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Intelligent Wireless Communication for Future Autonomous and Cognitive Automobiles

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Abstract— **Communication between vehicles based on ad-hoc networking principles has become a prominent research area. The main difficulties in designing such vehicle-to-vehicle (V2V) networks arise from the lack of infrastructure, necessitating fully distributed functionalities and self-organizing capabilities, and from their highly dynamic nature due to the mobility of nodes. A new research goal is to use V2V networks to realize autonomous vehicles which can cooperate in terms of cognition and trajectory planning while participating in traffic. This specific scenario imposes additional and very strict requirements on the communication network design. In this paper we present the requirements for the communication system and its security. Additionally, we present the essential building blocks and mechanisms to tune existing technologies for use in the autonomous vehicles scenario.**

I. INTRODUCTION

Over the last years, data communication via the Internet and especially using wireless networks has increasingly gained importance. The demand for connectivity, "anytime, anywhere" has led to the development of several new technologies for ubiquitous communication. The idea of spontaneously forming, self-organizing, so-called *ad hoc* networks, has probably received most attention.

Meanwhile, ad hoc networks have been expanded to support automobile applications in vehicular scenarios, so-called vehicular ad-hoc networks (VANETs). Apart from infrastructure-based services such as mobile Internet connectivity or information services "on the road", vehicle-to-vehicle (V2V) communication is an upcoming field of research. Using V2V communication, vehicles could exchange information on the current traffic or weather conditions, hazard events or even collision warnings, providing the driver and passengers with active and passive safety services. These use cases impose a number of different requirements concerning delay, reliability, and security on the network design. Therefore, many research initiatives and projects have been devoted to various aspects of VANETs over the last couple of years.

The new research centre "KogniMobil" which is sponsered by the German Research Foundation (DFG) uses V2V communication as the key to enable cooperation among autonomously driving vehicles. The goal of distributed cognition, i.e. perception and trajectory planning, calls for a carefully designed communication concept that is capable of transferring significant amounts of data while at the same time allowing high-priority, low-latency messaging.

In this paper we present the challenges and requirements for a V2V communication network supporting cooperative autonomous vehicles. Further, we will introduce a communication concept fulfilling these demands. In this context, medium access, routing, and security are some of the important issues to be discussed and adapted to the specific requirements of the scenario. The remainder of the paper is organized as follows: in Sec. II we present the requirements of the scenario. In Sec. III we introduce the new communication concept and discuss specific issues concerning medium access, routing, and security. Related work is presented in Sec. IV. Sec. V closes with a conclusion and an outlook on future work.

II. REQUIREMENTS

Autonomous vehicles perform two important tasks: first, they perceive their environment using cameras, radar or other sensors. The sensor information is interpreted and a representation of the surrounding is generated. In a second step, the representation is analyzed and a list of possible actions is compiled, containing possible maneuvers the vehicle can perform in the current environmental context. In the following, we will call this *cognitive behavior* and its two elementary processes *perception* and *trajectory planning* and we will use the term *cognitive vehicle* for vehicles equipped with these abilities.

Decisions that are generated in the behavior generation stage are based on a very limited range of perception (concerning geometric dimension, resolution and precision), resulting from a restricted range of sensor information. Also, there is no interactive trajectory planning between cognitive vehicles and other vehicles like there is between human-driven vehicles. Therefore, one of the main challenges in the context of the DFG research centre "KogniMobil" is the cooperation between two or more vehicles regarding both cooperative perception and cooperative trajectory planning.

Cooperative vehicles form so-called *cooperative groups*. Vehicles' memberships are based on criteria such as the lane used or direction of driving. Within cooperative groups, every vehicle's individual sensor information shall be shared with all other vehicles. Taking the additional information from other cars into account, each vehicle's perceived environment can not only be expanded beyond the reach of its own sensors but also enriched with detail. Also, the presence of perceived objects may be mutually validated.

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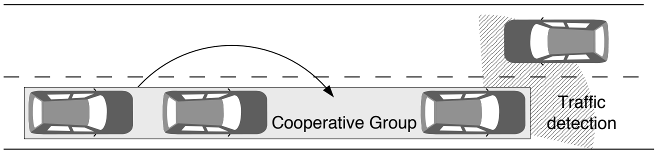


Fig. 1. Example for a cooperative group of vehicles

In Fig. 1 an example for a cooperative group is shown. The last vehicle in the cooperative group is trying to overtake the vehicle in the middle. However, this would lead to an accident since there is a vehicle approaching on the opposite lane. The leading vehicle in the group has already detected the approaching vehicle and will inform all members of the group and help actively to avoid an accident.

