Mobile Ad Hoc Networks (MANETs) Are Not A Fundamentally Flawed Architecture

Abstract

Millions of people nowadays have portable computers and they generally want to read their e-mail and access their normal file systems wherever in the world they may be. This demand for mobility has fueled the rapid progression of computer & communication technologies from networks consisting of both stationary hosts & routers, to networks consisting of mobile hosts and stationary routers, and more recently to the other extreme case of networks having both mobile hosts and mobile routers. This last case of infrastructure-less networks of mobile hosts and mobile routers are called ad hoc networks or MANETs (Mobile Ad Hoc NETworks). It has been claimed that MANETs are a fundamentally flawed architecture. This is because Mobile Ad Hoc networks are almost never used in practice and almost every wireless network nodes communicate to base-stations and access points, instead of co-operating to forward packets hop-by-hop.

In this paper, we take the position that MANETs cannot be declared a fundamentally flawed architecture. The reasoning behind this position is that MANETs are still an emerging technology that has received intensive attention only recently. All aspects of the MANET concept are yet to be identified and fully understood. Research on MANETs is still in its early stages and considerable research effort is still necessary.

1. Introduction

In the near future, a truly pervasive computing environment can be expected with traditional home appliances attached with computing & communicating powers and small devices like mobile phones, Personal Digital Assistants & wearable computers enhancing information processing and accessing capabilities with mobility. The MANET technology truly supports pervasive computing because in many contexts information exchange between mobile units cannot rely on any fixed network infrastructure but on rapid configuration of a temporary wireless network. This is the main motivation behind MANET.

Typical applications include:

1. Military, Industrial and Commercial applications involving cooperative mobile data exchange.

2. Inexpensive alternatives or enhancements to cell-based mobile network infrastructures.

3. Future military networking for robust, IP-compliant data services within mobile wireless communication networks consisting of highly – dynamic autonomous topology.

4. With satellite-based information delivery, MANET can be used for fire/ safety/rescue operations or other scenarios requiring rapidly–deployable communications with survivable, efficient dynamic networking.

The principle behind MANET is multi-hop relaying, which is nothing new as it traces its roots back to 500 B.C. Darius I, the king of Persia devised an innovative communication system based on this principle. He placed a line of shouting men positioned on tall structures and heights and this use of ad hoc communication proved to be 25 times faster than normal messengers at that time.

As a technology for dynamic wireless networks, Ad hoc networking has been deployed in military since 1970s. Commercial interest in such networks has recently grown due to the advances in wireless communications. A new working group for MANET has been formed within the Internet Engineering Task Force (IETF), aiming to investigate and develop a framework for running IP based protocols in ad hoc networks.

In Section 2, we start with the background information by giving a brief overview of MANETs, describing its architecture, its different traffic types and its characteristics. Section 3 states the argument, the assumptions on which the argument is based, and the position taken by this paper. Section 4 describes the arguments that favor declaring MANET a fundamentally flawed architecture. Section 5 refutes the arguments in the previous section and explains why MANET should not be considered a fundamentally flawed architecture. This section also details how the current research effort on MANET is expected to promote the development and accelerate the commercial applications of the MANET technology. Lastly, conclusions and implications of our position are presented in Section 6.

2) The MANET Technology

A MANET is a collection of mobile platforms (e.g., a router with multiple hosts and wireless communications devices) – herein simply referred to as "nodes" -- that can dynamically be set up anywhere and anytime without using any pre-existing network infrastructure. The nodes may be located in or on airplanes, ships, trucks, cars, perhaps even on people or very small devices, and there may be multiple hosts per router. It is an autonomous system in which mobile nodes connected by wireless links are free to move randomly. The system may operate in isolation, or may have gateways to and interface with a fixed network. In the later operational mode, it is typically envisioned to operate as a "stub" network connecting to a fixed internetwork.

2.1 MANET Architecture

The nodes in a MANET can be classified by their capabilities. A *Client or Small Mobile Host* (SMH) is a node with reduced processing, storage, communication, and power resources. A *Server or Large Mobile Host* (LMH) is a node having a larger share of resources. Servers, due to their larger capacity contain the complete DBMS and bear the primary responsibility for data broadcast and satisfying client queries. Clients typically have sufficient resources to cache portions of the database as well as storing some DBMS query and processing modules.

