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Recent advancements, review analysis, and extensions of the AODV with the illustration of the applied concept

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ABSTRACT

Mobile ad hoc networks provide a promising opportunity for the applications requiring instant networking in the resource constraint, multi-hop wireless environment. Routing protocols are the backbone of such networks to enable the routing under dynamic circumstances. Ad hoc on-demand distance vector routing protocol (AODV) is the predominant reactive routing protocol designed for mobile ad hoc networks (MANETs). It provides good performance in terms of hop count, packet delivery ratio, and control overhead in the network. AODV has an extensive research spectrum. Many variants of the protocol have been proposed by the researchers to achieve performance improvements and to address the variety of challenges. As there are hundreds of AODV related extensions, a systematic illustration is worth to present. In this review paper, we elaborate on the core of the protocol and discuss the evolution, its variants, extensions, and the applied concepts for improving the protocol. We have surveyed the broad domain of AODV extensions and have classified them based on the various criteria, e.g., quality, reliability, energy, security, and routing strategies, etc. This paper brings out the concept, design objective, research trends, and the current advancements in the research carried out for AODV improvement. Paper also summarizes various aspects of the research trends and portrays performance metrics, input parameters, applicable domains, and the adopted strategies for improving the protocol.

1. Introduction

Mobile ad hoc network is the networking paradigm to interconnect communicating devices in single or multi-hop without requiring any prior infrastructure and administrative support. These networks are autonomous, dynamic, infrastructure-less, and self-organized. The participating nodes in the network are auto-configured, possess wireless connectivity, and can move arbitrarily. These networks face many challenges incurred from the wireless nature and resource constraint comportment of the nodes. The dynamic topologies induced by the mobility of the nodes, make these networks more challenging from the routing perspective. The routing in the mobile ad hoc networks should adapt to the non-deterministic formations of the network. The reactive and proactive are the two mainstream routing strategies to find the intended route. The reactive routing approach finds the route only when required, while the proactive approach calculates and maintains the route in advance by periodic message exchange.

The reactive routing approach comprehends the advantage of having less control overhead as compared to its counterpart. In the reactive approach, on-demand route discovery requires the flooding of control messages for the limited time period, which assists in bandwidth-saving, power-saving as well as makes these protocols less exposed to the adversary. A large number of reactive routing protocols have been proposed for mobile ad hoc networks [11]. Many proposals extend the basic routing by incorporating concepts like bandwidth saving, energy efficiency, quality provision, delay sensitivity, link stability, reliable delivery, swarm intelligence, and opportunistic routing, etc. [15,29]. AODV is one of the most popular and widely accepted choices for reactive routing. In the routing domain, where the majority of the routing protocols are limited to the simulation-based analysis, this protocol has been implemented for real deployments also. A lot of research has been done around AODV; many variants and extensions have been proposed. In this paper, we systematically present the AODV concept, evolution, and the extensions under a single umbrella to help the researchers to scan the large AODV spectrum quickly. The related concepts of AODV like route discovery process, limitations, packet structure, and AODVv2 status have also been elaborated. Although many surveys have already been done on routing protocols, most

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of these surveys cover the limited aspects of the AODV [94,97]. This review analysis is focused on the AODV protocol and covers most of its aspects, including evolution, variants, extensions, and the recent advancements. The major contributions of the paper are as follows.

- The paper extensively surveys the research work done on AODV and systematically portrays its evolution over the last 20 years.
- Algorithm details, packet details, limitations, and the current status of the protocol have been presented.
- Classification of the AODV extensions in 5 major categories, i.e., quality, multipath, energy, security, and routing strategy has been done.
- The concepts used in 90 research proposals for AODV improvement have been briefly summarized in tabular form. Paper also extracts the techniques and approaches used for AODV improvement.
- Analysis of the AODV research trends in terms of performance metrics, input parameters, quality-of-service, and routing strategies has been done, and the outcome has been presented graphically.

The rest of the paper is organized as follows. First, we discuss the related work. In Section 2, we present the basic concept, algorithm, and the analysis of the protocol. In Section 3, we discuss the protocol evolution, packet structure, and the current status of the protocol. In Section 4, we cover variants and extensions of the protocol. We also classify the AODV improvements and systematically present the research addressing various issues. In Section 5, on the basis of the analysis of the reviewed papers, we derive and present the trends in AODV research. Finally, we conclude in Section 6.

1.1. Related work

In literature, several surveys and reviews have been reported on the routing protocols. Most of these surveys cover popular routing protocols based on different routing mechanism, e.g., reactive, proactive, hybrid, etc. and categorize them accordingly [15,119,120]. Some of the surveys cover the specific category of the protocols based on various parameters, e.g., bandwidth, energy, delay, etc. Most of the reported surveys cover many protocols and lack the details of the work on these protocols due to the large number of protocols [94]. There are only a few surveys that focus on a specific protocol to cover all its major aspects. In this survey, we mainly focus on the work related to the AODV. Since the release of the AODV, many extensions of AODV have been suggested in IETF Internet drafts [12,13,16], and [18–23]. There are many variants and extensions of AODV that have been reported in various research papers [17,24,25,29,35,39], and [40–48]. The research papers [49–54,56–69,71–73,75–79], and [80–89] also present the extensions of AODV. We highlight some of the work done on AODV review and illustration. A systematic analysis of the evolution and future direction on AODV was provided by Royer and Perkins in [1]. E. M. Belding-Royer *et al.* discuss path accumulation, improved broadcast, multipath routing, multicast, and IPv6 capabilities to improve the versatility of the protocol and also suggest security, global connectivity, clustering and quality of service aspects. In [6], the authors survey the AODV routing and provide an overview of the variants of AODV. In [8], a survey on AODV modifications has been done, in which authors list some of the AODV extensions based on the alternate route, routing techniques, and energy optimization. In the study of related work, it is observed that many of the extensions improve on a specific parameter but may lack in other aspects. A review on AODV modification to address link breakage has been done by Y. Choksi *et al.* A review on AODV based protocols focusing on the backup routing scheme is presented in [55]. Lu Ding and Li Wan in [70] suggested some improvements in AODV based on energy model and bandwidth estimation. R. H. Jhaveri *et al.* in [94] classify the routing protocols and present a study of the AODV routing protocol and the related research work. Extensions to improve upon the AODV performance have also been presented in [90–118]. Based on the study of the research work carried out around AODV and by analysing the related survey papers, we comprehend that mostly surveys cover a few popular extensions and variants of the AODV protocol. Many extensions and improvements of the protocol have not been covered in these surveys. This paper contributes by the comprehensive study of the work carried out on AODV and covers the majority of its extensions and related research. It covers the ubiquitous as well as new extensions of the AODV, like, MAODV, AOMDV, SAODV, QoS-AODV, BP-AODV, MA-DP-AODV-AHM, E-Ant-AODV, FLOW-AODV, MOAODV, MDRMA, AODV-ETX, GA-AODV, ReTE-AODV, etc. The various extensions of the protocol have been categorized into five categories, i.e., quality, multipath, energy, security, and routing strategy. The concepts used in AODV extensions, like multipath, overhead reduction, delay optimization, secure route, location information, quality of service, energy optimization, and nature-inspired techniques, etc. have also been covered, and linked with the extensions. In this study, we have considered more than a hundred research proposals related to AODV. The year-wise consideration of the proposals has been depicted in Fig. 1.

2. Protocol basics

For the creation and maintenance of the routes, destination sequenced distance vector (DSDV) requires frequent broadcasts in the networks governing high overhead$O(n^2)$, where n is the number of nodes in the network. To improve upon the DSDV performance, AODV has been conceptualized with the objective of minimizing the broadcasts in the network by the on-demand route creation [7]. AODV protocol is a reactive routing protocol in which each node behaves as a router, and routes are discovered as and when required, and these routes are maintained only for the duration of their uses [1]. To ensure loop freedom, AODV utilizes the concept of the destination sequence number, which is a monotonically increasing number maintained by each of the nodes of the network [7]. AODV falls under the destination-based routing protocol category in which node only needs to know the next hop when forwarding packet towards the destination. All the participating nodes have a similar role and assume a flat network structure [11].

2.1. Basic operations

AODV protocol, as defined in RFC [2], has been exemplified in this section. This on-demand distance vector protocol acquires and maintains routes only when needed [99]. The basic operations of the protocol include path discovery, forward & reverse-path setup, routing table management, local connectivity management, and path maintenance. Route-request(*RREQ*), route-reply(*RREP*), and route-error(*RERR*) are the messages used by the protocol. When a source node (*SRC*) intends to send the data to the destination (*DST*) for which it does not have a route, the *SRC* initiates the route discovery by broadcasting the *RREQ*. The *RREQ* contains the information of route request ID (*RREQ_ID*), IP addresses (*SRC_IP*, *DST_IP*), sequence number of the originator and the destination (*SRC_SEQ*, *DST_SEQ*), hop count(H_c), and request flags(F_q). On receiving RREQ, each neighbour node(N_h) checks the destination in *RREQ*. If ($N_h = DST$), it responds by unicasting the *RREP* to the *SRC*. The route reply contains the information of (*SRC_IP*, *DST_IP*, *DST_SEQ*), lifetime (T_l), reply flags(F_r), prefix size (P_s), and the hop-count. If ($N_h \neq DST$)but N_h knows the valid route to *DST*, it responds by sending the *RREP* to the originator (*SRC*). If an inter-

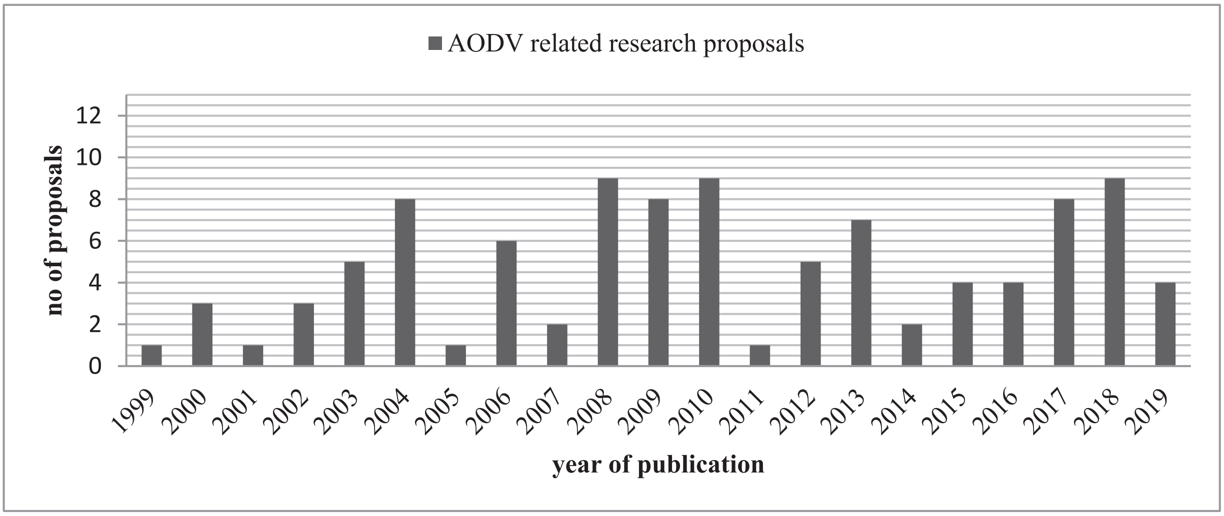


Fig. 1. Year-wise research papers considered for the analysis of AODV related work.

mediate node(N_i)does not have a route to *DST*, it rebroadcasts the *RREQ* to its neighbours and increments theH_c. If N_i receives a duplicate *RREQ*, it drops the packet and does not rebroadcast. Nodes receiving the *RREQ* setup reverse route to *SRC*, and this progression formulates a unicast path from *DST* to *SRC*. During unicast *RREP* propagation from *DST* to *SRC*, each node setup a forward pointer, and a path from *SRC* to the *DST* is created. Protocol considers the number of hop count as the routing metric, and the path with fewer hop count is preferred. If $C_p$is the cost of the path p from (S) to (D) and $d_{ij}$is the distance of the link (i, j), the cost function can be given by Eq. 1.

$$C_p = \sum_{(i,j)\in p} d_{ij} \forall (d_{i,i+1} = 1) \tag{1}$$

Nodes in the active route may utilize the hello message for the awareness of one-hop connectivity. The Hello messages are special-purpose route reply broadcast with hop-count equal to 1, i.e., $HELLO = \{RREP \forall (H_c = 1)\}$. If allowed hello loss is L_h and hello interval isI_h, the lifetime of the hello message (P_h) is given as$P_h = L_h \times I_h$. The route update mechanism of AODV makes sure that the updated route is fresh and ensures the loop freedom [46]. The route is updated if the destination sequence number and hop count satisfies the conditions of Eq. (2).

$$\begin{aligned} &if\,(SEQ_i < SEQ_j)\; or\; ((SEQ_i = SEQ_j)\; and\; (Hc_i > Hc_j))\; then \\ &SEQ_i = SEQ_j;\; Hc_i = Hc_j + 1;\; Next\_hop = j \end{aligned} \tag{2}$$

For the purpose of route maintenance, if link breakage or route error occurs, protocol utilizes route error (*RERR*) to notify the affected precursors. The *RERR* message contains the number of unreachable destinations (*UNR_DST_CNT*), unreachable IP addresses (*UNR_DST_IP*), and the unreachable destination sequence numbers (*UNR_DST_SEQ*). The basic operations of route request, route reply, local hello broadcast, and route error messages are shown in Fig. 2. The route discovery mechanism of the protocol has been illustrated in Algorithm 1, and the notations used are given in Table 1.

