A Survey of Inter-Vehicle Communication Protocols and Their Applications

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***Abstract*—Inter-vehicle communication (IVC) protocols have the potential to increase the safety, efficiency, and convenience of transportation systems involving planes, trains, automobiles, and robots. The applications targeted include peer-to-peer networks for web surfing, coordinated braking, runway incursion prevention, adaptive traffic control, vehicle formations, and many others. The diversity of the applications and their potential communication protocols has challenged a systematic literature survey. We apply a classification technique to IVC applications to provide a taxonomy for detailed study of their communication requirements. The applications are divided into type classes which share common communication organization and performance requirements. IVC protocols are surveyed separately and their fundamental characteristics are revealed. The protocol characteristics are then used to determine the relevance of specific protocols to specific types of IVC applications.**

***Index Terms*—Collaborative decision making, collision avoidance, cooperative driving, vehicle safety, intelligent transportation systems, inter-vehicle communication, mobile computing, mobile ad hoc networks, mobile robots, reliable broadcast.**

I. INTRODUCTION

PROVIDING vehicles with information on their peers may improve the safety, efficiency, and effectiveness of intelligent vehicle systems, from collaborating mobile robots to aircraft in flight formation. Originally, this information was conceived as originating from local sensor input, such as infrared, radar, or GPS. More recently, infrastructure-to-vehicle and inter-vehicle communication (IVC) links are being evaluated for a variety of applications. Direct communication between vehicles may be supported by the deployment of mobile ad hoc networks (MANETs), which do not rely on fixed infrastructure and can accommodate a constantly-evolving network topology. Research on MANETs covers application requirements and communication protocols for everything from sensor networks to handheld computers and vehicle systems. MANETs that span planes, trains, automobiles, and robots are called vehicle ad hoc networks (VANETs). The vast majority of VANET research has focused on road vehicles and safety, examining applications that include mobile Internet, intersection collision avoidance, and automated convoying. Some VANET applications, particularly general information services, have communication requirements that overlap with MANET applications that do not involve vehicles. However, many involve new challenges and motivate novel protocol architectures that exploit knowledge of vehicle dynamics and other data to improve IVC performance. For example, multicast amongst vehicles on a highway may be challenging from a routing perspective. A protocol that places nearby vehicles with similar velocities into broadcast groups that move with the vehicles and are connected by a multicast backbone may require fewer routing updates. Similar optimizations exist for other types of vehicles, such as robots on a factory floor or aircraft near an airport, since their motion is often predictable and can be approximated to one or two dimensions.

Despite an extensive amount of recent work on IVC applications and protocols for VANETs, few surveys exist, some examples being [1], [2], [3], [4], and [5], and we are not aware of any that take a systematic approach to analyzing application requirements and matching them to appropriate protocols. A close study of this relationship is important since each protocol design may involve trade-offs that are good for one application and detrimental to another. The solution space must be carefully navigated if demanding requirements, such as highly reliable, real-time communication, are to be satisfied within the context of rapidly-evolving vehicle networks.

In this paper, we apply a systematic approach to reviewing the applications and protocols related to IVC so as to best match the requirements of the former to the capabilities of the latter. We begin by orienting the reader with background on IVC in Section II. In Section III, we separate applications by communication paradigm and construct a taxonomy. This results in four classes:

1) General information services
2) Information services for vehicle safety
3) Individual motion control using inter-vehicle communication
4) Group motion control using inter-vehicle communication

We describe the reasoning behind this choice of classes and present a survey of applications for each. The communication requirements for each class are summarized in Section IV. In Section V, we discuss some key design decisions and trade-offs facing IVC protocol developers. A representative set of protocols are classified according to their architectures and applicability, and we explore some of them in more detail to provide an appreciation of their diversity. We discuss some important observations and suggest future work in Section VI, and we draw final conclusions in Section VII.

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II. Background

Inter-vehicle communication permits a mobile node, such as a robot or aircraft, to communicate directly with peers using wireless radio. It is an alternative to vehicles communicating through fixed infrastructure, such as a roadside cellular system or an access point in a building. Vehicles may route, source, and sink information for others in the network. This information may range from vehicle motion data to internet media content, depending on the application. The communication may be one-to-one, such as when two mobile robots cross paths and need to resolve the conflict; one-to-many, such as when a lead aircraft issues commands to a formation; and many-to-many, such as when automobiles announce their position to one another for collision avoidance. Additionally, many of the applications discussed in this paper make use of more than one communication style.

An example of an IVC application is shown in Fig. 1. In this truck platooning application, the lead vehicle sets the pace and communicates maneuvers to the followers. The followers attempt to maintain a constant time or distance headway to the vehicle directly in front of them. This can be done manually by a driver using, for example, a two-second following rule or remaining 50 meters behind the preceding vehicle. However, if the goal is to take advantage of draft aerodynamics for fuel economy and further increase traffic capacity, it may be desirable to tighten the vehicle spacing so much that human reaction times are challenged. To deal with this, each vehicle collects its position coordinates and other motion data using local sensor inputs and periodically broadcasts this information to its follower. Each follower computes the relative distance, velocity, and acceleration to its predecessor and uses these in closed loop control of acceleration and braking to reduce spacing errors, e. In addition, the lead vehicle broadcasts its motion data to all, which use it as a common reference to keep spacing errors from propagating and amplifying down the platoon's length. The leader may also broadcast control messages that reorganize the group or announce path plan changes. We will discuss this and other motion control applications in subsequent sections.

The application's demands, combined with the properties of the underlying VANET, guide design of the IVC protocol. Like the previous example, some applications require that messages reach vehicles by a deadline and with a certain degree of reliability, and the protocol must ensure that these requirements are met through efficient information dissemination, loss detection, and recovery techniques. Other applications require messages to be delivered to vehicles with a specific interest or residing in a particular region. The number of, and distance to, these vehicles greatly influences the architecture of the communication protocol. Additionally, if a group is involved, the protocol may be responsible for managing membership as the composition changes.

IVC is potentially vulnerable to security threats, such as injection of false data, corruption of data, jamming and denial of service attacks [6]. These threats can lead to severe consequences if they interfere with safety applications or target military operations. A wide range of approaches may be necessary to address the plethora of security concerns, ranging from encryption that permits bad data to be detected to laws that dissuade channel abuse. A number of these technical challenges are receiving attention from the Network on Wheels project [7], whose solutions are being considered by the Car-to-Car Communication Consortium for road traffic safety applications [8]. The security architecture is not addressed in this paper since such a discussion warrants separate, extensive treatment. The related issue of privacy must also be considered carefully, since only certain authorities may be permitted to identify occupants from vehicle data or inquire about a vehicle's route and destination.

IVC system models vary widely by application. We are focused on those that involve a significant portion of wireless communication routed directly between vehicles. The wireless media access control and physical layers are either the subject of the protocols reviewed in this paper or treated as service layers. In some implementations, especially those supporting information services, IVC may bridge to other network types through cellular basestations or wireless access points. Communication may also be augmented by specialized infrastructure, such as message relay appliances. For example, a message intended to reach all vehicles in a street grid may be retransmitted by a fixed relay at each intersection. Or, a delay-tolerant IVC network may temporarily store road condition alerts from passing vehicles in a relay box for later delivery. To get messages to recipients, the system model may include individual and group vehicle addressing schemes. These schemes may imply vehicle locations or be paired with location data so that vehicles can address each other in a relative sense (e.g., a car addressing another ahead of it in the same lane). GPS has become the baseline technology for location sensing and is commonplace enough in planes, trains, and automobiles to assume its presence in future models. Vehicles may also be equipped with infrared, sonic, or millimeter-wave proximity sensors and the PReVENT project [9] has looked at fusion of these data with that of IVC to improve the effectiveness of road safety applications. Vehicles may also be equipped with embedded computers to process communication data, execute IVC applications, operate vehicle control systems, and issue alerts to occupants.

III. IVC Applications

IVC-based applications attempt to solve diverse problems, each with specific communication requirements. For this reason, we start by grouping applications into type classes according to general aim, such as safety information services or individual motion control. We then propose an application taxonomy in the form of a tree. The leaves of this tree map directly into these classes. The branches of the tree describe why applications communicate, the idea being that those sharing one or more branches are more likely to have common protocol requirements. We go on to survey specific examples of applications in the literature. We proceed type-by-type, discussing the communication requirements for each. In Section IV, we describe how the requirements differ between these classes. We ultimately use these learnings to match protocols to each class.

Four types of IVC applications are listed in Table I, along with information each may communicate. Type 1 and Type 2

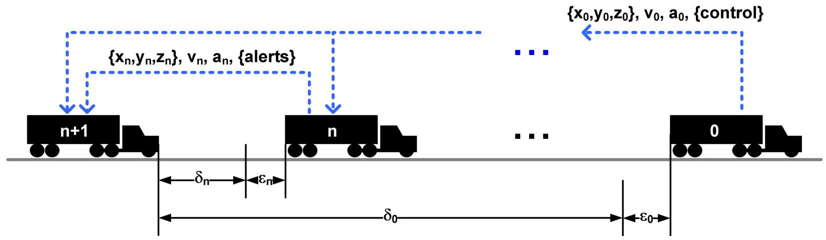

Fig. 1. Vehicle platoon using leader-predecessor following rules to achieve desired spacing, δ.

TABLE I
APPLICATION TYPES AND EXAMPLES OF THEIR USE OF INTER-VEHICLE COMMUNICATION.