In a MANET, each node has an area of influence. This is the area over which its transmissions can be heard. A LMH will initially have a larger area of influence as it generally has a more powerful battery. As the power level decreases, the area of influence of any node will shrink because the power available to broadcast is reduced. Network nodes may operate in any of three modes that are designed to facilitate the reduction in power used:

- ***Active Mode (or Transmit Mode)*****:** This is the mode using the most power. It allows both the transmission and reception of messages.
- ***Doze Mode (or Receive Mode):*** The CPU is capable of processing information and is also capable of receiving notification of messages from other nodes and listening to broadcasts.
- ***Sleep Mode (or Standby Mode):*** The CPU does no processing and the node has no ability to send/receive messages. The node is inactive. This mode allows a node to turn itself off for short periods of time without requiring power-up or re-initialization.

A node with no remaining power, or one that is off, is not currently a part of the network and cannot be reachable by any other node. Nodes can become disconnected from the entire network. When moving back in range of other nodes, they will become re-connected. Conversely, a node may be reachable by several LMHs or SMHs.

There are two approaches to providing network connectivity in a MANET:

1. ***Hierarchical network architecture***: This approach partitions the whole network into sub-networks. Each of the sub-network themselves then dynamically elects a node among themselves which acts as gateway to the other sub-network. This builds a hierarchy among the nodes and the hierarchy can be one-tire or multiple tier one. The advantages of this approach are
   - Easy mobility management procedures.
   - Better manageability.

2. ***Flat-routed architecture*****:** In this approach all the nodes are identical in terms of responsibility, and there is no concept of special gateways. The advantages of this approach are:
   - Increased reliability / survivability due to no single point of failure and alternative routes in the network.
   - Optimal Routing
   - Reduced use of wireless resources.
   - Better load balancing property
   - All nodes have one type of equipment.

2.2 Traffic Types in MANET

The traffic types in MANETs are as follows:

- ***Peer-to-Peer:*** Communication between two nodes that are within one hop. Network traffic is usually consistent.

- ***Remote-to-Remote:*** Communication between two nodes beyond a single hop but which maintain a stable route between them. This may be the result of several nodes staying within a communication range of each other in a single are or possibly moving as a group. The traffic is similar to standard network traffic.

- ***Dynamic Traffic:*** This occurs when nodes are dynamic and moving around. Routes must be reconstructed. This results in a poor connectivity and network activity in short bursts.

2.3 Characteristics of MANET

MANET has the following features:

- ***Autonomous Terminal:*** In MANET, each mobile terminal is an autonomous node, which may function as both a host and a router. In other words, besides the basic processing ability as a host, the mobile nodes can also perform switching functions as a router. So usually endpoints and switches are indistinguishable in MANET.

- ***Distributed operation:*** There is no background network for the central control of the network operations and so the control and management of the network is distributed among the terminals. The nodes involved in a MANET should collaborate amongst themselves and each node acts as a relay as needed, to implement functions e.g. security and routing.

- ***Multihop routing:*** Basic types of ad hoc routing algorithms can be single-hop and multi-hop, based on different link layer attributes and routing protocols. Single-hop MANET is simpler than multi-hop in terms of structure and implementation, with the cost of lesser functionality and applicability. When delivering data packets from a source to its destination out of the direct wireless transmission range, the packets should be forwarded via one or more intermediate nodes.

- ***Dynamic network topology:*** Since the nodes are mobile, the network topology may change rapidly and unpredictably and the connectivity among the terminals varies with time. MANET should adapt to the traffic and propagation conditions as well as the mobility patterns of the mobile network nodes. The mobile nodes in the network dynamically establish connectivity among themselves as they move about, forming their own network on the fly. Moreover, a user in the MANET may not only operate within the ad hoc network, but mat require access to a public fixed network (e.g. Internet).

- ***Fluctuating link capacity:*** The nature of high bit-error rates of wireless connection might be more profound in a MANET. One end-to-end path can be shared by several sessions. The channel over which the terminals communicate is subject to noise, fading, and interference, and has less bandwidth than a wired network. In some scenarios, the path between any pair of users can traverse multiple wireless links and the link themselves can be heterogeneous.

- ***Light-weight terminals:*** In most cases, the MANET nodes are mobile devices with less CPU processing capability, small memory size, and low power storage. Such devices need optimized algorithms and mechanisms that implement the computing and communicating functions.

