Exploiting the Wisdom of the Crowd — Localized, Distributed Information-Centric VANETs

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***Abstract*—Beyond the initial focus on vehicular safety application, there is considerable scope for the development of other information-rich applications which can provide convenience and comfort features to drivers and passengers. We argue that an Internet-like end-to-end networking framework might not always be the best fit for the unique nature of vehicular application — spatially and temporally localized, dynamic, and data-intensive. In this research challenge paper, we propose a top-down framework called Information-Centric Networking on Wheels (IC NoW) to develop a generic network architecture supporting futuristic information-rich VANET applications, ranging from location based services to real-time audio/video transfer.**

The key design philosophy of our proposed framework is that VANET communication is scoped by three key characteristics of information relevance: space, time, and user interest. Using this philosophy, we advocate the development of protocols for information dissemination and management that allow for localized, in-network operations. An important feature of the proposed IC NoW framework is that protocols and applications are implemented in a distributed manner using local decision rule sets taking into account fresh local information. We also pay special attention to ensure the proposed framework is easy to interface with existing cellular infrastructure, whenever needed. This framework enables modular design, facilitating easy application development and creating a smooth migration path during the deployment evolution path.

I. Introduction

Recent developments in the automotive industry point to a new emerging domain of vehicular wireless networks, which include not only vehicle-to-vehicle communications but also vehicle-to-infrastructure communications. In the past few years, several US industry initiatives supported by US Department of Transportation have focused on industry developments and commercialization of safety applications using off-the-shelf technical approaches. At the same time, there is also considerable scope for the development of more sophisticated information-rich applications which can provide more benefit to end users. However, it is increasingly clear that enabling a rich set of applications requires that Vehicular Ad hoc Network (VANET) technology be developed beyond the state-of-the-art. A number of unique factors and challenges must be addressed in designing VANETs. On the one hand, there are ***flexibility*** challenges imposed by the diversity of application needs. On the other hand, there are ***efficiency and robustness*** challenges imposed by short-term dynamics within the network. Most critically, there are also ***sustainability*** challenges imposed by the requirement of flexible long-term operations and gradual evolution of the VANET system in next few decades.

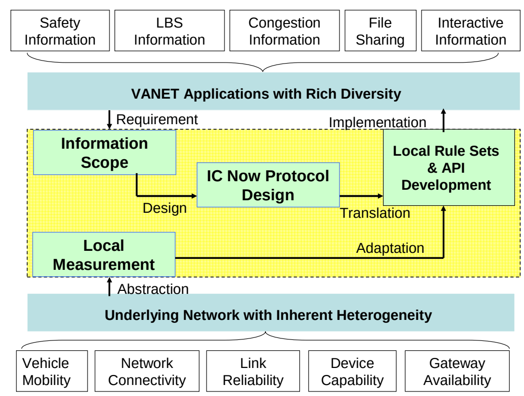

Fig. 1. The Information Centric Networking on Wheels Framework

Motivated by unique challenges imposed by VANET applications, we take a top-down framework called *Information-Centric Networking on Wheel (IC NoW)* to develop a generic network architecture supporting futuristic information-rich VANET applications. This framework focuses on the content and scope of the information, rather than the traditional address-centric end-to-end framework. The framework of this proposed research is illustrated in Figure 1. At the heart of our protocol design is communication of information identified by three key characteristics indicating the scope over which the information is relevant: **space, time**, and **user interest** (*Information Scope* in Figure 1). Under this framework, we seek to develop protocols for information management that allow for in-network data aggregation, storage, replication, and both push-based dissemination and on-demand pull-based querying (*IC Now Protocol Design* in Figure 1). We seek to implement these information management mechanisms in a completely decentralized fashion, with individual devices making appropriate decisions regarding communication, storage, and processing based not only on application requirements, but on local network conditions including connectivity and available bandwidth (*Local Rule Set & API Development* and *Local Measurement* in Figure 1). The framework and the components that we propose to develop will provide *flexibility*, in allowing the rapid development of new applications and allowing for their gradual evolution over time, as well as *efficiency and robustness* in handling the various link and network topology dynamics through decentralized decisions allowing for large-scale operation. Note that, in this research challenge paper, we focus on high-level design philosophy of information-centric IC NoW framework rather than the functionality of detailed mechanistic building blocks.

