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Leader Election in Cooperative Adaptive Cruise Control Based Platooning

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ABSTRACT

With the advancement of Vehicular Ad-hoc Network and Cooperative Adaptive Cruise Control (CACC) system, vehicle platooning has become feasible. The performance of the CACC based platoon highly depends upon the maneuver performed by its leader vehicle because its actions have a direct implication on follower vehicles in the platoon. The leader vehicle plays a significant role in intra-platoon coordination, synchronization, collision avoidance and path planning. Thus, an election of the most appropriate, trusted and best entity to take the role of a leader in a CACC platooning becomes crucial. For efficient and safe functionality of this system, leader election has to be fair to every vehicle and should assign leader with the consensus of the whole platoon. To this end, very few contributions are available. In this paper, we suggest an incentive strategy and propose an architecture and leader election mechanism to elect the best leader of the platoon efficiently.

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1 INTRODUCTION

The number of vehicles plying on roads (highways, expressways, urban roads) has gone up drastically, and these numbers are increasing every year. The increased number of vehicles is the reason for the traffic congestion, pollution, and road accidents. To ensure safer, comfortable and eco-friendly drive, we need to have some control and communication mechanism. The Cooperative Adaptive Cruise Control (CACC) based platooning is one such promising solution, which enables automated controls via cooperation among vehicles using vehicle-to-everything (V2X) communication. The platooning system can help address the problems mentioned above.

A vehicle platoon is a group of vehicles that travel close to one another and led by a vehicle called platoon leader. Other participating vehicles (one or more) are called followers, and they follow each other closely. Platooning enables the vehicle to drive closer and safer, which turns mobility similar to trains. However, participating vehicles are allowed to adjust their speeds whenever it is required. Cooperation among the vehicles is needed to run the platoon harmoniously. In platooning, follower vehicles face less air resistance (reduction in air drag), which reduces the consumption of fuel and carbon emission and makes it eco-friendly driving. In 2017, the pilot project [8] that tested fuel-economy of a three-vehicle truck platooning, the net fuel savings for the full vehicle platoon was measured between 5.2 and 7.8 percent compared to three vehicles traveling independently, and in isolation, from each other. If platoon size is larger (5 to 10 vehicles) it varies from 10 to 15 percent depending on various factors [17]. Besides, it improves traffic throughput and enhances safety because there is less variation in speed of vehicles and they maintain the safe gap.

CACC extends ACC by enabling vehicles to communicate with each other using vehicle-to-vehicle (V2V) communication, which create a platoon with a leader vehicle and

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followers. As shown in Figure 1, CACC enable vehicles besides relying on their sensors measurements (using RADAR, LIDAR, and cameras), also receive information from the platoon leader and its immediate preceding vehicle via V2V communication. The V2V communication provides enhanced mobility information so that vehicles follow with higher accuracy, shorter gaps, and faster response. This results in enhanced traffic flow stability and safety. The integrated V2X capability not only allows V2V communication but also enable them to exchange information with Road Side Units (RSUs).

1.1 Related Work

The concept of CACC-based platooning (mainly for heavy-duty vehicles) has been the focus of many research projects in the USA, Europe, and Japan. In the USA, the California Partners for Advanced Transportation Technology (PATH) [12], Safe Road Trains for the Environment (SARTRE) in Europe [14], and Japan's Energy ITS Project [18] for developing and testing CACC-based platoon. Researchers have also developed integrated simulation platform for CACC platooning.

Over the years significant work in the field of leader selection in wireless adhoc networks (mobile adhoc network (MANET)) [7, 10, 20, 21] has been done. However, these mechanisms cannot be directly applied to the platooning system because the objective of the leader election is not the same and its mobility and context also differs. One of the crucial aspects is electing the best leader efficiently and securely, and preventing the undeserving candidate to take the role of the leader in the platoon.

We could only find three relevant studies [1, 4, 5] in which emphasis is given on leader election in the CACC-based platooning. In [1], the authors talk about the role of the leader. A trained professional driver must drive platoon head/leader vehicle. The management protocol proposed by them uses a centralized platoon co-ordination mechanism, where leader coordinates all communications. Followers follow and send requests from/to the leader. The configuration of the platoon is stored and managed by the leader only (hidden to followers) to enhance the privacy. If a leader wants to leave, it calls for voting and asks followers to vote for new platoon leader. Authors proposed a distributed leader selection algorithm based on polling (via votes). However, it is merely a proposal without any detail, and in their case, they implemented the next follower vehicle takes over the leadership role when a leader leaves.