A. Communication System Requirements

From the vision outlined above, we can directly derive some of the requirements of the communication system that shall be designed. Concerning cooperative perception, a vehicle will find itself in a possibly highly mobile environment so that environmental information gathered using sensors outdates quickly. Therefore, this information needs to be disseminated to other vehicles within the cooperative group as fast as possible. Furthermore, the information may be detailed, containing a lot of objects thus presenting a considerable amount of data that needs to be communicated. Regarding cooperative trajectory planning, vehicles can move quickly with several meters per second. To avoid collisions, trajectory data, too, has to be exchanged between vehicles with a latency as low as possible. Such design objectives, like required data rate and acceptable latency, define the needed *quality of service* (QoS).

Another important issue is information security: a malicious vehicle may present fake data to other vehicles and trick these into crashing or may try to confuse other vehicles' perception. Both cases potentially impose dangerous situations on passengers. At this point, it is questionable which mechanisms of security are adequate and efficient for this case of application. However, the generally desired security mechanisms (e.g. authentication, authorization, non-repudiation) are needed in the autonomous vehicle scenario. To realize this prerequisite a trust environment has to be defined. Only vehicles being part of this trust environment will be accepted for cooperative actions.

An additional requirement for the security of the communication system is the use of tamper proof hardware, especially for the security related components. Using tamper proof hardware components can provide the reliability and trustworthiness needed for the security mechanisms and tasks like a secure logging of events.

B. Traffic Scenarios

The traffic situations that cooperative vehicles are faced with vary from highway scenarios to crowded urban scenarios. On a typical highway with medium load, we can assume a traffic density of about 10 vehicles per kilometer and lane (Fig. 3(a), Fig. 2) [1], [2], moving at high velocities of up to 200 km/h. On the other hand, we can expect a traffic density of up to 40 vehicles per kilometer and lane in an urban scenario (Fig. 3(b)). In such a scenario, vehicles are not expected to move with velocities of more than 70 km/h, especially not in scenarios with high traffic density. Highly congested traffic situations present scenarios where extreme traffic densities of up to 200 vehicles per kilometer and lane but at very low mobility should be expected.

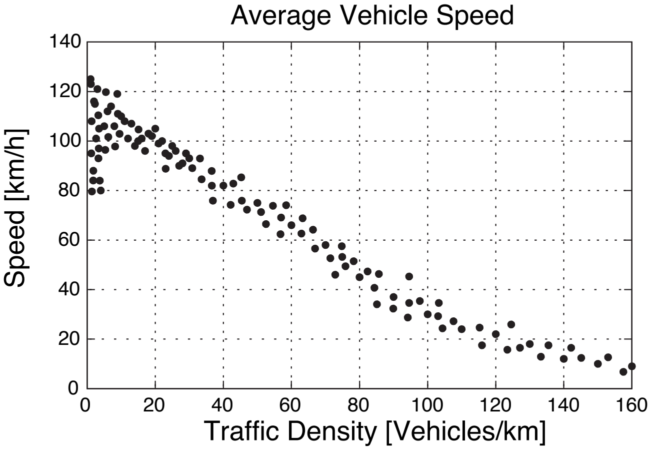
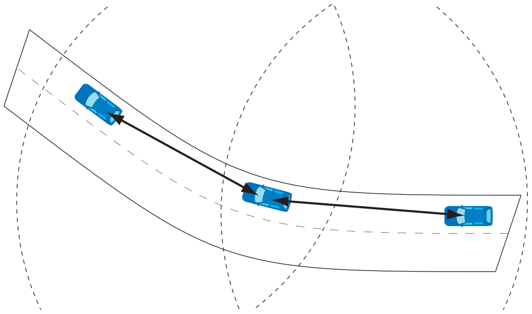