Type	Description	Communicated Information
1	General Information Services: Services for which delayed or lost information does not compromise safety or render application useless.	Information queries (weather reports, web browsing, business services, road conditions, traffic volume); context-specific broadcasts (advertising, entertainment feeds)
2	Vehicle Safety Information Services: Services for which delayed information may result in compromised safety or render application useless.	Context-specific safety alerts related to potential dangers, such as abnormal vehicle behavior or surface conditions
3	Individual Motion Control: Applications that issue operator warnings or regulate local vehicle actuators to ensure safe and/or efficient operation.	Motion and actuator state broadcasts for vehicle collision avoidance; look-ahead data to improve performance of adaptive cruise control
4	Group Motion Control: Vehicle motion planning involving global optimizations or negotiations and that may or may not involve group motion regulation.	Motion and actuator state broadcasts, as well as motion-related control messages for centralized or distributed applications

applications provide information services, primarily aimed at automobiles on public roads. The information source may be a vehicle or lie outside of the VANET, such as in the wired Internet, and the information may be propagated extensively. In any case, the data is not used to automatically control vehicles. We define Type 1 applications to be those services not involving vehicle safety, such as mobile Internet, peer-to-peer data queries, and data feeds. We define Type 2 applications to be safety-related services, such as accident warnings, road conditions, and obstacle awareness. Type 3 and Type 4 applications are concerned with the motion planning and regulation of vehicles that operate in tightly-knit groups or encounter one another. These applications are typically very sensitive to delayed or lost data since it may be used to control a vehicle's actuator systems (e.g., throttle and brakes) on a real-time basis. They often involve relatively short timescales of action, such as milliseconds. Type 3 applications keep vehicles out of each other's way using individual motion planning and regulation methods. Examples include runway incursion avoidance and adaptive automobile cruise control. Type 4 applications involve some degree of shared motion planning amongst vehicles that may also couple their motion regulation to one another. Examples include optimal path planning amongst robots, vehicle platoons, and aircraft formation flying. Shared planning may be executed jointly amongst vehicles or performed by a leader and communicated. With coupled motion, the group may depend on additional inputs from the leader and one another. If leader-based directives are not desirable, the vehicles may create a "virtual leader" reference through distributed consensus rules, as described later.

The application classes can be organized into a taxonomy based on how they use IVC, as shown in Fig. 2. The root of the tree represents all IVC applications. Moving to the right, the applications are first divided by whether they involve transmission of motion control data between vehicles; Types 3 and 4 do, whereas Types 1 and 2 do not. Going further, Type 2 safety applications are separated from Type 1 services that suffer less adverse consequences if information is delayed or lost. Motion control applications are first divided by whether they involve group planning; Type 4 do, whereas Type 3 do not. Going further, Type 4 group control applications are divided according to the control architecture they use to regulate their motion. We now look at examples of these applications and their requirements from the literature. Some involve entire vehicle systems that combine applications with protocol layers, and the pertinent aspects are discussed both here and in Section V on protocols.

A. Type 1 and 2 Applications: Information Services

Information services generally involve the dissemination of messages to a set of vehicles within a region or throughout the network. Groups may form to organize nodes, resulting in more efficient multicast or broadcast communication, or to provide a subscription method for sources to reach vehicles sharing common interests. Type 1 applications for general information services generally require low communication overhead and a high information delivery ratio. Communication overhead quantifies the amount of control and metadata per unit data delivered. The delivery ratio measures the fraction of intended receivers that receive information while it is still deemed useful. In the Type 1 application described

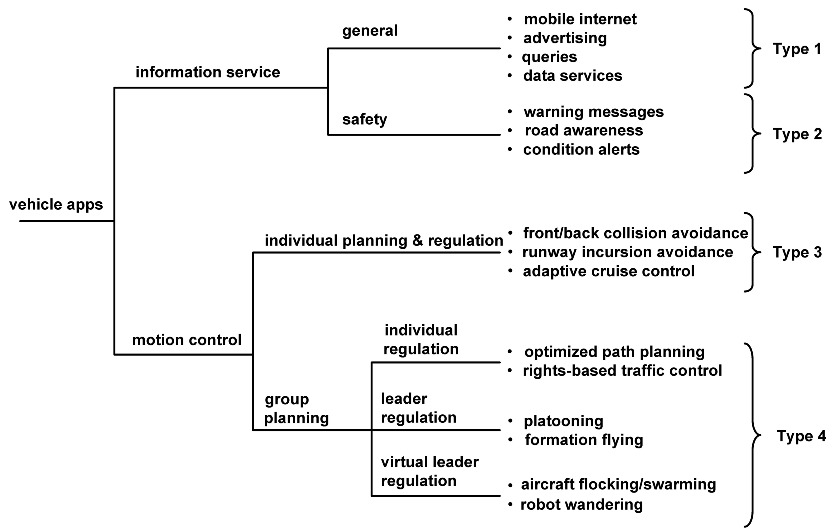

Fig. 2. A taxonomy for IVC applications.

in [10], vehicles with GPS and a wireless transceiver use an historical database to record encounters with other vehicles. Vehicles present queries to the databases of peers within the VANET using routed messages. Vehicles may locate others and monitor traffic flow conditions, among other things. In [11], vehicles provide information on resources they are aware of to others they encounter. The information may have either limited time or spatial value (e.g., stock market data or vacant parking spaces). The authors discuss the problem of determining to whom queries should be sent, how they are routed, and how answers are returned.

Type 2 safety applications are more likely to be sensitive to latency than throughput. Tolerance to latency will generally increase with source-receiver distance due to the physically-interactive nature of these applications. An example of a Type 2 application is presented in [12] as part of a road vehicle system, in which emergency warning messages are propagated through a VANET to identify the location and motion state (e.g., acceleration and velocity) of vehicles acting out of character due to an accident, mechanical breakdown, or some other failure. The work focuses on providing vehicles moving nearby the "abnormal vehicle" with an early warning. It is assumed that vehicles are equipped with GPS and short-range wireless communications. The CarTALK 2000 project proposed a similar information and warning function as part of a driver assistance system. In it, emergency messages are broadcast throughout a multi-hop region to warn others of breakdowns, traffic anomalies, and dangerous surface conditions [13]. The application requires processing and messaging delays as low as 40 ms and message repetition rates up to 50 Hz [14].

B. Type 3 Applications: Individual Motion Control

Type 3 individual motion control applications may use IVC broadcasts to exchange position, velocity, acceleration, bearing, and actuator state. If message latency is low enough, this information can be used to control vehicle acceleration and braking, or to generate a collision warning or avoidance plan. No group motion coordination is performed; vehicles simply control themselves using the information gathered from neighbors. Interaction between specific neighbors is typically transient, lasting only for seconds or minutes. References [15], [16], [17], [18], and [19] describe the use of IVC for collision detection and avoidance among aircraft. IVC can be used to convey the identification, position, velocity, altitude, and goals of other aircraft. [15] describes PathProx, an application in which this information is broadcast periodically to others within range. The information is extrapolated to assess time-to-collision and conditionally issue an alert to pilots. [16] uses path estimation and pre-programmed "rules of the road" to ensure pilots in nearby aircraft are given complementary guidance that prevents and resolves conflicts. IVC may also enable aircraft to reach destinations more efficiently. For example, [17] describes a "free flight" airspace, in which aircraft use direct routes of travel. Unlike the present "air highway" system, each craft would individually determine its trajectory towards a destination and avoid collisions with others. Advisories or warnings are issued to crew if other aircraft penetrate a protection zone. [18] and [19] describe how aircraft and other objects may be abstracted as potential functions. Such objects can be used to repel aircraft from each other, weather, and terrain, while simultaneously propelling them towards their destinations. Although the communication requirements are not described, sensors and IVC may work interchangeably.

IVC may reduce collisions between road vehicles. In [20], vehicles use GPS and digital maps to locate intersections. 50 meters from an intersection, vehicles broadcast their location, direction of travel, and speed so that others may take evasive action. The vehicles in [21] communicate similar information so that drivers receive an audio warning if their vehicles' estimated times to an intersection are close and little reaction time remains. [22] applies IVC to reduce rear-end collisions in a string of vehicles. Unlike line-of-sight sensor technologies such as laser, radar, and sonar, IVC can provide distance and velocity information on multiple preceding and following vehicles. The ability of vehicles to send and receive this information was shown to have a positive impact on braking response time. IVC may also provide data for continuous motion regulation in intelligent cruise control applications, permitting vehicles to operate safer and closer. The application in [23] assumes only line-of-sight information whereas [13] permits vehicles to react to actions taken by others within a multi-hop region.

C. Type 4 Applications: Group Motion Control

In the next several sections, we discuss Type 4 applications in which vehicles share a mission or destination. In these applications, vehicles are generally organized into groups to facilitate complementary trajectory planning and may couple their motion to one another. Explicit membership may be used to identify participants and establish relationships. Vehicles may remain within the same group for relatively long periods of time (e.g., minutes, hours, or days). To support coherent interaction, vehicles may need to exchange control and status information with certainty. In addition to planning, we consider several motion regulation architectures that may require low latency exchange of position data: individual, leader, and virtual leader regulation. Individual regulation was described for Type 3 applications. In the other two schemes, vehicles collaborate with each other for their real-time motion regulation. Those that travel together generally do so in a coherent fashion, but the movement may be complex, such as in flocking or wandering, and certain maneuvers may only involve a subset of vehicles. A group's motion may take cues from a lead vehicle or be entirely distributed, depending on the needs of the application.

