    if $receiveDenyMsg(s)$ **then**
        $continue$
    else
        $insertNextNodetoRoutingTable(s)$
        $break$
    $sendDataPacket(segment)$

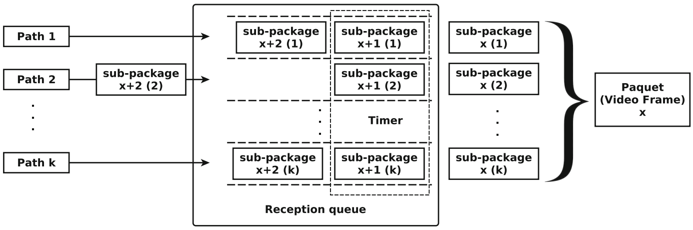

Fig. 14. Receiving and combining split packages [49]

In Fig. 7, the authors showed that a special node receives and reassembles all subpackets using a timer once the waiting threshold is required. If the threshold is not reached, the receiver does not perform the association of the subpackets. This mechanism is illustrated by the Algorithm 11.

Algorithm 11: Receiving and combining split packages [49]

$Input : \gamma = Packet(Segments)\ Reception\ Rate$
$Timer = Maximum\ Waiting\ Time$
if $Timer == End$ **then**
  if $count(ReceivedSegments) > \gamma$ **then**
foreach $s = slot[i]$ **do**
  if $s\ is\ empty$ **then**
    $s = NULL$
  else
    $continue$
$combine(thisFrame)$
else
  $eliminate(thisFrame)$
$Timer.restart()$

In the work of Xu et al. [54], the authors proposed an algorithm using the Suurballe method [102] to find the $k - chemins$ disjoint paths of minimum weight between the source and destination on a weighted graph. This approach is based on dynamic scheduling for relay assignment on each path to reduce energy consumption. The Suurballe method executes each iteration until there are k paths of disjoint nodes. During each iteration, this algorithm first adopts Dijkstra's method [103] to find the shortest paths, and modifies the weights of the edges of the graph. The weight modification preserves the non-negativity while allowing the Dijkstra algorithm to find the correct path. The formal description is presented in the Algorithm 12.

Algorithm 12: Formal Description of the CMPR

$Step\ 1 : Node - Disjoint\ Multi - Path\ Routing\ Construction$
foreach $l_{uv} \in G$ **do**
  $w_{uv} = \frac{b-1}{\delta_{uv}}$
$Adopt\ the\ Suurballe's\ algorithm\ to\ find\ out$ k $node -$
$disjoint\ paths\ on\ graph\ G, denoted\ by\ P_1, P_2, ..., P_k;$
$Step\ 2 : Relay\ Node\ Assignment$
foreach $searched\ path\ P_j = v_{j0}(s)v_{j1}...v_{jm-1}v_{jm}(d)$ **do**
  foreach $nodev_{jk}$ **do**
    $Compute\ a\ weight\ vw_k\ for\ node\ v_{jk};$

$$W_k = \begin{cases} 0 & \text{, k= 0,1} \\ max = \{W_{k-2+vw_{k-1}, W_{k-1}}\} & 2 \leq k \leq m \end{cases}$$

    if $W_k = W_{k-2} + vw_{k-1}$ **then**
      $state[k] = true$
  $W = W_m$
  foreach $node\ v_{jk}\ from\ node\ v_{jm-1}\ to\ node\ v_{j1}$ **do**
    if $W_k = W\ and\ state[k] = true$ **then**
      $node\ v_{jk-1}\ is\ selected\ as\ a\ cooperative\ relay;\ W = W - vw_{k-1}$

Meghanathan [104] proposed methods to define link-separated and node-separated $s-d$ routes on any graph G. The author first uses Dijkstra's approach to determine the $s-d$ path with a minimum hop on an original graph with n nodes, while removing the links defined on the p route. The author introduces the route $s-d$ with the minimum hop p usually P^L when he has at least one route. The Algorithm 13 presents the pseudo-code of the above approach.