State-of-the-art automotive telematics systems take such an approach: After collecting sensor data directly from vehicles via cellular connections, cyber-space data aggregation centers (such as Google or Onstar) process data and then publish analyzed results. Because of its centralized nature, the major effort in this framework is spent on locating relevant vehicles, identifying their IP addresses and maintaining seamless connections between vehicles and data aggregation centers. Such a centralized, end-to-end network framework is appropriate for exchanging *light* data between *remote* vehicles (or between vehicles and cyberspace); on the other hand, we argue that this purely centralized framework lacks efficiency and flexibility for supporting *spatially and temporally localized, data-intensive* vehicular applications for a number of reasons:

1) The over-the-air communication cost needed for such a centralized system could be expensive for vehicular users if they happen to be nearby;
2) While most information in vehicular applications are of localized nature, the usage of remote data aggregation centers as the intermediate processing agents creates the dilemma of ‘triangle routing’, wasting cherished bandwidth and introducing latency;
3) Gradually upgrading this system needs a close collaboration between wireless ISPs and automotive OEMs.

Instead, we argue that an in-network processing paradigm is more efficient for developing *spatially and temporally localized, data-intensive* vehicular applications on the roads. The key for developing such localized vehicular communication applications is information content itself, rather than addressable vehicle entity like traditional IP networking paradigm. However, we do not advocate that a fully distributed VANET should replace existing cellular systems; instead, distributed VANETs supplement the cellular systems.

II. Technical Challenges in Vehicular Networking

VANET technology faces a number of *Application Challenges*, *Network Challenges* and *Operation Challenges*.

A. Application Challenges

Local and Dynamic Nature of Information: Consider a simple traffic congestion application on the vehicular network. With many slowly moving cars reporting traffic conditions, the traffic congestion information can be aggregated and used to estimate that vehicular traffic congestion has occurred, and this aggregated information is dispatched to all vehicles within some spatial range. The information in vehicular context is *spatially and temporally localized*: Road condition information (e.g., congestion, pothole) is consumed locally by other nearby vehicles. Moreover, the information is also *dynamic* and *interactive*, changing frequently over time.

In this simple application, the information is not communicated between a pair of addressed entities; rather, there is a dynamic group of vehicles that initiates and consumes the information within some spatial and temporal scope. Information scope and content itself are more relevant to users. Therefore, we argue that *an end-to-end framework targeting for addressable entity is not able to provide an efficient solution for the unique applications in a vehicular setting*. A purely centralized solution also might not be the most efficient solution. The network framework we proposed here more closely resembles data-centric network framework for sensor networks and peer-to-peer systems than traditional address-centric networks.

Application Diversity: We also envision a rich set of vehicular applications that span a wide design space (as listed in Section III-A). In particular, the spatio-temporal scope of the communication can vary from application to application, as can the nature and composition of the user interest group involved. However, there are some underlying characteristics pertaining to information scope that suggest that a unifying framework for application development is achievable.

B. Network Challenges

Vehicular networks show large spatio-temporal variations even in the short-term time.

Spatio-Temporal Variation of Vehicle Density: Using real traffic data obtained from the Gardiner expressway in Toronto, 1998 and the I-80 freeway in Berkeley, 2007, Ref. [4] reported that there is a substantial fluctuation of traffic density conditions over time and across different geographic locations; e.g. within the same day, the vehicle density during rush hours could be as large as 90 times of its counterpart in late night.

Spatio-Temporal Variation of Link Quality: Vehicular wireless environments also result in harsh link quality conditions, showing dramatic variations over space and time. We conducted a set of controlled experiments under urban freeway environments in Feb. 2007, as we drove vehicles in a way that separation distance between vehicles was roughly fixed and vehicle speed was constant. These vehicles were equipped with Dedicated Short Range Communication (DSRC) radios, and they periodically broadcast a packet every 100 *msec*. As shown in Figure 2, we observe that the packet delivery ratio drastically changes over time for all three pairs of vehicles, illustrating the dramatic change of link quality over time.

