The field of adaptive routing is large, and undergoing active research efforts for applicability into various physical network deployments. These networks have varying topologies, and in some cases focus on particular media. Decentralised control forms the common element shared by such networks, where nodes negotiate amongst themselves how routes are to be formed. This document tours of the various different adaptive routing algorithms available for such “ad hoc” decentralised networks.

The description here does not attempt to explain how each routing protocol functions, which is documented thoroughly both by the originators of the protocols themselves, and by other third parties providing overviews of functionality. Rather, the approach here is to identity how extant protocols relate to each other within the same field.

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## Taxonomy

Several studies have attempted to categorise the large and rapidly-developing area of adaptive routing, particularly for Mobile Ad hoc Networks (MANET) and Vehicular Ad hoc Networks (VANET). [Saeed12]

Our arrangement here is based on a taxonomy undertaken by the Finish defence forces [Kuosmanen02], which builds on [Feeny99]

Here this hierarchy is revised again, to reflect the developments in that field to date. The branches irrelevant to the scope of this document (static routing, broadcast and geocast) are omitted.

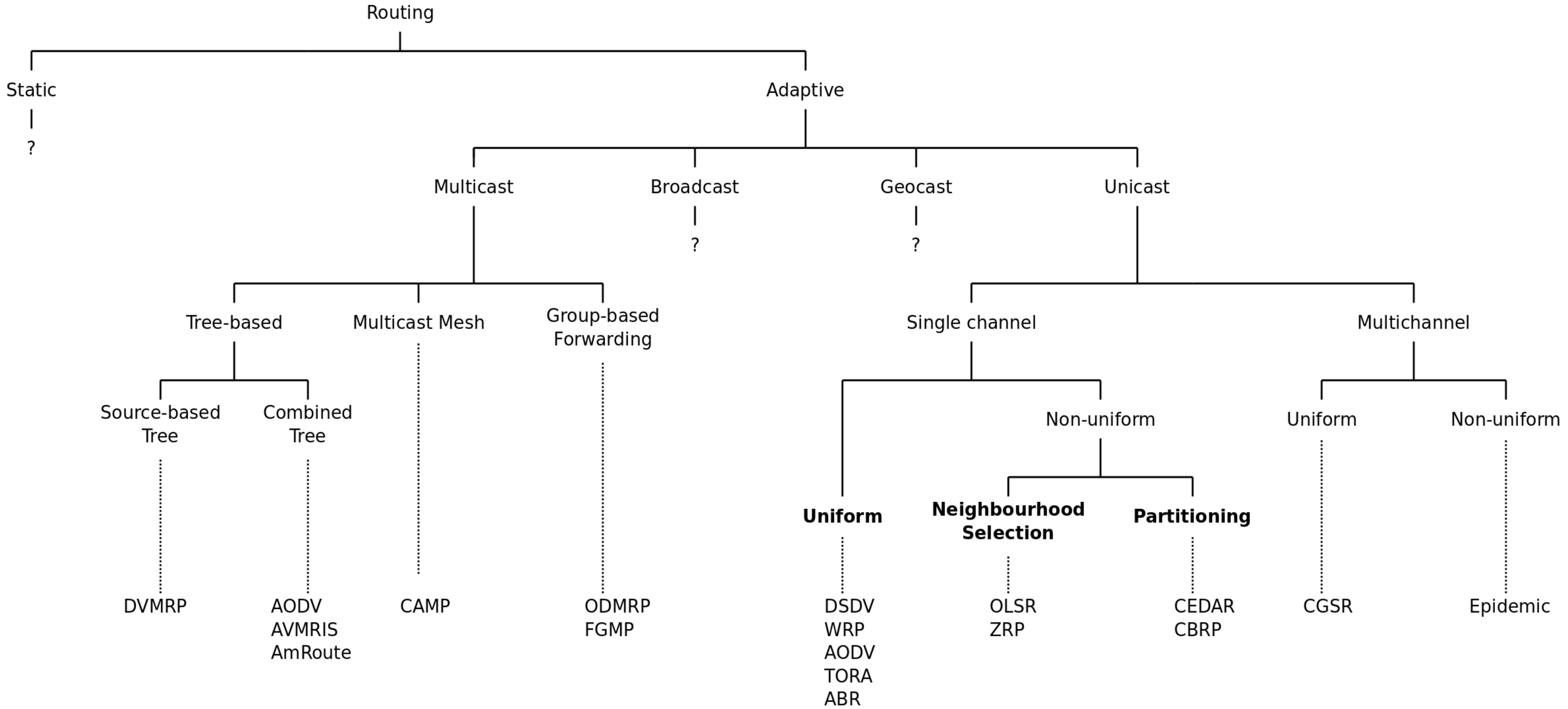


**Figure 1.** Taxonomy of adaptive routing protocols

A closer examination of the space under Single-channel unicast:

| | Uniform | Neighbourhood Selection | Partitioning | |
|---|---|---|---|---|
| **Proactive** | DSDV, EIGRP, WRP, Babel, RIP, BATMAN, ZRP-IERP | BGP | | **DV** |
| **Proactive** | GSR, QSPN, ZRP-IARP | OLSR OSPF IS-IS | | **LS** |
| **Hybrid** | DYMO | | | **DV** |
| **Hybrid** | | ZRP | OORP | **Hybrid** |
| **Hybrid** | HSLS | | | **LS** |
| **Reactive "on-demand"** | AODV, ACOR, TORA, ABR, MRAODV | | CGSR, CBRP | **DV** |
| **Reactive "on-demand"** | HWMP | | | **Hybrid** |
| **Reactive "on-demand"** | SSA/SSR, DSR, LQSR, MR-LQSR | FSR | CEDAR | **LS** |

**DV:** Destination-based "Distance-Vector"
**LS:** Topology-based "Link-State"

**Figure 2.** Classification of single-channel unicast adaptive routing algorithms

Link-state algorithms are theoretically attractive because they find optimal routes. However they incur the costs of keeping the entire topology known to each node in the graph. Usually this involves some kind of broadcast mechanism (either proactively or reactively), often flooding the network periodically with updates. This can produce a significant level of traffic; enough to be unsuitable for low-bandwidth networks.

Distance-vector algorithms do not distribute topological knowledge of the entire graph, but rather are only concerned with the next hop. This can lead to non-optimal routes, but avoids both the problems of background levels of traffic, and avoids the possibility for nodes routing by stale information.

Proactive algorithms incur a cost of keeping route information (either distance-vector or link-state) accurate even though that node may not need to communicate at the time. A node's knowledge of the network can lag behind reality when these updates do not propagate in time. Reactive algorithms avoid this by requesting routes “on demand”. This comes at the cost of an initial start-up latency while a route is requested.

## Applicability

Although parts of the network do carry multicast, previous experimentation has shown that routers throughout the network as a whole (in particular edge devices) cannot carry multicast. The consumers for that traffic are typically within one particular geospatial region, and in this way the network may be viewed as consisting of distinct clusters. [Sharony97]

In large-scale deployments, each cluster is typically well-connected within itself, with relatively poor links between clusters. Various adaptive routing protocols offer different characteristics, and so it is natural to take advantage of this by using protocols suited to each physical region of a large network, and redistributing routes at the borders between clusters.

In particular that some networks comprise regions which behave differently from others; for example, some may be relatively static, and others VANETs, and frequently changing topology.

Reproduced verbatim from [Kuosmanen02]:

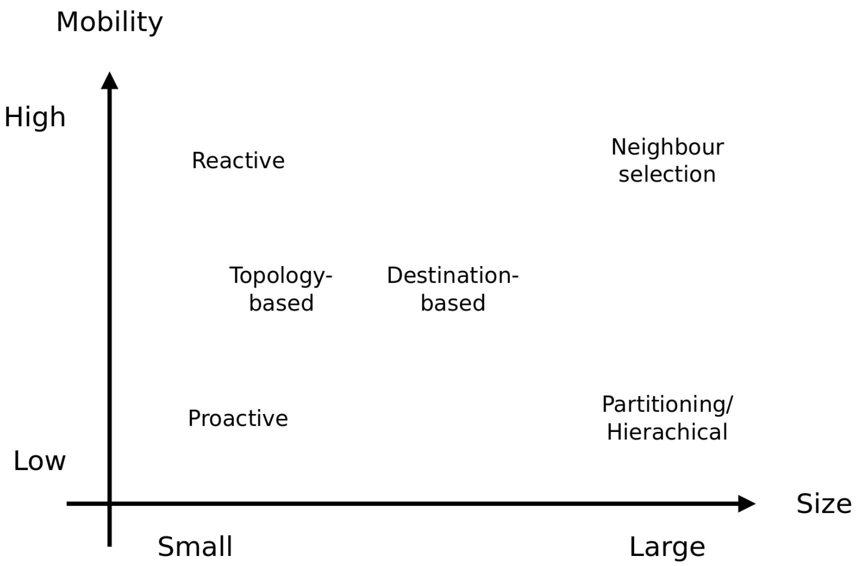


**Figure 3.** Applicability of adaptive routing to network characteristics

Our current approach is to transport that data over unicast point-to-point links until within the destination area, and then map it back to multicast for local distribution. [1]

Despite using unicast transports for the bulk of the transport between areas, we may be able to take advantage of the empiric knowledge that data destined for multicast is being transported over unicast connections. It is therefore possible that routing algorithms designed for multicast (i.e. the “Multicast” sub-tree in the taxonomy) may be re-purposed to unicast environments.

1 Bubblephone has undertaken previous work in this area, and has produced a product, MCT, which can provide this capability for mapping multicast to unicast over point-to-point links.

## Portable implementations

Multiple implementations exist for all but the most experimental protocols. When constrained to operate at lower network layers, the majority of these implementations are necessary tied to a particular operating system—typically for access to the privileged resources involved in presenting data at the relevant network layers.

We present here only the major projects providing portable implementations of adaptive routing algorithms. These are available for multiple operating systems, and are all open-source under various licences.

| Project | Standard Protocols | Platforms |
|---|---|---|
| Quagga[2] Routing Suite (neé Zebra) | OSPF: v2, v3, v3 for IPv6<br>IS-IS<br>RIP: v1, v2, RIPng for IPv6<br>BGP: BGP-4+, Multicast, IPv6<br>Babel: IPv4, IPv6<br>PIM: qpimd | FreeBSD, Linux, NetBSD, Solaris |
| XORP[3] | RIP: v1, v2, v5-MD5 auth., RIPng (IPv6)<br>BGP: v4, Capabilities Ad., Multicast, IPv6, Communities, Route Reflection, AS Confederations, Flap Damping, Four-Octet AS Number Space<br>OSPF: v2, v3, NSSA, v3 for IPv6<br>PIM-SM<br>IGMP: v1, v2, v3<br>MLD: v1, v2, v1 for IPv6, v2 for IPv6<br>VRRP: v2 | DragonFlyBSD, FreeBSD, Linux, NetBSD, OpenBSD, Windows |
| Bird[4] | BGP: v4<br>RIP: v2<br>OSPF: v2, v3<br>IPv6 router advertisements | FreeBSD, Linux, NetBSD, OpenBSD |

**Figure 4.** Multiple-protocol suites

2 Quagga: http://www.nongnu.org/quagga/

3 XORP: http://www.xorp.org/

4 Bird: http://bird.network.cz/

| Project | Standard Protocols | Platforms |
|---|---|---|
| OpenBGPD[5] | BGP: v4 | FreeBSD, Linux, NetBSD, OpenBSD |
| OpenOSPFD[6] | OSPF: v2 | FreeBSD, Linux, NetBSD, OpenBSD |
| NRL-OSLR[7] | OLSR: v1<br>MPR: NS-MPR, S-MPR, MRP-CDS, E-CDS | Linux, MacOS, Windows |
| olsrd[8] | OLSR: v2 | Android, FreeBSD, Linux, MacOS, OpenBSD, NetBSD Windows |

**Figure 5.** Single-protocol suites

Most of these implementations target POSIX, and may be ported to other operating systems with relative ease.

Due to their relative project maturity, these implementations serve well not only for proof-of-concept demonstrations, but (with suitable audits) for production deployment.

5 OpenBGPD: http://www.openbgpd.org/

6 OpenOSPFD: http://www.openospfd.org/

7 NRL-OSLR: http://cs.itd.nrl.navy.mil/work/olsr/

8 olsrd: http://olsr.org

## Security concerns

Due to the decentralised nature of ad hoc routing protocols, one concern is that nodes joining the network may either be malfunctioning or purposefully participating in a malicious manner.

