Byzantine Consensus in Vehicle Platooning via Inter-Vehicle Communication

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***Abstract*—Cooperative driving and platooning have gained a growing focus recently. Letting vehicles to reach a consensus and make a joint decision is necessary for some applications. To address this problem, we propose a novel consensus protocol named BFT-ARM that fits real sensor values and can tolerate $t(< n/3)$ Byzantine nodes out of n. BFT-ARM guarantees that the decision is close to the median of all good nodes. We also present the simulation framework ArteryLTE to evaluate our protocol.** [1]

***Keywords*—Cooperative driving, Byzantine consensus, Inter-Vehicle Communication**

I. Introduction

In recent years, an increasing amount of Advanced Driver Assistance Systems (ADASs) can be seen in automobiles. This also includes the development of cooperative driving functions. Many of these applications can be improved by exchanging data via Inter-Vehicle Communication (IVC) to improve safety, resource usage, energy efficiency and driving experience [1]. One example of cooperative driving is *platooning*, where a group of vehicles can follow each other automatically and keep the optimal distance among each other [2, 3]. Apart from following passively, there are also a number of useful applications which first need to agree on a common value for a cooperative decision. For example, in certain application scenarios vehicles will need to detect the traffic condition or weather condition in their surroundings to adjust their operations to, or to calculate the best route according each vehicle's own navigation device, or to set a preferred speed for the cruise control, etc. The common properties of such applications are: 1) The value is required to be agreed among all vehicles. 2) The value to be agreed upon can be measured individually by each vehicle. 3) Even if some faulty vehicles do not follow the common decision, the safety of others is not violated.

We also consider the existence of faulty or malicious nodes in the group. Faulty behaviours include not only crash faults but also arbitrary faults like bit flip or providing inaccurate, inconsistent and even malicious values. All these faults are referred to as Byzantine faults [4]. The Byzantine consensus protocol is aiming at achieving consensus among all correct participants, despite of a limited number of faulty nodes. Examples of such protocols can be found in [5, 6].

Most Byzantine consensus problems assume the value domain is discrete and limited, for instance the binary consensus [5] or multi-value consensus [7]. However, in automobile applications, especially those involving sensor values, the values can be continuous and "smooth" e. g. speed, distance, temperature, etc.

In this work, we designed a new consensus protocol for the continuous value domain in vehicle platooning named BFT-ARM (Byzantine Fault Tolerant and Asynchronous Real-value consensus with Median validity). We also built a simulation framework based on our previous work, and will use it to evaluate the consensus protocol.

The paper is organized as follows. Section II discusses some related work. Section III defines the system model and problem. Section IV presents the design of BFT-ARM and section V introduces the evaluation framework. Section VI concludes the paper.

II. Related Work

In the *Byzantine consensus problem*, each node has an input value and try to make a consensus on one of them, and there are a limited number of Byzantine nodes [5]. An important aspect of Byzantine consensus problem is how to define the validity of the agreed value. There are different opinions from different viewpoints. E.g., Neiger distinguishes the *Validity* and *Strong Validity* [8]. The former requires that if all correct nodes have the same input value, they will decide on that value, but does not guarantee anything when the input values are different. And Strong Validity requires that the decided value comes from a correct node. Then Neiger proves that achieving Strong Validity requires at least $t \cdot |\mathcal{D}|$ nodes, where t is the maximum tolerable Byzantine nodes and $\mathcal{D}$ is the domain of the input values. This means a tremendous number of nodes are necessary when the input value domain is large.

A recent work of Stolz and Wattenhofer proposes a weaker requirement compared to the strong validity, called *median validity* [9]. It only requires the agreed value is close to the median of all good nodes. This is especially useful

[1]This work is part of the DFG Research Unit *Controlling Concurrent Change*, funding number FOR 1800.

with a continuous value domain. However, their protocol assumes a synchronous communication where message transmission time has a known upper bound. This assumption is not applicable in IVC scenario. So we designed the new BFT-ARM protocol to achieve the median validity.

