Red or Green: Analyzing the Data Delivery with Traffic Lights in Vehicular Ad Hoc Networks

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Outline

• Overview
• Influence of Traffic Lights on Data Delivery
• Analysis Model - Mobility Prediction
• Analysis Model - Data Delivery
• Transmission Control Scheme
• Performance Evaluation
• Conclusion
Overview

• Vehicular Ad-hoc Network (VANET)
  – V2V: wireless communication among vehicles
  – V2I: wireless communication among vehicles and infrastructures
Traffic Light

• The mobility of vehicles is not only affected by itself, but also by the traffic lights.
• Stop at a red light:
Catch Up with Traffic Lights

• The vehicles stopped by the red light could wait for the vehicles moving behind, which could increase the opportunities for vehicles moving behind to catch up in data forwarding.
Contribution

• We conduct a comprehensive investigation of the influence of traffic lights on the data delivery in VANETs.
  – We develop an analytical model to evaluate the data delivery among the vehicles along a path with multiple traffic lights.
  – Based on this model, we propose a transmission control scheme to decide which data packets can be delivered, by giving the deadline of reachable destinations, in order to reduce the resource consumption.
Influence of Traffic Lights on Data Delivery

• Increase delay by stopping vehicles by the waiting time at the traffic light \( T_1 \) (denoted by \( w_1 \)).
Influence of Traffic Lights on Data Delivery

• Traffic hole problem:
  – When a vehicle stops at the intersection due to the red light, the vehicle ahead goes away, and a gap appears between them.
Influence of Traffic Lights on Data Delivery

- Catch up (denoted by $C$)
- Immediate transmission (denoted by $I$)
Analysis Model - Mobility Prediction

• For evaluating the mobility of vehicles along the path with traffic lights, we define four sets of time as follows:
  – Initial time \((U)\)
  – Departure time \((T)\)
  – Arrival time \((S)\)
  – Waiting time \((W)\)
Analysis Model - Mobility Prediction

• \( x_i(t) \) is defined as the function for calculating the distance of the vehicle \( V_i \) from the initial point \( O \) at time \( t \).

\[
x_i(t) = \begin{cases} 
0, & \text{if } 0 \leq t \leq u_i \\
K_i(t) - 1 \sum_{r=1}^{K_i(t)-1} L_r + v\alpha_{K_i(t)}(u_i, t), & \text{if } t > u_i 
\end{cases}
\]

We define \( K_i(t) = k \) if, at time \( t \), the vehicle \( V_i \) is in the \( k^{th} \) road segment. The length of the \( k^{th} \) road segment from \( T_{k-1} \) to \( T_k \) is denoted by \( L_k \).

We define \( \alpha_k(u, t) \) as the duration while the vehicle \( V_i \) has moved on the \( k^{th} \) road segment with the speed \( v \) at time \( t \).
Analysis Model - Data Delivery

• The vehicle $V_q$ is defined as the first car that receives a message at the initial point $O$, and $\sigma_q$ denotes the time when it receives the message. $\sigma_i$ can be recursively calculated as follows:

$$\sigma_i(\sigma_q) = \begin{cases} 
\sigma_{i+1} + t_{hop}, & \text{if } V_{i+1} \xrightarrow{I} V_i \\
 s_j(u_{i+1}) - \frac{R}{v} + t_{hop}, & \text{if } V_{i+1} \xrightarrow{T_j} V_i \\
\infty, & \text{Otherwise}
\end{cases}$$
Analysis Model - Data Delivery

• The condition that the vehicle $V_{i+1}$ can immediately transmit the message to the vehicle $V_i$ means: when the vehicle $V_{i+1}$ receives the message at time $\sigma_{i+1}$, $V_i$ is in its communication range. Thus, the condition can be calculated with the indicator function, as follows:

$$\mathbb{1}_{V_{i+1} \xrightarrow{I} V_i} = \mathbb{1}_{x_i(\sigma_{i+1}) - x_{i+1}(\sigma_{i+1}) \leq R}$$
Analysis Model - Data Delivery