Heterogeneity of Network Access and Device Capability: When vehicles with wireless devices are integrated with the existing wireless infrastructure – including long-range connections like Cellular, WiMax; or short-range connections like WiFi, DSRC – the vehicular network must inherently handle heterogeneity in network access.Whenever needed, the proposed network framework should enable vehicles to be seamlessly integrated into the existing cellular infrastructure. In addition, the mix of different ages of cars implies that several generations of wireless devices may coexist together in the network, resulting in a heterogeneous mix of platforms on the road with varying capabilities in terms of storage, computation, and bandwidth.

Thus, *VANET design must ensure robust operation despite dramatic short-term variations in connectivity, device capability, link quality and access to external networks.*

We therefore indicate explicitly that we do not aim to develop traditional unicast or multicast routing protocols for wireless ad hoc networks. There have already been dozens

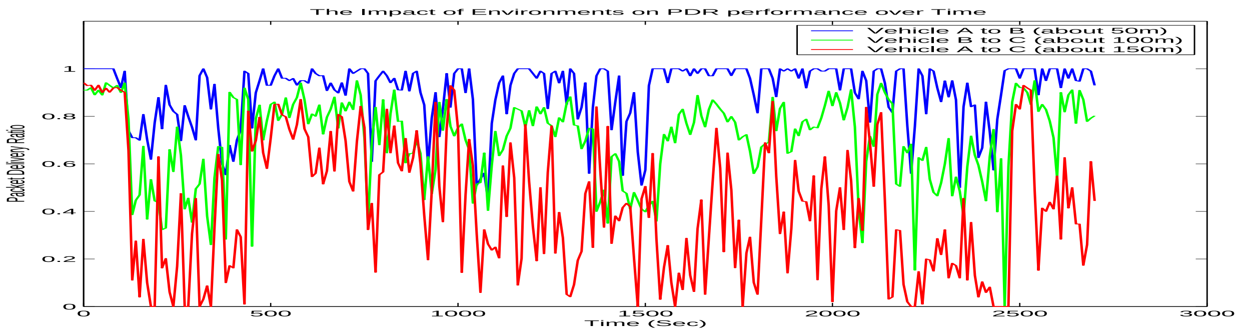

Fig. 2. The Packet Delivery Ratio over Short-Term Duration (50 min) on the I-696 Freeway in Detroit Metropolitan Area. The seperation distance between three moving vehicles (on the same direction) are roughly fixed and the vehicle speed is constant.

of proposals in the existing work that can be used for this purpose.

C. Operation Challenges

Flexible Long-Term Operations: VANETs face a fundamental challenge pertaining to market penetration – the adoption of wireless device in cars is likely to be a slow and gradual process taking many years to reach the state where a significant proportion of cars are equipped. A rough estimate can be obtained as follow: There were a total of 244 million registered vehicles in the U.S. in 2006, while the annual U.S. nation-wide vehicle production volume is 16 million vehicles. Even if all new vehicles are equipped with wireless devices, it will take around 14-15 years to reach close to 100% market penetration.

The market penetration problem is a unique research challenge faced in the VANET domain, since researchers need to design a networking system that can handle various levels of market penetration rate in a smooth way, over 10-20 years after the initial deployment.

Gradual Evolution of VANET Systems: The cars equipped with these devices stay on the road for a long time (potentially ten years or more). During 10 years, there can be substantial changes in the network and in the demands of new applications. Keeping this in mind, it is important not only to ensure backward compatibility, but also to ensure *future compatibility through a flexible and scalable network framework that is inherently change-friendly and can accommodate new developments*.

In the next three sections, we lay out the IC NoW framework that addresses all these challenges in a coherent manner.