Algorithm 1 AODV route discovery process.

```
Find Route(S, D, C_i)
in :Control packets R_req; R_rep; R_err
out :unicast route to destination
if S has route to D then
    send to next hop towards D
else                                  ▷ route discovery
    S create R_req
    H_c ← 0 and broadcast R_req
    I ← {nodes receiving C_i}
    for all i ∈ I do
        if (C_i = R_req) then
            if Invalid R_req then
                discard old or duplicate
            end if
            if (N_i = D) then
                Dest seq (R_rep) ← Dest seq (D)
                H_c(R_rep) ← 0; R_rep to S
            else if (N_i has active route to D)
                Dest seq (R_rep) ← Dest seq (N_i)
                H_c(R_rep) ← H_c(N_i to D)
                R_rep to S
                if (G = TRUE) then
                    gratitous R_rep to D
                end if
            else
                RT ← Org seq (R_req)
                H_c ← H_c + 1; setup reverse route
                rebroadcast R_req
            end if
        else if (C_i = R_err) then
            mark route invalid
        else if (C_i = R_rep) then
            if (N != S) then
                H_c ← H_c + 1; setup forward route
                send towards S
            end if
        end if
    end for
    update RT of S
    send to next hop towards D
end if
return R_i
```

2.2. Analysis review and limitations

In this section, we present the analysis of AODV carried out using the UPPAAL toolbox [4,5] [31] [36–38]. The analysis reveals the limitations associated with the protocol and is useful to improve the protocol. The automated analysis of AODV in [5] checks the protocol behaviour in the topologies of up to five nodes. It considers three desirable properties of the routing protocol. First, if all the routing messages have been processed, a route from source to destination has been found. Second, the route should not be sub-optimal. These two properties infer that the optimal route will be found if all messages are processed. The third property state that no sub-optimal route will be found. Analysis highlight that AODV does not guarantee the optimal routes or even the routes at all. Au-

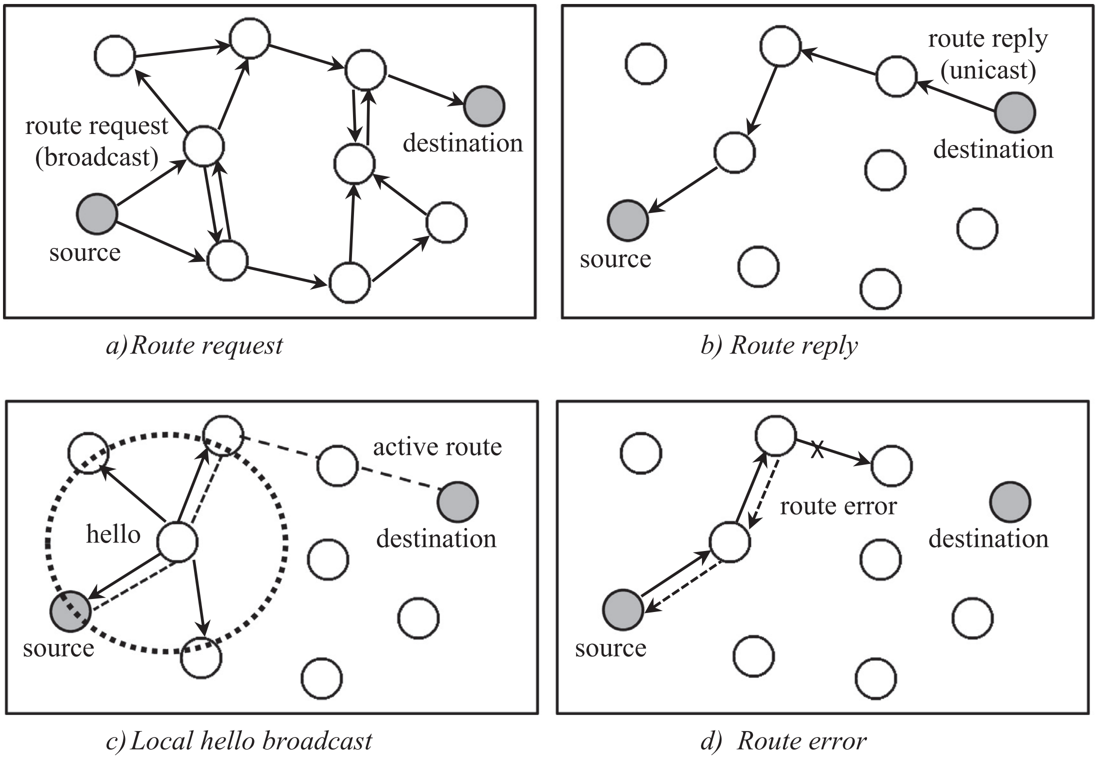


Fig. 2. Route discovery, hello and route error propagation.

Table 1
Explanation of notations used in Algorithm.

N_i	Node i
S	Source node
D	Destination node
C_i	Control info
R_i	Route info
G	Gratuitous flag
RT	Routing table
R_{req}	Route request
R_{rep}	Route reply
H_c	Hop count
Org *seq*	Originator sequence number
Dest *seq*	Destination sequence number

thors [5] suggest the possible solutions and propose three variants, first by forwarding every route reply. Second, if subsequent route requests arrive via a shorter path, then reply to the improved request and also suggest the recovering mechanism from the failed route replies. In [4], DYMO and AODVv2-16 have been investigated for route establishment and routing loops on 3×3 grids using UPPAAL statistical model checking (SMC). Routing loops have been reported in AODV by many studies. The investigation of [4] reports that when the intermediate node sends a route reply like in AODV and DYMO, there is the chance of a routing loop. When route reply is sent only from the destination as in AODVv2, it avoids the routing loops but increases the time for route discovery. A scenario of linear topology is shown in Fig. 3 (a) to exemplify the presence of the routing loop in the DYMO variant of AODV, in which the intermediate node can send the route reply. In this scenario as shown in Fig. 3 (b), when the link between A and B breaks and B has a packet to send to A, the node B broadcasts RERR message to its neighbours. As depicted in Fig. 3(c), if RERR reception at C is lost, node C does not omit the route entry for A through B. If B has a packet for A, node B initiates RREQ, and C responds by RREP as an intermediate node, Fig. 3(d). In this case, a false interpretation

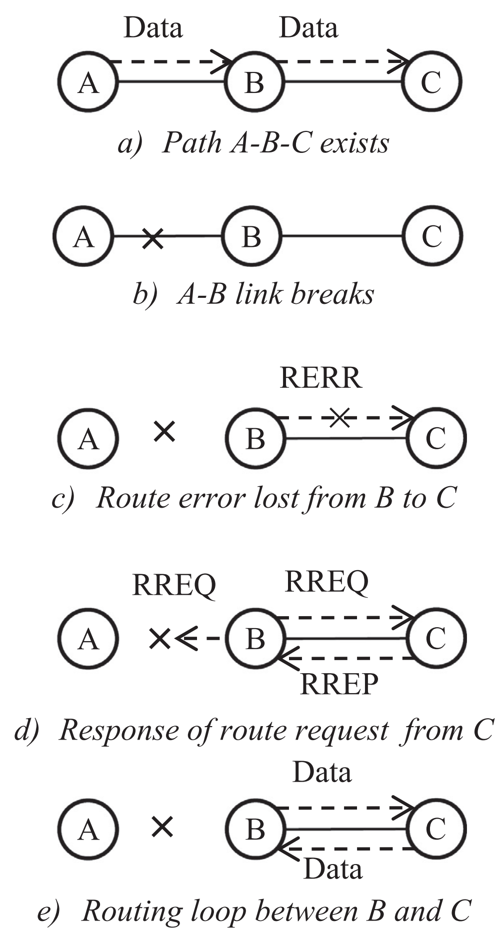


Fig. 3. Depiction of the formation of routing loop [4].

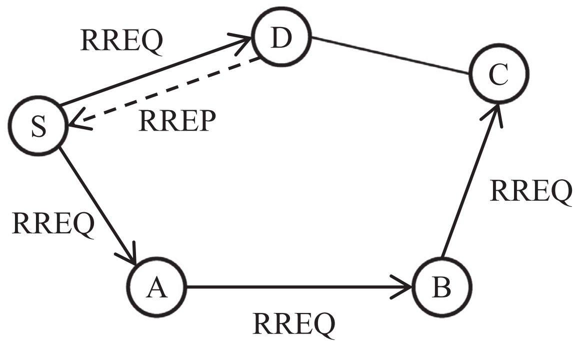


Fig. 4. Non-optimal route from C to S via B [31].

is formed that B has the route to A through C, and similarly, C assumes that it has the route to A through B, and as shown in Fig. 3 (e) this creates a routing loop between B and C.

Analysis in [31] presents the problem of AODV caused by the lost route reply and also shows the accidental formation of the non-optimal path by some of the nodes in the network. In the ring topology of Fig. 4, when RREQ comes at C via node B, node C establishes a non-optimal route to S via B in spite of the optimal route via D.

The experiments conducted in [36] set up a linear topology of three nodes and mention the specific sequence of events for which there is the possibility that AODV does not establish the route. In [37], algebra for wireless networks (AWN) has been proposed, and it presents the core components and detailed analysis of AODV. The modelling of the AODV RREQ process has been discussed in [38], and it models the scheme to address the limitations of non-optimal route selection and failure of the route discovery process.

3. Protocol evolution

Since AODV conceptualization and its initial proposal in the Internet Engineering Task Force (IETF), the protocol has evolved in a number of ways to incorporate many improvements [1]. It is one of the promising routing protocols in the charter of the IETF MANET working group, falling under the reactive family of the protocols. The protocol was proposed for use by mobile nodes in an ad hoc network with the notion to ensure loop freedom by making use of destination sequence numbers and providing the solution of the classical problem of count to infinity in distance vector protocol. AODV was published by C.E. Perkins and E.M. Royer, in proceedings of IEEE Workshop on mobile computing systems and applications [7]. The protocol has gone through many iterations, and improvements and the RFC-3561, defining the Ad hoc on-demand distance vector (AODV) routing in the experimental category, was published in 2003 [2]. A progressive inheritor of the AODV was released as the dynamic MANET on-demand routing protocol (DYMO) [9]. The protocol was considered the descendant of the design of previous reactive protocols, especially AODV and dynamic source routing (DSR). The DYMO internet draft-22 released on March 12, 2012, coined the acronym AODVv2 for the protocol [31]. In March 2013, *draft-ietf-manet-aodvv2,* an AODVv2 series, was instantiated. The current series of AODVv2 *draft-perkins-manet-aodvv2* was released in March 2017. The recent Internet draft on AODVv2 at the time of writing is *draft-perkins-manet-aodvv2-03*, which was published in Feb 2019 as a proposed standard [3]. During protocol evolution, many features have been improved. Some new concepts have been added while few features have been removed. The evolution of the protocol from 1997 to 2019, representing AODV, DYMO, and AODVv2, has been depicted in Fig. 5.