1) Group Planning with Individual Regulation: IVC may be used to globally optimize the path plans of vehicles that encounter one another but do not necessarily share the same route or destination. Vehicles individually regulate their motion, adjusting their velocity and heading in response to others nearby and changes in the environment. [13] describes cooperative driver assistance for highway mergers and intersections. Vehicles exchange trajectory plans to coordinate actions. The application requires processing and messaging latency below 100 ms, a message repetition rate up to 50 Hz, and a reliable unicast link [14]. Multiple projects have applied IVC to mobile robots for path planning. In the simplest case, a unicast link may permit two robots that encounter one another to exchange path plans and appoint one to dictate the plan [24]. More typically, multiple robots within a multi-hop region may simultaneously compute different versions of a global path plan and then agree to use the best one [25], [26], [27]. The selected plan may minimize total distance, total time, number of turns, or optimize some other metric. Planning may continue independently within different network partitions. Collisions may either be avoided by inserting predetermined delays into the plans or by robots stalling when they encounter one another. Deadlocks, such as when a circular dependency exists between robots waiting for each other to move, can be resolved by re-planning paths.

IVC groups may also help optimize the use of intersections and other resources. Rights-based intersection collision avoidance is described in [28] and [29]. Unlike the Type 3 applications that rely on IVC to warn of an impending collision, collisions are prevented by having vehicles explicitly request and be granted use of an intersection before occupying it. Such mechanisms may replace or augment conventional traffic control, offering additional safety and increased capacity. [28] presents a decentralized scheme in which vehicles, or vehicle platoons, must receive a token before entering an intersection and return it when clear. Vehicles request permission based on queue position and a calculation used to improve flow rate, reduce energy consumption, and instill fairness. The four-way stop problem in [29] describes a shared data space that is used to control intersection access. Vehicles must join a group as they approach and are placed into lane queues. They monitor the shared data to determine intersection occupation and right-of-way. The scheme can survive network partitions and vehicle process failures.

2) Leader-Based Motion Regulation: In leader-based regulation, one vehicle broadcasts motion reference and commands to the group. Each vehicle combines this leader's information with motion data from others nearby to determine its own course of action. References [30], [31], and [32] use this style of regulation to coordinate the acceleration and deceleration of vehicle strings. In [32], each vehicle uses the communicated relative spacing of both the preceding and lead vehicle to stabilize platoon motion when vehicles are separated by a distance that is independent of velocity, which may improve fuel efficiency and traffic throughput. Using this information with a linear control law, spacing errors are shown to decrease as they propagate away from a disturbance, and required actuator effort is shown to be bounded. In [30], a platoon of trucks achieves the desired steady-state spacing using the velocities and accelerations of the preceding and lead vehicles. It is determined that all vehicles must buffer received motion data and update their control inputs synchronously in order to prevent instability. The maximum spacing and velocity errors are determined by the largest delay within the group, emphasizing the need for low latency packet delivery.

In realistic vehicle systems, leadership may be more complex and involve more responsibility. For example, platoon leaders may coordinate vehicles joining, leaving, and performing maneuvers. Such actions may demand inter- and intra-platoon communication, with periodic, reliable information delivery [33]. The Automated Highway System (AHS) in [34] and [35] describes these responsibilities in the context of a complete traffic system that utilizes both roadside-to-vehicle and inter-vehicle communication. AHS is discussed further in Section VI. [36] describes a traffic control application that moves small vehicle platoons through blind intersections safely and with minimal delay. Leaders communicate with one another to agree on when, and in what order, they will use the intersection. Leadership may also be augmented by the teamwork concept, in which vehicles take on roles in tasks, such as being the "gap creator" or "safety observers" for vehicle merges [37]. This is shown to complete maneuvers faster and safer than with a leader-only approach, while requiring a moderate amount of control message overhead.

3) Virtual Leader Motion Regulation: To coordinate motion, common directives must be communicated amongst vehicles. The directives may be dictated by a lead vehicle or arrived at using a distributed consensus process, supported by communication amongst peers and copies of a program that executes on each vehicle. The latter approach is referred to as the virtual or distributed leader model. Distributed leader applications may use many-to-many IVC to carry out relatively complex group maneuvers, such as flocking or swarming, while maintaining safe vehicle distances. The distributed nature of the communication and control permits this architecture to scale up to hundreds or thousands of vehicles. This approach is applied to swarming behavior in aircraft formations, robots, and sensor networks in [38]. The agents use IVC to update a common state space with their motion data and perform a weighted average computation on the data from others to determine their trajectory in the next time step. The authors analyze the conditions under which communication will permit agents to determine a consensus on a data value guiding their motion. Unidirectional communication is shown to offer a weaker convergence guarantee than bidirectional and information must reach all agents in a uniformly bounded time. [39] describes a formation of robots that carry out maneuvers in which the desired destination depends on a shared parameter. The parameter is computed by each robot using noisy and inconsistent estimates communicated by peers. Parameter error may be bounded if their communication supports a spanning tree and the estimates are periodically retransmitted.

IV. Comparison of Communication Requirements for IVC Applications

In this section, we explore the communication requirements for the IVC applications discussed in Section III. We use our findings to match the applications to appropriate communication protocols in Section V. Although many of the requirements that we examine generally apply to MANETs, many MANET applications will tolerate lost or delayed information, whereas these may be catastrophic events for VANET applications involving vehicle safety or motion control. Therefore, many of the protocols developed for MANETs are not appropriate for some vehicle applications.

We compare applications based on the following communication requirements: 1) information delivery latency, 2) information delivery reliability, 3) scaling, 4) communication scope, and 5) communication group structure. Delivery latency and reliability are critical performance measures for safety and motion control applications. Scaling is important since a good portion of IVC is one-to-many or many-to-many and may involve a large number of vehicles. Communication scope, or the extent of communication, has a profound effect on how messages are forwarded and the network organized, and it can influence the scaling requirement. Group structure refers to whether vehicles establish specific persistent relationships or simply communicate with others they encounter. Applications that rely on long-term collaboration generally require a protocol that explicitly manages vehicle adds and drops. The applications are listed in Table II by their type, as assigned in the taxonomy in Fig. 2. Applications of the same class typically share the same requirements. Thus, a specific application's needs are generally met by any protocol satisfying its class. An exception is Type 4 applications, which have some diversity with respect to latency, scaling, and scope requirements.

As shown in Table II, Type 1 general information services are the only applications that can tolerate typical network delays and operate correctly. They can deal with variations in delay by increasing data prebuffering for streaming or simply waiting. In contrast, Type 2 safety-related services and Type 3 individual control applications have a hard real-time requirement and may fail with even infrequent delays beyond tens of milliseconds. These applications use IVC to ensure safe, optimized separation and operate essentially blind to hazards when information is delayed. Some Type 4 group control applications change the rules of vehicle engagement to prevent this risk. For example, rights-based intersection collision avoidance requires that vehicles join a broadcast group and receive exclusive rights to an intersection before occupying it. Loss of information in this negotiation leads to delayed use of the intersection, which may degrade performance but not cause a failure. A path planning application that operates separately from vehicle control can also tolerate information delay without failure; routes simply get planned slower and vehicles may need to stop or slow movement if they get ahead of their route. These applications have a soft real-time requirement.

Information may be lost as a result of network partitions, equipment failures, or severe congestion that prevents message forwarding. Type 1 applications may tolerate best effort service with intermittent communication failures, such as loss of a query response or dropped media data frames. Type 2 and 3 applications rely on highly-probable delivery and need to fall back to alternate control or extrapolate data if too many packets are lost. Type 4 applications require the additional ability to determine that information was received. For example, if a leader commands a vehicle formation to reconfigure, each individual must receive the command for the reorganization to be successful. With this level of service, the application can take alternate action if delivery is not confirmed by a deadline.

Protocol architecture is greatly influenced by the number of vehicles that need to communicate. We classify this scaling requirement as "low" for under ten vehicles, "medium" for ten to one hundred, and "high" for over one hundred. The requirement may depend on the communication distance and density of vehicles in a region. For example, Type 1 and 2 information services often require high scaling to permit the broadcast of messages throughout a large area. Additionally, many users may simultaneously demand bandwidth and the protocol should adapt to load and maintain low overhead. Type 3 and 4 applications typically require medium scaling to provide localized communication. However, the scaling requirement may be lower for deadlock resolution amongst pairs of vehicles or higher for global planning that involves vehicles that are well out of maneuvering distance.

The communication range is defined by the scope requirement. The scope may span the entire network or a distance along a trajectory. It may be defined about vehicles (i.e., peer-centric) or relative to a position on a map (i.e., location-centric). For example, location-centric accident alerts may only apply to traffic north on a highway for several kilometers, whereas a peer-centric air-to-air collision detection application may require every aircraft to communicate with others within

TABLE II
COMMUNICATION REQUIREMENTS FOR VARIOUS INTER-VEHICLE COMMUNICATION APPLICATIONS.