III. Analysis of Vehicular Applications and Information

First, we study a rich set of vehicular applications under development, and analyze their common characteristics.

A. Application Analysis

Consider the following application scenarios that require varying degrees of sophistication to be implemented:

Safety Application: Each car shares its kinematic status (e.g., location, speed, acceleration/braking information) with its neighboring nodes within its broadcast domain. This information is used by receivers to determine whether some safety response is needed such as slowing down and changing lanes to avoid a potential crash.

Location-Based Service: A tourist driving through a town looks for a nearby bookstore. The device in his/her car requests and obtains this information through communication with road-side units as well as passing cars. The information is based on a broadcast advertisement from the local store directly or through a local business district directory information service. The information scope is of a reasonably large temporally (days to years) but localized spatially (only of interest within about 5 km).

City-wide alert: Some information is to be propagated to all cars within the city. A good example of such information is the notification of planned road construction and closures in an urban region.

Road Congestion Information: A commuter returning home after work inquires "Is there any congestion (or road construction) ahead that I should be aware of?" The information is again to be propagated through both stationary road-side units and mobile vehicles. The information may originate through local speed readings from vehicles ahead (in this case there is potentially a lot of redundant data available in the network). The scope is localized in both time (few minutes to hours) and space (1-5 km).

File Sharing: A passenger goes through a repository of popular audio/video clips available through the vehicular network at the moment by browsing an index and selects one. The content pertaining to the selected clip in the index is played back in near real-time as pieces of it are downloaded from nearby cars. The information itself resides network-wide over long temporal and spatial scales, but is communicated quickly and in a localized manner.

Interactive Information Service: Different participants enter/leave an interactive group conversation or game, sharing the same interest at different times, which "persists" virtually within the network beyond individual user's participation duration. The group is interactive – at any given moment all current users belonging to the group can communicate their information and receive fresh updates from others. The information itself is rich and multi-layered. There is a hierarchy of temporal scopes (from short individual moves being communicated, to long persistence of the game across multiple participants), and the spatial scope may be primarily localized (few km) but may also allow final results to be propagated to former players currently far way.

Application	Spatial Scope	Temporal Scope	Interest Scope
Safety Information	250 m	10s	all cars
Location-Based Service	1-5 km	weeks	subscribers
City-wide Alert	20km	hours	all cars
Road Congestion Information	5km	minutes	all cars
File Sharing	250m	minutes (index)	all subscribers (index)
		days (content)	client-server pair (content)
Interactive Service	1-5 km	minutes	subscribers

TABLE I
APPLICATION DIMENSIONS

We find that, for most of the cases, the information in vehicular context is produced and consumed locally, in terms of spatial scope and temporal scope. The IC-NoW Paradigm targets to tackle these types of applications.

B. Information-Centric Packet Address

The IC NoW framework requires a new packet address scheme by which packets are sent, manipulated and delivered. This scheme should be different from traditional entity-based address scheme.

Information used in the above applications is generated, distributed, stored, and consumed by a dynamic group of vehicles sharing the same interests within some spatial and temporal scope. We therefore argue that the key is the social aspects of information (i.e., information scope):

1) When is information generated? How long is it valid? (temporal scope)
2) Where is information generated? How far away should it be disseminated? (spatial scope)
3) Who generates information? Which user group (who) cares about this information? (user interest scope)

The basic unit of communication, a packet, has a header which identifies the corresponding user interest scope along with the spatial and temporal scope. As shown later, the header of a packet will be used to locally determine appropriate network operation at each node by following local rule sets.

We illustrate these dimensions in Table I by describing them for each of the applications we considered above.

IV. INFORMATION-CENTRIC NETWORKING ON WHEELS

From the perspective of information management, mobile users who generate or bring useful information are *Information Producers*; mobile users that are interested in consuming information provided by other users are *Information Consumers*; intermediate mobile nodes that participate in the process of information gathering, processing, communication and storage are *Information Facilitators*. Information facilitators could be relay nodes forwarding packets to other nodes, or can be storage nodes that cache information, or can be medium points for information aggregation and processing.