3.1. AODV packet structure

The operations of the AODV protocol are executed by *RREQ*, *RREP*, *RERR*, and *HELLO* messages. Local connectivity information might be offered by the *HELLO* message, which is the special case of *RREP* message with TTL = 1. The fields, size, and structure of messages defined by the protocol have been summarized in Table 2.

3.2. AODVv2 status

We highlight some of the key notions of the recent *AODVv2* version *perkins-manet-aodvv2-03*[3]. The basic route discovery process of *AODVv2* resembles with the *AODV* specification in [2]. In *AODVv2, RREQ* messages are multicast, and *RREP* is unicast and includes the metric value to indicate the cost of the route. The route discovery and node's routing tables have been depicted in Fig. 6.

AODVv2 has an improved mechanism for bi-directionality verification during route discovery. The receipt of route-reply acknowledgment (*RREP_ACK*) confirms the bidirectional connectivity of upstream node while receipt of *RREP* containing the route to destination confirms the bi-directionality of the downstream router. The neighbour states have been indicated in Table 3.

The expanding ring search and intermediate route reply features have been moved out of the scope of [3] and have been specified in a separate document. The *RREQ, RREP, RREP_ACK,* and *RERR* are the four message types utilized by the protocol and have been depicted in Table 4. The generalized format has been adopted for all the control messages. The generalized representation has been depicted in Table 5.

AODVv2 [3] has been improved to have the provision of alternate metrics to determine the route quality as compare to the primary metric of distance expressed in the number of hops by AODV. The metric values are conveyed by *RREQ* and *RREP* messages. The currently supported cost metric of the protocol is strictly increasing and can be given as $C_r = \sum_{i \in r} L_i$, where C_r is the route cost and L_i is the link cost in the route r. If $(C_{R1} \leq C_{R2}) \Rightarrow R_2$ *notsubsectionof*R_1, and that indicates the loop freedom. Although the protocol supports multiple metric types, only one metric might be used in a single discovery process. This version support multi-interface IP addresses. The participating nodes can have multiple interfaces, multiple IP addresses per interface, and may use the same IP address on multiple interfaces. The protocol supports the multi-homing concept. The hello messages and the local repairs have been removed from the protocol. Table 6 summarizes the comparative features of the AODV, DYMO, and AODVv2 protocol.

4. AODV modifications, extensions, and variants

Variants of AODV proposed in the form of extensions, simplification, variation, improvements, and IETF Internet drafts have been covered in this section.

4.1. IETF drafts on AODV extension

Many IETF Internet drafts have also been released on the extension of the AODV protocol. In this section, we highlight some of the work in this direction, as depicted in Fig. 7.

Perkins *et al.* have extended quality-of-service parameters in *AODV-QoS.* The delay and bandwidth parameters have been envisioned for the quality provisions such that delay does not exceed a maximum value, and a certain amount of bandwidth is made available along the route. The protocol adds extensions in the route discovery messages to provide quality of services support [12]. M. G. Zapata proposed *SAODV*, a secure ad hoc on-demand distance

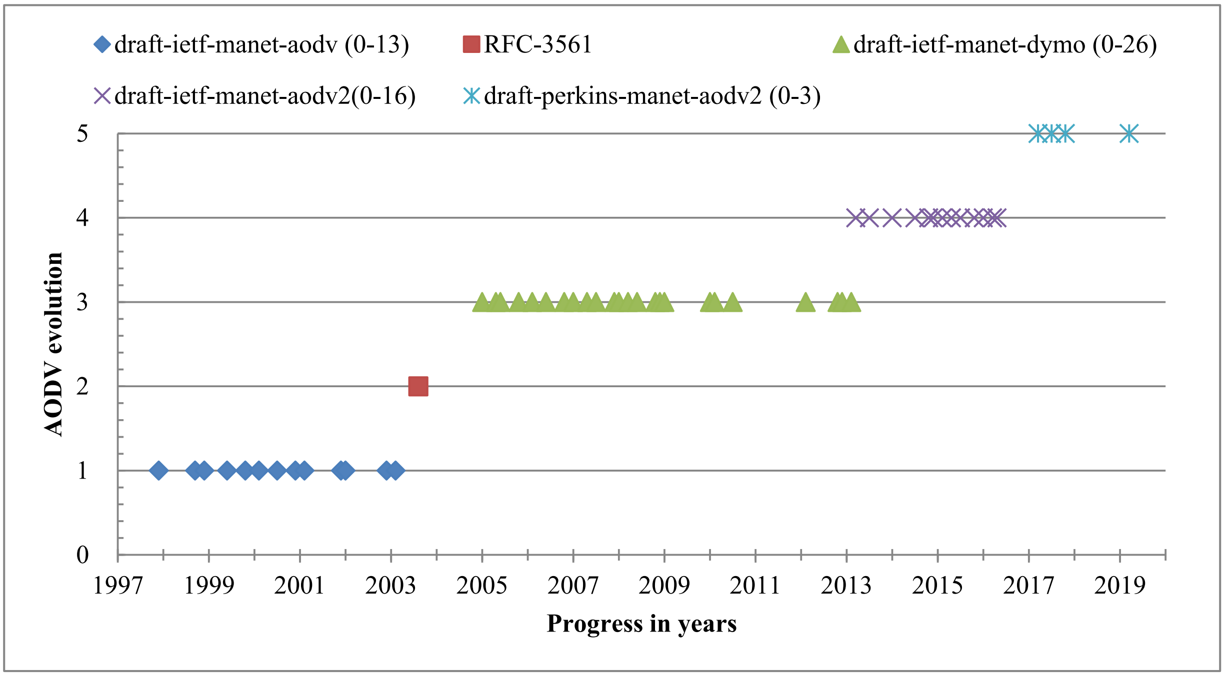


Fig. 5. IETF AODV evolution -Internet drafts and RFC.

Table 2
AODV messages.

Route request (RREQ)	Route reply (RREP)	Route error (RERR)
Type (8 bits)	Type (8 bits)	Type (8 bits)
J, R, G, D, U flags (5 bits)	R, A flags (2 bits)	N flag (1 bit)
Reserved (11 bits)	Reserved (9 bits)	Reserved (15 bits)
Hop count (8 bits)	Prefix size (5 bits)	Destination count (8 bits)
Request ID (32 bits)	Hop count (8 bits)	Unreachable destination IP (32 bits)
Destination IP (32 bits)	Destination IP (32 bits)	Unreachable destination sequence (32 bits)
Destination sequence (32 bits)	Destination sequence (32 bits)	Additional unreachable IP (if needed)
Originator IP (32 bits)	Originator IP (32 bits)	Additional unreachable destination sequence numbers (if needed)
Originator sequence (32 bits)	Lifetime (32 bits)	
RREQ size = 24 bytes	*RREP size = 20 bytes*	*RERR size =12 bytes (if DST count =1)*

Table 3
Neighbour states.

State	Connectivity	Remark
Heard	Initial	New entry
Confirmed	Bidirectional	Used for forwarding packets
Blacklisted	Unidirectional	Not confirmed as bidirectional

vector routing as an extension of AODV. It utilizes security features like authentication and integrity to protect the route discovery mechanism [13,14]. The multicast ad hoc on-demand distance vector routing protocol, *MAODV* proposed by Royer and Perkins, offers the multicast operation of AODV [16]. In *AODV6* [19], Perkins, Royer, and Das modified the AODV messages that enables the protocol to work with the IPv6 addressing. The protocol incorporates necessary changes to allow the transmission of 128-bit addresses of IPv6 instead of 32-bit addresses of IPv4. *AODV-stable-route* proposed by the authors in [18] defines route stability field in route request message of the protocol to inform the stability of the route to the destination. The protocol tries to select the route with more stable intermediate nodes. *Clustering-AODV* an AODV Extensions for MANET clustering was proposed by S. Ahn to allow the clustering of nodes. The scheme requires some nodes to become cluster heads and other nodes to belong to any one of the clusters. AODV control messages are extended to support clustering, which allows improvement in scalability [20]. *AODV-RPL* is an asymmetric AODV-P2P-RPL in LLNs for low-power, and lossy networks (LLNs) propose reactive point-to-point route discovery mechanism for both hop-by-hop routing and source routing, using AODV based RPL protocol (Routing protocol for LLN) [21]. In *LoWPAN-AODV*, Montenegro *et al.* [22] describe the utilization of AODV for the IEEE 802.15.4 network that targets low power personal area networks. It specifies the pro-

Table 4
Control message contents [3].

RREQ	RREP	RREP_ACK	RERR
Message hop limit Address list Prefix length list (optional) Orig. Sequence number Target sequence number (optional) Metric type Orig. metric	Message hop limit Address list Prefix length list (optional) Target sequence number Metric type Target metric	Ack. Request (optional)	Packet source Address list Prefix length list (optional) Seq. number list Metric type list

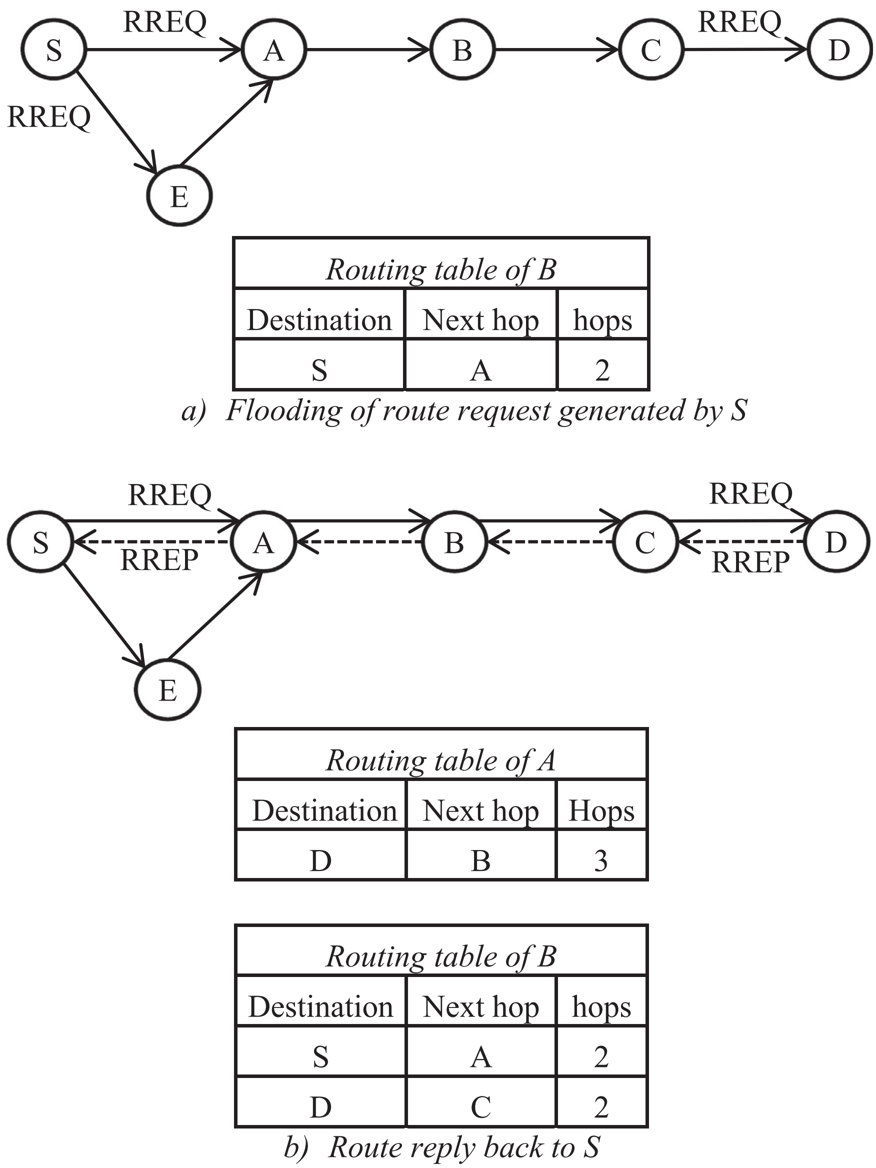


Fig. 6. Route discovery and routing table.