Fig. 2. Average vehicle speed measurements on a highway

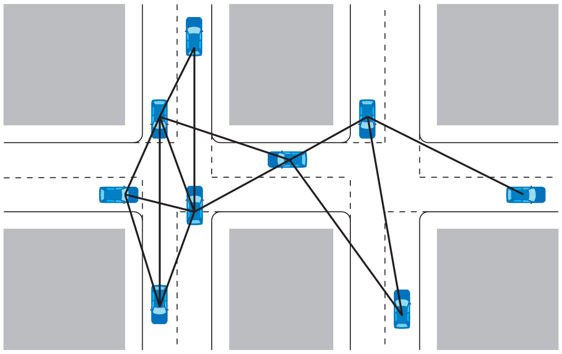
C. Scenario-specific Challenges

Combining the requirements and the traffic scenarios described above, we can already isolate some issues related to inter-vehicle communication. In communication systems that employ competitive channel access such as Carrier Sense Multiple Access (CSMA), as used in Wireless LAN 802.11, high vehicle densities result in high channel utilization which, in turn, causes higher probabilities of packet collisions and disturbed communication between vehicles. This affects the reliability of the communication channel and increases the latency a packet experiences before it reaches its destination and undermines the desired quality of service. Communication systems that employ pre-allocated frequencies or time slots (FDMA or TDMA-based techniques) can more easily provide quality of service but require a central instance that assigns frequencies or time slots to communication partners. This coordination may be done by road-side infrastructure that acts as a coordination point. However, it can not be assumed that vehicles always move in areas where infrastructure is available, therefore a fully decentralized channel access technique needs to be designed that can handle highly utilized channels and guarantee high-priority packets to reach their destination in time. A suitable approach may be found in the *e*-extension of the 802.11 standard which proposes a technique to provide prioritized channel access [3].

Also, communication partners do not necessarily need to be able to communicate directly but rather using a communication path (a *route*) through nearby intermediate vehicles,



(a) Highway



(b) Urban Environment

Fig. 3. (Simplified) Connectivity graphs of vehicles

called *multi-hop communication* (Fig. 3(b)). Especially in urban scenarios with buildings that separate communication partners in term of wave propagation, multi-hop routing effectively extends the range of communication possibilities by repeated relaying. On the other hand, at every intermediate node, repetition and, most important, contention occurs that introduces additional delay to communication paths and decreases the overall achievable data rate; therefore, choosing optimal paths in the routing layer is an important issue to keep packet delay low.

III. A COMMUNICATION CONCEPT FOR AUTONOMOUS VEHICLES

In Sec. II, we have already outlined the main problems that inter-vehicle communication is faced with: dramatically varying vehicle density and mobility. Furthermore, the communication concept to be designed needs to be able to handle the complete absence of centralized coordination instances and work in a fully decentralized manner.

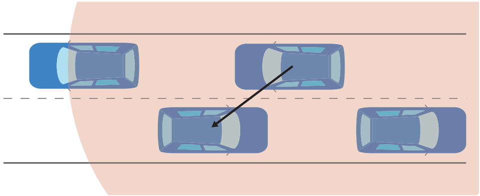
When it comes to capacity planning in fixed networks, exact knowledge of a network's topology allows engineers to precisely dimension and provide bandwidth for desired applications. The same holds true for wireless networks, for instance for cellular, infrastructure-based networks: sophisticated channel models and methods for wave propagation analysis allows precise planning of cell structure and dimensioning. However, these methods are applicable only to *fixed infrastructure* scenarios.

In the case of V2V networks, we find ourselves in possibly highly dynamic scenarios with changing channel properties and quickly varying topologies. To provide high routing efficiency and low delays, we have decided to build our solution around a technique that we call *topology awareness*: Every vehicle shall have an up-to-date yet geometrically restricted knowledge of the local network topology, i.e. every node has a local routing table that represents channel conditions and communication capabilities of vehicles in its vicinity or at least its current cooperative group as a directed graph. This graph shall not only represent the direction of possible communication (no, uni- or bidirectional communication) and data rates but also contain other vehicles' positions along with their direction and speed of movement (motion vectors). To make this possible, a complex analysis of data available from different instances in a vehicle is necessary: channel condition measurement from the physical network interface, routing table exchange with other vehicles and position updates are inevitable pieces of information. Therefore, our approach calls for a unified concept that combines different layers, usually denoted as a *cross-layer design*.