Vehicular networking applications require the protocol designers of *distributed information dissemination* and *management protocols* to take into account – and take advantage of – unique characteristics of the vehicle-domain information being collected (such as removing spatio-temporal correlations through aggregation) and the underlying mobility (which can be used as a positive benefit through mobility-assisted techniques rather than being treated only as a problem to be overcome.)

A. Distributed Information Dissemination

We emphasize that the IC NoW framework is agnostic to a large extent on the particular network-layer strategy employed, only caring (1) that packets may be described in their header using a more general tuple giving the information relevance scope rather than end-addresses alone, and (2) that they be implementable using distributed rule sets (to be described in the next section). This framework allows developers (including ourselves) to leverage the vast body of knowledge on routing protocols in MANETs, VANETs and DTNs to the extent relevant, without reinventing the wheel. A hybrid of different frameworks is needed to distribute information to relevant users within a given spatio-temporal scope.

Spatial-domain dissemination: Like conventional MANET routing protocols, spatial-domain information dissemination scheme attempts to establish and maintain routes between information source and destination(s) over connected network topologies.

Temporal-domain dissemination: When vehicle density is very low or during early technology adoption phase, vehicular networks may not enjoy the luxury of well-connected network topology; instead of establishing end-to-end connectivity between nodes over spatial domain, delay tolerant network protocols [7] smartly utilize vehicle encounters as a chance to forward information to targeted destinations, over temporal domain [15], [1].

B. Distributed Information Management

The following are some of the key components involved.

Information Generation: Information internal to vehicular networks (i.e., traffic jam, accidents, and road grade) is detected by sensors equipped in vehicles. For instance, traffic congestion is detected by speed sensors. On the other hand, there may also be external information (i.e., http traffic, video/audio clip) brought by road-side units which are connected to Internet.

Information Relay: One possible carrier-based approach to information management and dissemination that is of particular relevance to a vehicular network is to develop a *Mobile Infrastructure (super vehicles)*. A set of highly mobile "super vehicles" (such as buses, taxis, or utility trucks) are designated as intermediate agents, collecting road information from other vehicles or bringing information from external Internet (via cellular, WiFi or WiMax). Super vehicles process, store and carry relevant information during their motion. If information is needed, consumer vehicles query nearby super vehicles for the latest results.

Information In-network Aggregation & Processing: Vehicular networks can be considered a form of mobile sensor network. While energy is not at a premium here, bandwidth and robustness still pose considerable challenges. To ensure efficiency, therefore, in-network information aggregation and processing algorithms are also needed here, e.g., distributed source coding schemes to remove redundant congestion updates, etc.

Information Replication: A replication scheme would allow mobile nodes to dynamically create storage points in vehicular networks for content to be distributed quicker and more robustly.

Information Elimination: To reduce bandwidth and storage usage, elimination scheme is needed to remove stale, redundant or incorrect information. Either explicit *Cancellation* messages or automatic expiration timer could be employed.

Information Consumption: End users can specify what types of information they are interested in, and only this information will be displayed to them (though they may need to participate in storing/relaying/processing other information).

As in classic peer-to-peer systems, information dissemination can be managed through either a producer-driven push approach or a consumer-driven pull approach (employing suitable unstructured/structured querying mechanisms). For many vehicular applications, hybrid mechanisms integrating both approaches may be needed to provide optimal performance.

V. Local Rule Set Implementation

The network framework we advocate aims to implement information dissemination and management protocols as well as entire applications in a completely decentralized manner, through what we refer to as “rule-sets” involving series of purely local measurements and local decisions. The benefits are twofold:

First, by providing easy-to-use API interfaces, local rule sets make the development process of vehicular applications easier for application developers. This feature can enable these 3rd-party developers only with limited VANET knowledge to develop their specific VANET applications without worrying about fine-granularity details of VANET protocol design.

Second, local rule sets also enable gradual migration and evolution under different technology deployment phases, since network operators only need to upgrade local rule sets and inject newly developed applications/protocols into the vehicular network over time through “on-the-fly” software updates.