Table 5
Generalized message representation [3,32].

Element	Contents	Representation
Packet	Packet header, messages ≥ 0	<packet header><message>*
Message	Message header, message TLV block, address blocks ≥ 0, address block TLV blocks ≥ 0	<msg-header><tlv-block>(<addr-block><tlv-block>)*
Message TLV block	Message TLVs ≥ 0	<tlvs-length><tlv>*
Address block TLV block	Address block TLVs ≥ 0	<tlvs-length><tlv>*
TLV	Type, length, value	<tlv-type><tlv-flags> <tlv-type-ext> (<index-start><index-stop>)(<length><value>)

vision of mesh routing. *Multipath-AODV* [23] is a multipath routing protocol exhibit the potential of providing load balancing and reliability. The protocol extends the route request option in the AODV options header to support multiple routes. Support of *Internet connectivity* for AODV proposed by Hyun-Wook Cha *et al.* in [26] is based on auto-configuration of global address, in which sender nodes execute the route determination algorithm and the intermediate nodes run the forwarding algorithm. J. Jeong *et al.* [27] presented ad hoc *IP Address auto-configuration* for AODV, which includes the selection of the random address, uniqueness verification of the address, and the assignment into network interface. In [28], C. Perkins suggests the *endpoint message authentication* for AODV route messages of AODVv2 by enabling the authentication mechanism used in RFC 7182 on integrity check value and timestamp TLV definitions.

4.2. AODV simplification

Trimmed down version *AODVjr* [34] removes many features like sequence number, gratuitous route reply, hop count, hello mes-

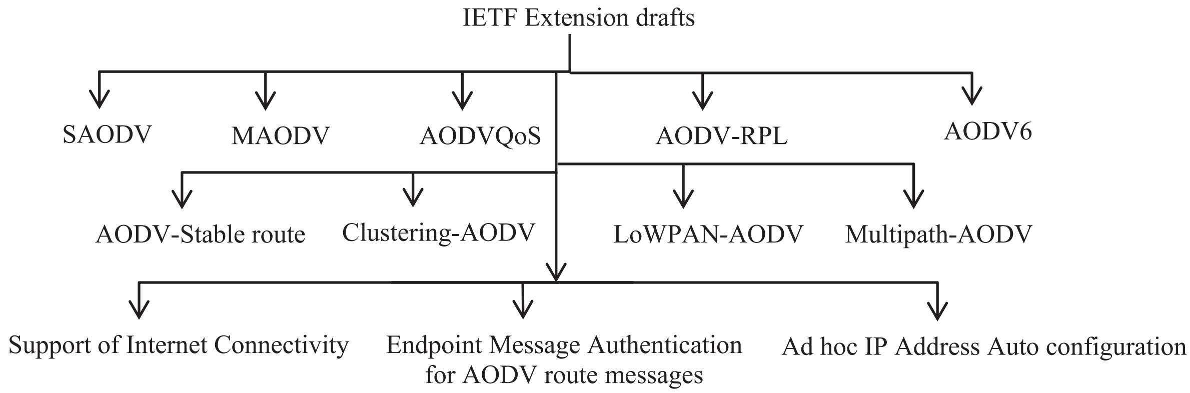


Fig. 7. IETF Internet drafts on AODV extension.

Table 6
Comparison table of AODV, DYMO & AODVv-2: [2] [3] [9] [10] [30].

Features	AODV [2]	DYMO	AODV-V2 [3]
Expanding ring search	Yes	Yes [9]	Moved*
Generalized packet & message	No	Yes [9]	Yes
Multiple metric types	No	No [9]	Yes
Multiple Interfaces	Yes	Yes	Yes
Multi-interface IP addresses	No	No	Yes
Hello exchange	Yes	No	No
Path accumulation	No	optional [10]	No
Local repair	Yes	No [10]	No
Intermediate route reply	Yes	Yes [9], optional [10]	Moved*
Precursor list	Yes	No[10],optional[30]	optional
Gratuitous route reply	Yes	No	No
Route reply ACK	Yes	No[9],optional[30]	Yes
Multi-homing support	No	No	Yes

* out of the scope of [3], specified in a separate document

Table 7
Comparison of AODV & AODVJr: [2] [7] [34].

Protocol	Evolution	Emphasis	Evaluation	Outcome
AODV	Designed to improve upon DSDV	On-demand discovery of loop-free routes with little or no reliance on periodic updates	Initially evaluated on PARSEC, an event-driven, packet-level simulator.	Goodput ratio avg. 97.98%, 95.91% & 72.32% for 50, 100 & 1000 nodes respectively using 64 bytes packets of 20msec inter-arrival [7].
AODVjr	Simplification of AODV	Trimmed down specification	25, 50 & 100 nodes with max speed 5 m/s simulated using NS2	Performs nearly the same as AODV but less time & effort in the program and debug [34].

sages, route error, and precursor list from AODV and simulated the trimmed down version of AODV. This protocol is based on end-to-end strategy, destination responds the first route request it receives, and for the route-maintenance destination requires to send a packet to the source occasionally. It is the simplification of AODV rather than an extension. The comparison of AODV and AODVJr is given in Table 7.

4.3. AODV extensions and variants

There are many extensions and variants proposed in the literature. The common strategies adopted for the ADOV extensions are shown in Fig. 8. Based on the various techniques, we have subdivided the proposed variants into five major categories, i.e., quality, multipath, energy, security, and routing strategy. Many extensions consider more than one technique; hence, some of these proposals may fall in more than one category.

4.3.1. Quality and performance

The AODV protocol has been extended to improve the quality of service in mobile ad hoc network. There are many parameters like throughput, congestion, signal strength, load, bandwidth, delay, jitter, mobility, and routing overhead, etc. that have been considered for performance improvement. The quality of service routing selecting the high bandwidth path is shown in Fig. 9. Protocol extensions in quality and performance categories have been summarized in Table 8. In this subsection, we exemplify some of the protocols of this category.

QoS-AODV: Quality of service extension of the AODV has been proposed by Perkins *et al.* in [12] for QoS parameters like delay and bandwidth by considering the QoS object and the accumulated value extension during route discovery. The extension considers that delay does not exceed the prescribed maximum value, or it ensures that minimum network bandwidth is made available along the route. The accumulated value extension is used with delay and jitter, while bandwidth does not require it. If the delay parameter has been specified by the QoS object in the RREQ, the forwarding nodes should satisfy the delay condition of Eq. (3). The current value of the forwarding delay (D_f) is compared with the difference of the maximum delay (D_m) in the QoS object extension and the delay value in the accumulated delay extension (D_a). The forwarding delay is the measure of the average time taken the

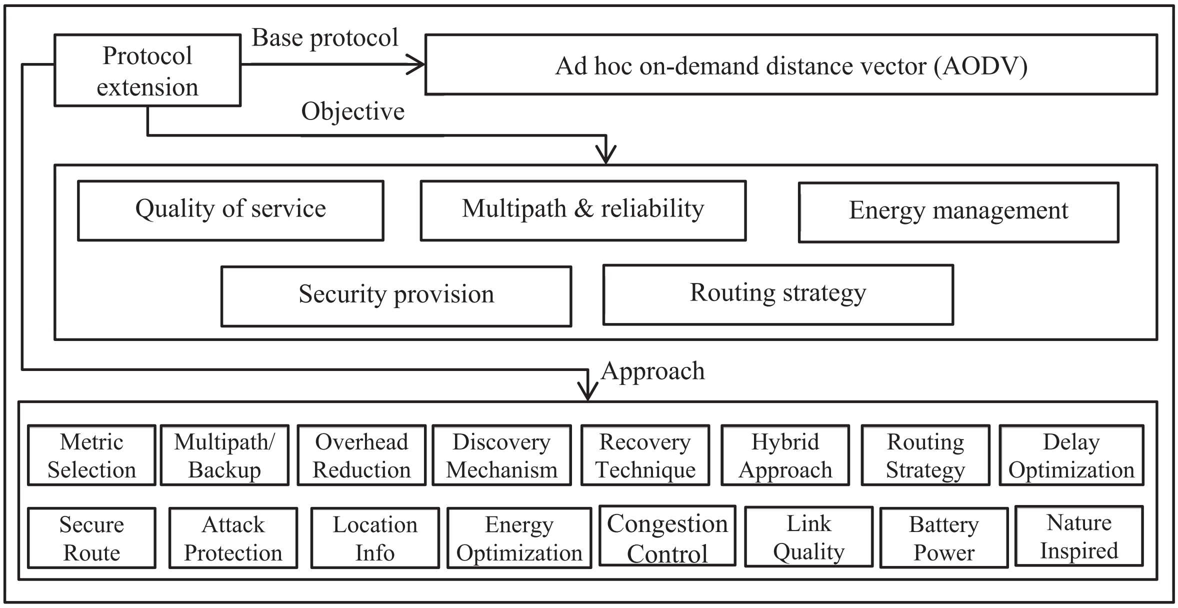


Fig. 8. AODV extension basic strategies.

Table 8
AODV Quality and performance extensions.

Protocol	Descriptive name	Concept	Objective/Improvement
QoS-AODV	Quality of Service AODV	Extensions in route discovery messages to carry the QoS information	Quality of service assurance for delay and bandwidth parameters [12]
MOAODV	Multi-Objective AODV	Meta-criterion function to combine the multiple routing objectives	To improve the quality of service [29]
MD-AODV	MAC Delay AODV	Uses of MAC delay routing metric	Throughput improvement in multi-rate wireless networks [39]
AODV PLRR	Pre-emptive Local Route Repair AODV	Preemptive local route repair when link break is about to occur	Avoid route failure [44]
AODV_LFP	AODV based on Link Failure Prediction	Link failure forecast during the data transmission	Improvement in packet delivery and the reduced end to end delay [47]
Q-AODV	Queue AODV	Control the flooding of control packets in the network by using the queue size	Less congested route [50]
MA-AODV	Mobility Aware AODV	Periodic quantification of mobility and its variation	Stable path [51]
AODVLP	AODV with Link Prediction	Signal strength based prediction of link breakage.	Improvement in packet loss and end to end delay [57]
EAODV	Enhanced AODV	Hello message extension by Hong P. Wang and L. Cui	Local connectivity awareness
AODV-ETX	Expected Transmission Count (ETX) metric within AODV	Expected transmission count metric, and use of the link probe packets for ETX measurement	Better end-end delay and packet loss ratio [63]
CC-AODV	Congestion Control AODV	Make use of congestion counter and flag	To control congestion in the network [65]
AODVLM	Load and Mobility based AODV	Considers traffic load on the node for route selection, and utilize path reset scheme	Reduction in network congestion [71]
AD-AODV	AD-AODV	Metric based on route mobility and route hops	Stable route [73]
MAODV	Modified AODV	Uses preferred nodes for rebroadcasting RREQ. Make use of GPS information.	Reduction in overhead [75]
IAODV	Intelligent AODV	Provision of two phases, signal strength and hop count	Stable path [78]
AODV-2T	AODV-2T	Signal strength, battery monitoring, and backup route	Improvement in route failure and packet loss [80]
AODV-LR	AODV Local Repair	Repair broken link in the active path locally	Path break is transparent to the originator [2,86]
SP-AODV	Semi-Proactive AODV	Some special nodes update routing tables proactively while others do the reactive routing	Packet delivery ratio and end-to-end delay improvement [88]
Trusted AODV	Trust-based AODV	Based on mutual trust of packet transmission or packet drop. Trusty nodes participate in routing	Improved packet delivery ratio [118]
QS-AODV	QoS routing on AODV	Includes bandwidth requirement, and uses session id to identify the flow, local repair	Routes as per application quality of service requirement [111]
PAODV	Prior AODV	Restricting the distance and the number of discovered routes	Reduction in control overhead and usability in VANET [89]
QAODV	QoS-AODV	Uses hop count and load for route metric calculation and also considers bandwidth and delay in route selection	Quality of service in a wireless mesh network [92]
MDA-AODV	Mobility and direction aware AODV	Guide route request, reply based on speed and directions of nodes	Decrease the effect of link breakage by stable and reliable path [96]

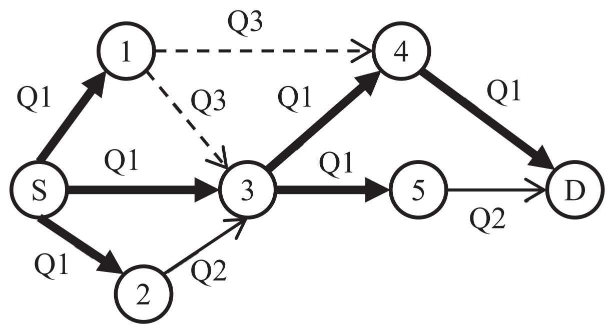


Fig. 9. Quality of service routing (bandwidth Q1>Q2>Q3, path S-3-4-D).

node to forward the data and is given by the sum of the processing delay (T_p), queuing delay (T_q), and the propagation delay (T_g).

$$D_f < (D_m - D_a)\ ,\ \forall\ \ D_f = \{T_p + T_q + T_g\} \tag{3}$$

Simulation results on QoS-AODV investigating the integrated route discovery and bandwidth reservation protocol in TDMA network [74] have been presented by Gerasimov *et al.* in their bandwidth-reservation mechanism for on-demand path-finding. QoS-AODV has also been analysed by Renesse *et al.* with respect to the traffic rate, and it reported better utilization of the bandwidth resource.