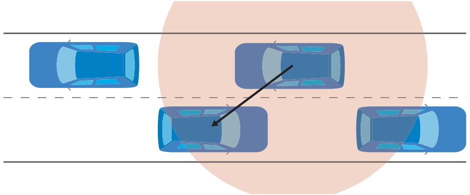
The first anchorpoint of our design is therefore the act of exchanging positions and routing tables between communicating vehicles. This exchange is done through a mechanism that is called *beaconing*: Every vehicle periodically advertises its presence along with its position and routing table to other vehicles in its surrounding. Vehicles receiving beacons can update their information about vehicles in their vicinity, update their routing tables, and use channel state measurements to perform link quality estimation. We call this mechanism *neighborhood sensing and topology discovery*.

The second component of our design is called *neighborhood mobility estimation*. Using the position information of surrounding vehicles and these vehicles' respective motion vectors, the mobility of the surrounding can be estimated. Knowing a vehicle's and its surrounding's mobility helps other communication components fine-tune vital communication parameters; for example, the interval of beaconing can be greatly increased in a scenario with slowly moving vehicles (for example on congested roads) where one would expect positions as well as the network topology to be rather static. In such a scenario, the maintenance overhead imposed on the network due to beaconing can be reduced without losing important information. In a high-mobility scenario such as on a highway, beaconing intervals can and need to be decreased to update quickly changing vehicle positions and network topologies more frequently.

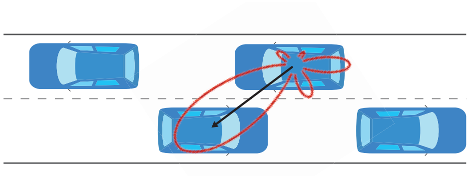
Our design also employs a third component, called *topology prediction*. The conditions of wave propagation that determine a vehicle network's topology are usually dependent on the physical surrounding of the communication partners and their geometric position within this surrounding. By observing the network topology and its changes in (traffic) areas ahead of it, e.g. an intersection it is approaching, a vehicle can predict to some extent the connectivity it will experience, and the tasks it will have to perform once it reaches this area. As an example, a vehicle can expect to assume the role of a relay node once it reaches the center of an intersection. By analyzing physical surroundings, such



(a) Broadcasting

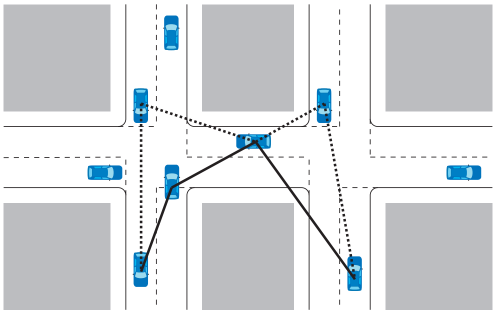


(b) Power Control

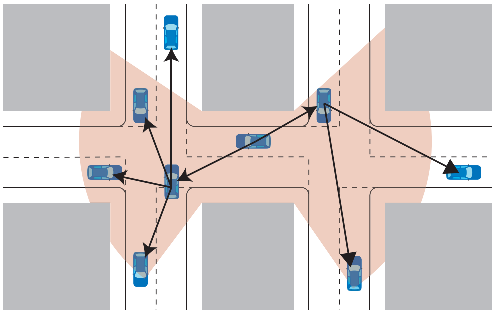


(c) Beamforming

Fig. 4. Methods for reducing load



(a) Optimal route selection



(b) Broadcast router selection

Fig. 6. Routing enhancements

topology prediction can even be performed for areas outside the currently available connectivity graph of the vehicle.

A. *Medium Access Strategies*

In a fixed network, a particular message would be routed through a fiber that connects sender and receiver, yet in a wireless network all users share the same medium (Fig. 4(a)). Therefore messages between a pair of communication partners will interfere with other communications in the vicinity, resulting in blocking or dropping of packets.

The key to estimate the blocking probability in a larger scenario is the traffic per area which we will denote as *load* in the following. Obviously, the blocking probability increases with channel busyness and load. Therefore, we are faced with two different design goals: keep the traffic per vehicle low and keep the area in which traffic is broadcasted small.