In [4], the authors introduced Software Defined Networking (SDN)-enabled platoon. The study mention that how crucial it is to select the most appropriate entity as the leader of the platoon. They also discuss that the centralized controller of the SDN can help leader vehicle in detecting various attacks (jamming and replay) and also plays a significant role in security. However, this work does not propose any mechanism for the leader election.

Hu et al. [5] proposed trust and recommendation based scheme to select a trusted platoon head vehicle based on their performance. The recommendation is made by the follower vehicles to mitigate the problem of distrust. This study also covers security analysis of the proposed mechanism against various possible attacks. However, the authors do not consider any incentive strategy for the leader vehicle. Although SARTRE project [14] introduced one incentive strategy, however, raises various questions on the proposed approach.

1.2 Problem Definition and Motivation

The platoon leader takes the lead role of the whole platoon while driving on the road; It is responsible for the safety of follower vehicles. The leader plays a significant role in path planning, intra-platoon performance, and synchronization, inter-platoon coordination, collision avoidance, etc. The behavior of the leader and maneuver performed by it greatly affects the traffic throughput, stability, and operation efficiency. One can easily imagine that leader of the platoon has vital roles in the system. Thus, it is crucial that a qualified vehicle, and an experienced, well trained, professional, and capable driver must be elected as leader of the platoon. Therefore, by knowing the importance of the role played by the leader, how to carefully elect the trusted and deserving candidate as a platoon leader in such a dynamic environment is one of the most significant challenges. Apart from this, incentive strategy must also be introduced for the platoon leader who carries a lot of responsibilities during travel and has a significant role to play in the platoon stability.

1.3 Contribution

Our main contributions in this paper is threefold.

- We provide a systematic study of CACC-based platooning that covers communication details, platooning scenarios, maneuvers, size, control logic, etc.
- We propose incentive strategy and architecture for helping to implement our proposed leader election mechanism.
- We demonstrate the importance of the role played by platoon leader. Finally, we propose leader election mechanism to elect the best leader from the platoon.

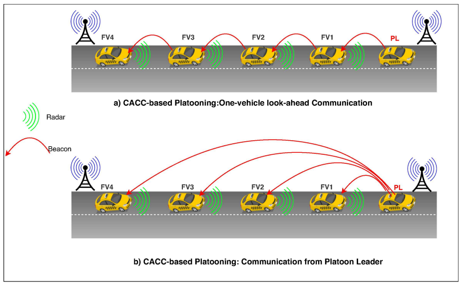
The paper organization is as follows. The next three sections, Section 2, Section 3 and Section 4 cover details of our contribution, respectively. Finally, we conclude our paper in Section 5.

2 CACC-BASED PLATOONING

2.1 Platooning

The fundamental concept behind CACC-based platooning is the integration of cooperation to Level-1 Automated vehicles (defined by National Highway Traffic Safety Administration (NHTSA) [11]) using V2X communication. The V2V communication provides mobility and other related information about the preceding vehicle or vehicles. The infrastructure-to-vehicle (I2V) and V2I communication help to connect PKI, ITS, Cloud, insurance, payment services, etc. Using V2I/I2V communication platoon leader can also get prior information about traffic, which helps it to change its mobility (speed, route, etc.) to avoid the congestion. It can also assist in improving traffic throughput by providing information about signal status. Any vehicle who wants to join the platoon can use V2I to get the information about approaching platoons on the same route, which can help to select the best platoon.