Multi-objective AODV: MOAODV utilizes the meta-criterion function given by Eq. (4) to calculate the cost of the chosen path p [29]. In which, $m_1 = d(distance)$, $m_2 = c(cost)$, $m_3 = e(delay)$, $m_4 = l(load)$, and r = *reliability*.

$$C_p = \sum_{t=1}^{4}\left(\sum_{i,j\in p} m_t(i,j)\right) - \prod_{i,j\in p} r(i,j) \tag{4}$$

Authors also propose the swarm intelligence variant of AODV and incorporate the ant colony optimization (*ACO*), bee colony optimization (*BCO*), and firefly algorithms (*FA*) to determine the route in the network.

MAC delay AODV: Z. Fan in [39] proposed the modifications in AODV by introducing the MAC delay metric instead of the hop count metric. The suggested metric is calculated as $C = \alpha f + \eta$, where $\alpha$and η specify the data rate and modulation, and f specifies the frame size. The protocol adds the path cost field in the *RREQ* and *RREP* packets. Scheme exhibits good results in multi-rate ad hoc networks.

Queue AODV: Authors in [50] proposed the modifications in the route-finding mechanism of AODV based on the queue size. The authors suggest a random probability field inside the RREQ packet. The proposed algorithm decides to rebroadcast or drop the *RREQ* based on the rebroadcast probability (P_r) calculated by output queue size$P_r = (Q_{out}(\max) - Q_{out}(current))/Q_{out}(\max)$.

AODV-ETX: Nenad J. Jevtic [63] proposed the use of the expected transmission count (ETX) metric in the AODV protocol implementation of the NS-3. $ETX = (1/p_t \times p_r)$, where p_t and p_r are the probabilities of successful transmission of packet and reception of acknowledgment, respectively. To measure ETX, the fixed size link probe packets (*LPP*) are broadcasted at an average periodτ. The probability p_r over the window of last w seconds is given as $count((t-w), t)/(w/\tau)$. The protocol modifies the *RREQ* and *RREP* packets to include the ETX value. In the protocol, ETX values are cumulative; the route metric is given as the sum of the link metrics in the route r, i.e. $ETX_r = \sum_{l\in r} ETX_l$.

4.3.2. Multipath and reliability

The AODV protocol has also been extended to incorporate the multipath, backup, and alternate routes mechanism to improve the reliability and performance of the protocol. In this subsection, we mention some multipath extensions. Such extensions have been summarized in Table 9. The multipath routing depicting the node disjoint, link disjoint, and backup path has been shown in Fig. 10.

AOMDV: Ad hoc on-demand multipath distance vector routing [46] provides multiple link-disjoints paths, as shown in Fig. 10(a). The protocol has two main components, i.e., route update rule to commute multiple loop-free paths and a distributed protocol to find the link-disjoint paths. To ensure the loop freedom, authors suggest the notion of advertised hop count as the maxima of the hop counts of multiple paths to a destination, and it replaces the hop count of AODV. The advertised hop count(*Ahc*) update by the node i for the destination d can be given by Eq. (5). For the two successive nodes i and j on a valid route to the destination d, route update rule of the Eq. (6) hold true, where Sq_i^d represents the sequence number at node i for the destination d.

$$Ahc_i^d = \max_k\{hc_k|(next\_hop_k, hc_k) \in route\_list(i)_d\} \tag{5}$$

$$(-Sq_i^d, Ahc_i^d, i) > (-Sq_j^d, Ahc_j^d, j) \tag{6}$$

QoS-MRAODV: QoS-based multiple-route AODV protocol has the provision of multiple routes in order to meet an application's QoS requirement. It maintains one QoS based primary route (1) and several backup routes ($M > 1$) to counter the frequent route failure problem in the ad hoc network. In case the primary route fails, the protocol selects a backup route as the primary route. The protocol provides redundancy ($1 + M$) and offers QoS support [24]. Only the destination node generates the route reply of the RREQ packet with a maximum of (M+ 1) RREP packet, each corresponding to the response of a route request packet. Authors of [24] suggest the value of M in the range of 2 to 5.

Resilient AODV: In Resilient AODV [102] establishment of multiple routes between source and destination has been proposed. The approach suggests in the case of primary route failure an alternate route may be adopted immediately without requiring immediate route discovery. In the situation of the non-availability of the alternate route, the route break information is propagated backward to intimate the previous node to choose the alternate route. The protocol utilizes *MRREQ*, *MRREP*, and *MRERR* messages by modifying RREQ, RREP, and RERR, respectively.

AODV-ABR: Wei Kuang Lai *et al.* [84] proposed the Adaptive backup route (AODV-ABR), and Adaptive backup route and local repair (*AODV-ABL*) protocols. The proposals are based on the modifications of *AODV-BR* [42] to improve the adaption for topology changes. AODV-BR establishes the mesh and creates alternative multi-path by overhearing the RREP messages. In AODV-ABR, alternative routes are created by overhearing RREP and data packets also, while AODV-ABL further adds the local repair concept.

AODVM: AODV multipath [85] was proposed by Zhenqiang Ye *et al.* to provide the multiple node disjoint path from source to destination in the ad hoc network, as shown by Fig. 10(b). In this scheme, the intermediate nodes record the information of the duplicate *RREQ*, instead of discarding these packets. The intermediate nodes do not generate *RREP* for the source. The *RREP* is generated by the destination and contains the additional field *last-hop-id* to indicate the neighbour from which this copy of the RREQ was received. The RREP traverse the reverse path of the RREQ copy. Multiple copies of the RREQ assist in creating multiple paths, and the concept provides the robustness from the node failure in the network. As a part of the reliable framework, in [85], it is proposed to populate some of the reliable nodes (*R-nodes*) in the network. The authors suggest the deployment strategy of the reliable nodes based on the randomized min-cut algorithm considering the position and trajectories of these nodes to create the framework for improved reliability.

Table 9
AODV multipath and reliability extensions.

Protocol	Descriptive name	Concept	Objective/Improvement
AOMDV	Ad hoc On-demand Multipath Distance Vector	Multiple loop-free and link disjoints paths	Multipath extension, Improvement in end-to-end delay [46]
QoS-MRAODV	Quality of Service based Multiple-Route AODV	One primary and multiple backup routes for redundancy	Resilient to dynamic changes in network topology [24]
EMAODV	Efficient Multipath AODV	Determine path for route discovery rather than flooding the entire network	Control the congestion caused by RREQ rebroadcast [35]
AODV-BR	AODV with Backup Routes	Overhear RREP from its neighbours for the alternate route table	Creates a mesh structure, robustness to the mobility [42]
MP-AODV	Multipath AODV	Node disjoints routes. Backup route discovery process during the data transmission	Provides backup routes, reduced end to end delay [93]
RAODV	Resilient AODV	Establish many possible alternate routes, on route break immediately adopt an alternate route	Reduction in packet loss [74]
Robust AODV	Robust AODV	Multiple backup routes are built, the highest priority backup-route becomes active if active route break or less preferred. Local proactive routing updates	Robust against mobility [82]
AODV-ABR	Adaptive Backup Route AODV	Alternative routes by overhearing RREP and data packets	Adaptation to topology changes [84]
AODVM	AODV-Multipath	Node disjoint multipath, record the information of duplicate route request	Robustness to node failure [85]
AODV-GBR	AODV with Guaranteed Bandwidth Route	Backup routing and guaranteed bandwidth	Improved data delivery and end-to-end delay and guaranteed bandwidth [86]
LBAODV	Load Balancing AODV	Simultaneous multiple paths. Load balancing over multiple paths and energy consumption is distributed across many nodes.	Load balancing and energy distribution [90]
AODV-BRL	AODV Backup Routing with Least hop count first (LHF)	An improvement over AODV-BR, Least hop count first (LHF), backup routing, and extends Hello & RREP	Adaptation to topology changes [91]
EAOMDV-MIMC	Extended AOMDV for Multi-Interface Multi-Channel networks	Multipath routing, Multiple homogeneous network interface, and nodes are allowed to make use of available channels.	Multiple network interfaces in Multiple channels for performance improvement [114]

Table 10
AODV energy and power extensions.

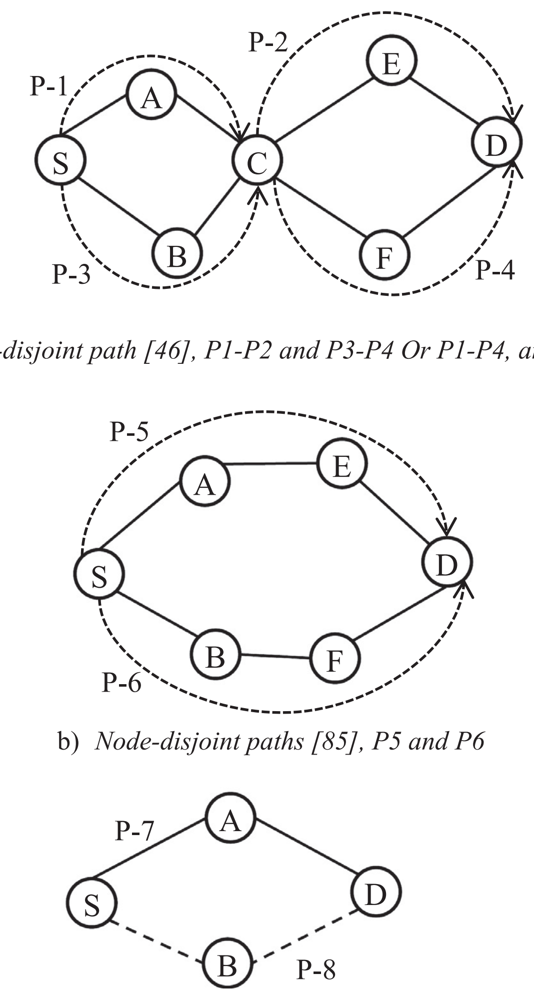
Protocol	Descriptive name	Concept	Objective/Improvement
EM-AODV	Energy Multi-path AODV	Multiple route reply and residual energy in route metric	Energy conservation [40]
RSEA-AODV	Route Stability and Energy-Aware -AODV	Link stability and residual energy of nodes	Route reliability [41]
New-AODV	AODV based Energy Efficient Routing	Energy mean-value algorithm, Piggyback energy-related information in the *RREQ* messages using the reserved field.	Extends the network lifetime [45]
SQ-AODV	Stability-based, QoS-capable AODV	Cross-layer, residual node energy, and make before break approach	Stable route and make before break [48]
PH-AODV	Power-Hop based AODV	The node power level and hop count for route selection	Improvement in throughput and packet drop [60]
EAODV	Energy-Aware AODV	Route selection based on less energy consumption and more energy capacity	Avoid over dissipation of energy [61]
LEAR-AODV	Local Energy-Aware Routing based on AODV	Local information about remaining battery level for participation in routing	To balance energy consumption [69]
PAR-AODV	Power-Aware Routing based on AODV	Transmit power and remaining battery capacity	The service life of the network [69]
LPR-AODV	Lifetime Prediction Routing based on AODV	Battery lifetime prediction, prefer the route with a maximum predicted lifetime	Route with a maximum lifetime [69]
ES-AODV	Energy Saving AODV	Energy emission control & energy governed metric.	Node lifetime improvement [87]
PHAODV	Power-aware Heterogeneous AODV	Heterogeneous protocol considers residual energy and the power consumption in selecting the route	Power awareness in the MANET of heterogeneous nodes [103]
FE-AODV	Fuzzy Energy-based AODV	Fuzzy concept considering power consumption	Optimality in bandwidth, hop count and network life-time [110]
EA-AODV	Energy-aware AODV	Energy-based routing measure, directional antennas, and cross-layer interactions	Energy optimization for CDMA MANETs [117].