It has been shown that routing protocols can be constructed which still deliver data to the correct destination, even over an ad hoc network with “Misbehaving” nodes present. [Lee02]

This however is academic research, and the feasibility of a practical implementation would be the subject of a further study.

Routing to layers below ISO layer 3 typically requires the routing engine to run as root (if in userspace) or in kernel mode (if implemented as a kernel module).

For protocols orchestrating e.g. topology updates over higher layer protocols (in most cases as UDP), standards compliance requires binding to a privileged well-known port. This may be mitigated by dropping privileges in the usual fashion, which is suggested rather than binding to an (unprivileged) high port, which entails the risk of interjection or hijacking from other programs.

Proactive routing does not permit listening passively for one-way traffic, because link updates are required to participate in the routing mesh. Reactive protocols would be more suitable for situations where radio silence is desirable.

Traffic analysis attacks may be mitigated by multiple routes. This idea has been used to design adaptive routing protocols with the explicit goal of avoiding monitoring by purposefully distributing traffic over multiple bearers where available, for example in MSR. [Hu09]

## Glossary

### Routing protocols (industry standard)

| | |
|---|---|
| ACOR | Admission Control enabled On-demand Routing |
| AODV | Ad hoc On-Demand Distance Vector |
| Babel | – |
| BATMAN | Better Approach to Mobile Ad hoc Networking |
| BGP | Border Gateway Protocol [RFC1105] [RFC1654] |
| CBRP | Cluster Based Routing Protocol |
| DSDV | Destination-Sequenced Distance Vector routing |
| DSR | Dynamic Source Routing protocol [Broch99] |
| EIGRP | Enhanced Interior Gateway Routing Protocol |
| HSLS | Hazy Sighted Link State Routing Protocol |
| HWMP | Hybrid Wireless Mesh Protocol [IEEE 802.11s] |
| IARP | [ZRP] Intrazone Routing Protocol |
| IERP | [ZRP] Interzone Routing Protocol |
| IMEP | Internet MANET Encapsulation Protocol |
| IS-IS | Intermediate System to Intermediate System [RFC1142] |
| LQSR | [MCL] Link Quality Source Routing protocol |
| MMARP | Multicast Manet Routing Protocol |
| MRP | Media Redundancy Protocol |
| NHDP | [OLSRv2] Neighborhood Discovery Protocol [RFC2461] |
| OLSR | Optimised Link State Routing protocol |
| OSPF | Open Shortest Path First [RFC1131] [RFC1247] |
| QSPN | Quantum Shortest Path Netsukuku |
| RDMAR | Relative Distance Micro-discovery Ad-hoc Routing protocol |
| RIP | Routing Information Protocol [RFC1058] [RFC2453] |
| RSTP | Rapid Spanning Tree Protocol |
| SSA/SSR | Signal Stability-based Adaptive routing [Dube97] |
| STP | Spanning Tree Protocol [Perlman85] |
| TORA | Temporally Ordered Routing Algorithm |
| VRRP | Virtual Router Redundancy Protocol |
| ZRP | Zone Routing protocol [Beijar02] |

**Metrics**

| | |
|---|---|
| ETX | Expected Transmission Count |
| ETT | Expected Transmission Time |
| Hop Count | – |
| PktPair | Per-hop Packet Pair Delay |
| RTT | (Per-hop) Round Trip Time |
| WCETT | Weighted Cumulative Expected Transmission Time |

**General**

| | |
|---|---|
| AS | Autonomous System |
| CBT | [Multicast] Core-Based Trees [RFC2201] [RFC2189] |
| CIDR | Classless Inter-Domain Routing [RFC1519] |
| DBF | Distributed Bellman-Ford algorithm |
| MANET | Mobile Ad hoc Network |
| MBGP | [Multicast] Multiprotocol Extensions for BGP [RFC2283] |
| MCL | [Microsoft] Mesh Connectivity Layer |
| MLD | Multicast Listener Discovery |
| MSDP | Multicast Source Discovery Protocol |
| NRLI | [BGP] Network Layer Reachability Information |
| PIM | [Multicast] [RFC2117] [RFC2362] |
| QoS | Quality of Service |
| RIB | Routing Information Base |
| RPF | Reverse Path Forwarding |
| VANET | Vehicular Ad hoc Network |

