# Geo-localized Virtual Infrastructure for VANETs: Design and Analysis

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*Abstract*— **Supporting future large-scale vehicular networks is expected to require a combination of fixed roadside infrastructure and mobile in-vehicle technologies. The need for an infrastructure, however, considerably decreases the deployment area of VANET applications. In this paper, we propose a self-organizing mechanism to emulate a geo-localized virtual infrastructure (GVI). This latter is emulated by a bounded-size subset of vehicles currently populating the geographic region where the virtual infrastructure is to be deployed. An analytical model is proposed to study this mechanism. More precisely, this model is proposed to study the GVI in the frame of its main use: data dissemination in VANETs. Despite being simple, the proposed model can accurately predict the system performance such as the probability that a vehicle is informed, and the average number of duplicate messages received by a vehicle, and allows a careful investigation of the impact of vehicular traffic properties and system parameters on performance criteria. Analytical and simulation results show that the proposed GVI mechanism can periodically disseminate the data within an intersection area, efficiently utilize the limited bandwidth and ensure high delivery ratio.**

***Index Terms*–Vehicular networks, Virtual infrastructure, Dissemination, Analytical modelling, Performance evaluation**

## I. INTRODUCTION

Vehicular Communication Networks (VCNs) have emerged as the cornerstone of the envisioned Intelligent Transportation Systems (ITS). By enabling vehicles to communicate with each other via Inter-Vehicle Communications (IVC) as well as with roadside base stations via Roadside-to-Vehicle Communications (RVC), vehicular networks could contribute to safer and more efficient roads. The opportunities and areas of applications of VCNs are growing rapidly, with many vehicle manufacturers and private institutes actively supporting research and developments in this field. The integration with on-board sensor systems and the progressive diffusion of on-board localization systems (GPS) make VCNs suitable for the development of active safety applications (including collision and warning systems), driver assistance applications and intelligent traffic management systems. On the other hand, VCNs also fuels the vast opportunities in online vehicle entertainment (such as gaming or file sharing), and enables the integration with Internet services and applications [1]. Many of these applications rely on distributing data, e. g., on the current traffic situation, or on free parking lots. Often, data needs to be distributed over long distances, for example to allow a driver to choose between different arterial roads when driving into the city center. Typically, such applications are based on some form of proactive information dissemination in an ad hoc manner - i.e. by forming Vehicular Ad hoc Networks (VANETs).

Proactive information dissemination is, however, a difficult task due to the highly dynamic nature of VANETs. Indeed, VANETs are characterized by their frequent fragmentation into disconnected clusters that merge and disintegrate dynamically [2]. In addition, the results presented in [3] clearly show that during the rollout of VANET technology, some kind of support is needed. Otherwise, many envisioned applications are unlikely to work until a large fraction of vehicles participates. One of the largely accepted solutions towards efficient data dissemination in VCNs is by exploiting a combination of fixed roadside infrastructure (e.g. Road Side Units, RSU) and mobile in-vehicle technologies (e.g. On Board Units, OBU). For example, in [4], roadside base stations are used to bridge network partitions in vehicular networks. A car already informed of an accident forwards the alert when passing by a roadside base station. Subsequently, the base-station forwards the message to other base-stations located in the alert zone. Each of the informed base-stations periodically broadcasts the alert to inform passing vehicles. Another recent example of broadcasting protocol specifically designed for vehicular networks with infrastructure support is the Urban Multi-hop Broadcast (UMB) protocol presented in [5]. UMB gives insightful results in terms of successful delivery rate. However, this is obtained with the help of repeaters at the road intersections. The need for an infrastructure considerably decreases the deployment area of UMB-based networks as UMB fails to handle intersections without a repeater. So, while such infrastructure-based approaches may work well, they may prove costly as they require the installation of new infrastructures on road network, especially if the area to be covered is large.

In this context, the main contribution of the paper is twofold. First, we propose a self-organizing mechanism to emulate a geo-localized virtual infrastructure (GVI) by a bounded-size subset of vehicles populating the concerned geographic region. This is realized in an attempt to both approaching the performance of a real infrastructure while avoiding the cost of installing it. Second, we propose an analytical model for the study of such mechanism. As proved by the presented results, despite being simple, the model can accurately predict the system performance and allows a careful investigation of the impact of vehicular traffic properties on the performance.