3) The Argument

The debate in this paper centers on the argument that MANETs are a fundamentally flawed architecture. This argument is based on the observation that MANETs are almost never used in practice: i.e., almost every wireless network nodes communicate to fixed base-stations and access points (which constitute the Traditional Mobile Network and will be referred to as such in subsequent sections), instead of co-operating to forward packets hop-by-hop as is done in MANETs. In other words, MANETs are flawed in the sense that the architecture of MANETs prevents it from being widely deployed & hence widely used.

The argument seems to be based on the following assumptions:

- Traditional Mobile Network has been successfully implemented and is widely used On the other hand, MANET has been deployed but it has failed to gain popular acceptance.

- MANETs have been around for a long time after Traditional Mobile Network was implemented. And during that sufficiently long time, all the challenges & the difficulties posed by the architecture of MANETs have been thoroughly researched.

- Research has proved that the challenges posed by MANET are so many and so difficult as to be virtually insurmountable. Hence, it can be considered to be a fundamentally flawed architecture that it is unfit for large-scale deployment.

- Traditional Mobile Network can provide all MANET functionality, and so is a popular alternative to MANET.

This paper considers all these assumptions to be invalid and hence the argument to be totally incorrect. It takes the position that MANETs are not a fundamentally flawed architecture.

4) Counter claims

The design of MANET involves some very critical & difficult issues that have defied a common solution yet and these issues touch all aspects of communication networking. These issues are preventing wide spread use of MANET. So, it can be claimed that MANETs are a fundamentally flawed architecture.

The following lists the issues that support this claim.

1) ***Implementation***: Traditional Mobile Networks consist of fixed routers and mobile hosts while MANETs have mobile routers & hosts. This means that MANET is just an extreme case of the Traditional Mobile Network. Ethernet connectors in all the arm rests of an airplane in which mobile computers can plug in is an example of Traditional Mobile Network being successfully implemented and widely used. But there is no such corresponding example for MANET.

2) ***Traditional Mobile Network as alternative to MANET:*** MANETs are supposed to provide mobility in communication and this has already been provided by the Traditional Mobile Networks.

3) Medium Access: An optimal Medium Access Control protocol for MANET has not been designed yet because of the following issues:

- Bandwidth available for communication being very limited, the control overhead must be kept as minimal as possible to maximize bandwidth efficiency.
- Since nodes are mobile, bandwidth reservation made at one point of time may become invalid once the node moves out of the region where the reservation was made. An optimal resource reservation mechanism does not exist yet.
- Exchange of control packets are required for achieving time synchronization between nodes but this might consume too much of the limited network bandwidth available.
- Since both the sender and the receiver are wireless nodes, the hidden and exposed terminal problems are significantly increased.
- High packet collisions due to multiple nodes contending for simultaneous channel access.
- Due to the distributed nature of MANETs, node scheduling will require exchange of control information, which will increase bandwidth consumption.

4) ***Routing:*** Conventional routing algorithms do not perform well in MANETs and the issue of routing packets in MANETs is a challenging task due to the following reasons:

- As the network is highly dynamic, an on-going session suffers frequent path breaks due to the movement of intermediate and end nodes.
- Due to the frequent changes in topology, maintaining consistent topological information at all the nodes involves control overhead that consumes the limited bandwidth available.
- Search for path with less congestion to avoid collision of data and control packets.
- Optimal management of limited battery life and processing power.

5) Multicasting: Conventional multicast routing protocols do not perform well in MANETs because of the dynamic nature of the network topology. Multicast tree structures are not stable and need to be reconstructed continuously as connectivity changes. This incurs substantial control traffic that consumes the limited bandwidth available.

6) ***Transport Layer***: Existing Transport Layer protocols don't work well on MANETs because of the following reasons:

- Rapid changes due to network topology.
- Induced traffic adversely affects throughput.
- Separation of congestion control, reliability & flow control is necessary in MANETs but these generates additional control overhead.
- Limited power and bandwidth severely affects transport layer protocol performance.
- Packet loss can occur due to path breaks caused by the mobility of nodes and node failure due to a drained battery. In traditional protocols, this might be misinterpreted as congestion.

