Toward Neighborhood Prediction Using Physical-Layer Network Coding

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Abstract—**In this paper we investigate the improvements in the capability of neighborhood prediction when the Physical-Layer Network Coding (PLNC) is used for relaying messages in Vehiculars Ad Hoc Networks (VANETs). We compute the probability that a link between two nodes is available at a given time in a three-node cooperative network, and we demonstrate that the use of PLNC, compared to the use of Network Coding (NC)-based or traditional routing (TR)-based relaying techniques, leads to a better accuracy of the neighborhood prediction. We also demonstrate that the accuracy of the prediction is tightly related to the mobility model used and that this tight relationship can be relaxed by using PLNC-based relaying neighborhood prediction (PRNP). The results demonstrate that PRNP can improve the accuracy of neighborhood prediction due to the high network capacity of PLNC-based networks.**

I. Introduction

Vehicular ad hoc Networks (VANETs) are gaining lots of interests as they promise a host of a new innovative services to drivers and passengers on the road. Contrary to many other ad hoc networking scenarios, VANETs bring new challenges in terms of mobility dynamics, speed, and data dissemination rates. Location information is usually very important in ad hoc networking, even with static nodes [1], as it helps improve service continuity, routing, etc. However, due to the high mobility of vehicles, many errors occur during the location and neighborhood prediction in VANETs; this, in turn, results in performance degradation of the used protocols. For instance, in the case of a three-node linear topology network, and when PLNC is used, any topology change after the multiple access stage, and before the broadcast stage of the PLNC [2] [3], could result in an inefficient broadcast stage if the relay node cannot longer communicate with the sinks.

Many efforts are undergoing to avoid such inconvenient situations. A main direction is the use of prediction techniques to locate the nodes in a near future. For this, a variety of approaches are proposed: First, those based on measurements (such as the measurement of signal strength). Second, the approaches based on mobility models. A survey of mobility models used in VANETs can be found in [4] and the references therein. Lastly, there are the approaches based on the use of historical location information. Following the latter approach, the authors in [5] propose a neighborhood tracking scheme. In our work, we are interested in utilizing mobility models to make neighborhood prediction when using PLNC. In [6], the authors propose the neighborhood prediction protocol (NPP) which tries to anticipate link availability in VANETs. However, contrary to our approach, the control messages are not relayed among the nodes, and the authors do not make use of PLNC.

To improve network discovery and neighborhood prediction, we assume that nodes can relay control messages within $p-$hops. Although such an assumption has been used in previous works [7] [8], the number of hops, p, has to be small due to the mobility of the nodes.

Several relaying techniques can be found in the literature. The basic one is the traditional routing-based relaying, in which the relay node forwards the received packet to the destination node, using either amplify-and-forward (AF) or decode-and-forward (DF) [9] or even store-carry-and-forward (SCF) for Delay Tolerant Networks [10]. Another popular technique used in messages relaying is network coding [11], in which the intermediate node sends out a linear combination of its packets, instead of the packets themselves.

In this paper, we consider PLNC-based relaying [2] [3] [12], to spread out the data in the network. Contrary to the other relaying techniques, PLNC exploits simultaneous transmissions to increase the throughput of the network. In fact, in PLNC, the relay node forwards the packets naturally and linearly combined through interference. Our main purpose deals with the positive impact of using PLNC on the performance of the neighborhood prediction. To the best of our knowledge, this is the first time PLNC is used to relay control messages in the process of discovering or predicting neighborhood. An attempt of using PLNC for node localization in a wireless ad hoc network is done in [13]. However, the proposed approach is limited to a fixed network and the authors do not intent to predict nodes position in the future.

Considering a linear highway model in which nodes move independently from each other according to a normal distribution, we demonstrate that, in the case of the basic cooperative three-node relay network and for any type of configuration, the use of PLNC increases the accuracy of location prediction of nodes. **Our contribution** is as follows:

- We provide the analytical expression of the cumulative distribution function (CDF) of the relative distance between two nodes at any instant with respect to their relative distance at a given instant in the past; this CDF gives the probability that the link between the two nodes will be available at that instant.
- We propose the use of PLNC as relaying scheme, not only to achieve a higher network capacity, but also to improve

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the prediction accuracy of nodes location. We demonstrate that PRNP outperforms NC-based and TR-based relaying techniques in the process of neighborhood prediction.