Among the various choices that influence the design and the analytical modelling of the GVI is the question related to where to position the GVI in order to allow for a best-possible support of VANETs. As we are dealing with the city environment, an intersection sounds suitable as geographic region because of its better line-of-sight and also because it is a high traffic density area. Hence, the proposed GVI mechanism can periodically disseminate the data within a signalized (traffic lights) intersection area, controlled in fixed-time and operated in a range of conditions extending from under-saturated to highly saturated. Thus, it can be used to keep information alive around specific geographical areas [6] (nearby accident warnings, traffic congestion, advertisements and announcements, available parking lot at a parking place, etc.). It can also be used as a solution for the infrastructure dependence problem of some existing dissemination protocols like UMB [5].

The rest of this paper is organized as follows. Section II describes the GVI scheme. Section III presents the derived analytical formulas that provide the necessary guidelines for choosing the system parameters. These are followed by a discussion of simulation and analytical results in section IV. Finally, Section V concludes the paper depicting some future research directions.

## II. GEO-LOCALIZED VIRTUAL INFRASTRUCTURE

The geo-localized virtual infrastructure mechanism consists on electing vehicles that will perpetuate information broadcasting within an intersection area. To do so, the GVI is composed of two phases: (i) selecting the vehicles that are able to reach the broadcast area (i.e. a small area around the intersection center, where an elected vehicle could perform a local broadcast); then, (ii) among the selected vehicles, electing the local broadcaster which will perform a local single-hop broadcast once it reaches the broadcast area (i.e. at the intersection center).

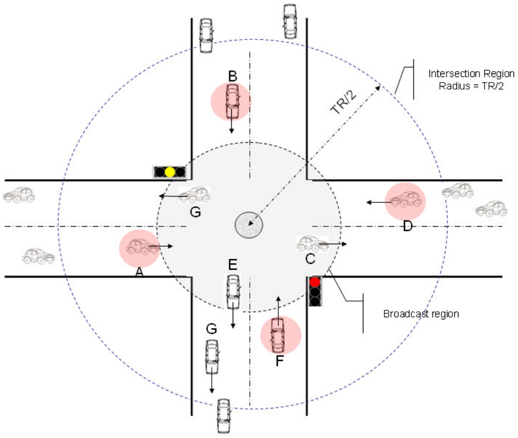


**Figure 1** – *Selecting vehicles candidates in the GVI mechanism.*

### *A. Selecting candidate vehicles*

Among the vehicles which are around the intersection, only those which are within the intersection region could participate to the local broadcast. They are selected as candidates if they are able to reach the intersection center. The intersection region is an area around the intersection starting at TR/2 m before and extending to TR/2 m beyond the intersection where TR is the transmission range. Figure 1 illustrates the candidate vehicles selection where vehicles {A, B, C, D, E, F, G, H} could participate to the GVI mechanism since they are located within the intersection region and only vehicles {A, B, D, F} are selected as candidates because they are moving towards the broadcast area.

### *B. Electing the local broadcaster*

Each vehicle selected as candidate vehicle starts by computing the time period Δ needed to reach the intersection center by considering its geographical location, direction and speed. According to this time period, it computes a weight $P(\Delta)$. This one has to be minimal when the expected delay matches the desirable broadcast cycle time $T$ of the GVI and it increases when we are far from $T$. One possible function for computing the weight is given by (1) ($\sigma$ is a constant) but other functions (e.g. triangle) can also be considered.

$$P(\Delta) = 1/\left(\sigma.\sqrt{2\Pi}\right)\times \exp\left( -1/2 \left( \left(\Delta - T\right)/\sigma \right)^2\right) \quad (1)$$

After the weight calculation, a waiting time $WT(P)$ = MaxW (1 - $P/P_{\max}$ ) will be assigned to each candidate vehicle. The candidate vehicle with the highest weight $P$ will have the shortest waiting time $WT$ to broadcast a short informative message telling other candidate vehicles that it has been elected as the local broadcaster.

One may also note that the probability of having a collision between two informative messages is weak. This is due to two reasons, the length of these messages and the number of vehicles that may compute similar weight $P$. In the unlikely event of a collision among two broadcasted messages, the GVI will have multiple elected nodes which will perform the local broadcast while arriving at the intersection center instead of one. So, such collisions will not break the GVI (i.e. no dramatic effect).