The primary radio access technology (RAT) for V2V communication is Dedicated Short Range Communication (DSRC), specially designed for vehicular communication standardized in IEEE 802.11p [6]. DSRC is the key enabler of CACC-platooning. It operates at 5.9 GHz in the USA. It supports data rates up to 27Mbps (with 10 MHz) and can transmit up to 1000 meters. Another upcoming technology is cellular-V2X (C-V2X), which is in its advancement phase and can be one of the candidates for platooning in future. For V2I/I2V connectivity vehicles can use any available RATs alongside the road such as LTE, DSRC, and Wi-Fi to which they are subscribed/authorized for access.



a) CACC-based Platooning:One-vehicle look-ahead Communication

b) CACC-based Platooning: Communication from Platoon Leader

Figure 1: V2V CACC-based Platooning Variants

2.1.1 *CACC-based platooning Variants.*

The CACC-based platooning driven by V2V and supported by I2V/V2I communication has two variants:

- **One-vehicle look-ahead communication:** As illustrated in Fig. 1.a, where each vehicle listens to beacon messages from its immediate preceding vehicle. This is a most basic approach in which pairwise sharing of the information takes place between a vehicle and its immediate predecessor.
- **CACC-Platoon with communication from platoon leader:** As illustrated in Fig. 1.b, where each vehicle listens to beacon messages from platoon leader. In this structure, the follower vehicles adapt its mobility based on the information received from its platoon leader via V2V communication.

Note: There is a third variant called bidirectionally assisted platoon, which is not widely considered.

2.1.2 *Beaconing.*

Beaconing is a periodic single-hop message broadcast by vehicles of the platoon. It enables active communication between CACC-enabled vehicles so that they can exchange necessary parameters over DSRC/IEEE 802.11p for their longitudinal control. The beacon message should at least consist header, source, and destination IP address, location, acceleration, max deceleration, lane ID and platoon related information.

2.1.3 *Vehicle Types.*

The CACC string formation can have following vehicle types:

- Heavy Motor Vehicles (HMVs) such as Truck platooning.
- Light Motor Vehicles (LMVs) such as car platooning.
- Mixed String of HMVs and LMVs (coexist together).

In case of a mixed string, the position of HMVs and LMVs is one the most significant concern related to safety, communication, and size of the platoon.

2.1.4 *Longitudinal control logic for CACC-based platooning.*

Various control mechanisms have been proposed over the years, based on constant spacing [13], constant safe-space [9], velocity-dependent spacing, consensus [3] etc. These mechanisms are considered in various research studies as longitudinal control logic for theoretical analysis and simulation of CACC-based platooning [1, 15]. The control logic can have various levels such as upper-to-lower that correspond from regulation to physical layer, respectively [1]. In a constant spacing controller, the vehicle maintains a fixed space based on the measured distance and the received speed and acceleration of the leader and preceding vehicle. The controller designed with consensus-based approach uses speed, acceleration, and position information of all the participating vehicles in the platoon.

2.1.5 *Platoon Size.*

There are various reasons, such as safety, stability, and performance, for which there should be a limit on the number of vehicles allowed to be in the CACC-based platoon.

In CACC variant-1 (Figure 1.a), where pairwise communication delay matters, the number of vehicles up to which string stability can be maintained is one of the important factors in deciding the platoon size.

In CACC variant-2 (Figure 1.b), where all CACC-enabled following vehicles require direct communication from the platoon leader, the wireless communication range of V2V could be one of the important factors in deciding the upper limit of the platoon size.

2.2 Maneuvers

Figure 2 shows the various platooning scenarios and its related processes, maneuvers and commands. Due to space constraints, we are not discussing them. Given figure itself is self-explanatory and more details are also present in [1].

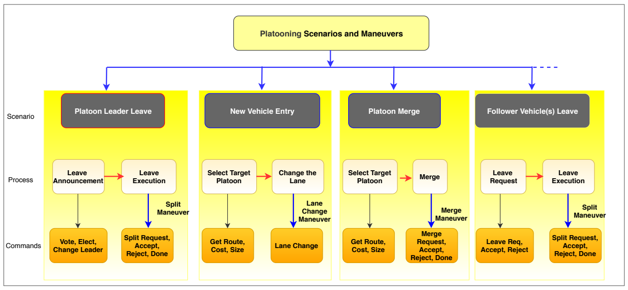


Figure 2: Platooning: Scenario, Maneuvers and Commands

3 PROPOSED INCENTIVE STRATEGY & ARCHITECTURE

In this section, we discuss the proposed incentive strategy and the vehicular network architecture to facilitate the incentive strategy and leader election process in a CACC-based platooning.