• The condition that the vehicle $V_{i+1}$ does not catch up $V_i$ at the $j^{th}$ traffic light means: before $V_i$ leaves the $j^{th}$ traffic light, $V_{i+1}$ cannot arrive in its communication range. Thus, the condition can be calculated as follows:

$$\frac{1}{V_{i+1}} \xrightarrow{C_j} V_i = \frac{1}{x_i(t_j(u_i)) - x_{i+1}(t_j(u_i))} > R$$
Analysis Model - Data Delivery

• On the contrary, the condition that the vehicle $V_{i+1}$ can catch up to $V_i$ at the jth traffic light means: before $V_i$ leaves the $j^{th}$ traffic light, $V_{i+1}$ can arrive in its communication range.

$$\mathbb{1}_{V_{i+1} \xrightarrow{c_j} V_i} = \mathbb{1}_{x_i(t_j(u_i)) - x_{i+1}(t_j(u_i)) \leq R}$$
Analysis Model - Data Delivery

• The condition that the vehicle $V_{i+1}$ catches up with $V_i$ and transmits the message at the $j^{th}$ traffic light:

$$\mathbb{1}_{V_{i+1} \xrightarrow{T_j} V_i} = \begin{cases} 0, & \text{if } j < K_i(\sigma_{i+1}) \\ \prod_{K_i(\sigma_{i+1}) \leq r < j} \mathbb{1}_{V_{i+1} \xrightarrow{C_r} V_i} \mathbb{1}_{V_{i+1} \xrightarrow{C_j} V_i}, & \text{if } K_i(\sigma_{i+1}) \leq j \leq m \end{cases}$$
Reachable Destinations

- We define **reachability** of the destination as whether the data packets could be successfully delivered from the source to it.

- 1) RSU as Destination: the delivery delay of this message from the source $V_q$ to the destination at $T_k$

\[
\delta_{V_q \rightarrow T_k} = \sigma_{min(M)} \lor S_k(u_{min(M)}) - \sigma_q
\]

- 2) Vehicle as Destination: the reachability of the message from $V_q$ to $V_p$

\[
\gamma_{q \rightarrow p}(u_q) = \prod_{i=p}^{q} 1_{\sigma_i < t_m(u_q)}
\]
Reachable Destinations

• **Theorem 1 (Temporally Reachable):** On a finite path with m traffic lights, if the data packet carried by $V_i$, whose destination is $V_j$, is unreachable at time $t_0$, and thus is in the future time $t_0 + \Delta t$ ($\Delta t > 0$), it is also unreachable.

• **Theorem 2 (Spatially Reachable):** At the time $t_0$, if the vehicle $V_i$ is the reachable destination for the data packets carried by $V_i$, it is also the reachable destination for the data packets carried by $V_j$ ($j < i$), which moves in front of $V_i$ along the path.
Transmission Control Scheme

Algorithm 1 Transmission control scheme

Input: $F/G$, the sets of the received/generated packets
Output: $S$, the set of the packets which need to be sent
1: Select Reachable packets in $F$ and $G$ to $S$;
2: Clear the sets of $F$ and $G$;
3: Sort the packets in $S$ by their deadlines in ascending order;
Analytical model compared with simulations

(a) Mobility of vehicles
(b) Data delivery delay
Impact on data delivery delay

(a) Interval of arrival time

(b) Cycle time of traffic light
Reachable destinations

(a) Interval of arrival time

(b) Ratio of traffic lights (green/red)
Conclusion

• We investigate the influence of traffic lights on data delivery in VANETs.
• We propose an analysis model to evaluate the influence by given initial headway times of vehicles, and the schedules of traffic lights.
• Based on the analysis model, we propose a transmission control scheme at the transmitters; this scheme filters suspicious transmission requests, which are unlikely to be accomplished.
• The proposed analytical model is under a linear topology. In our future work, we plan to evaluate the data delivery under a two-dimensional topology, such as a ladder or a grid.
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