The reason to choose the intersection region starting at TR/2 m before the intersection is that the elected vehicle has to inform the other candidate vehicles. In the worst case, the elected vehicle is TR/2 away from the intersection and it can cover the points up to TR/2 away at the other side of the intersection. An example of vehicle election is illustrated in Figure 2: Candidate nodes, vehicles A, B & C compute the time period Δ to reach I (the intersection center) considering their position, direction and speed. B will have a long time period $\Delta_B$ since it is stopped at the traffic light. C has a very short time period $\Delta_C$ since it is very close to I. A requires a time period $\Delta_A$ very close to the broadcast cycle time $T$. Consequently, A will have the highest value of $P$ and the shortest $WT(P)$. A will be the first to send a message to vehicles B and C informing them that it has been elected to perform the local broadcast once it reaches the broadcast area around the intersection center I. Once vehicles within the transmission range of the elected vehicle receive the broadcasted message, they will participate in the election of the next local broadcaster.

Note that the elected vehicle has always the closest time duration to $T$. Hence, we can ensure that our GVI will perform a periodic local broadcast. To avoid a too high variability between two successive broadcast messages, we define a margin *M*, such as an elected vehicle may have an estimated time period to reach the center within the interval $\left[T-M;T+M\right]$.

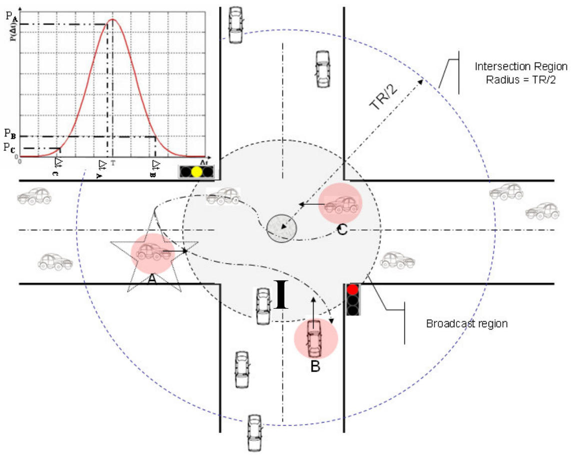


**Figure 2** – *Electing the local broadcaster in the GVI mechanism.*

A critical question that arises is how to choose the broadcast cycle time in order to achieve a good trade-off between the probability to inform a vehicle (that is a measure of quality of service) and the number of copies of the same message received by a vehicle (that is a measure of cost to provide the service). This is closely related to the time spent by a vehicle to go through the intersection area. Furthermore, the GVI is emulated by vehicles residing in the intersection area: a vehicle that enters the intersection region of a GVI attempts to participate in the mechanism; a vehicle that leaves the geographic region ceases to emulate the GVI. So, the other question concerns the risk that the GVI breaks, especially when the vehicular traffic density within the intersection area is very low. In other words, what is the probability to fail during the election of the next local broadcaster? In the following section, we present an analytical model allowing the study of these issues.

## III. Analyzing the GVI Performance

In this section, we present an analytical model to study the GVI mechanism. First, we want to determine the dissemination capacity of our mechanism and thus, it is necessary to estimate the delivery ratio and the mean number of reception of the broadcasted message. When considering the broadcast cycle time *T*, the optimal value of such parameter has to be chosen so that all the vehicles receive once the broadcasted message. Consequently, the periodicity of the mechanism is closely related to the sojourn time of the vehicles within the reception area (radius TR). Intuitively, this parameter has to be of the same magnitude order than the minimum sojourn time of a vehicle within this area. Accordingly, this sojourn time corresponds to the travel time a vehicle would have experienced in the absence of traffic signal control (i.e. traffic lights).

Furthermore, the GVI mechanism is based on inter-vehicle ad-hoc communications. Consequently, when a message is broadcasted, it is necessary that at least one vehicle is still within the intersection area (radius TR/2) and located before the traffic signal so that it could rebroadcast the message later on. The impact of the margin has also been considered. The second performance criterion is thus the probability *p* that no vehicle can be elected within the considered interval. Note that this situation does not mean that the mechanism fails. Indeed, the vehicles within the reception area (radius between TR/2 and TR) may broadcast later on the message.