3.1 Incentive Strategy

In a CACC-based platooning, not all vehicles get the equal benefit. In particular, driver of the leader vehicle has to pay much more care and attention while driving in compare to followers. The platoon leader also cannot save much energy than others because it has to face the air resistance. Some incentive has to be given to the vehicle taking the lead role.

SARTRE project [14] introduced incentive strategy: following vehicles pay some amount to the platoon leader as an incentive. However, the main concerns related to this strategy are: What should be the appropriate amount? Do followers agree to pay? Who will be ready to lead when there are no payments? In [16], the authors proposed that incentive could be given through a reduced toll because CACC-based platoon increases traffic throughput. However, whether all the participating vehicles or leader only will get the incentive has not been discussed.

With increasing global capitalism, vehicle insurance companies are taking major steps towards making insurance terms very robust and flexible so that both the parties (vehicle owners and insurance companies) get benefited. For this, insurance companies are tracking record of every vehicular activity which is generated by the vehicles and sent to insurance companies servers where that data is analyzed and stored. As being a leader is a task of responsibility, the insurance company can give incentives to the driver if elected as a leader of that platoon. Once the leader has been elected, the incentive can be marked in the data center and provided in the form of subsidy (rebate) to that vehicle's next insurance premium.

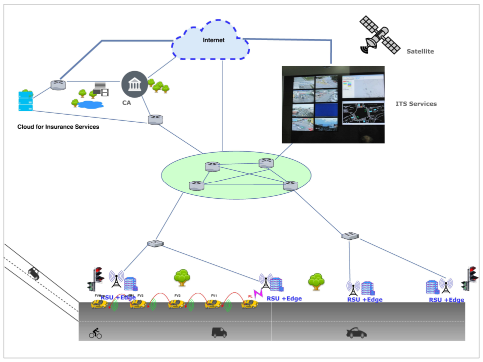


Figure 3: Vehicular Network Architecture

3.2 Architecture and Components

The architecture to facilitate above strategy, and leader election is shown in Figure 3. Three major components of the architecture are the Adhoc plane, RSU with Edge computing and Service plane. The services can be Intelligent Transportation System (ITS), insurance, security, Internet, etc. In particular, our primary focus is on three fundamental entities: CACC-based platoon in the Adhoc plane, edge node in the RSU plane (stationary RSUs with edge computing to facilitate V2I communication and computation and caching at the edge), and insurance and ITS data centers in the service plane.

Both industry and academia are adopting PKI-based security framework for future VANETs deployments. Even in the USA, and Europe, their security frameworks are based on PKI, which is specified in standards IEEE 1609.2 and ETSI 102941, respectively. In this work, we propose similar security framework to secure the communication between the platoon and the roadside unit.

4 PROPOSED LEADER ELECTION MECHANISM

4.1 Impact of Leader Vehicle Motion on Platooning

A CACC-based platoon needs to behave as a single vehicle on the road driven by a professional driver. There are various definitions given for a string (platoon) to be stable. In this literature, we consider two points for the string stability.

- The control logic must be able to attenuate any jerk or disturbances in motion at the leader vehicle towards the tail of that platoon [15].
- Maintains 1-norm of the transfer function: The platoon eventually converges to a stable state when the platoon leader maintains a specific velocity perfectly [19].

To demonstrate the characteristics of string stability mentioned above, we simulated CACC-based platooning on VENTOS simulator (Figure 4.a and 4.b). The speed and acceleration graphs are shown in Figure 4.c and 4.d respectively, which demonstrates the impact of leader motion. We introduce the disturbances by frequent slowdown and speed up of the motion of platoon leader (at the simulation time of 100 seconds), which represents if a badly behaving vehicle/driver gets elected as a leader how it can affect the platooning operation.

4.2 Leader Election Scenarios

When a platoon leader has to leave the platoon, it needs to handover the charge to some other vehicle in the platoon. The following cases depict the circumstances when the election of a new leader is required.

- **Leadership change due to Leader Leave Maneuver:** On reaching its destination the leader vehicle requires to handover its leadership charge to someone else in the platoon. Otherwise whenever a Leader Leave Maneuver is performed a new leader has to be selected.
- **Leadership change due to termination of duties of existing leader:** Since the driver of the leader vehicle has to pay regular attention during driving it is apparent that he/she will get tired and need a break. In these circumstances, the charge of leadership should be handed over to another vehicle.
- **Leadership change due to technical issues in existing leader:** Some technical problem may arise in the leader vehicle when the platoon is on the move. Making the entire platoon stop to check the issues of the leader vehicle will reduce the efficiency of vehicle platooning. Thus a new leader is required to lead the platoon.
- **Leadership change during merging of two platoons:** A new leader has to be elected when two different platoons with different leaders merge.