Application		**Communication Requirement**				
Type	**Examples**	**Latency**	**Reliability**	**Scaling**	**Scope**	**GroupStructure**
1	Queries (global/regional) [10],[11]	typical network	best effort	high	trajectory or entire network	non-persistent
2	Emergency warnings [12],[14]	hard real-time	highly probable	medium-high	trajectory or entire network	non-persistent
3	Robot collision avoidance [25],[24] Air-air collision detection [15],[17],[19],[16]Air-air collision resolution (potentials) [18]Intersection collision avoidance [20],[21]Look-ahead braking [22]Front/back intelligent cruise [14],[40],[23]	hard real-time	highly probable	low-medium	nearby peers	non-persistent
4	Cooperative driver assistance [14] Robot path planning (local sensors) [25]Robot deadlock resolution [24]	soft real-time	deterministic	low-medium	nearby peers	persistent
4	Intersection collision avoidance (rights-based) [28],[29]	soft real-time	deterministic	medium	small region	persistent
4	Robot motion planning (global) [26],[27]	soft real-time	deterministic	medium-high	small region to entire network	persistent
4	Aircraft/robot flocking, swarming, or wandering [38],[39] Platooning/formation maneuvers [30],[31],[32],[37],[33],[36],[34],[35]	hard real-time	deterministic	medium-high	nearby peers	persistent

a radius. The useful scope of Type 1 and 2 information may be larger than Type 3 and 4 since it may be used by vehicles that do not physically interact.

Finally, we evaluate whether applications call for long-term relationships between vehicles. We refer to this characteristic as group persistence, which is discussed in [41] as it relates to teamwork applications such as robotic soccer and military operations. Application Types 1, 2, and 3 typically involve non-persistent groups and the relationships are typically transient. Communication in Types 1 and 2 targets any vehicle that can forward or use the message. Similarly, Type 3 applications typically involve any nearby vehicles. On the other hand, Type 4 applications involve persistent relationships between specific vehicles that may share a common mission or destination. The vehicles may be required to explicitly register their membership to share data, understand roles and responsibilities, or track the motion of a specific set of peers. The globally-optimized motion planning in [26] and [27] would not seem to require persistent groups since the applications attempt to coordinate all vehicles in the network. However, in practice the planning would not likely include every vehicle and a closed group would be defined. In the next section, we turn our focus to how communication protocols can be designed to meet the requirements of these vehicle applications.

V. IVC PROTOCOLS

The diverse application requirements discussed in Section IV call for diverse protocol architectures. For example, a vehicle platooning application would not use a protocol designed for media content delivery that broadcasts packets throughout an extensive grid of streets. As such, protocols should be classified by application fit prior to comparison with one another. Since almost all of the applications in Section III rely on group communication, we focus our attention in the following sections on broadcast and multicast protocols for IVC. Table III presents desirable protocol characteristics that result from our analysis of communication requirements in Section IV, along with examples of supportive protocol mechanisms. We discuss how to achieve these characteristics as we review several important protocol design decisions in Section V-A. A number of recently developed protocols are classified by their key characteristics and ability to satisfy application requirements in Section V-B. Finally, we provide a short review of one protocol suitable for each application class in Section V-C.

A. Protocol Design Issues

IVC protocols take many different approaches to addressing application requirements while coping with the VANET environment. The goal of this section is to review important protocol design considerations and describe how these impact communication effectiveness. We focus on functionality corresponding to the data link, network, transport, session, and application layers of the OSI model, where apparent architectural differences exist among the protocols surveyed. The discussion is organized as a series of issues that face designers, such as selection of medium access control, each issue involving decisions that impact one or more of these layers. A good design decision may have a positive effect on multiple aspects of the communication service, such as packet prioritization leading to both lower latency and improved scaling. Typically, trade-offs are involved, such as increased latency for a higher probability of delivery. These are often

TABLE III
PROTOCOL CHARACTERISTICS DESIRED BY APPLICATIONS.

Attribute	Description	Enabling Mechanisms
Low Latency	Low end-to-end network delay, which meets application requirements; addresses real-time constraints	Mesh-based routing or flooding; low contention or reserved channel resources; packet prioritization
High Reliability	Highly-probable information delivery to an intended group; support of delivery confirmation	Packet retransmission mechanisms; dedicated or low-contention channel resources; opportunistic store and forward buffering; gossip or mediation algorithms
High Scaling	Ability to uphold service requirements over a range of vehicle densities, receiver count, and network diameters	Adaptive packet suppression, filtering, and prioritization; efficient network routing; clustering techniques
Well-Defined Scope	Supports selective message delivery based on trajectory, region, vehicle proximity, or vehicle identification	Direction, zone, or target vehicles communicated in message; group memberships established; proximity or hop-based forwarding; clustering techniques
Membership Services	Provides group membership services for persistent group structures, processing vehicle adds and drops	Group address space; central or distributed registration algorithm; member drop detection mechanism

acceptable, given that not all attributes are equally important to all applications.

1) Medium Access Schemes: Medium access control (MAC) refers to the data link mechanisms that operate directly above a radio's physical layer. It provides physical addressing and access control for multiple radios, or vehicles, contending for airwave resources. Research has examined MAC schemes and methods for mapping vehicle access rights to them. For example, TDMA, frequency-hopping TDMA, and CDMA were evaluated for vehicle platoons in [42] using a statistical model of the radio channel. The authors found that CDMA provided the lowest packet erasure rates and TDMA required the least amount of bandwidth for a successful transmission, given interference between adjacent platoons. If reliability is deemed more critical than bandwidth conservation, a protocol may blindly retransmit messages. For example, the Dedicated Omni-purpose IVC Linkage Protocol for HIghway Automation (DOLPHIN) uses CSMA and five data transmissions on 20 millisecond intervals to reliably deliver data every 100 milliseconds in a platooning application [43]. The Automatic Dependent Surveillance - Broadcast (ADS-B) protocol, described in Section V-C3 and [44], also uses CSMA and repeated broadcasts in an aircraft collision avoidance application.

When blind retransmission is insufficient, the MAC protocol may be complemented with another layer that implements an acknowledgement handshake. This and other measures are taken in the IEEE WiFi amendment known as 802.11p, which defines Wireless in Vehicular Environments (WAVE) [45]. WAVE is the foundation for the U.S. Department of Transportation's Dedicated Short Range Communications (DSRC) project [46]. It defines multi-channel wireless radio, including a control channel for safety messages and service channels for non-priority messages. The DSRC licensed spectrum operates at 5.9 GHz and consists of seven 10 MHz channels that use orthogonal frequency-division multiplexing (OFDM). Tight control of the spectrum is used to reduce congestion and increase broadcast performance [47]. The packet inter-reception time (IRT), which is the time between two successive packet receptions at a vehicle, is suggested as one performance metric [48]. The MAC improves the IRT by estimating the number of neighbors and optimizing both the safety message rate and transmission power on the control channel. The performance may be monitored using acknowledgement data included within broadcasts. Reception may also be improved by repeating previously sent messages, which may be included in new messages.

The European Commission and car industry has favored a MAC that uses a Time Division-Synchronous CDMA (TD-SCDMA) air interface in the UMTS band, in part due to the unlicensed 2010-2020 MHz spectrum. This is being standardized by the 3rd Generation Partnership Project as UTRA Time Division Duplex-Low Chip Rate (UTRA TDD-LCR). In TD-SCDMA, timeslots are allocated for the uplink and downlink (i.e., they are TDD), with CDMA separating users within each slot. The timeslots are continuously synchronized between nodes. UTRA TDD was initially designed to operate with a centralized network architecture and the CarTALK 2000 project has solved a number of technical challenges to make it appropriate for used in a VANET. Proposed changes include a distributed synchronization technique, new power control, a new method for assigning the control channel used to establish traffic channels, and new policies for reservation of traffic capacity [49].

MACs may also provide multi-hop message forwarding. In [50] the CarTALK 2000 project considers ADHOC-MAC, a protocol in which all nodes know the timeslots used by their two-hop neighbors and can use a shared signaling channel to assign relays for broadcasts. The scheme in [43] provides directional single-hop forwarding for the transmission of periodic control information within platoons. Receivers decide whether to forward messages based on their location relative to the transmitter. However, the packet loss rates for CSMA are quite high (e.g., $\sim$0.1) at moderate offered channel load per vehicle (e.g., 0.0275). With respect to reliability, five transmissions are required for 96 percent of 20 vehicles to receive an emergency packet at a load of 0.11. The Urban Multi-hop Broadcast protocol (UMB) in [51] introduces a new request- and clear-to-broadcast handshake for IEEE 802.11 that enables the farthest node from a transmitter to retransmit a packet. Repeaters at street intersections rebroadcast packets in all directions, as shown in Fig. 3. The delivery ratio is much higher, and the bandwidth utilization lower, than standard 802.11 over a range of packet loads and vehicle densities. However, the packet dissemination speed (in meters/sec) is

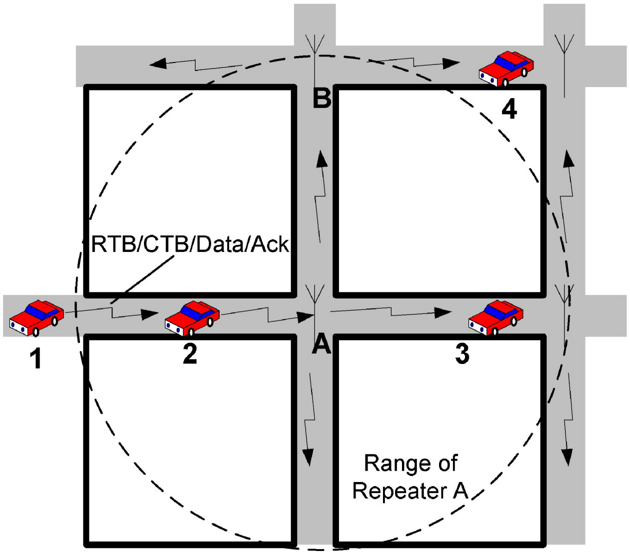

Fig. 3. Distribution of a packet within a street grid using UMB (adapted from [51]).

significantly slower for small packets and gets relatively worse as the transmission rate is increased.