Algorithm 13: To Determine the Set of Link-Disjoint s-d Paths in a Network Graph

$Input : Graph\ G\ (V, E), source$ **s** $and\ destination$ **d**
$Output : Set\ of\ lien - disjoint\ paths\ P_L$
$Auxiliary\ Variables : Graph\ G^L(V, E^L)$
$Initialization : G^L(V, E^L) \longleftarrow G(V, E), P_L \longleftarrow \varphi$
begin
  while $(\exists\ at\ least\ one\ s-d\ path\ in\ G^L)$ **do**
    $p \longleftarrow Minimum\ hop\ s-d\ path\ in\ G^L$
    $P_L \longleftarrow P_L\ U\ \{p\}$
    $\forall\ G^L\ (V, E^L) \longleftarrow G^L\ (V, E^L - \{e\})$
    $edge, e \in p$
  return P_L

To determine the node-disjoint paths, the author also used Dijkstra's approach to find the $s-d$ path in the original graph, while removing the intermediate nodes that define the p route. If there is at least one path $s-d$ in G, the author includes the path $s-d$ with minimum jump p generally P^N. The procedure is repeated until there are no more paths $s-d$ in the network. We now say that the set P^N contains the node-disjoint paths in the original graph G. The Algorithm 14 presents the pseudo-code for determining the set of node-disjoint paths in a graph.

Algorithm 14: Set of Node-Disjoint s-d Paths in a Network Graph

$Input : Graph\ G\ (V, E), source$ **s** $and\ destination$ **d**
$Output : Set\ of\ node - disjoint\ paths\ P_N$
$Auxiliary\ Variables : Graph\ G^N(V^N, E^N)$
$Initialization : G^N(V^N, E^N) \longleftarrow G(V, E), P_N \longleftarrow \varphi$
begin
  while $(\exists\ at\ least\ one\ s-d\ path\ in\ G^N)$ **do**
    $p \longleftarrow Minimum\ hop\ s-d\ path\ in\ G^N$
    $P_N \longleftarrow P_N\ U\ \{p\}$
    $\forall\ G^N\ (V^N, E^L) \longleftarrow G^N\ (V^N - \{v\}, E^N - \{e\})$
    $vertex, v \in p$
    $v \neq s, d$
    $edge, e \in Adj - list(v)$
  return P_N

6.6 Analysis of Routing Algorithms

Table 9, presents a technical comparison related to the performance in terms of complexities provided by various disjoint routing algorithms and their routing techniques.

Table 9. Technical comparison of some disjoint routing algorithms

Algorithm	Properties		
	Time Complexity	**Deterministic routing**	**Non-deterministic routing**
Algorithm 1	$O(n)$	×	√
Algorithm 2	$O(n)$	×	√
Algorithm 3	$O(n)$	×	√
Algorithm 4	$O(n)$	√	×
Algorithm 6	$O(n)$	-	-
Algorithm 7	$O(n)$	×	√
Algorithm 5	$O(n^3)$	×	√
Algorithm 10	$O(n)$	×	√
Algorithm 11	$O(n)$	×	√
Algorithm 12	$O(n^2)$	×	√
Algorithm 13	$O(n)$	×	√
Algorithm 14	$O(n)$	×	√

7 Conclusion

In this paper, we reviewed the existing literature in general on disjoint routing algorithms across several categories of graphs and application domains. However, disjoint routing algorithms seem to be effective solutions in networks, allowing to facilitate network security, to increase the reliability of delivery, to ensure the continuity of services in case of failure of the path taken and to distribute the load in a rational way between the source and the destination on several paths. These improve the performance of communications and aggregate the resources available in the network. Although disjoint routing algorithms improve network performance, they also have several limitations among others; longer path, message control mechanism, large route demand, duplicate packet processing and dynamic environment in a network. These limitations may provide a direction for future research.

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