In all the cases mentioned above, a decision of electing a new leader has to be made.

4.3 Leader Election Mechanism

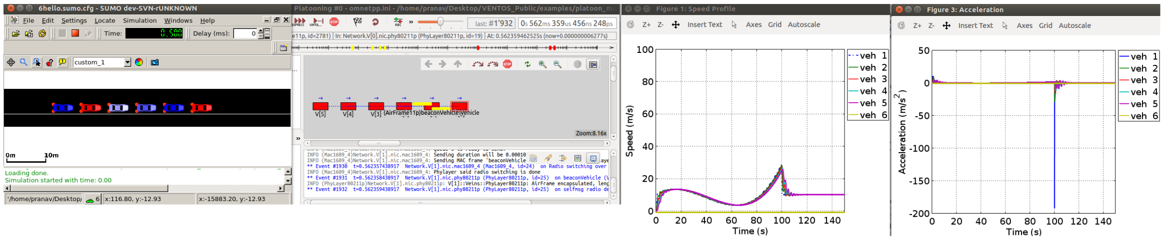
ITS server and insurance company can profile the vehicle and driver behavior. The profile can consist of various useful information (history), which can help to offer incentive and elect the best leader of the platoon. For example, some of the data can be vehicular characteristic (fuel and insurance status, mileage), driver ranking (rating, trips, accidents reported, traffic violation record), journey remaining, etc. All these information can be stored and updated at insurance, and ITS server ends in a proper format. This information has to be utilized in the consensus algorithm. Various such features can be added to enhance the knowledge base about the driver and vehicle. The proposed leader election consist following steps:

- **Step1:** When a leader has to leave it will send a multicast message to all its follower, asking them to provide their information.
- **Step2:** The leader verifies the collected data from the data present at the RSU-edge via a secure channel (PKI). This data has been offloaded from the insurance and ITS server to the RSU-edge (prior knowledge of platoon heading).
- **Step3:** The collected and verified information of each vehicle is multicasted from platoon leader to all the followers.
- **Step4:** All the followers execute consensus mechanism on the received data and elect the best leader. The consensus approach which is inspired from [2] is given as follows:

In a platoon with n vehicles, the resultant value of each vehicle generated using their previous history (can be gathered from insurance and ITS data-centers) and current journey statistics are used for the leader election process. We use a round-based consensus algorithm to select one amongst n proposed values, also called *1-of-n* selection algorithm [2]. In this work, the authors proposed three decision algorithms called the *optimistic*, the *pessimistic*, and the *moderately pessimistic* decision criteria. Using their observations for these three strategies with a different number of rounds, different values of n and different message loss probability, we suggest the best approach for leader selection would be the *optimistic* decision criteria. Given the number of rounds = 2, size of platoon should be less than equal to 10 and the message loss probability is falling within 0-0.2 the *optimistic* decision criteria guarantees more than 0.9 probability of agreement. Also with symmetric and asymmetric failures, we conclude the use of the *optimistic* decision criteria under our constraints.

Algorithm 1 shows the pseudo-code of 1-of-n selection algorithm executed by each vehicle in platoon. Each vehicle initially constructs a message msg_i which contains the resultant value $resultant_i$ and a bit-vector v_i of length n. Each element of v_i represents the view of each vehicle from the resultant value of a vehicle in the system. Initially, $v_i[i] = 1$ and ∀j $v_i[j] = 0$.