2) Access Mapping: MAC resources, such as time slots, frequency divisions, and codes, can be assigned to vehicles based on their location or other criteria. These "access mapping" functions can reduce MAC contention and increase fairness without centralized control. The Location-based Channel Access (LCA) protocol in [52] is typical of a space division multiple access (SDMA) scheme in that the roadway is divided into geographical cells and vehicles transmit using a cell-to-channel mapping function compatible with TDMA, FDMA, or CDMA. The Adaptive Space Division Multiplexing (ASDM) protocol in [53] optimizes SDMA for platoon applications by permitting vehicles adjacent to vacant cells to use the unallocated time slots and lower bandwidth utilization. Alternately, a protocol may use cells to reduce CSMA contention. For example, the Vehicle Position Environment Acquisition and Communication Evolution (V-PEACE) scheme in [54] avoids packet collisions by timing initial transmission based on vehicle position. Subsequent retransmissions use conventional 802.11b CSMA. In contrast to cell-based mapping, the Wireless Token Ring Protocol (WTRP) in [55] describes a token-based scheme to support rapid, periodic communication within a platoon. A vehicle receives the token, transmits its data, and explicitly passes the token to a one-hop neighbor in its ring. A reliable transport (e.g., TCP) is required to ensure tokens are not lost. The throughput performance compares favorably to IEEE 802.11 DCF for simultaneous transmitters.

3) Communication Organization: Vehicle communication may be organized to maximize the effectiveness of information forwarding. Network layer protocols must be carefully selected to provide an organization that leads to efficient use of the limited wireless channel resources without compromising network connectivity. The one-to-many and many-to-many nature of information dissemination in IVC applications make peer-to-peer broadcast and multicast semantics highly relevant. We briefly touch upon several common approaches to group communication organization in this section.

a) Flooding: Broadcast flooding, in its simplest form, is a flat organization that involves each vehicle forwarding a copy of each new message once to all one-hop peers. Since the communication follows a mesh instead of a tree, it offers many redundant message paths and trades increased bandwidth utilization for improved connectivity. Forwarded messages can be assembled with others and retransmitted in a single packet for more efficient use of the communication channel [56]. Retransmitters can be selected using a relay algorithm that reduces the number of broadcasts while maintaining radio coverage. For example, a vehicle may choose not to rebroadcast a periodic alert if it overhears a peer farther from the source doing so [12]. The solution in [57] adjusts the probability and delay of rebroadcast based on the number of one- and two-hop neighbors. Compared to a fixed probability of rebroadcast, this is found to lower broadcast overhead at high densities without compromising the delivery ratio. In the TRAcking DEtection (TRADE) relay algorithm [58], peers are interrogated for their locations and driving contexts (i.e., road, direction of travel, etc.) before relays are appointed. Messages then identify the intended relay vehicles and the context to use for subsequent forwarding. The forwarding delay is higher than for simple broadcast, but the protocol delivers less irrelevant data to each vehicle while maintaining the delivery ratio.

b) Opportunistic flooding: Broadcast protocols may use opportunistic flooding for packet dissemination, which is one of a larger class of techniques used in delay-tolerant and intermittently-connected networks [59]. In opportunistic flooding, a vehicle stores messages when a network partition is encountered. Messages that remain relevant are forwarded if a vehicle is encountered that will move them closer to their destination. This often leads to a higher proportion of delivered messages and lowers transmissions, but message propagation may be relatively slow. A vehicle may use GPS to decide whether a rebroadcast will advance stored messages following a period of motion.

The Regional Alert System (RAS) in [60] uses opportunistic flooding to pass a token containing an alert message between vehicles in the presence of temporary partitions. Fig. 4a shows an example in which vehicle X desires to pass the token to Y traveling in the same direction. X's broadcast range does not extend to Y, but it does reach Z traveling in the opposite direction. After storing the token and traveling a short distance, Z is within range of Y and the network path X $\rightarrow$ Z $\rightarrow$ Y is completed, as shown in Fig. 4b. The mobility-centric data dissemination (MDDV) protocol in [61] uses opportunistic flooding to propagate a message along a trajectory and deliver it to geographical destination region by a deadline. A detailed description of MDDV is provided in Section V-C1.

c) Clustering: A VANET can be organized hierarchically using a clustering protocol that partitions nearby vehicles into groups to reduce the amount of routing information, permit spatial reuse of channels, and identify message recipients [62]. Clusters may move with vehicles or be fixed to locations, such as intersections. The protocols in [63], [64], and [65] support both definitions. The first level of the hierarchy is typically a routing protocol that connects clusters to one another, as shown in Fig. 5. Messages may be forwarded by clusterhead

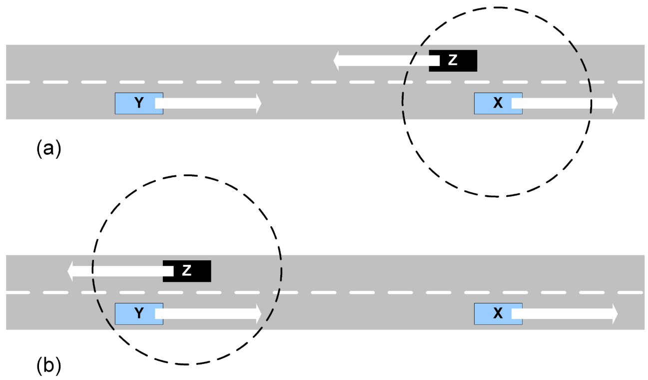

Fig. 4. Opportunistic flooding with a) vehicle X passing message to Z, and b) Z storing for Y.

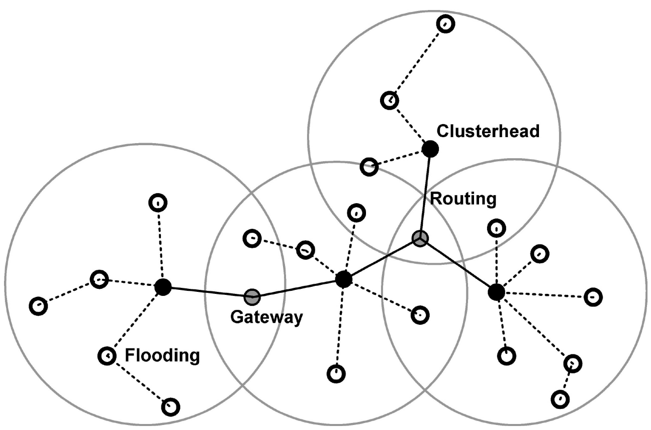

Fig. 5. Message dissemination using a clustering protocol (cf. [66]).

and gateway vehicles along a routing backbone (cf. [66]), and adjacent clusters may use mesh communication to reduce forwarding latency, as BROADCOMM does in [67]. Within clusters, broadcast may be used to further reduce routing state and increase connectivity in the presence of vehicle mobility. Clustering works well for systems that require both neighbor- and network-level communication. For example, the Local Peer Groups (LPGs) in [63] use MAC-level communication to coordinate the motion of nearby vehicles and a networking backbone for more remote information dissemination.

A downside to clustering is the overhead required to form and maintain organization. As an example of formation, the first vehicle to transmit a message may elect itself clusterhead and then define the cluster to be all two-hop connected neighbors. In BROADCOMM [67], hello messages are used to establish communication limits. A cell border is established at the first vehicle down a highway that cannot reach all of the vehicles in the initial cell. Other cell borders are defined at regular distances from this vehicle. The clusterhead is chosen as the vehicle closest to the center of the cell. Clusterhead maintenance can be simplified if the role is assigned to fixed infrastructure, such as a cellular basestation. [65] incorporates fixed message relay boxes that essentially act as "parked vehicles." The relay boxes may periodically retransmit messages to a region and serve as cluster controllers, and may have particular value when mobile deployment is sparse. There may be a maintenance delay when a vehicle is explicitly handed

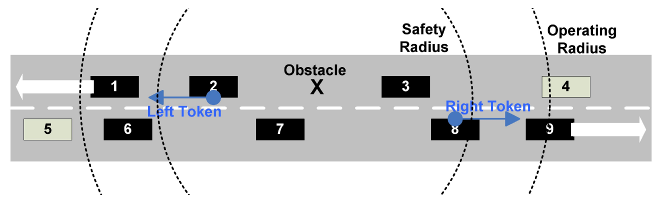

Fig. 6. BiPP propagation being used to alert vehicles of a road hazard (adapted from [60]).

off from one cluster to another and [68] deals with this by maintaining overlap between adjacent clusters so that vehicles are continuously in communication with a set of neighbors.

4) Definition of Receiver Group: The ultimate purpose of organized communication is to efficiently deliver messages to an intended receiver group. The group should be defined as narrowly as possible in order to maximize performance and conserve network resources. This is of particular importance for safety-related applications that rely on real-time communication. In a cluster-based organization, the set of receivers may be defined by cluster membership. The set may also be identified by geographical location, source-receiver distance, or trajectory. The use of geographical coordinates to constrain the scope of message forwarding and define a multicast receiver group has significant value in VANETs. This technique, known as geocast [69], permits applications to take advantage of map data and vehicle location information to optimize message routing and narrow the receiver set.