### *A. Notation and system assumptions*

The sojourn time at signalised intersections constitute a very significant part in the GVI mechanism since it has an important impact on the system parameters and performance. It can be represented by two parts: the on-move sojourn time and the queuing sojourn time. Note that many models have already been proposed for the queue length and the delay analysis at traffic signals [7][8][9][10], but none of them answers our needs. This is what motivated the following model.

In order to develop our model, the following assumptions will be adopted:

- The arrival process of vehicles constitutes a Poisson process with parameter $\lambda$.
- Without lake of generality (i.e. it has no impact on the model), the possibility to turn left or right is not considered.
- The queuing sojourn time *W* is computed as the difference between the travel time actually experienced by a vehicle while going across the intersection and the travel time this vehicle would have experienced in the absence of traffic signal control.
- The moving speed of a vehicle is constant. Therefore, the on-move sojourn time can be represented by the sum of:
  * *J*: the required time to join the queue
  * *L*: the necessary time to leave the intersection.
  * *C*: the time needed to cross the intersection.

The sojourn time of a vehicle within the reception area *S* is thus equal to: $S = J + W + C + L$

- The amber period is modeled as follows [8], when a vehicle wants to enter the intersection, if the residual green period is lower than the necessary time *C* to cross the junction, the vehicle stops and wait for the following green period.

Table 1 gives the parameters which have been considered:

**Table 1** Parameters of the analysis

| SCENARIO | |
|---|---|
| Green, amber, red Intervals (*Tg,Ta,Tr*) | (38s,2s,40s) |
| Capacity of the intersection = 1/*C* | 0.5 veh/s |
| Transmission range | 200 m |
| On-move sojourn time (J,L,C) | (10s,10s,2s) |
| Broadcast time cycle = *T* | 40s |
| Cycle Duration *Tc*=*Tg*+*Ta*+*Tr* | 80s |
| Vehicle velocity (city) | 30 km/h |

### B. Analyzing the GVI mechanism

*1) Probability of having no local broadcaster for a given broadcast cycle time*

Let us first consider the case when the Broadcast cycle timee $T$ is equal to 40s which is also equal to the red Interval and to the (green + amber) duration. In this case, it is more convenient that the broadcast instants fit the beginning of the green intervals. Indeed, this one corresponds exactly to the instant that maximizes the probability of having non-empty queues. An accurate lower bound $l$ of such probability can be derived. When the system is under-saturated, the probability that at the end of a green period the queue is empty is high [10]. Thus, at the end of the following period, the probability that no vehicle is present in the system nearly corresponds to the probability that no vehicle enters the queue in both directions during the amber and the green period: $l = \exp(-2\lambda(T_r + T_a))$.

Let us now consider the case when the margin is higher. Let us suppose that the broadcast instant corresponds to the instant when the light turns green (plus the necessary time for the first vehicle to join the intersection center). The eligible vehicles are those which are within the intersection area. Among them, the mechanism will favor those for which the light is red. They are waiting if they arrived during the amber or red period, or they are still rolling within the intersection area located before the crossroad. We can easily derive an upper bound of the probability $p$ to find no eligible vehicle in the opposite direction: $p = \exp(-2\lambda(J/2 + T_a + C/2))$.

This will constitute an upper bound of the probability that no vehicle can be elected when the margin $M$ is negligible.

Note that with the considered value of TR, only a negative value of the margin can be used. A positive margin would correspond to the selection of a vehicle which will enter the junction while the light is already green which is not possible as $J/2 << T_r$. A negative value of the margin will consist on selecting a vehicle which will send the broadcast message during the same green interval. It is thus among the vehicles which are moving towards the intersection or waiting, the supposed last one to cross the junction before the following amber signal.

Since at least one vehicle was waiting when the light turned green, one can derive the probability distribution of the number of vehicles within the intersection area. In order to be sure that one vehicle is already within the intersection area and that it will cross the intersection within the time interval $[T - M; T]$, it is necessary that at least in one direction, there are more than $k = (T - M)/C$ vehicles. The vehicles which are currently within the junction are excluded. Assuming that at the end of the previous green period, the queue was empty, the probability that no candidate can send the broadcast message during the next period is lower than: $q = p\,\gamma(\gamma + 2\exp(-\lambda Z))/(1 - l)^2$

where $\gamma = \sum_{i=1}^{k+1} (\lambda Z)^i / i! \exp(-\lambda Z)$ and $Z = T_r + T_a + (J + C)/2$

Note that this expression is a little more complicated because it is necessary to differentiate the vehicles waiting when the light turns green and the vehicles which are still joining the junction. The same method can be applied to derive the probability that no broadcast message can be sent given the previous one occur within a green period but not exactly when the light turned green. The occurrence of such an event is so weak that this term has been omitted in the following results.