Especially in very crowded scenarios with a high density of vehicles in urban environments with high-rises that act as waveguides along streets, load is an important problem and broadcast areas should be as small as possible. Ideally, a vehicle should be able to communicate with at least one vehicle in its cooperative group, and at the same time limit its transmission range to as few other vehicles as necessary. Power control (Fig. 4(b)) is generally a good solution to tackle this problem, yet the impact of interference between broadcast areas as well as the effect of hidden terminals need further investigation. A very new approach to limit load and interference is beam forming: Using an array of antennae and sophisticated signal processing, it is possible to change the radiation profile from broadcasting to more or less distinct radiation lobes (Fig. 4(c)). Knowing the geographic location of the destination or the spatial channel impulse response of a communication, beams can be precisely steered to only cover the area between the sender and a given destination. Both approaches, power control and beam forming can profit from the previous knowledge of network topology and location of communication partners.

We have already spoken about how to keep maintenance overhead per vehicle low, yet, mechanisms to help the application layer to reduce payload have to be provided as well. In the context of our project, we deal with payload that is subject to continuous cognition and may therefore age and outdate. Our concept includes a transmit scheduler (Fig. 5) that not only tries to send data before a certain deadline but also allows higher-layer software to prioritize, withdraw or alter payload according to the actual state of cognition. Also, the scheduler allows prioritized channel access using a modified contention scheme like in 802.11e for urgent, near-realtime communication, for example for emergency maneuvers.

B. *Routing Strategies*

We have already mentioned the need for optimally chosen routes in multi-hop environments to keep communication latency low. Therefore, we chose the design of topology aware routing derived from a protocol known as TBRPF [4]: as all necessary information about the local network topology is known to a vehicle before setting up a communication with another vehicle, an optimal route can be planned and used. This is called *proactive* routing and in contrast to *reactive* routing (such as AODV [5] or DSR [6]), no time is lost for finding a route from sender to destination, therefore, no

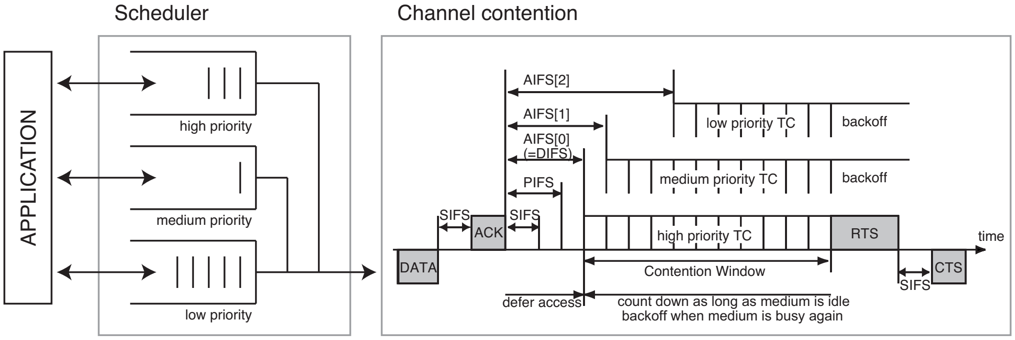


Fig. 5. Intelligent scheduling with 802.11e channel contention

additional delay is introduced. Furthermore, the combination of geographical locations of vehicles allows addressing of vehicles based on their actual location, a technique called georouting [7]. For local, few-hop connections, route optimality may be achieved by means of topology-based proactive routing. However, since every vehicle has only a locally valid view on the network topology, long-distance routes may need to be corrected on the way. An example applying topology-based routing principles is shown in Fig. 6(a): two vehicles communicate over a two-hop connection that represents the ideal route between the vehicles. In contrast to the ideal route, the dashed line shows another valid but suboptimal route.

Broadcasting and multicasting in a multi-hop environment calls for dedicated repeater vehicles [8], [9]. Suboptimal repeater selection causes unnecessary load on the medium, especially in a multicast scenario where communication is by definition limited only to a certain subset of vehicles. Therefore, repeaters should be carefully selected, optimally located at the border of the area covered by the previous hop and within reach of a maximum of yet uncovered vehicles (Fig. 6(b)).

To further reduce load, a novel approach called network coding [10], [11] can be used in multi- and broadcast scenarios and in situations where protection by disjoint redundant routes is needed. A vital prerequisite for network coding is the knowledge of a network's topology as provided by our concept.