For Type 1 and 2 information services, the receiver group is often defined within a limited scope of broadcast or opportunistic flooding. For example, the Vehicular Collision Warning Communication (VCWC) protocol in [12] and the Vehicular Information BROadcasting Relay (VIBROR) protocol in [56] flood emergency messages to recipients along a trajectory. MDDV in [61] uses a trajectory in conjunction with a geocast region. The group may also be delineated by direction of travel and other motion data [58]. Optimized Adaptive Probabilistic Broadcast (OAPB) in [57] delivers emergency alerts to a two-hop zone around road vehicles operating abnormally (e.g., stalled or involved in an accident). In [60], alerts are confined to a safety region and delivered using Bidirectional Perimeter-based Propagation (BiPP), which is illustrated in Fig. 6. In this example, Vehicles 1-3 and 6-9 have received the alert. BiPP defines perimeter tokens that include the alert. The protocol is bidirectional in the sense that both inbound and outbound vehicles can pass tokens. Vehicles with a token inside of the safety radius periodically transmit the alert. Tokens may be kept alive until they reach the operating radius. Perimeter protocols are effective at delivering information to a large proportion of vehicles and scale well with vehicle density. Bidirectional protocols, like BiPP, may scale to lower densities than unidirectional protocols, such as [70].

For Type 3 and 4 applications, receiver groups may be based on the proximity or relative motion of vehicles, such as in platoons or the Peer Spaces (PS) in [64] that share traffic safety interests. Additionally, the organization of receiver groups can be decoupled from the clustering or flooding structure by using an overlay system. For example, all vehicles in [65] communicate using the same underlying network organization but each application uses a virtual cluster, or overlay, to define its receiver group. Cluster controllers ensure that application information is only collected from, and disseminated to, the subscribers in each overlay. The Reliable Neighborcast Protocol (RNP) in [68] is an overlay on multiple overlapping reliable broadcast groups. The overlay permits each transmitter to define a neighborhood of vehicles that should receive its message. The underlying broadcast protocol ensures that all vehicles in each group receive the message, and multiple groups form a superset that contains the neighborhood.

5) Network Resource Allocation: The inherent nature of the wireless medium severely limits the amount of available communication bandwidth. Thus, the protocol designer may attempt to lower consumption and maintain connectivity through additional network, transport, and application layer mechanisms. For example, the packet time-to-live defined in [58] exploits the limited time value of information to reduce irrelevant message forwarding. VCWC in [12] throttles the packet retransmission rate to lower congestion and improve delivery reliability. Packets may also be prioritized for retransmission, providing those with more relevance or higher severity first rights to the resources. VIBROR in [56] prioritizes message retransmission based on required delivery latency and scales in response to vehicle density by not forwarding packets as far in dense networks.

Some protocols assign "mediation" nodes to aggregate information shared by peers, filter it according to policy, and forward it on to those missing it. The protocol in [65] achieves low overhead, high reliability, and data consistency through its use of a node that filters application information for cluster subscribers. The Peer Spaces in [64] permits an intermediate node to selectively forward messages to cluster peers based on what it observes they are missing. The authors state that the protocol provides high bandwidth utilization with low overhead. These techniques can be highly effective but may increase delivery delay if the mediator is involved in all forwarding.

6) Group Membership Services: Communication group membership can be explicitly or implicitly defined. Examples of implicit definitions include all vehicles within a map region or a specific number of hops from the message source. Explicit membership can be provided by a session layer service that registers vehicle addresses, or identifiers, with the group and removes vehicles that drop out. Each approach possesses unique benefits and disadvantages. For example, implicit membership permits a message to be directed at relevant vehicles without the control overhead and delay of a registration process. On the other hand, a registration process permits message sources to be explicitly aware of the intended receivers and implement mechanisms that verify message reception and drive retransmission using positive acknowledgement schemes. This provides deterministic message delivery in cases where highly-probable delivery is not sufficient.

The Peer Spaces in [64] may be organized as clusters with explicit group memberships. All members of a cluster are required to maintain information on all other peers, from the time they join until they leave. In [65], membership is monitored by a centralized cluster controller. The controller attempts to maintain the most up-to-date application information and forward it to all members, thereby ensuring data consistency. The controller can serve as a group coordinator in applications such as intersection control. The broadcast protocol used in conjunction with RNP in [68] maintains a shared list of members so that a token can be passed between them that acknowledges messages and assigns sequence numbers. The group takes votes on the messages and their sequence numbers to ensure that all receivers use the same set of messages in the same order. Because the token transmissions are anticipated and include references to the messages, missing tokens and references are detected and retransmitted, adding reliability.

B. Protocol Classification

In Section III, we classified the applications by communication requirement and divided them into four types. Each type has distinct requirements concerning latency, reliability, scaling, scope, and group structure. The design decisions discussed in the previous section greatly influence the quality of the communication services provided by the protocol to the application. We summarize the direct and indirect impacts in Table IV. The primary impacts follow fundamentally from the respective decisions and are unavoidable. The secondary impacts are indirect outcomes of adjusting the primary requirements and are typically less sensitive to the respective decision.

Through a better understanding of how protocol architecture affects communication service, we can appropriately match protocols to each application class. We apply the mapping in Table IV, along with our analysis, to classify a set of IVC protocols developed principally over the past decade. Table V summarizes the important architectural characteristics of these protocols. Table VI lists how effectively each protocol addresses the communication requirements of IVC applications and matches each protocol to one or more classes.

C. Selected Protocols

We have surveyed a number of IVC protocols and matched them to application classes. To further clarify selected concepts and emphasize the diversity required to address the applications, we are providing additional detail on a protocol appropriate to each class. In this section we review MDDV for general information dissemination within a large region, VCWC for safety-related message propagation, ADS-B for aircraft collision detection and avoidance, and RNP for vehicle motion coordination applications.

1) MDDV Protocol for Type 1 Applications: The mobility-centric data dissemination protocol described in [61] combines opportunistic flooding with elements of geocast-based trajectory forwarding. The objective of MDDV is to forward a message along a trajectory to a region as fast as possible while dealing with rapidly-changing and partitionable VANET topologies. Unlike some geocast routing protocols (cf. [69]), nodes do not selectively transmit messages based on known locations of nearby receivers. Rather, they transmit meta-data including the estimated "message head" location, or farthest position any vehicle has carried the message, and its last

TABLE IV
EXAMPLES OF HOW PROTOCOL DESIGN DECISIONS IMPACT COMMUNICATION SERVICES.

Design Decision	**Impact on Communication Service**	
	Primary	**Secondary or Indirect**
Access Scheme and Mapping	Scaling w/ Vehicle Density, Reliability, Latency	–
Communication Organization	Scaling w/ Vehicle Number, Scope	Reliability, Latency
Definition of Receiver Group	Group Structure, Scope	Scaling, Reliability, Latency
Network Resource Allocation	Scaling w/ Vehicle Density & Number, Latency, Reliability	Scope
Group Membership Services	Group Structure, Reliability	–

transmission time. Vehicles request the associated message if they can advance the message head. Given the message head pair <*l*,*t*>, where *l* is the location and *t* is the time, a receiver with location l_c at time t_c will help propagate the message if $t_c < t + T_2$ and $|l\text{-}l_c| < |l\text{-}L_2|$, where T_2 and L_2 are estimated by individual vehicles based on traffic flow heuristics. If $t_c < t + T_3$ and $|l\text{-}l_c| < |l\text{-}L_3|$, where $T_2 < T_3$ and $L_2 < L_3$, the receiver will only transmit meta-data if an outdated version is overheard. If neither condition is satisfied, the vehicle will not transmit. Using these rules, a message is only propagated by vehicles near the known message head, which can generate new message head information. Messages are only valid for a specified period of time.

A simulation of MDDV in rush hour traffic on Interstate 75 in Atlanta, Georgia, demonstrated that 90-100% of messages reach the destination region before expiring when at least 20% of vehicles participate. When compared, its delivery ratio is ∼50-70% of that for an ideal, centralized knowledge scheme that requires a similar amount of message overhead [61]. The opportunistic forwarding policy may benefit the delivery ratio since the dissemination delay varies widely from seconds to minutes due to network partitioning.

2) VCWC Protocol for Type 2 Applications: The Vehicular Collision Warning Communication protocol in [12] introduces a form of application-specific congestion control for the broadcast of emergency warning messages (EWMs) used to indicate abnormal vehicle (AV) behavior, such as emergency braking, unusual speed, or sudden swerving on roads. The congestion control involves a retransmission rate decreasing algorithm and the selection of specific vehicles to relay EWMs, starting with the troubled vehicle, or "initial AV." The initial AV periodically transmits EWMs until a time elapses or the EWM is overheard from a follower that has become a relay, or flagger. Likewise, flaggers that overhear the EWM from followers become non-flaggers. Non-flaggers will revert if no EWM is received from a follower for some time. Vehicles with backlogged EWMs can raise a busy tone, which causes other vehicles with lower priority messages to defer transmission. Fig. 7 illustrates the alert propagation caused by an accident (Vehicle A) with a traffic backup. A and B overhear Flagger C and become non-flaggers. D is decelerating rapidly and has initiated an alert that has not yet suppressed C. The other vehicles, including E, are not affected.