4.3.3. Energy and network lifetime

AODV extensions for energy optimization, battery power, link and path stability, and network survivability have been covered in this subsection. The concept of some of the protocols has also been illustrated. The energy-oriented AODV extensions have been summarized in Table 10.

LEAR-AODV: In [69], three extensions, i.e., LEAR, PAR, and LPR of AODV were suggested based on energy consumption. Local energy-aware routing (LEAR) balances the energy consumption among all participating nodes. In the route discovery mechanism of *LEAR*, if remaining battery energy (E_r) is less than the threshold (τ), i.e. ($E_r < \tau$), the RREQ is dropped, as shown in Fig. 11. The other suggested variant power-aware routing (PAR) extends the service life of the network. *PAR* defines the cost function as $C(t) = p_i(E_f/E_r)^w$, where $P_i$is the transmit-power of node i and E_f,E_r are the full and remaining battery capacity of the node. The third extension, lifetime prediction routing (LPR), favours the route with maximum lifetime.

RSEA-AODV: A variant on route stability and energy-aware routing for mobile ad hoc networks was proposed in [41]. The protocol makes use of the residual energy and stability of the node for the computation of the reliability factor for the route selection.



a) Link-disjoint path [46], P1-P2 and P3-P4 Or P1-P4, and P3-P2

b) Node-disjoint paths [85], P5 and P6

c) Backup path [82] P7 (S-A-D) and P8(S-B-D)

Fig. 10. Multipath routing extensions in AODV.

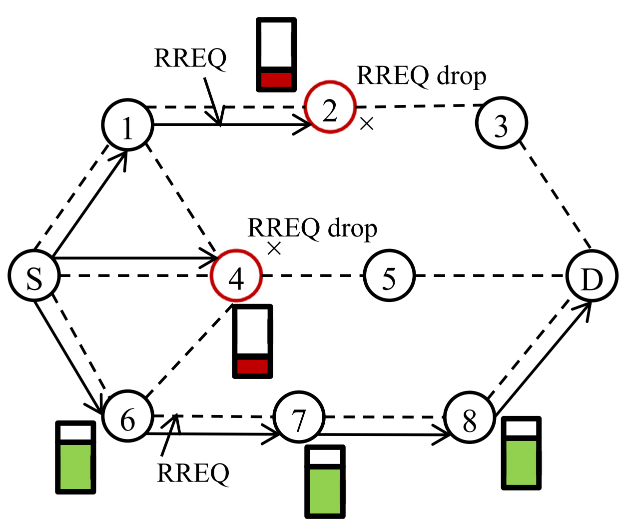


Fig. 11. LEAR-AODV dropping RREQ based on remaining battery power [69].

The stability has been defined as the product of the link stability of the edges, and the energy metric is calculated on the basis of remaining and full battery capacity. For path p, the stability $S(p)$ and energy metric $E_m(p)$ can be given by Eq. (7), where $LS(l)$represent the stability of link l. Er and Ef represents the remaining and full battery capacity, respectively. The proposal defines the reliability factor R_f of the path p by combining route stability and residual energy metric into a single objective function and is given by Eq. (8). The protocol has shown improved packet delivery ratio in the simulation study of [41]. The authors also present the route stability and energy-aware QoS routing *(REAQ-AODV)* as a quality of service extension of the *RSEA-AODV* protocol.

$$S(p) = \prod_{l \in p} LS(l), \& E_m(p) = \prod_{k=1}^{n} Er_k / Ef_k \tag{7}$$

$$R_f(p) = w_1 S(p) + w_2 E_m(p) \tag{8}$$

PH-AODV: Proposal in [60] suggests the power-hop based AODV making use of the power and hop count parameters in route selection. The protocol suggests the route cost (C_r) can be expressed as the function of hop count and power level and is given as $C_r = w_h \times (1/hop\_count) + w_p \sum (node\_power\_level/hop\_count)$**.**

EAODV: In [61], energy-aware AODV has been proposed. The concept lies in the selection of a path that consumes less energy but has a larger residual battery capacity. The weight factor at time t is given by $C_i(t) = \{E_r(t)/E_c(t)\}^2$, where $E_r(t)$ is residual energy, and $E_c(t)$ is the consumed energy at time t. The optimal route for

Table 11
AODV security extensions.

Protocol	Descriptive name	Concept	Objective/Improvement
BP-AODV	Black-hole Protected AODV	Challenge-response-confirm pattern, based on chaotic map	Protection against black hole and cooperative black hole [17]
A-SAODV	Adaptive SAODV	An adaptive mechanism to tune SAODV behaviour, Adaptive reply decision	A prototype implementation of Secure AODV [14]
Trust AODV	Trust-based AODV	Trust model with the node trust value	Secure route [52]
R-AODV	Reliable AODV	Prevents black-hole and gray-hole nodes from participation in routing	The secure route towards destination [56]
MR-AODV	Modified R-AODV	Tackle black-hole and gray-hole attacks, update malicious node entry in the routing table and discard such route reply	The secure route, black-hole and gray-hole protection [56]
SHS-AODV	Secure Hand Shaking AODV	RSA algorithm and symmetric encryption algorithm AES	Improve security [66]
SAODV	Secure AODV	Security features like authentication and integrity use digital signature and hash chain	Protect route discovery [13]
DPRAODV	Detection, Prevention, and Reactive AODV	Detection and notifying the malicious node	Black hole attack protection [76]
GAODV	Gratuitous RREP AODV	Make use of the gratuitous RREP as a confirm packet	Counter single and collaborative black hole [79]
SEAODV	Security Enhanced AODV	Pairwise transient key and group transient key	Secure AODV extension [109]
FLOW-AODV	Flooding Awareness AODV	Detects attackers by counting the received requests, considers the trustworthiness of neighbours	Flooding detection and prevention in the smart meter network [112]
ReTE-AODV	Refined Trust and Energy-based AODV	Refinement of TE-AODV, Bayesian probability for trust management	Trust management and energy optimization for secure routing [116]

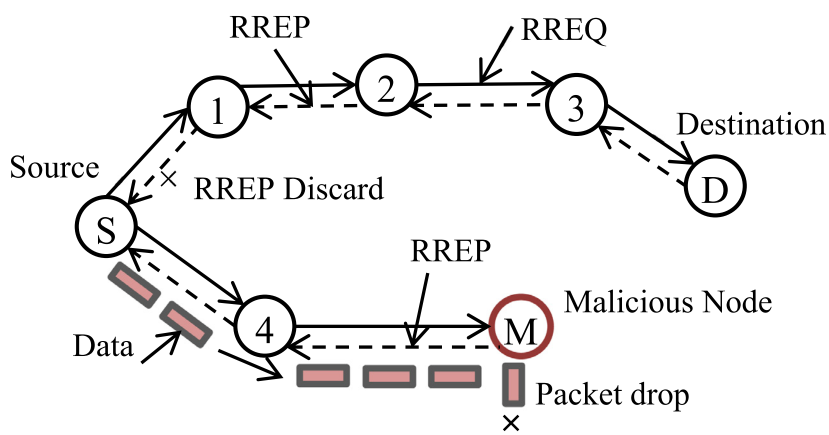


Fig. 12. Malicious route reply in AODV by node M [17].

the network energy efficiency and life-time is given as $R = Max(C_i)|i \in r$.

4.3.4. Security provision

The AODV protocol has also been extended to provide protection against security threats in the ad hoc network. Protocols considering the security improvement and routing attack protection have been covered in this subsection. Table 11 summarizes the AODV extensions for security provisions. A black hole attack scenario for the AODV protocol is shown in Fig. 12 in which malicious node falsely send the route reply in an intention to drop the packets.

BP-AODV: In [17], the authors proposed the black-hole protected AODV to overcome the security breaches of AODV and SAODV. The protocol protects against the black-hole attack and the cooperative black-hole attack during the routing process. BP-AODV extends the AODV and makes use of the chaotic map features. It uses the challenge, response, and confirm pattern to establish up to three trusted routes that are achieved by three rounds of request, reply, and confirm. The modified route request message (*MRREQ)* of *BP-AODV* extends *RREQ* to accommodate the challenge value generated by source (C_s) and the time value (T_s). The modified route reply (*MRREP)* contains the response value (V) generated by the destination. The route-confirm message (*RCON)* conveys the secret values during route confirmation. The value of V is given by $[x(\eta) \times 10^{14}]$ where, $x(\eta)$ is the Logistic chaotic map and is given by Eq. (9).

$$x(\eta) = \beta x(\eta-1)[1 - x(\eta-1)] \,\forall\, x(0) \in (0,1) \& \beta \in (0,4] \tag{9}$$

Trust-based AODV: In [52], trust-based communication has been adapted to establish a secure route between source and destination. Each node has a trust opinion about neighbours' trustworthiness. The protocol calculates the trust value based on the collective opinion of the neighbours. If there are n trust categories and $w(i)$ is the weight and $T(i)$ is the situational trust in i^{th} the trust category, the trust value can be given as $T_x^y = \sum_{i=1}^{n} w_x(i) T_x(i)$.

MR-AODV: The modified reliable AODV is an improvement over R-AODV (Reliable AODV). The protocol eliminates the black-hole and gray-hole nodes during route discovery. On detecting the malicious node, protocol marks the node as malicious in the routing table and does not forward the *RREP.* The process also helps in the reduction of the control overhead generated from malicious nodes [56].

DPRAODV: Detection, Prevention, and Reactive AODV [76] detect the possible occurrence of the malicious node by the unexpected higher value of the RREP sequence number. The protocol

Table 12
AODV routing strategy and other assorted extensions.

Protocol	Descriptive name	Concept	Objective/Improvement
AODV-PA	AODV with Path Accumulation	Path accumulation during route discovery	Performance improvement under high load and moderate to high mobility [33]
A-AODV	Any-cast AODV	Any-cast group-ID field addition in RREQ, maintenance of the field in the routing table	Provision of any-cast service, Enhance the service availability [43]
R-AODV	Reverse AODV	Flooding of reverse request	Counter the loss of RREP messages [72]
Geo-AODV	GPS-Enhanced AODV	Make use of the GPS, limit the route discovery in the likely region of the destination	Limit the route discovery region [59].
Multi-channel AODV	Multi-channel AODV	Diversity of the channel, group-based multi-channel allocation algorithm, multi-interface, multi-channel	Improved throughput in WMN [64]
CM-AODV	Cooperative Multicast AODV	Cooperative Multicast, tree-based multicast routing	Efficient network bandwidth [67]
AODV-NDC-SS	AODV based on Node Degree Clustering and Second Search	Clustering algorithm to control flooding	To reduce the control message, energy-saving, targeted for WSN [68].
MAODV	Multicast-AODV	Bidirectional shared multicast trees, group leader for maintaining a group sequence number	Multicast operation [16]
Ant-AODV	Ant AODV	Ant-based agents, hybrid of Ant routing and AODV	Real-time applications [77]
CB-AODV	Content-Based AODV	Position-based RREQ forwarding	Flooding control [81]
DAODV	Direction AODV	Considers direction and position to select the next-hop during route discovery	A stable route in high mobility like VANET [83]
E-Ant-AODV	Enhanced-Ant-AODV	Combines AODV with Ant colony optimization (ACO). The protocol calculates the pheromone values considering multiple factors.	Optimal path selection [104]
iAODV	Irresponsible AODV	Modifies flooding mechanism, and make use of probabilistic forwarding technique	Reduction in control overhead in vehicular communications [108]
GA-AODV	Genetic-Algorithm based AODV	uses the genetic algorithm to optimize the routing	Network performance improvement [115]

prevents the black hole attack by notifying the malicious detection to the other nodes of the network. The protocol makes use of the threshold value for detection and *ALARM* packet for the notification.