C. Security Aspects

Security for the communication between autonomous vehicles is a mandatory requirement. Otherwise the communication system of autonomous vehicles can be easily obstructed by external actors, thus, endangering the safety of vehicles and passengers. Several building block will be used to secure the communication system.

To introduce a trust anchor as a basis for the security of the communication system, a public-key infrastructure (PKI) will be used. Every vehicle will own at least one certificate issued by the shared certificate authority (CA) of the PKI. Hence, these certificates will be used for authenticating nodes as valid cognitive vehicles to communication peers. Besides peer authentication also the exchanged data has to be identifiable. *Non-repudiation* of sending and receiving a piece of information is a very crucial security feature of the communication system. This again will be realized using the certificates. Since short processing delay and low distribution latency is crucial for many operations between cognitive vehicles the security algorithms have to be very efficient and fast without reducing the level of security. In this context the elliptic curve cryptography (ECC) schemes are promising candidates. Especially due to their small key sizes (160 bit compared to 2048 bit for an RSA scheme) ECC is interesting for the application in V2V communication, since data overhead related to security shall be as small as possible to keep protocols efficient.

A very important security building block will be a key agreement protocol for cooperative groups of vehicles. Several group key agreement schemes have been proposed, however, the application in V2V communication with its specific requirements has not yet been examined. An efficient scheme based on the Diffie-Hellman technique [12] is most likely to be used.

IV. RELATED WORK

In the context of VANETs and V2V communication multiple publications have already been presented over the years. Projects like FleetNet [13] or Network on Wheels [14] have looked into various aspects of the V2V communication. An overview of V2V communication aspects and on the current research activities as well as challenges in the field has been given in [15].

The general challenges posed on V2V technology and specifically communication protocols are the limited capacity and the scalability of protocols. In [16] an in-depth look into the capacity issue of ad hoc wireless networks has been presented. The authors show that the capacity of these networks is proportional to $\mathcal{C} \sim \frac{1}{\sqrt{N}}$, where N equals the number of participating nodes. Hence, especially large networks have capacity problems, thus, needing new efficient protocols and mechanisms.

In addition to the general capacity problem also the so-called Broadcast Storm Problem is very relevant for V2V networks. In [17] this problem related to flooding-based protocols has been presented. Since flooding and broadcast-based communication is an important mechanism for V2V communication this is an important challenge to solve in future protocols.

To realize reliability and time critical message exchange for V2V communication, QoS is necessary. In several previous publications the QoS-issues have been addressed [18], [19], however, the proposed solutions are not yet suitable for the requirements of communication between autonomous and cooperative vehicles. Therefore, new solutions and mechanisms need to be developed, extending and improving the existing work. Besides QoS also the subject of scheduling is an important aspect for the time critical message exchange needed. Some of the previously proposed scheduling schemes for ad hoc environments have been presented in [20] and [21]. However, like for the previous work concerning QoS the previous work on scheduling will not provide sufficient performance for the required data communication.

The application of so-called smart antennas is currently gaining momentum in the wireless community within multiple scenarios. These concepts, e.g. presented in [22] and [23], promise to improve scalability as well as capacity of ad hoc networks. Hence, they will most likely be an important building block for V2V communication between autonomous vehicles.

The use of the IEEE 802.11e QoS extension in VANETs and similar approaches have been proposed in several publications. In [24], [25] a detailed description of a possible communication system setup and extensive simulation results have been presented. This work can be used as a starting point using prioritized contention for cognitive automobiles.

V. CONCLUSION AND OUTLOOK

In this paper, we have presented several challenges of inter-vehicle communications in the context of cooperative cognitive vehicles. Addressing these challenges, we have proposed a set of essential building blocks including mechanisms and approaches which will serve as a basis for a full communication system architecture we are currently developing. As a central aspect, we have argued that topology awareness in wireless V2V networks is a crucial enabler for effective distributed medium access and routing. Our approach provides quality of service at the lower layers while offering an interface to the application to (re)order and (re)prioritize messages and event to change their payload to keep up with the outcomes of continuous cognition. Therefore, we expect to see superior performance compared to traditional wireless networks. However, a practical implementation and simulation results are needed to prove the expected benefit in terms of performance, reliability, and quality of service.

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