The goal of the rate-decreasing algorithm is to keep the delivery latency short while minimizing the network load. The latency is comprised of two parts: the wait for an AV's message to be serviced by the channel and the expected delay

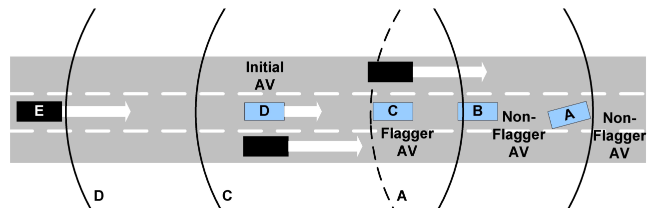

Fig. 7. Emergency alert propagation from abnormally-behaving vehicles in [12].

before the message is received, D_r, which may take multiple transmissions. If λ_0 is the initial transmission rate and it is decreased by *a* after every *L* transmissions until it reaches the minimum rate, λ_{min},, the rate, *f*, after the *k*th transmission is:

$$f[\lambda_0, k] = \max\left(\lambda_{\min}, \lambda_0 \big/ a^{\lfloor \frac{k}{L} \rfloor}\right) \quad (1)$$

A larger *a* supports more simultaneous AVs but may increase delivery delay. A lower λ_{min} increases maximum delivery delay while lowering channel service time and network load. If p is the probability that a message is correctly received, then:

$$D_r = \sum_{i=2}^{\infty} (1-p)^{i-1} \cdot p \cdot \left(\sum_{j=1}^{i-1} \frac{1}{f[\lambda_0, j]} \right) \quad (2)$$

Performance was assessed in [12] for end-to-end delay, number of messages versus time, and the impact on throughput of lower-priority traffic with *p*=0.5 and *p*=0.9. Good results were found with *a*=2, *L*=5, λ_0=100 messages/sec, and λ_{min}=10 messages/sec. End-to-end delay scales well as the number of involved vehicles is increased and shows benefit from the rate decreasing algorithm. The relay suppression mechanism keeps the number of EWMs transmitted per second low (i.e., ∼10-20) and constant, even as traffic backs up and more vehicles become eligible to transmit messages. Non-priority traffic is relatively unaffected after an initial spike in channel use by EWMs.

3) ADS-B Protocol for Type 3 Applications

Automatic Dependent Surveillance - Broadcast is an enabling technology being pursued by the FAA and NASA for air-air collision avoidance and other air traffic management. Aircraft use ADS-B to automatically broadcast periodic motion reports for surveillance by others and ground facilities [71]. Broadcasts are not acknowledged and aircraft are not interrogated for status. The MAC system, or transponder, is dependent on GPS and other flight instruments to determine

TABLE V
IMPORTANT ARCHITECTURAL CHARACTERISTICS OF IVC PROTOCOLS.

IVC Protocol	Access Scheme & Mapping	Communication Organization	Receiver Group Definition	Network Resource Allocation	Group Membership Services
ADS-B [44]	CSMA	1-hop broadcast	1-hop peers	None	None
App Clu [65]	–	Cluster	Fixed or moving cluster	Mediation filtering	Subscribers
ASDM [53]	TDMA w/ location mapping	1-hop broadcast	1-hop peers	None	None
BROADCOMM [67]	802.11, various	Cluster	Moving cluster	None	Cell membership
CarTALK 2000 [14]	UTRA TDD-LCR with ADHOC-MAC	Multi-hop broadcast	Multi-hop peers	Signaling channel, relays	None
DSRC [46]	OFDM w/ control channel	1-hop broadcast	1-hop peers	Priority channel	None
DOLPHIN [43]	CSMA	2-hop flooding	Intra-platoon	None	n/a
LCA [52]	FDMA w/ location mapping	1-hop broadcast	1-hop peers	None	None
LPG [63]	DSRC, other	Cluster	Fixed or moving cluster	None	Implicit w/ zip codes
MDDV [61]	802.11, various	Opportunistic flooding	Region	Priority filtering	None
OAPB [57]	802.11, various	Broadcast flooding	Fixed region	Congestion control	None
PS [64]	802.11, various	Cluster- or peer-oriented	Fixed or moving cluster	Mediation filtering	Interest-dependent peer spaces
RAS [60]	–	Opportunistic flooding	Fixed region	Transmit tokens	None
RNP [68]	802.11, various	Cluster	Neighborhood overlay	None	Explicit per broadcast group
TRADE [58]	–	Broadcast flooding	Trajectory	Relay roles	None
UMB [51]	Modified 802.11	Broadcast flooding	Street grid	None	None
VCWC [12]	DSRC, 802.11	Broadcast flooding	Trajectory	Rate limiting, relay roles	None
VIBROR [56]	S-ALOHA, other	Broadcast flooding and packet aggregation	Trajectory	Priority, distance and time filtering	None
V-PEACE [54]	CSMA w/ location mapping	1-hop broadcast	1-hop peers	None	None
WTRP [55]	CSMA w/ token control	Unicast	Platoon	None	Connectivity table

altitude, velocity, position, and identity. It can interoperate with the Traffic Alert and Collision Avoidance System to provide warnings to pilots.

An aircraft's transponder will interrogate others on one channel and reply to interrogations on another. Interrogation packets are shorter than replies, and replies include data parity. Access to both channels is randomized and use is shared with other aviation applications. The key to successful operation of the system is a high information update rate. The required rate is determined from the closing distances involved and the required probability of receiving an update within a specified period. The application experiences an update period, e, according to:

$$e[p, P, N] = N \frac{\ln(1-P)}{\ln(1-p)} \tag{3}$$

where N is the nominal update period, P is the required confidence of success, and p is the probability of reception [72]. From this expression, the number of message transmissions per update is determined. NASA has modeled reception using a Poisson probability distribution that takes into account range and interference [73]. To achieve application goals with high confidence may require information update rates of three times per second or higher. Since multiple report types, such as position and velocity, are independently transmitted, it is possible that the reception of one can be used to infer information on the others.

4) RNP Protocol for Type 4 Applications

The RNP overlay in [68] introduces the concept of neighborcast to disseminate motion state, maneuver intentions, and warning messages between road vehicles. Each vehicle communicates with a set of others nearby, or its neighborhood. RNP ensures that all vehicles within the neighborhood use the same set of messages in the same relative order and can verify message reception. These attributes permit copies of a distributed motion coordination program to use the same data and make consistent decisions. RNP establishes communication between vehicles by placing them into at least one common broadcast group with one another. The size and overlap of broadcast groups are maintained in one, two, or three dimensions, such that vehicles will always join the necessary broadcast groups before penetrating the safety zone

TABLE VI
CLASSIFICATION OF IVC PROTOCOLS BASED ON APPLICATION COMMUNICATION REQUIREMENTS.

IVC Protocol	Application Type	Latency	Reliability	Scaling	Scope	Comments
ADS-B [44]	3	Very low	Highly prob	Medium density	Peers	MAC-level protocol
App Clu [65]	1 and 2	Low-med	Deterministic with mediation	Medium-high	Peers, network	W/o mediation, may satisfy Types 3 and 4
ASDM [53]	3	Very low	Highly prob	High density	Peers	MAC-level protocol
BROADCOMM [67]	1 and 2	$<$ 20 ms up to 800 meters	Highly prob	High	Trajectory	May be suitable for Type 3 within cell
CarTALK 2000 [14]	2, 3, and 4	Very low	Highly prob, Deterministic	Medium	Multi-hop peers	System with MAC, routing, and car applications. Deterministic for reliable unicast
DSRC [46]	3	Very low	Highly prob	High density	Peers	MAC-level protocol
DOLPHIN [43]	4	sub-5 ms for platoon	Highly prob	Low	2-hop peers	Lacks deterministic communication
LCA [52]	3	Very low	Highly prob	High density	Peers	MAC-level protocol
LPG [63]	1, 2, and 3	–	–	High	Network, trajectory	MAC and routing not specified
MDDV [61]	1	med-high	Highly prob	High	Network, region	High delivery ratio for region of vehicles
OAPB [57]	2	Under 0.35 s for $\sim$40 cars	Highly prob	High	Trajectory, region	High delivery ratio for two-lane road
PS [64]	3	–	–	High	Peers	MAC and detailed protocol not specified
RAS [60]	2	–	Highly prob	High	Region	High delivery ratio for vehicles entering region
RNP [68]	3 and 4	Low	Deterministic	High	Peers	Some delay due to deterministic protocol
TRADE [58]	1	–	Typical reachability	High	Multiple trajectories	Much lower bandwidth utilization vs. simple flooding
UMB [51]	1 and 2	Very low	Highly prob	Medium	Region	Packets propagate faster than standard 802.11
VCWC [12]	2	Very low	Highly prob	High density	Trajectory	Tested with mixed network traffic
VIBROR [56]	1 and 2	Low for short distances	–	High	Network, region	Scales well w/ vehicle density
V-PEACE [54]	3	Very low	Highly prob	High density	Peers	MAC-level protocol; more reliable than 802.11
WTRP [55]	3 and 4	Highly bounded, real-time	Highly prob	Low	Peers	Token controls medium access

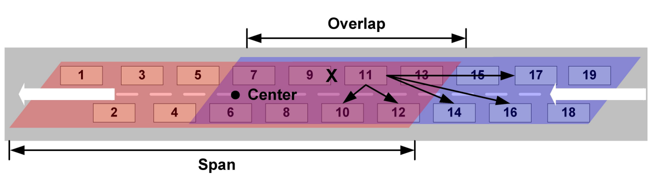

Fig. 8. A vehicle on a two-lane highway uses RNP to signal intent and coordinate movement.

provided by the neighborcast group. The target overlap is $OVT = L + C + \Delta$, where L is the overlap to guarantee that a vehicle can communicate with its neighborhood, C is the additional overlap that prevents a vehicle from entering an adjacent group's span before its join is processed, and Δ is additional overlap to prevent vehicles from transitioning in and out of a group as the boundaries move. A vehicle does not request to join a new group until it is Δ past the boundary. Fig. 8 illustrates Vehicle 11 reliably broadcasting to Neighbors 10 and 12-17 that it needs to swerve and brake to avoid obstacle X. 11 belongs to both the Red and Blue broadcast groups.