SEAODV: The security mechanism of the protocol makes use of a pairwise transient key (*PTK*) and group transient key (*GTK)* for the protection of the unicast and broadcast routing messages, respectively. SEAODV uses Blom's key pre-distribution scheme and the enhanced *HELLO* message for establishing the pairwise transient key (*PTK*). The protocol utilizes *PTK* to distribute *GTK*. The scheme extends the message authentication code to the AODV routing messages [109].

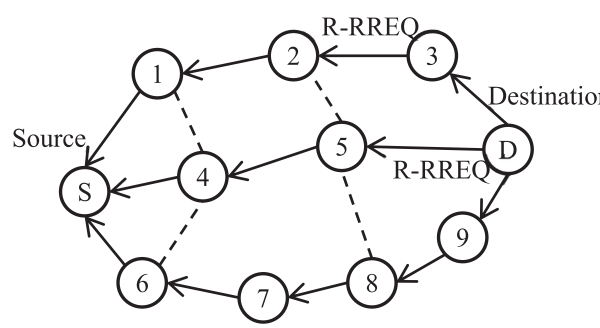


Fig. 13. Reverse RREQ flooding in R-AODV from destination to source [95].

4.3.5. Routing strategy

AODV has been extended based on various strategies like flooding techniques, path accumulation, reverse approach, location, anycast, multicast, multi-channel, clustering, and nature-inspired approach, etc. Extensions based on routing techniques and various assorted techniques have been summarized in Table 12.

AODV-PA: AODV with path accumulation, include the source route accumulation feature of the dynamic source routing protocol. The protocol incorporates the concept of path accumulation during route discovery by appending the own addresses by the nodes in route request and route reply messages. Nodes also update its routing table by the information contained in the routing messages [33].

A-AODV: Any-cast AODV proposed in [43], used the reserved bits of *RREQ* message to discriminate against the unicast and anycast addresses. In *RREQ*, out of the reserved bits, the first bit is used as a flag, and the subsequent 4 bits are used for any-cast group id. *if* (*flag* = 0) {*unicast*}, *if* (*flag* = 1) {*anycastgroup*}. The format of *RREP* and *RERR* messages are unchanged for the protocol operation.

R-AODV: Chonggun Kim *et al.* proposed the reverse AODV routing protocol in which destination floods the reverse request to find the source, as shown in Fig. 13. The approach mitigates the route reply delivery failure problem [95]. Rua Yang *et al.* [72] proposed the stability routing protocol *(SR-AODV)* based on R-AODV. The protocol attempts the link stability in reverse request (*R-REQ*).

Ant-AODV: S. Manvaha *et al.* [77] proposed the hybrid technique using Ant-based routing and AODV routing protocol. In this approach, ants work independently and provide routes to the nodes. In case, nodes do not have fresh enough entry for the destination. The node can launch the on-demand route discovery. The protocol makes use of the *HELLO* messages to maintain the neighbour table and relies on RERR for maintenance purposes.

4.3.6. AODV in related networks

AODV protocol has also been extended for many related wireless networks having the influence of the MANET mechanism. Some of the protocol extensions for vehicular ad hoc network (VANET), flying ad hoc network (FANET), wireless mesh network (WMN), wireless sensor network (WSN), etc. have been summarized in Table 13.

5. Trends in AODV research

Based on more than a hundred research proposals on AODV related work, we have presented the summary on various aspects

Table 13
AODV extensions for MANET like networks.

Protocol	Descriptive name	Concept	Objective/ Improvement
AODV-DF	AODV with Directional Flooding	Directional flooding, Topology-based scheme, does not require location information	Reduce RREQ routing overhead in Wireless Mesh Networks (WMNs) [25]
ME-AODV	Multipath Energy-aware AODV	Logical clustering, multipath and minimum battery cost routing	Routing performance improvement in IEEE 802.15.4 Zig-Bee network [49]
G-AODV	Grade-AODV	Grade of the nodes based on the hop count from the sink node.	Reduced energy consumption, applicable for WSN [53]
EQ-AODV	Energy and QoS supported AODV	Adaptation of the routing process based on the sensors energy and the types of packets	Performance improvement in wireless multimedia sensor networks (WMSN) [62]
AODV-MR	Multi-Radio AODV	The multi-homing extension uses multiple interfaces and spectrum to minimize interference and contention	Targeted for a wireless mesh network (WMN) [58]
MA-DP-AODV-AHM	Mobility Aware and Dual-Phase AODV with Adaptive Hello Messages	Build a route considering vehicle speed and direction adopts an adaptive packet announcement mechanism.	Targeted for the vehicular network (VANET), tries to mitigate network instability [97]
CCC-CR-AODV	Common Control Channel-Cognitive radio AODV	Intended to transmit the data from IoT nodes to the cognitive radio destination, which can be the gateway to the external network.	Cognitive radio access based Internet of Things (IoT) [98]
P.A.AODV	Enhanced Power-Aware AODV	Enhances flooding mechanism by excluding all non-bridge slaves	Targeted for Bluetooth Scatternet network [100]
IA-AODV	Interference Aware-based AODV	Based on global interference perceived by the nodes and the interference on the link involved in communication	Ultra-wideband (UWB) system routing protocol [101]
Pro-AODV	Proactive AODV	Node broadcast the *RREQ* if the number of entries in the routing table is below a defined parameter; otherwise, *RREQ* is dropped with *p* probability.	Minimize congestion in VANET [54]
EAODV	Extended Ad hoc On-Demand Distance Vector	Based on distributed mini-mum transmission (DMT) multicast routing	Multicast routing for wireless sensor network (WSN) [105]
Z-AODV	ZigBee AODV	Utilizes the communication and storage resources on 5G nodes to share the loads in ZigBee devices	ZigBee heterogeneous networks in a 5G environment [106]
FB-AODV	Flow-Based AODV	Flow-based routing, Weighted contention, and the Interference routing metric	Performance improvement in IEEE 802.11-based WMNs [107]
MDRMA	Multi Data Rate Mobility Aware protocol	Extension of Mobility Aware Dual-Phase AODV with Adaptive Hello Messages	Routing protocol for Flying Ad hoc Network (FANET) [113].

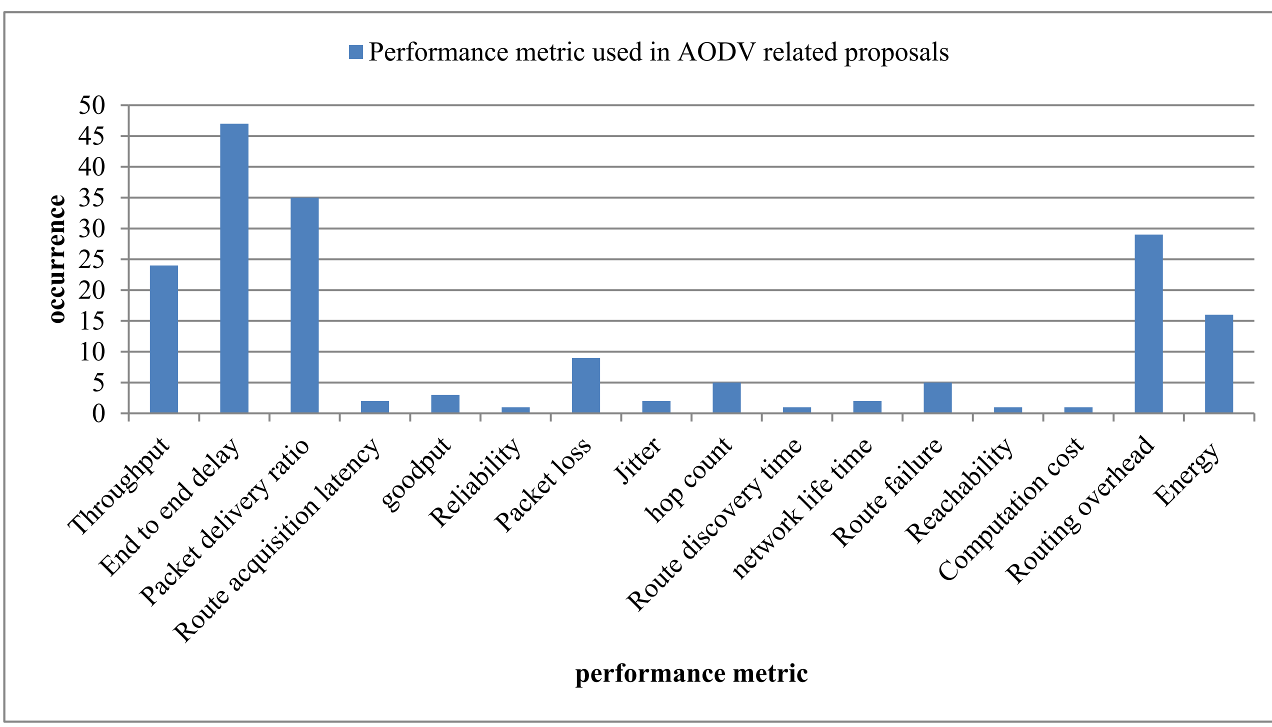


Fig. 14. Occurrence of performance metrics in the reviewed papers.

like performance metrics, input parameters, quality of service parameters, routing strategy, and research trends. The appearance of the performance metrics in the various research papers used to measure the performance of the protocol has been depicted in Fig. 14. This graph clearly indicates that end-to-end delay, packet delivery ratio, routing overhead, energy, and throughput has been considered by the majority of research papers for evaluating the performance of the routing protocols.

Input parameters considered for analysis by various research papers have portrayed in Fig. 15. The graph depicts that the number of participating nodes in the network, the speed of the nodes, and traffic/load in the network have been used mostly to analyse

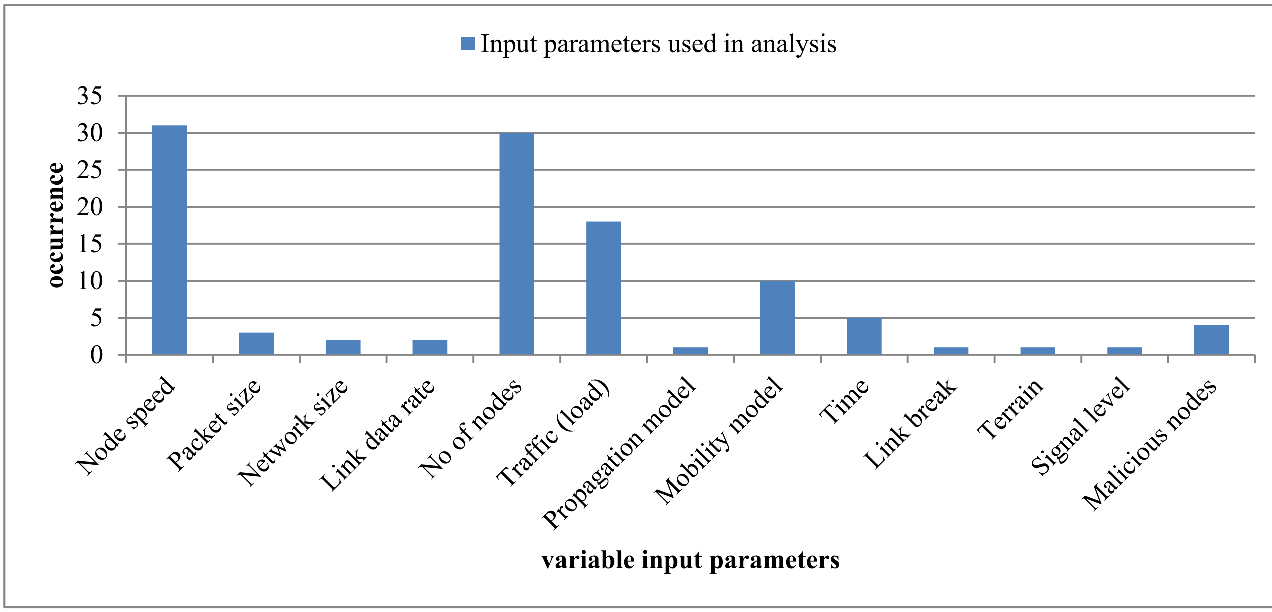


Fig. 15. Input parameters used for analysis in reviewed research papers.