There are also some other work from the viewpoint of control theory to manage platooning via consensus approach [10]. This is useful for another family of applications like instant speed and distance control, which is an orthogonal direction to our work.

III. System Model and Problem Statement

System Model: The platooning consists of n vehicles, or nodes as abstraction: $\{p_1, p_2, \ldots, p_n\}$. Every node has an input value $x_i \in \mathbb{R}$ [2], e.g. from its sensor or configuration. A node is called *correct* if 1) its input value is correct and 2) it exactly follows the protocol. Among all the nodes up to t ($< n/3$) nodes can be *faulty*, meaning that they can behave arbitrarily such as take an incorrect value from a malfunctioning sensor or not follow the protocol.

Consensus problem: BFT-ARM achieves consensus on a value $v \in \mathbb{R}$ satisfying the following conditions:

- *Agreement*: No two correct nodes decide differently.
- *Termination*: Every correct node eventually decide.
- *Validity*: The decided value of correct nodes v is *valid* (see definition below).

Inspired by the work of [9], the validity is defined in the following way. Assuming there are actually f ($\leqslant t$) faulty nodes during runtime (not known by the consensus algorithm). Let SG be the sorted array of input values of all good nodes (the index starts from 0). Then $SG[\lceil \frac{n-f}{2} \rceil - 1]$ represents the median value of SG.

Definition 1. *Validity: a decision v is valid, if*

$$SG[\lceil \frac{n-f}{2} \rceil - 1 - t] \leqslant v \leqslant SG[\lceil \frac{n-f}{2} \rceil - 1 + t] \quad (1)$$

In other words, a valid value is the one within the range of the middle $(2t+1)$ correct nodes.

Network: Nodes communicate via messages. The network is asynchronous. That means messages can experience an unbounded delay, get lost, duplicated or corrupted. However an eventually synchronous connection is required to overcome the FLP impossibility [11]. BFT-ARM does not rely on the synchrony to achieve agreement. So termination needs an eventually synchronous connection.

Digital Signature and Trusted Subsystem: The messages are signed with digital signatures. A message m signed by a node i is notated as $\langle m \rangle_{\sigma_i}$. We also assume that every node possesses a trusted subsystem for message authentication and verification with a monotonic counter. The value of the counter can be used to authenticate some special messages, and increases by 1 after that. The partner who receives one of these messages can also verify that this message has the valid counter value without any gaps to the previous ones. Examples of such subsystem applied in Byzantine fault tolerant systems can be found in [12, 13]. We assume that faulty nodes cannot break the digital signature mechanism nor the trusted subsystem.

[2]In practice, the value space is still a finite set limited by the platform. We do not discuss Turing uncomputable numbers or real computation here.

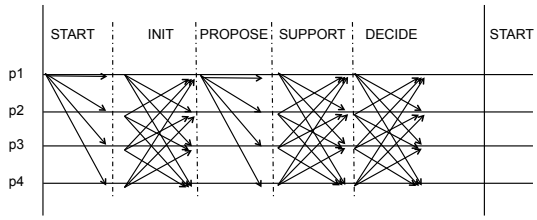

Figure 1. BFT-ARM in normal case.

IV. BFT-ARM Design

A. Normal case operation

The normal case protocol is illustrated in Figure 1.

It can be divided into 6 steps:

1) The leader p_i periodically activates a consensus request with a broadcast $\langle \text{START}, seq, p_i \rangle_{\sigma_i}$. seq is a sequence number generated by the trusted counter.
2) Upon received START message, each node p_j firstly verifies the sequence number. If it is a valid sequence number, it broadcasts (including to itself) with its input value in $\langle \text{INIT}, seq, p_j, x_j \rangle_{\sigma_j}$.
3) Upon the leader received $(n-t)$ values (including itself), it sorts the received values and picks the median value v_{med}. Then it proposes v_{med} together with the $(n-t)$ original signed INIT messages attached as a certificate $\vec{cm}$. Namely: $\langle \text{PROPOSE}, seq, p_i, v_{med}, \vec{cm} \rangle_{\sigma_i}$.
4) Upon a node p_j received the PROPOSE message, it verifies that v_{med} is really the median of all the values in $\vec{cm}$. If so, it broadcasts $\langle \text{SUPPORT}, seq, p_j, v_{med} \rangle_{\sigma_j}$.
5) Upon a node p_j received $\lceil (n+t+1)/2 \rceil$ SUPPORT for the same v_{med}, it broadcasts $\langle \text{DECIDE}, seq, p_j, v_{med} \rangle_{\sigma_j}$.
6) Upon a node p_j received $\lceil (n+t+1)/2 \rceil$ DECIDE for the same v_{med}, it decides v_{med}.

From step 3 on, BFT-ARM is similar to the PBFT protocol [6]. So if the leader proposes the correct v_{med} matching the certificate, all correct nodes will decide v_{med}.

Now we prove v_{med} is valid according to Definition 1.

Theorem 1. *Let SA be the sorted array of the input values of any $(n-t)$ nodes. The median of SA is denoted as $v = SA[\lceil \frac{n-t}{2} \rceil - 1]$. Then v is valid.*

Proof. According to the definition of median, there are at least $(\lceil \frac{n-t}{2} \rceil - 1)$ nodes whose value is no greater than v. Among them there are at least $(\lceil \frac{n-t}{2} \rceil - 1 - f)$ good nodes.

And because $f \leqslant t < n/3$, we have $\lceil \frac{n-t}{2} \rceil - 1 - f \geqslant \lceil \frac{n-f}{2} \rceil - 1 - t \geqslant 0$. So $v \geqslant SG[\lceil \frac{n-t}{2} \rceil - 1 - f] \geqslant SG[\lceil \frac{n-f}{2} \rceil - 1 - t]$. Similarly, we can prove that $v \leqslant SG[\lceil \frac{n-f}{2} \rceil - 1 + t]$. Because of the Definition 1, v is valid. □

Thus the validity of the proposal can be confirmed by comparing with the certificate of $(n - t)$ values in step 4.

We use the trusted counter to generate a sequence number for every START message from the leader. The sequence number is monotonically increasing by one every time, so there is exactly one sequence number assigned to every consensus period. In this way, faulty nodes cannot provide an outdated value (replay attack). If a node detects that the sequence number does not belong to this period, it will discard the message. A synchronized clock is not required here, but the interval of the period is known to everyone. From the first time a node receives the sequence number from the leader, it can determine the correspondence between the sequence number and period.

B. Suspect leader protocol

When the leader is faulty or disconnected from the group, leading to a fail of consensus within a predefined timeout, the other nodes will initiate a suspect leader protocol, basically similar to the PBFT view change protocol (without considering about the history). When a node p_j suspects the leader p_{cur}, it broadcasts a $\langle \text{SUSPECT}, p_j, p_{cur}, p_{new} \rangle_{\sigma_j}$, where p_{new} is the next leader according to a deterministic rule, e.g., based on the position information of the platoon to choose the one behind the current leader until the end and then change the direction forwards.

When p_{new} receives $(\lceil (n + t + 1)/2 \rceil - 1)$ messages suspecting current leader, it takes over the leader role and broadcasts $\langle \text{NEWLEADER}, p_{new}, seq_{new} \rangle_{\sigma_{new}}$ with its own sequence number, and operates as in the normal case.

V. Evaluation

To evaluate BFT-ARM in platooning environments, we intend to use an extended version of the *ArteryLTE*[3] simulation framework, which is detailed in [14].

A. Simulation Framework

ArteryLTE is based on the renowned open-source *Vehicles in Network Simulation (Veins)* framework [15]. The *Veins* project[4] combines the dedicated network simulator OMNeT++ with the microscopic traffic simulator *Simulation of Urban Mobility* (SUMO). In addition, Veins also provides an implementation of the US Wireless Access in Vehicular Environments (WAVE) Dedicated Short Range Communication (DSRC) stack based on IEEE 802.11p.