RNP operates as a layer above the Mobile Reliable Broadcast Protocol (M-RBP), described in [74], which provides receiver-driven message retransmission, message ordering, and a voting process that ensures that all vehicles in a broadcast group use the same messages. RNP extends M-RBP's properties to multiple broadcast groups covering a neighborhood and permits a source to identify the receivers that should commit its message. M-RBP uses a timed token passing mechanism to ensure that messages are committed by a deadline. When a vehicle transfers the token, it broadcasts its motion data along with an updated geometric center and span for the broadcast group. The center and span are adjusted to maintain the target overlap and group size.

VI. DISCUSSION AND SUGGESTED FUTURE WORK

The wireless medium access control protocols surveyed are particularly effective when paired with spatial or token mapping schemes, such as ASDM, LCA, V-PEACE, or WTRP, that reserve channel resources for each vehicle in the network. The resulting combination provides highly probable single-hop message delivery by lowering communication contention. As such, it is appropriate for simple position sensing applications and can be extended to serve others when combined with additional protocol layers. The forwarding capabilities of the DOLPHIN, UMB, and CarTALK 2000 MAC protocols supplant the use of an additional networking layer, the primary benefit being low end-to-end message latency. The capabilities are extremely basic and limit the utility of these protocols to very specific applications. For example, UMB may work well for some information service applications but would be inappropriate for motion control. As wireless transceivers and embedded processors continue to increase in speed relative to vehicle velocities, it is not clear that the benefit of high integration will continue to outweigh the limitations, and more flexible, layered protocol architectures may prevail.

Many of the protocols developed for group motion control and planning applications comprehend the requirement for highly probable delivery of position information to nearby vehicles while neglecting the need for deterministic control exchange. Without this provision, vehicles cannot enter contracts with one another and assume that actions, such as joint trajectory planning and complex maneuvers, will be executed properly, and they are unlikely to deal effectively with unforeseen eventualities that occur in real environments. The addition of reliable broadcast and multicast services that offer source- or receiver-driven retransmission algorithms and delivery confirmation may address this shortcoming. Another consideration often neglected is the partitionable nature of wireless VANETs. To cope with the possibility of short- and long-term loss of communication, vehicle groups need the ability to rapidly reform their structure or even dissolve, permitting vehicles to fall back to individual, uncoordinated motion control.

Some distributed applications, such as the four-way stop problem in [29], may benefit from additional communication guarantees mentioned briefly in our survey, such as data consistency and message ordering for multiple sources. Data consistency attempts to ensure that all vehicles in a group use the same information, even in the presence of independent packet loss at each vehicle. Causal message ordering involves an agreement that a group will use two messages from the same or different sources in the same relative order, even if the received sequence is different between vehicles. By implementing both of these, copies of a distributed program running in each vehicle can maintain a shared view of control and data spaces. Because the enforcement of data consistency may lower packet delivery statistics, and because ordering can increase message processing delay, these techniques should be applied selectively. For example, a group motion control application may perform best if a data consistency rule is used to ensure each vehicle's membership table matches following a join while position data is delivered without qualification. In any case, data ordering and consistency are easier to achieve with explicit group membership services since the receiver group is then a closed, known set. The challenge is to develop mechanisms that tolerate rapid changes in network topology and membership, as will be encountered in vehicle applications. Research on these topics in VANETs is relatively new but there is an extensive body of work in MANETs that may be leveraged, including the mutual exclusion algorithms in [75] and the work on reliable broadcast in [76], [77], and [74]. Additionally, some work that does not even consider mobility remains highly relevant, such as the total multicast ordering in [78], the data consistency protocols for distributed systems in [79], and the virtual synchrony concept described in [80].

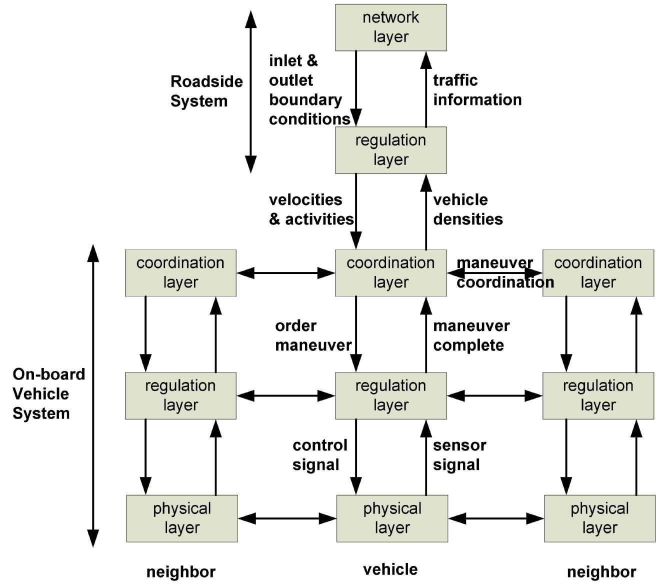

Fig. 9. The five-layer model of the Automated Highway System described in [34].

As transportation applications become more sophisticated, they will likely evolve into complete systems that address multiple IVC applications using multiple protocols that operate under a common management framework. One such system is the Automated Highway System described in [34] and [35]. In this intelligent transportation system, a driver enters a trip plan and then relinquishes control of the vehicle as it is queued at the highway entrance. The vehicle is controlled by an onboard computer system until it reaches its destination. En route, the computer and control systems coordinate with peer vehicles and roadside systems to carry out traffic admission, routing, maneuvers, lateral motion control, and longitudinal motion control. The multi-layered system model is shown in Fig. 9. The physical layer is comprised of a vehicle's sensors and actuators, and it interfaces with the regulation layer, which views a vehicle as a particle and executes specific maneuvers ordered by the coordination layer. The coordination layer includes the IVC protocol and a coordination process that interacts with peer vehicles and the roadside system. The roadside system is constructed of a link layer, which is concerned with traffic flow monitoring and control for a segment of highway, and the network layer, which optimizes routing and traffic admission control. Each layer has an architecture that is independently optimized for its mission (e.g., fluid flow for link layer regulation and finite state machines for the coordination layer).

Another system taking an open standards approach to combining GPS capability with wireless technology optimized for road vehicle applications is CALM (Continuous Air interface for Long and Medium distance) [81]. CALM provides seamless and continuous vehicle-to-vehicle, vehicle-to-infrastructure, and infrastructure-to-infrastructure communications for the deployment of an intelligent transportation

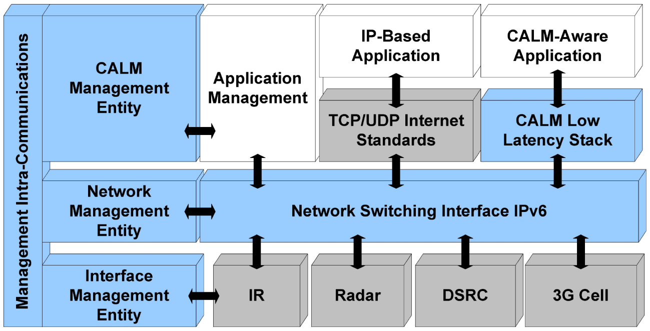

Fig. 10. CALM architecture [82], including applications (white) and communication standards (gray).

system. Its system architecture permits ISO TC204 ITS applications (e.g., fleet management and traffic flow measurement), low-latency applications (e.g., toll collection and emergency messages), and Internet applications to use a multitude of network interfaces for their in- and out-of-vehicle needs. CALM provides the management and routing for seamless interface selection and handover. The supported air interfaces are numerous and include infra-red, GPS broadcasts, millimeter-wave radar, DSRC, and wireless LANs such as WiFi. A given vehicle may implement a subset. An example of the CALM system architecture adapted from [82] is shown in Fig. 10. The CALM Management Entity registers ingress and egress interfaces, matching the network's configured capabilities to application policy. Applications are connected to appropriate transport and network services by the Network Management Entity. In turn, the Interface Management Entity connects these layers to the appropriate link service. The routing and media interface can be used to create in-vehicle networks, connecting multiple vehicle devices, computers, and sensors to each other using IP-based communication.

VII. Conclusion

We have performed an extensive survey of inter-vehicle communication applications and systematically classified them into four types within a taxonomy. This organizational approach permitted us to identify the communication requirements unique to each type and focus on the most important protocol design issues facing developers. We carefully reviewed these issues and illuminated the options using protocol examples taken from the past decade of research on IVC. The design decisions involve trade-offs that can greatly impact the quality of communication services provided to the application. These were highlighted and used to analyze a representative set of protocols, which were classified by both their architectural characteristics and application relevance. We presented additional detail on selected protocols appropriate to each of the defined application types, and we discussed some important strengths and weaknesses of current research. We also considered the future evolution of inter-vehicle applications into complete transportation systems that support multiple protocols operating under a common management framework.

The developing paradigm of inexpensive, ubiquitous processing and wireless technologies, combined with the increasing congestion of all major transportation systems, is likely to accelerate the deployment of IVC systems over the next decade. Effective communication will improve the safety, capacity, and convenience of vehicle systems while simultaneously lowering traditional barriers to adoption, such as infrastructure cost and complexity. Application and protocol researchers will be spurned on by this demand and face a number of new and existing issues. Additionally, there is a general need for application researchers to state more complete communication requirements, while remaining practical, and for protocol researchers to address application needs more comprehensively, while taking into account realistic operating environments. This survey may serve as a starting point for these efforts.

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