*2) Determining the dissemination capacity of the system (number of copies of a received message, non informed vehicles)*

The second performance criterion which has been considered is the mean number of broadcast messages received by a vehicle. It may be derived from the delay distribution. If we neglect the influence of the margin, a first approximation is equal to the mean sojourn time of a vehicle within the reception area divided by the period $T$: $m \approx E[S]/T = (J + E[W] + C + L)/T$

In order to estimate the mean waiting time, we propose two methods. The first one uses the well-known Webster's formula [9] and introduces the amber phenomenon [8]:

$$E[W_{webster}] \approx \frac{T_c(1 - T_g/T_c)}{2(1 - \lambda C)} + \frac{x^2}{2(1 - \lambda x)} - 0.65\left(\frac{T_c}{\lambda^2}\right)^{1/3} x^{2+5T_g/T_c}$$

The second one is derived from a fluid approximation of the functioning of the system which assumes that when the system is under-saturated [10], the queue is empty when the light turns red. During the red period, the number of vehicles linearly increases with rate $\lambda$ while during the green interval, it will decrease with a rate $\mu = 1/C - \lambda$. The waiting delay is equal to the number of vehicles at the arrival instant multiplied by the necessary time to cross the junction. By considering that the cycle begins when the light turns amber, we get:

$$n(t) = \begin{cases} \lambda t & 0 \le t \le T_a + T_r = \theta \\ -\mu(t - \theta) + \lambda\theta & \theta \le t \le (1 + \lambda/\mu)\theta \\ 0 & (1 + \lambda/\mu)\theta \le t \le T_c \end{cases}$$

and finally $E[W_{fluid}] = C\,\lambda(T_a + T_r)^2 / 2(1 + \lambda/(1/C - \lambda))$

In order to take into account the margin $M$; we can multiply $m$ by probability $q$: $\tilde{m} \approx mq$

The last performance criterion is the probability $\pi$ that a vehicle does not receive the broadcast message. As previously mentioned, the probability of two successive absences of broadcast message is negligible when $T$=40s and the system is nearly empty at the end of a green period; thus: $\pi \approx q/\tilde{m}$

Finally, it is worth noting that a more complex model could be derived in order to compute the distribution of the number of received message. According to our initial motivation (cf. §II, last paragraph), this one is not the target of this study. It will be the subject of our future research.

## IV. Results and Analysis

In this section, we analyze the results derived through our previous formulas and discrete event simulations. The objective is to investigate the impact of traffic properties and system parameters (broadcast cycle time, margin) on performance criteria. The simulated scenario is the same as the system used to develop the analytical model (signalized, two-direction intersection without turning movement); Poisson arrivals with parameter λ in the four directions. Since the saturation flow is nearly equal to 0.25 veh/s, the arrival rates of two directions range from 0.1 veh/s to 0.2 veh/s.

Figures 3 and 4 show the dissemination capacity of the proposed mechanism. Figure 3 depicts the relation between the margin *M (the tolerated delay around the broadcast cycle time T = 40s)* and the percentage of vehicles which fail to receive the data. It can be noticed that the percentage of vehicles which pass the intersection without getting data is very low. This is expected since the broadcast cycle time is higher than the minimum elapsed time within the reception area.