The remainder of the paper is organized as follows. In section II, we present the system model and the mobility model considered, and we derive both the link availability probability between two nodes and the prediction accuracy metric. We show in Section III that PLNC outperforms both NC-based relaying and TR-based relaying to quickly spread location information of nodes. The numerical results are presented and discussed in Section IV. Finally, in Section V, we conclude the present work.

II. System Model and Analytical Approach

In this paper, we consider the same mobility model as in [14]. The movement of each node, as a function of time, consists of a sequence of random intervals called epochs. The epoch duration τ of each node is independent identically distributed (i.i.d.) with exponential distribution with parameter λ. We assume that the mobility of the node during an epoch is constant, and the mobility of the node is updated only at the starting point of each epoch. Also, the speed V_i of each node (S_i) varies randomly from epoch to epoch according to a normal distribution of mean μ and variance σ^2 ($V_i \sim \mathcal{N}(\mu, \sigma^2)$). Since the epoch durations are exponentially distributed, the number of epochs over any interval of time follows a Poisson distribution. We further consider a sparse network, thus we assume that the mobility of the nodes are independent from each other. Although such an assumption has been already used in previous works [15] [16], it is not applicable for dense vehicular networks. The unidirectional highway model considered is illustrated in Fig. 1.

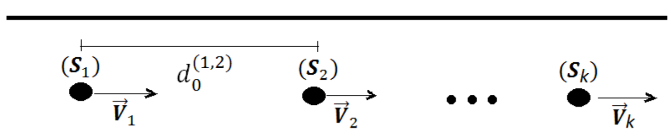

Fig. 1. Relative distance between two nodes (S_1) and (S_2) at t_0.

A. Link Availability Probability

Let $X^{(i)}(t)$, the distance travelled by the node (S_i) after a period of time $(0, t)$ from the service point at which the node has arrived in the highway of consideration. It is shown in [14] that $X^{(i)}(t)$ can be approximated as a random variable following a normal distribution with mean and variance respectively given by

$$\mathrm{E}\Big[X^{(i)}(t)\Big] = \mu t, \tag{1}$$

$$\mathrm{Var}\Big[X^{(i)}(t)\Big] = 2\frac{\sigma^2}{\lambda^2}(\lambda t - 1 + e^{-\lambda t}). \tag{2}$$

If we assume that the distance travelled by the node (S_i) after a period of time $(0, t_0)$ is known, that is, $X^{(i)}(t_0) = x_0^{(i)}$, the distance travelled by the node (S_i) after a period of time $(0, t)$ (with $t \geq t_0$) from the service point, given that $X^{(i)}(t_0) = x_0^{(i)}$ is given by

$$X^{(i)}(t|t_0) = x_0^{(i)} + X^{(i)}(t - t_0). \tag{3}$$

(3) can be easily verified assuming that the service point from which the node (S_i) is travelling is at its position at t_0. Therefore, $X^{(i)}(t|t_0)$ can be assumed to be a random variable having a normal distribution with mean $\mu_{t|t_0}$ and variance $\sigma_{t|t_0}$ respectively. Considering (1) and (2), we have

$$\mu_{t|t_0} = \mathrm{E}\Big[X^{(i)}(t|t_0)\Big] = x_0^{(i)} + \mu(t - t_0), \tag{4}$$

$$\begin{aligned}\sigma_{t|t_0} &= \mathrm{Var}\Big[X^{(i)}(t|t_0)\Big] \\ &= 2\frac{\sigma^2}{\lambda^2}\Big(\lambda(t - t_0) - 1 + e^{-\lambda(t-t_0)}\Big).\end{aligned} \tag{5}$$

Let us consider two nodes (S_i) and (S_j) travelling in the same highway. The relative distance between (S_i) and (S_j), denoted by $D_{ij}(t|t_0) = \Big|X^{(i)}(t|t_0) - X(j)(t|t_0)\Big|$ or $D_{ij}(t|t_0) = X^{(i)}(t|t_0) - X(j)(t|t_0)$ for simplicity of notation, will be, as the difference of two independent normally i.i.d. random variables, a normally distributed random variable with mean $\Delta\mu_{t|t_0}$ and variance $\Delta\sigma_{t|t_0}$ respectively given by

$$\Delta\mu_{t|t_0} = \mathrm{E}\Big[D_{ij}(t|t_0)\Big] = d_0^{(i,j)}, \tag{6}$$

$$\begin{aligned}\Delta\sigma_{t|t_0} &= \mathrm{Var}\Big[D_{ij}(t|t_0)\Big] \\ &= 4\frac{\sigma^2}{\lambda^2}\Big(\lambda(t - t_0) - 1 + e^{-\lambda(t-t_0)}\Big),\end{aligned} \tag{7}$$