7) ***Security and Reliability***: MANETs are highly vulnerable to security attacks compared to wired networks or infrastructure-based networks. The unique characteristics of MANET that cause this vulnerability are as follows:

- Since all nodes within its direct transmission range receive data transmitted by a node, a malicious node could easily obtain data being transmitted in the network.
- In battlefield applications, as nodes move in and out of hostile and insecure enemy territory, the nodes will be highly vulnerable to security attacks resulting in an insecure operational environment.
- Due to lack of central authority, traffic monitoring is not possible.
- As a node can join or leave the network at any point of time, an intruder would be able to join the network quite easily and carry out his/her attacks e.g. denial of service
- Due to scarcity of bandwidth, battery power and computational power, it is difficult to implement complex cryptography–based security mechanisms.
- Nodes in this network are usually compact and hand-held in nature and can be easily stolen.

8) ***Quality of Service (QoS):*** Providing different quality of service levels in a constantly changing environment is a challenge because:

- Unrestricted mobility causes QoS sessions to suffer due to frequent path breaks, thereby requiring such sessions to be reestablished over new paths.
- The link-specific and state-specific information in the nodes is inherently imprecise due to the dynamically changing topology and channel characteristics. Hence, incorrect routing decisions may cause some real-time packets to miss their deadlines.
- Hidden terminal problem necessitates the retransmission of packets, which may be unacceptable under stringent QoS requirements.
- Limited bandwidth, battery life, storage space and processing capability significantly affect the performance of the QoS provisioning mechanism.
- As MANETs are highly vulnerable to security attacks, it is very difficult to provide secure communication guarantees.

9) ***Internetworking***: In addition to the communication within an ad hoc network, internetworking between MANET and fixed networks (mainly IP based) is often expected in many cases. The coexistence of routing protocols in such a mobile device is a challenge for the harmonious mobility management.

10) ***Power Control***: MANETs face power problems because:

- Battery power is limited
- Recharging or replacing batteries may be difficult.
- Large relay traffic in multi-hop routing might cause faster depletion of the node power source.
- Increased battery size increases the size and weight of the node, while decreased battery size results in less capacity.
- Consumption of battery charge increases with an increase in the transmission power.

5) Claims

In this section, we reiterate our initial assertion that MANETs are not a fundamentally flawed architecture.

Indeed, MANETs pose a host of difficult challenges, but then MANETs constitute a completely different communication paradigm. When it comes to MANETs, the usual rules about fixed topologies, fixed and known neighbors, fixed relationship between IP address and location, and more are suddenly tossed out the window. But what is most important is that though MANETs are an emerging technology, yet the remarkable research progress that has already been made in such a short time belies the claim that MANETs are a fundamentally flawed architecture.

It is true that there exist no common solutions to the various problems e.g., routing and medium access, but then MANETs have such diverse applications, that ultimately, it might be more desirable to divide MANET applications into broad categories and then devise specialized optimal solutions for each such category.

Since MANETs are still an emerging technology, nothing much exists in concrete form. So, our plan of defense is to refute the arguments in the previous section by detailing the various solutions that have been proposed to deal with the concerns in each area. The idea behind this approach is to demonstrate that none of the existing issues defy solution and as research progresses, these will cease to be issues.

We provide below a refutation of all the arguments made in the previous section.

1) ***Implementation***: Currently MANETs are widely used in the military and are slowly entering the civilian sector too. Medford, Oregon deploys city – wide mobile broadband MANET network to support their law enforcement applications. MIT RoofNET is being used to provide broadband Internet access to users throughout Cambridge. On 22nd, September 2004, Harris Corporation announced the third successful field demonstration test validating its open-architecture, Mobile Ad-hoc Networking (MANET) waveform. As the technology improves, commercial deployments are going to speed up.

2) ***Traditional Mobile Network as alternative to MANET:*** Traditional Mobile Networks provide mobility in communication, but are infrastructure dependent and cannot be used in areas where supportive infrastructure is non – existent. The very idea behind MANETs is to provide mobility without any supporting fixed infrastructure. So, though both provide mobility in communication, yet they cannot be an alternative to each other.

3) Medium Access: MAC protocols can be classified into three basic types based on various criteria such as initiation approach, time synchronization, and reservation approaches. Each protocol provides solution to one or more of the problems associated with Medium Access.