A. Distributed Rule Set APIs

While individual applications may show variations, such rule-sets or components of rule-sets may be shared across different applications. Each application and protocol in our framework is fundamentally described by a set of *distributed, localized rules that decide how a corresponding packet should be handled by a given node in the network*. These nodes take into account their roles, application requirements, and local dynamic conditions while making these decisions.

Once a producer transmits a packet labeled by the corresponding tuple indicating its spatio-temporal-interest group, the following are core packet-handling decisions that are undertaken by mobile users (we acknowledge that this list is not a complete list):

1) **REJECT** the packet.
2) **ACCEPT** the packet to vehicles.
3) **CONSUME** the packet, i.e., hand it to a local application at upper-layer.
4) **STORE** the packet in storage device.
5) **REMOVE** the packet from storage device.
6) **BROADCAST** the packet based on some suitably defined local event (such as encounters or timers).
7) **PROCESS** the packet - this could involve some form of application-specific aggregation and information manipulation.

Each packet-handling decision rule is associated with one or more operation parameters. For instance, TTL and broadcast delay timer are two operation parameters associated with BROADCAST decision rule. As discussed in the following section, these parameters are not only decided by coarse-grained application priority and specific application QoS requirement, but also determined by locally measured network conditions. Defining a complete set of “local rule set” semantics as well as choosing appropriate local operation parameters to achieve global network optimality are not trivial tasks; we are in the process of building an implementation of IC-NoW and deepening our own understanding through this process.

B. Local Measurement

The decentralized decisions for different applications must take into account local network conditions obtained through measurements in addition to application-specific requirements. The local measurements should take into account the various conditions regarding communication, storage, and aggregation, including queue occupancy, available bandwidth, number of neighbors in vicinity, and even the type of wireless link available (e.g., whether a high data rate cellular or WiMax link is available or only V2V connections are possible, etc.) For example, in disseminating information, some form of broadcast suppression is required if the node density is high (to avoid congestion and redundant traffic). On the other hand, when vehicular network is sparse, a store-carry-forward (delay tolerant network) framework should be applied. Beside node density, the implementation of BROADCAST also should take into account other local network conditions (such as wireless link quality) as well as message priority level associated with specific applications.

VI. Application Synthesis: Road Congestion Notification

Following the proposed methodology, we give a pseudocode-level example of how applications can be composed using such purely local decisions and rule sets APIs. By directly employing a set of simple-to-use APIs, application developers with basic knowledge of VANET are able to develop a variety of vehicular network applications without worrying about fine-granularity details of VANET protocol design. In the following example, Algorithm 1 illustrates how the application of road congestion notification

Algorithm 1 Local Decision Rule Sets for Road Congestion Service (RCS)

1: New Incoming Packet: P
2: Existing Estimation of Road Congestion: CN_E
3: Updated Estimation of Road Congestion: CN_U
4: Packet Header Field: [*Spatial-Scope*, *Temporal-Scope*, *User-Interest-Scope(**RCS**)*]
5: Current Status of Local Vehicle: [*Current-Location*, *Current-Time*, *Current-Interest*]
6: Packet Handling Rule:
7: **if** (P already exists in STORAGE) **then**
8: REJECT P
9: **else**
10: **if** (*Spatial-Scope* $\neq$ *Current-Location*)$||$(*Temporal-Scope* $\neq$ *Current-Time*) **then**
11: REJECT P
12: **else**
13: ACCEPT P
14: STORE P
15: PROCESS: AGGRATE(P, CN_E) $\Longrightarrow CN_U$
16: STORE CN_U until (*Spatial-Scope* $\neq$ *Current-Location*)$||$(*Temporal-Scope* $\neq$ *Current-Time*)
17: BROADCAST CN_U with parameter (TTL, broadcast timer)
18: **if** (*User-Interest-Scope(i.e.,**RCS**)* $=$ *Current-Interest*) **then**
19: CONSUME CN_U
20: **else**
21: REMOVE P
22: **end if**
23: **end if**
24: **end if**

can be implemented using the same set of local decision APIs defined in Section V-A. The same methodology could be easily applied to other applications like Location Based Service or File Cooperative Sharing, while we could not provide detailed pseudocode-level examples due to lack of space.