ArteryLTE integrates several extensions to Veins:

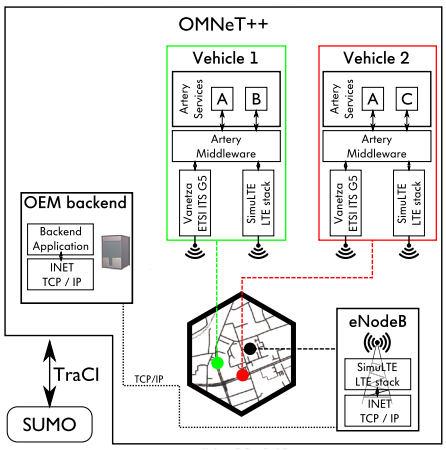

Figure 2. Architecture of the *ArteryLTE* simulation framework.

First, a modular middleware for Veins called *Artery*[5] [16] is used to implement heterogeneous vehicle capabilities. Multiple applications (so-called Artery services) can be implemented and dynamically configured for vehicles per market penetration rates. Furthermore via *Vanetza*[6], the European equivalent to the WAVE stack, the European Telecommunications Standards Institute (ETSI) Intelligent Transport System (ITS) G5 protocol stack, is brought in and used to disseminate Cooperative Awareness (CA) messages [17].

Second, *ArteryLTE* integrates Long Term Evolution (LTE) support for vehicles as introduced to Veins by the *VeinsLTE* [18] project, thus enabling heterogeneous communication technologies on the network nodes. VeinsLTE's *decision maker* is replaced by an option in *Artery*'s middleware that allows Artery services to choose between either the ITS G5 or the LTE stack for communication.

Third, *ArteryLTE* includes support for backend-based applications. A backend is represented by a static network node in the network which is connected to the eNodeBs of the LTE network.

The overall architecture of the *ArteryLTE* simulation framework is depicted in Figure 2. In the presented cell of the eNodeB two vehicles are shown, both equipped with an LTE and an ITS G5 stack. Different Artery services (A,B and C) are deployed on the vehicles respectively. Data transmitted via LTE by the vehicles is forwarded using a Transfer Control Protocol (TCP) connection between the eNodeB and the backend.

Furthermore, local perception sensors for advanced ADASs are the latest addition to *ArteryLTE* [14].

[3] https://github.com/ibr-cm/artery-lte
[4] http://veins.car2x.org/
[5] https://github.com/riebl/artery
[6] https://github.com/riebl/vanetza

B. Extension of the Framework

We are bringing yet another extension into the *ArteryLTE* framework: The *Plexe* extension [19] to Veins enables the simulation of vehicle platoons with corresponding control algorithms, such as for cruise control, and the implementation of cooperative driving applications. We are in the process of porting the changes made by *Plexe* to Veins to *ArteryLTE*'s codebase so that ArteryLTE is able to interact with Plexe's SUMO version via the Traffic Command Interface (TraCI) protocol. We will use the platooning examples and the included control algorithms of Plexe as the basic scenario for our application. Vehicles of the platoon will—in a first step—be equipped with IEEE 802.11p for local communication to run the presented consensus protocol.

VI. Conclusion and Future Work

As soon as the basic setup of BFT-ARM is implemented, in a first step we evaluate the characteristics of the consensus protocol among vehicles via IVC. We then intend to use the whole potential of our communication environment to improve the consensus process as well as to introduce further features. For example, to take advantage of the available heterogeneous networks, we envisage the ability to fall back to cellular communication in cases where local communication of a group is disrupted. Furthermore, in the case of ADASs that are tightly coupled to an Original Equipment Manufacturer (OEM) backend, running an agreement might be assisted by this backend as, e. g., the backend may initiate a consensus, or a leader change based on data available to the backend such as network metrics or local traffic data [14].

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