- In **Contention-Based Protocols**, (e.g. MACAW), nodes do not make any resource reservation a priori but contend with neighboring nodes for channel access, whenever a packet has to be transmitted. These protocols are not suited for real-time traffic, as QoS guarantees to sessions are not provided. Following sub-types of these protocols exist:
    - *Sender – initiated protocols*
        - Single-channel sender-initiated protocols
        - Multi-channel sender-initiated protocols
    - *Receiver-initiated protocols*
- In **Contention-Based Protocols with Reservation Mechanisms**, (e.g. D-PRMA), bandwidth reservation is made a priori to provide QoS support to real-time traffic. Following sub-types of these protocols exist:
    - Synchronous protocols requiring global time synchronization for bandwidth reservation.
    - Asynchronous protocols that uses relative time–synchronization for effecting reservations.
- In **Contention-Based Protocols with Scheduling Mechanisms,** (e.g., DPS, DWOP), node scheduling is done in a manner so that all nodes are treated fairly and no node is starved of bandwidth. Scheduling-based schemes consider various factors like flow priority, battery characteristics, remaining battery power etc.

Apart from these categories, the following protocols don't strictly fall into any of the above-mentioned categories but solve one/more issues:

- **Multi-channel MAC Protocol** uses simple hardware and achieves throughput higher than that of IEEE 802.11 when the network load is high.

- **Multi-channel CSMA MAC Protocol** reduces chances of collisions even at high traffic rates.
- **Power Control MAC Protocol** achieves throughput very close to that of 802.11 protocols while using much less energy.
- **Receiver-Based Autorate Protocol** employs an efficient quality estimation mechanism and achieves a high overall system throughput.
- **Interleaved Carrier-Sense Multiple Access Protocol** performs better than the 802.11 DCF protocol in terms of metrics such as throughput and channel access delay.

4) ***Routing:*** Many protocols have been proposed for MANETs and these protocols attempt to provide solutions to the problems like path breaks, topology changes, and congestion & resource management. The routing protocols for ad hoc wireless networks can be broadly classified as follows:

- **Routing information update mechanism Protocols,** (e.g., DSDV) attempt to maintain consistent topological information and are further sub-divided into:
  - *Protocol or table-driven routing protocols* in which every node maintains the network topology information in routing tables. Routing information is periodically flooded in the whole network.
  - *Reactive or on-demand routing protocols* in which network topology information is not maintained, but obtained when required.
  - *Hybrid routing protocols* that combine the best of the other 2 categories. For routing within a given zone, a table-driven approach is used; otherwise an on-demand approach is used.

- **Protocols using Temporal Information for Routing** attempt to minimize the frequent path break problem by using temporal information regarding the lifetime of the wireless links and the lifetime of the paths selected. The sub-types of this category are:
  - *Routing protocols using past temporal information*
  - *Routing protocols that use past temporal information*

- **Protocols using Routing Topology** attempt to minimize control overhead (due to maintaining state information) by using either:
  - *Flat topology routing protocols* that assume the presence of a globally unique addressing mechanism.
  - *Hierarchical topology routing protocols* that make use of a logical hierarchy in the network and an associated addressing scheme.
- **Protocols based on Utilization of Specific Resources** can be either of:
  - *Power-aware routing protocols* aiming to minimize the consumption of battery power.
  - *Geographical information assisted routing* aiming to improve routing performance and to reduce control overhead by utilizing the available geographical information.

5) ***Multicasting:*** The main motivation behind the multicast routing protocols is to reduce control traffic due to changes in the multicast tree. These protocols update the mesh only periodically and not continuously. Based on the type of operation, multicast protocols can be broadly classified into the following two types:

- **Source Initiated Protocols** where the multicast tree or mesh is updated only periodically by means of control packets generated only by the source (s) of the multicast group. Route repair is generally the responsibility of the upstream node.
- **Receiver Initiated Protocols** where the receiver uses flooding to search for paths to the sources of the multicast groups to which it belongs.