We define v_i as *complete* if all of its elements are set to 1. Similarly, we define v_i as *incomplete* if at least one of its elements is 0.



```
e11p, id=2781) | In: Network.V[0].nic.phy80211p (PhyLayer80211p, id=19) | At: 0.562359462525s (now+0.000000006277s)
INFO (Mac1609_4)Network.V[1].nic.mac1609_4: Sending duration will be 0.00010
INFO (Mac1609_4)Network.V[1].nic.mac1609_4: Sending MAC frame 'beaconVehicle
** Event #1930  t=0.562357438917  Network.V[1].nic.mac1609_4 (Mac1609_4, id=24)  on Radio switching over
INFO (Mac1609_4)Network.V[1].nic.mac1609_4: Phylayer said radio switching is done
** Event #1931  t=0.562358438917  Network.V[1].nic.phy80211p (PhyLayer80211p, id=25)  on beaconVehicle (V
INFO (PhyLayer80211p)Network.V[1].nic.phy80211p: V[1]::Veins::PhyLayer80211p: AirFrame encapsulated, leng
** Event #1932  t=0.562359438917  Network.V[1].nic.phy80211p (PhyLayer80211p, id=25)  on selfmsg radio de
```

Loading done.
Simulation started with time: 0.00
'/home/pranav/Desktop/ 6 x:116.80, y:-12.93 x:-15883.20, y:-12.93

a) Traffic View (SUMO) b) Network View (OMNET++) c) Speed Graph d) Acceleration Graph

Figure 4: VENTOS Simulation Snapshot and Results obtained from CACC-based Platooning

Algorithm 1 Generic algorithm for 1-of-n selection for each vehicle

```
$msg_i \leftarrow \{ resultant_i, v_i \}$
for r = 1 to R do
    begin_round
    $send(msg_i)$
    $receive()$
    compute $(msg_i)$
    end_round
$decision\_algorithm()$
```

Here R is the number of rounds this algorithm should run. Send function is a unicast message from the followers to platoon leader and receive is to get data from the platoon leader (an array of size n). In this work, we follow *Optimistic* decision criteria, for compute and decision algorithm.

Algorithm 2 compute (msg$_i$): Optimistic criterion (p$_i$)

```
$\forall p_j \in \Pi - \{p_i\}$
if $p_i$ received $msg_j$ then
    if $resultant_j$ does not match then
    Return
    if $resultant_i < resultant_j$ then
        $resultant_i \leftarrow resultant_j$
    end if
    $\forall p_k \in \Pi - \{p_i, p_j\}$
    if $v_j[k] = 1 and v_i[k] = 0$ then
        $v_i[k] \leftarrow 1$
    end if
    $v_i[j] \leftarrow 1$
end if
$msg_i \leftarrow \{ resultant_i, v_i \}$
```

Algorithm 2 shows the compute function for a process p$_i$ running in ith vehicle. Here $\Pi = \{p_1, p_2, ..., p_n\}$. Vehicle checks the resultant$_j$ value at Edge node (in RSU plane) which was computed and cached before the start of leader election algorithm. Value does not match implies a false value has been sent by other vehicle or any third party has changed the value. In that case it rejects the value and continue the compute function on other received messages. If the value is correct, it compare its resultant value with the recieved resultant and if its resultant is smaller than the received one, it updates its resultant value with the received one. Also, each vehicle updates its v$_i$ vector at the end of each round as follows: For all the elements of v$_j$ that are set to 1, process p$_i$ sets the corresponding elements in its view (v_i) to 1.

Algorithm 3 decision_algorithm(): Optimistic_criterion (p$_i$)

```
if $v_i$ is complete then
    $p_i$ selects $resultant_i$
else
    abort;
end if
```

Algorithm 3 shows the description of the *optimistic* decision criterion. Executing the optimistic decision criterion, if at the end of the Rth round, the view of a process p_i is *complete*, p_i must select its $resultant_i$ as the highest value. Indeed a process with *complete* view optimistically assumes that all the other processes have also *complete* views and select a value. A process with an *incomplete* view at the end of the Rth round decides to abort. Entire platoon has a single largest value and the vehicle with that initial resultant value is elected as leader.

5 CONCLUSION

In this paper, we proposed a consensus-based leader election mechanism for CACC-based platooning. We used the optimistic criteria for computation and decision process. We proposed edge at RSU to cache the required information about the vehicle and the driver so that the platoon leader can verify collected data in real time. We discussed the role of leader vehicle, the incentive strategy to be adopted, scenarios for leader election, and the architecture to facilitate leader election process. We have also demonstrated the impact of leader vehicle's behavior on platooning operation. Our next step is to simulate the proposed leader election mechanism and evaluate the performance in terms of communication overhead and impact on string stability.

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