**Notable algorithms**

| | |
|---|---|
| Bellman-Ford algorithm, Richard Bellman. | [Bellman56] |
| Dijkstra's algorithm, Edsger W. Dijkstra. | [Dijkstra59] |
| Distributed Bellman-Ford algorithm, | |
| Luleå algorithm, Degermark et al. | [Degermark97] |
| Spanning tree algorithm, Radia Perlman. | [Perlman85] |

## Appendix A: Rejected protocols

Various existing protocols are intended for use at certain network layers in the OSI model. Our approach is to keep a view to adapting these to our own needs, re-purposing their general algorithms and message formats where possible, and applying those to layers which better suit our needs. However for some protocols this is impractical, either because message data is too intrinsically tied to a particular layer, or because the algorithmic behaviour depends on semantics particular to a certain underlying layer.

These rejected (but well-known) protocols are listed here for sake of completeness:

| | | |
|---|---|---|
| ARP | Address Resolution Protocol; tied to a specific layer | [RFC1027] |
| DFR | Directional Flow Routing; Utilises specific hardware (directional radio antennas) | [Budhaditya04] |
| DFR | Directional Flooding-Based Routing protocol; Targets specific operating environment (long propagation delay for sub-marine radio networks) | [Shin12] |
| EGP | Exterior Gateway Protocol; | [RFC0827] |
| | Lacks CIDR; [RFC1817] obsoleted by BGP [RFC1105] | |
| NDP | Node Discovery Protocol; too tied to a specific layer | |
| OORP | Orderone Routing Protocol; Patent restrictions | |
| VS | Virtual Subnets; This is an architecture, rather than a routing protocol. (Various routing protocols may be employed) | [Sharony97] |
| ExOR | Extremeley Oportunitistic Routing protocol; Ad hoc routing, but with media access control intrinsic to the routing and therefore only suitable for a particular media (wireless networks). | |
| MRP | Media Redundancy Protocol; too tied to a specific layer | [IEC 62439-2] |

## Appendix B: Academic Research

The following protocols may well be suited to our requirements. However these are either academic proposals, and represent active areas of research. As such convenient implementations do not exist. The techniques employed by these protocols are characteristically novel, and solve real-world problems and should not be overlooked.

A thorough investigation of these is beyond the scope of this project; these require further investigation to determine suitability, and where found appropriate, implemented for trial:

| | | |
|---|---|---|
| ABR | Associativity-Based Routing | [Toh96], [Toh99] |
| CGSR | Clusterhead Gateway Switch Routing protocol | [Chiang97] |
| CHAMP | Caching and Multipath Routing Protocol | [Valera07] |
| DFR | Direction Forward Routing | [Lee06] |
| FSR | Fisheye State Routing | [Iwata99] |
| GPSR | Greedy Perimeter Stateless Routing | [Karp00] |
| GSR | Global State Routing | [Chen98] |
| HRPLS | Hybrid Routing Protocol for<br>Large Scale MANETs with Mobile Backbone | |
| HSR | Hierarchical State Routing | [Iwata99] |
| LAR1 | Location Aided Routing – Scheme 1 | [Ko98] |
| LAR2 | Location Aided Routing – Scheme 2 | [Ko98] |
| VBR/DVB | Dynamic Virtual Backbone Routing protocol | [Melvin06] |

The following are amateur efforts, and essentially academic:

AWDS

These rejected protocols are not listed in the glossary for this document.

## Appendix C: Uncategorised protocols

Note these are not necessarily all single-channel unicast protocols.

Proactive:

- LCMP: Light Client Management Protocol
- TBR: Tree-Based Routing protocol
- OTR: Optimized Tree-based Routing protocol

Uncategorised:

- OCTBR: Optimized Clustering Tree Based Routing Protocol
- DVMRP: Distance Vector Multicast Routing Protocol [RFC 1075]
- CAMP: Core-Assisted Mesh Protocol

AOMDV
ARA
AWDS
CHAMP
DFB
DFR
DSRP
EIGRP
GSR
HRPLS
HSR
LAR1
MMARP
MRP
MSR
NHDP
ODMRP
OLSR
RDMAR
RSTP
SSI
STP
VBR/DVB
VRRP
zigbee

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