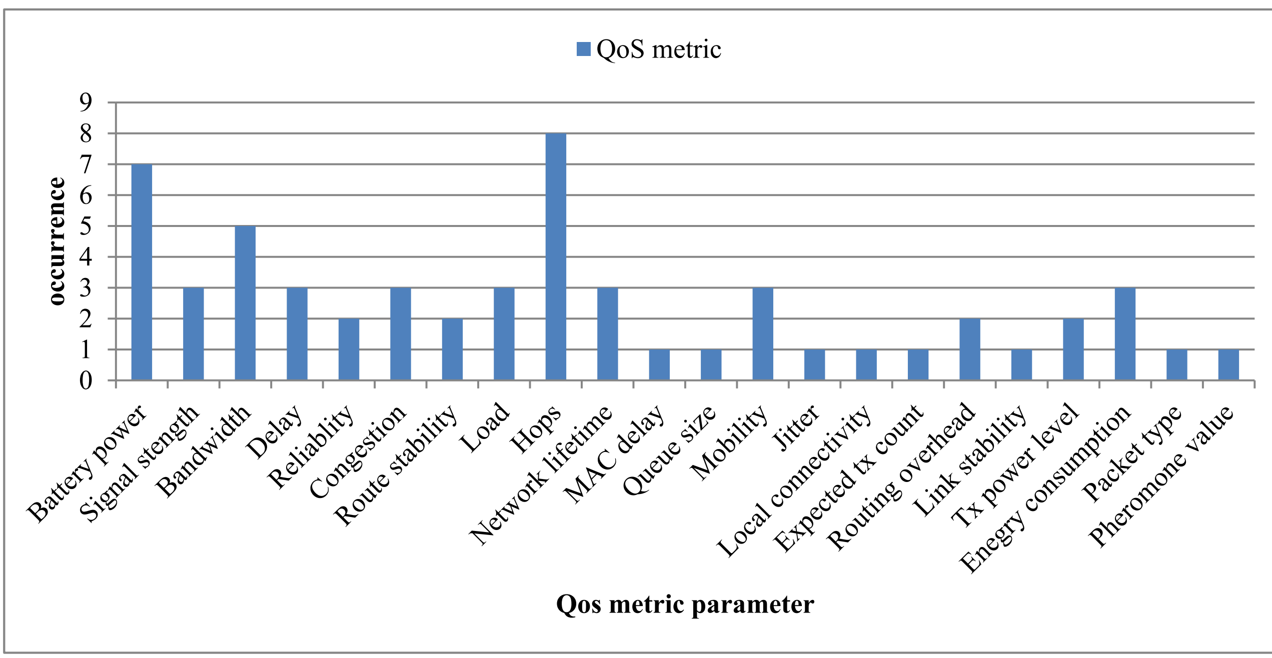


Fig. 16. Frequency of occurrence of various QoS parameters.

the protocol behaviour. The packet size, mobility models, link conditions and node integrity, etc. have also been used to analyse the protocol behaviour in mobile ad hoc networks.

We have also analyzed the various quality-of-service parameters considered by the researchers for the AODV improvement. Apart from the traditional metric of hop-count, many other metrics have been reported in the research proposals. The frequency of various parameters that appeared in the reviewed papers has been depicted in Fig. 16. Some of the popular parameters are battery capacity, bandwidth, delay, congestion, load, overhead, energy, etc. The large sets of QoS metric parameters indicate that wide research has been done around AODV to improve its quality in the ad hoc network. Many proposals have worked on improving the routing strategy of the protocol by considering various techniques. Such strategies have been shown in Fig. 17. Some of the common techniques are clustering, cross-layer, location-information, failure prediction, and nature-inspired, etc.

We have also done an analysis of the research trends for the protocol extension. Based on the data of reviewed papers, we found four major research trends in which most of the AODV extensions have been proposed. The percentage distribution of the research proposals in performance, security, multiple routes, and energy optimization has been depicted in Fig. 18. The analysis of the data of surveyed papers indicates the trends of the research to extend and improve AODV.

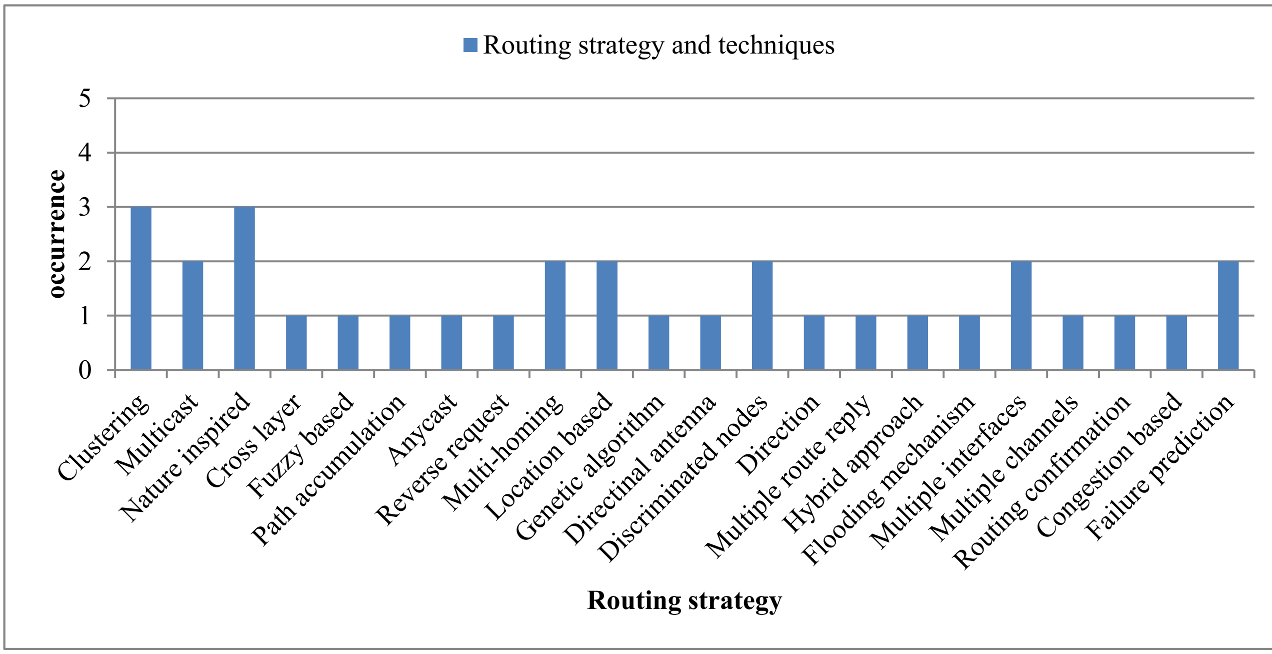


Fig. 17. Various routing strategy used in reviewed papers.

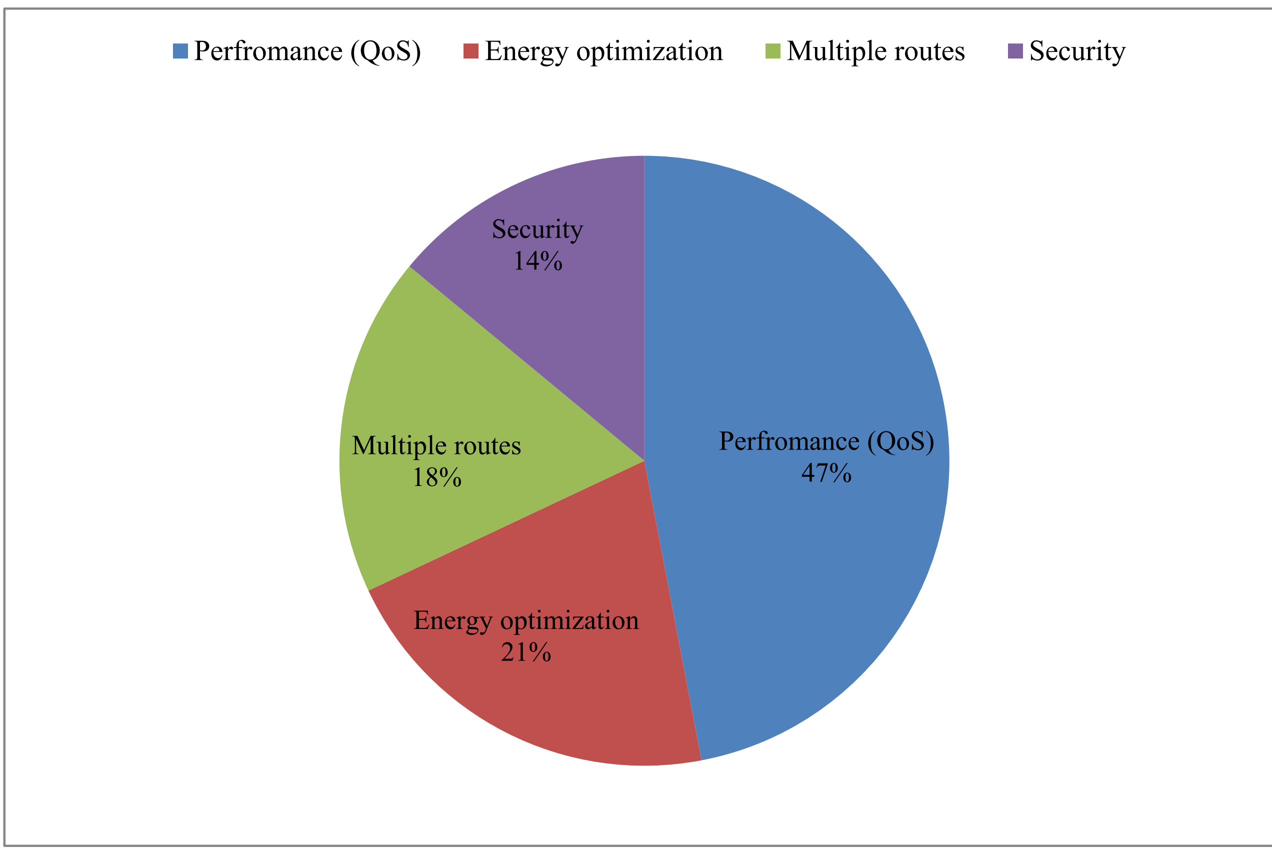


Fig. 18. Distribution of AODV extensions in four major research domains.

6. Conclusion

The reactive routing protocol AODV has been widely accepted and explored by the research community. By this study, we can state that many variants of the protocol with the diversified approach and objective have been proposed. In this paper, we highlight the basic concept of the AODV and present the review of the analysis performed by the UPPAAL tool. We present the evolution of the protocol since its conceptualization to the latest version of the AODVv2 Internet draft released in the year 2019. We highlight the advancements and the difference of AODV with AODVv2. The contributions of this paper include the detailed survey of the AODV extensions available in IETF Internet drafts and proposed by the research community. For the systematical illustration, we arrange variants and extensions of AODV in five categories of quality, multipath, energy, security, and routing strategy. We investigated the approach, objective, and the concept of the proposed extensions and found that many extensions have been devised to improve and extend the specific aspect. In the study, we realized that QoS-AODV, MAODV, AOMDV, and SAODV are some of the exemplary improvements for the quality of service, multicast routing, multipath routes, and security provision, respectively. The paper provides an overview of all major aspects of AODV that will be helpful for the researchers working in this domain. On the basis of this study, we draw the opinion that despite huge work on AODV, there is still scope for the protocol improvement to ensure the quality in the unpredictable, and resource constraint mobile ad hoc network.

Declaration of Competing Interest

None.

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