As each new packet P is generated by an information producer, it specifies three relevance scopes of this packet (*Spatial Scope*, *Temporal Scope*, and *User Interest Scope*). Similarly, the status of mobile user is described by three characteristics: *Current Location*, *Current Time*, and *Current Interest*.

As such a packet arrives at a mobile user, the mobile user checks the spatio-temporal relevance of the packet (Line 10). If not relevant, the packet is discarded (Line 11). Duplicated packet is also automatically dropped (Line 7 & 8). If the above procedures pass, this mobile user is deemed as an information facilitator, and packet P is accepted and stored to memory (Line 13 & 14). Even if it is not a consumer, this user participates the data aggregation procedure: the updated estimation of road congestion CN_U is an aggregated result of the existing estimation of road congestion CN_E and the estimation of road congestion reported in packet P (Line 15) (The forms of data aggregation functions could be different, depending on particular applications [13]). After that, the aggregated information CN_U is stored until it becomes invalid (Line 16). At the same time, the new result CN_U is broadcast (Line 17) with appropriate operation parameters.

If the *User Interest Scope* specified in the packet header matches the *Current Interest* expressed by the mobile user, this user is identified as an information consumer and the packet is displayed to drivers/passengers (Line 18 & 19). If this user is not interested in the information, packet P is no longer needed and it is removed from storage (Line 21).

We acknowledge that other implementations are possible to achieve the same functionalities for the above application. For instance, road congestion service is implemented in push-based algorithm. However, it can also be implemented in pull-based algorithms, which can be developed in a similar pattern.

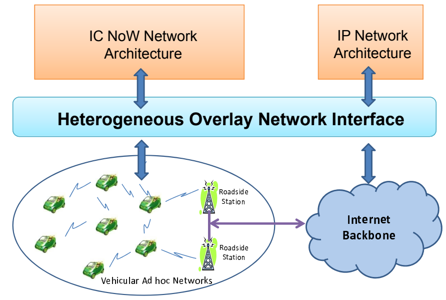

Fig. 3. An Overlay Network Interface Integrates the IC NoW into IP Network frameworks.

VII. Considerations

Like any new approach deviating from conventional practice, IC-NoW is expected to raise a number of interesting technical, business or even societal questions because of its potential positive/negative impact on the telematics industry. Though we do not have all the answers, we hope that our paper engenders open discussions and makes the case for a clean-slate design of the next-generation network architectures in the telematics industry.

Integration into Existing Architectures: The IC-NoW framework should be able to co-exist with IP protocols in cellular telephony systems, especially when vehicles need to communicate with servers in the cyber space. We envision that an overlay network will be engaged to accomplish this goal, with the gatways (e.g., WiFi/DSRC road-side units or cellular base stations) between vehicle cloud and cyber cloud playing active roles. Fig. 3 illustrates how IC NoW framework on the vehicular domain can be seamlessly integrated into IP network framework. Through the heterogeneous overlay network interface, packets in vehicular domain (following the address format of *temporal scope, spatial scope and user interest*) can be encapsulated in the IP packet format.

Cooperative Behaviors: Designing incentives for encouraging cooperative behaviors could be a challenging task, but it is not unique to our case. We plan to leverage a large body of works for peer-to-peer systems. We believe that, with appropriate incentive mechanisms, selfish but rational users would choose to participate as long as the benefits they gain from this collaborative process overcome the resources they contribute. Moreover, one embodiment for cooperation enforcement is to establish virtual credit mechanisms for monitoring, policing and punishing the selfish entities of cooperative systems.

Security Issues: The security aspects of the IC-NoW paradigm are unique: e.g., the lack of unique ID for each vehicle might prevent conventional end-to-end trust establishment (and non-repudiation) protocols from being re-used, while the anaoymity property could be easily implemented; the in-network collaboration nature requires misbehavior detection and eviction mechanisms in place to combat disruptances caused by malicious nodes.