6) ***Transport Layer*:** TCP in its present form does not perform well on MANETs. So, several enhancements to TCP have been proposed to make it more suited to MANET and thus to

improve the performance of TCP on MANETs. These enhancements are discussed below:

- **Feedback-Based TCP (TCP-F):** This requires the support of a reliable link layer and a routing protocol that can provide a feedback to the TCP sender about the path breaks. The protocol is expected to repair the broken path within a reasonable time period.
- **TCP with Explicit Link Failure Notification (TCP-ELFN):** This is similar to TCP-F, except for the handling of explicit link failure notification (ELFN) and the use of TCP probe packets for detecting the route reestablishment. The ELFN is originated by the node detecting a path break upon detection of a link failure to the TCP sender.
- **TCP-BuS:** This is similar to TCP-F and TCP-ELFN in its use of feedback information from an intermediate node on detection of a path break but it provides additional buffering capability and sequencing information.
- **Split-TCP:** Splits the transport layer objectives into congestion control and end-to-end reliability.
- **Ad Hoc TCP:** This is similar to TCP-F and TCP-ELFN but on receiving feedback information from the intermediate nodes, it changes state to avoid unnecessary retransmissions.

7) ***Security and Reliability*:** Various security-aware protocols have been proposed for MANETs where security is a main concern. Some of these protocols are discussed below:

- **Security-Aware Ad Hoc Routing Protocol:** This protocol uses security as one of the key metrics in path finding and also enables the use of different levels of security for different applications that use this protocol.
- **Secure Efficient Ad Hoc Distance Vector Routing Protocol:** This protocol is based on the destination-sequenced distance vector routing protocol and is mainly designed to overcome security attacks such as denial of service and resource consumption. The operation of the routing protocol remains unaffected even in the presence of multiple uncoordinated attackers corrupting the routing table.

8) ***Quality of Service (QoS):*** The QoS solutions can be classified in two ways:

- **QoS approach employed:** There are 3 distinct approaches employed which are:
    - *Based on interaction between the routing protocol and the QoS provisioning mechanism:* There are 2 sub-types:
        - **Coupled:** the routing protocol and the QoS provisioning mechanism closely interact with each other for delivering QoS guarantees.
        - **Decoupled:** the QoS provisioning mechanism does not depend on any specific routing protocol to ensure QoS guarantees.
    - *Based on the interaction between the network and the MAC layers:* There are 2 sub-types:
        - **Independent:** network layer is not dependent on MAC layer for Qos Provisioning.
        - **Dependent :** MAC layer needs to assist the routing protocol for QoS provisioning.
    - *Based on the routing information update mechanism:* There are 3 categories:
        - **Table-driven:** where each node maintains a routing table
        - **On-demand:** no routing table is maintained
        - **Hybrid:** incorporates features of both above-mentioned categories.
- **Layer at which QoS solutions operate in the network protocol stack:**

- MAC Layer Solutions
- Network Layer Solutions
- Cross-layer Solutions

9) ***Internetworking*:** Enhancements to TCP for a seamless integration between MANETs and the fixed network has already been discussed in (6). The Internet Engineering Task Force (IETF), is investigating the development of a framework for running IP based protocols in

ad hoc networks and thus integrate MANETs with Mobile IP..

10) ***Power Control*:** This problem can be minimized if the protocols adopt energy awareness needs at all layers in the protocol stack. Energy conservation can be implemented using the following techniques:

- **Battery management schemes:** e.g.
  - Battery scheduling,
  - Lazy packet scheduling,
  - Modeling and shaping of battery discharge patterns,
  - Routing based on battery status.
- **Transmission power management schemes**: e.g.
  - Dynamic power adjustment
  - Distributed topology control
  - Distributed power control loop
  - Centralized topology control
  - Globalized power-aware routing
  - Localized power-aware routing
  - Determination of critical transmission range
  - Congestion control.
- **System power management schemes**: e.g.
  - Power-saving modes
  - Low-power design of hardware.

6) Conclusion

The previous section undeniably establishes the fact that MANETs are not a fundamentally flawed architecture. Every new technology needs time to evolve & mature and MANETs are no exception. MANETs represent a progression of technology, and given a little more time & effort will usher in a new era in telecommunications. Condemning MANETs as a fundamentally flawed architecture while its still being in its emerging state, amounts to a denial of the human spirit that seeks challenges, remains undaunted by challenges and ultimately triumphs against all odds.

A primitive ad hoc MANET-like communication system, as used by Darius I, was sufficient to carry the Persian Empire to its largest extent. Similarly, today's Mobile Ad Hoc NETworks (MANETs) will propel our human civilization to dizzying heights in the future.

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