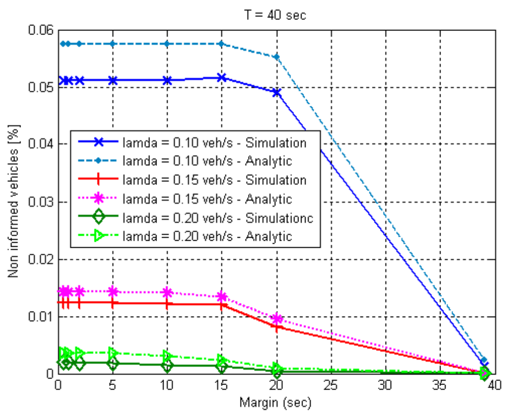


**Figure 3 -** *Non informed vehicles vs. Margin - Analytical/Simulation results (T=40s)*

It is also shown that under a given vehicle traffic load, less vehicles fail to receive the data as the margin is high. Indeed, in that case the probability to find a local broadcaster becomes also high. Furthermore, more vehicles get the data when the vehicle traffic density increases. This can be explained by vehicles intersection stay: when increasing vehicular traffic density, the speed of vehicles decreases [11] which in turn increases the intersection stay. Under low vehicle traffic load, vehicles move faster and then may pass the intersection without getting data.

Figure 4 reports the mean number of received copies as a function of the margin. It shows that this number is low (less than two). This is expected since the broadcast cycle time is long with regard to vehicles intersection stay. The margin parameter does not have a significant effect on the obtained results.

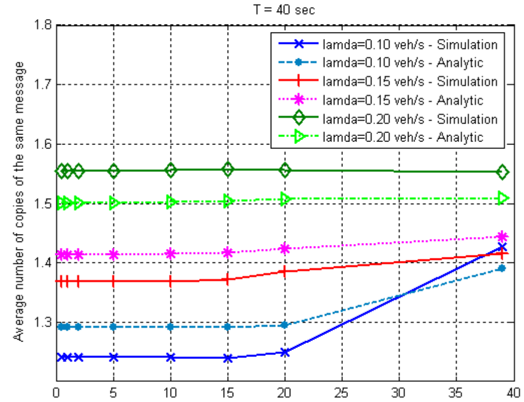


**Figure 4-** *Average number of copies of the same message –Analytical Models/Simulations, T=40s*

Figure 5 shows the probability that no broadcast is performed within a time period as a function of the tolerated delay margin around the broadcast time cycle and under various vehicular traffic loads. The analytical and simulation results show that the probability that the decentralized GVI mechanism fails is very low and it decreases as the traffic density increases. Furthermore, under the same vehicle traffic load, this probability decreases when increasing the margin. The probability of finding an eligible vehicle increases with the margin value.

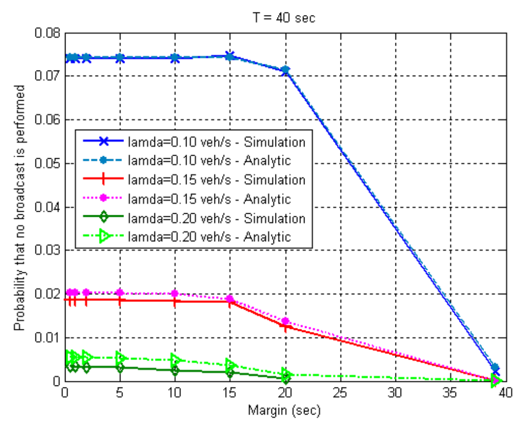


**Figure 5** - *Probability that no broadcast message is sent within a period vs. Margin - Analytical/Simulation results, (T=40s)*

The three figures report both analytical and simulation results. The curves obtained from the simulation are close to those obtained from the analytical model, which indicate that the analytical model captures well the qualitative behavior of the proposed scheme. Let us note that the probability that no vehicle within the reception area receives the message is negligible. For instance, with a margin $M$ nearly equal to $T$, we have to multiply $q$ by the probability that no vehicle is within the reception area but not in the intersection area (they are not able to signal that they receive the previous one). In the worst case, $\lambda$=0.1 veh/s, we get an upper bound $\tau$= 1.31E-6. This configuration never appeared during our simulations.

## V. Conclusion

In this work, we presented an elegant solution for building a Geo-localized Virtual Infrastructure using inter-vehicle ad-hoc networks. The proposed mechanism has various potential applications ranging from safety to convenience applications, solving by the way the infrastructure dependence problem of some existing dissemination protocols. Analytical and simulation results show that the proposed GVI mechanism can periodically disseminate data within an intersection area, efficiently utilize the limited bandwidth and ensure high delivery ratio.

As a future work, we intend to derive other analytical expressions for the considered performance criteria while changing the values of the broadcast time cycle. We are also working on designing a new dissemination protocol based on the GVI mechanism.

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