QoS and Priority: The IC-NoW paradigm inherently provides different classes of information priority. With intelligently manipulating the operation parameter field of APIs, information producers specify the priority parameters of messages (e.g., latency, reliability, and other QoS parameters); information facilitators thus act differently depending on the priority parameters of the received messages.

VIII. Related Works

There are several strands of research in the literature that are relevant to our study. We discuss these briefly below.

Unlike generic ad hoc networks, VANETs have unique application needs, requiring an application-oriented approach for network framework design. Though still lacking a coherent research theme guiding future research, this newly emergent field has identified a few principle research challenges – high mobility, limited bandwidth, high spatio-temporal variations in connectivity, network scalability, flexibility to support a large number of applications, and gradual deployment strategy caused by market penetration issues. The current VANET research has been mainly focused on developing Vehicular Safety Communication (VSC) systems, which is the principle interest of automotive industry and governments worldwide [3]. VSC system on a vehicle is able to announce that vehicle's kinematic information and issue safety alerts to other vehicles [3].

The majority of MANET protocols have focused on developing generic routing protocols and other network mechanisms to provide end-to-end connectivity between addressable entities in the face of topology changes due to mobility. Different with MANETs which focus on developing generic routing protocols to provide end-to-end connectivity between addressable entities, VANET protocols should operate under a wide spectrum of network connectivity conditions. In particular, the idea of exploiting opportunistic connections between vehicles (especially during early market penetration period) to implement disruption-tolerant network protocols [15], [1] and applications [6] using a combination of heterogeneous connectivity (WiFi, Bluetooth, and cellular) [9] has recently gained tremendous momentum. Our focus is quite different in that our proposed top-down framework for information centric network architecture mainly focuses on localized mutual information dissemination within groups scoped by space, time and interest (i.e., scoped group communication).

Beyond safety-oriented VANET systems, a number of researchers have been proposing to migrate the peer-to-peer networking of Internet to VANET scenarios, including work on content placement in C2P2 networks [8], Bit-Torrent File/Video download, P2P network (e.g., TIS) [13], information aggregation, processing and discovery [2]. These network services are appropriate to serve a number of futuristic applications, such as urban collective sensing and commercial ad [11]. However, strikingly, there is virtually no prior work on developing a systematic and coherent data-centric network framework which is able to (1) handle different underlying environments and (2) provide a flexible development interface for VANET application development. This key observation motivates the proposed study. Furthermore, unlike structured Distributed Hash Table approaches like GHT [12] or TIS [13] which still requires global network operations and information dissemination, the IC NoW framework is centered on unstructured local group communication which only requires localized operations.

We also build our related work on mobile databases and publish-subscribe model [5]. In recent years, this literature focuses on efficient implementations of particular kinds of queries such as nearest-neighbor queries and continuous query [10] over mobile data sources. Our focus, however, is on a generic information management and networking framework that can accommodate different kinds of in-network processing. Our notion of distributed rule sets is reminiscent of the concept of active networks in which users are allowed to inject customized programs into the network [14]. We believe this framework allows for essential flexibility in the composition of different applications, particularly to accommodate long-term evolution of the heterogeneous vehicular networks and applications that run on them.

IX. Conclusions

In this research challenge paper, we have proposed a generic networking framework called *Information Centric Networking on Wheels (IC NoW)* to support futuristic information-rich VANET applications. Exploiting the localized and dynamic nature of information used in these vehicular applications, this framework focuses on the content as well as temporal, spatial and interest scope of the vehicular-domain information.

This framework enables the development and deployment of distributed protocols for information management that allow for various types of in-network operations (e.g., information aggregation, storage, dissemination, replication and query). An important feature of the proposed framework is that the designed protocols are implemented in a decentralized manner using local decision rule sets taking into account local information, thus enabling *flexible* modular design and facilitating easy and rapid development for various applications.

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