where $d_0^{(i,j)} = x_0^{(i)} - x_0^{(j)}$ is the relative distance between (S_i) and (S_j) at t_0. Therefore, the probability density function (PDF) and the CDF of $D_{ij}(t|t_0)$ are respectively given by (8) and (9)

$$\begin{aligned}f_{D_{ij}(t|t_0)}(d, d_0, \Delta t) &= \Pr\Big\{D_{ij}(t) = d\Big|D_{ij}(t_0) = d_0\Big\} \\ &= \frac{e^{-(d-d_0)^2/2\Delta\sigma_{t|t_0}}}{\sqrt{2\pi\Delta\sigma_{t|t_0}}}\end{aligned} \tag{8}$$

$$\begin{aligned}F_{D_{ij}(t|t_0)}(d, d_0, \Delta t) &= \Pr\Big\{D_{ij}(t) \leq d\Big|D_{ij}(t_0) = d_0\Big\} \\ &= \int_0^d f_{D_{ij}(t|t_0)}(\delta, d_0, \Delta t)\mathrm{d}\delta \\ &= \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{d - d_0}{\sqrt{2\Delta\sigma_{t|t_0}}}\right)\right],\end{aligned} \tag{9}$$

where $\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-u^2}\mathrm{d}u$ is the error function, and $\Delta t = t - t_0$. Note that the CDF also corresponds to the probability that the link between two nodes will be available at a given time in the future.

B. Analysis of the accuracy of prediction

In the rest of the document, we use $F_{D_{ij}(t|t_0)}(d, d_0, \Delta t)$ and CDF interchangeably. In the context of the present work, the accuracy of the prediction corresponds in absolute value to the difference between the CDF for the corresponding time difference and the CDF at the steady state, i.e., for very large time difference. Indeed, after a short period of time, the randomness introduced by the mobility model is too small, so that the behavior of the node during that period is quasi-deterministic. For larger period of time, the high predictable behavior of the node decreases and the behavior of the node becomes completely random, thus very lowly predictable. Let's $\mathcal{A}$ represent the prediction accuracy metric, i.e., the deterministic nature of the prediction scheme. Given the setup considered, i.e., $\lambda = 2$, $\mu = 1$, we have $\lim_{\Delta t \to \infty} \text{CDF} = 1/2$, thus

$$\mathcal{A} = 2\left|\text{CDF} - \frac{1}{2}\right|. \quad (10)$$

Substituting (9) into (10), and considering (2), we have

$$\mathcal{A} = \left|\text{erf}\left\{\frac{\lambda(d - d_0)}{\sqrt{8\sigma^2(\lambda\Delta t - 1 + e^{-\lambda\Delta t})}}\right\}\right|. \quad (11)$$

III. Relaying-based Scheme for Neighborhood Prediction

In this section, we review the TR-based, the NC-based and the PLNC-based relaying techniques, to show the outperformance of PLNC-based relaying over both TR-based and NC-based relaying techniques. For simplicity of illustration, and without loss of generality, we consider the basic cooperative three-node linear relay network presented in Fig. 2. We further assume that the connectivity of the network is guaranteed, the nodes transmit according to a time scheduled based medium access such as time division multiple access (TDMA), and the sinks are out of the communication range of each other.

A. Traditional relaying

Given the three-node relaying network, the TR is a four-step relaying technique (Fig. 2). In the first two time slots, the sinks transmit their messages in different time slot. In the last two slots, the relay forwards the messages of interest to the corresponding nodes. Let $\tau_i^{(\text{tr})}$ be the delay between two

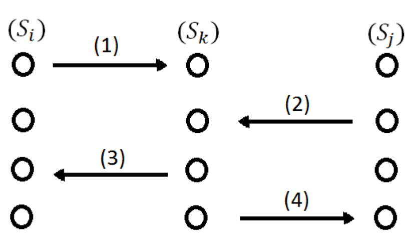

Fig. 2. TR-based relaying.

consecutive receptions at the node (S_i), and $T_p^{(\text{tr})}$ be the sum of the processing times at the nodes in the case of TR technique. Therefore, $\tau_i^{(\text{tr})}$ can be simply computed as follows

$$\tau_i^{(\text{tr})} = T_{kj}^{(p-1,4)} + T_{ik}^{(p,1)} + T_{jk}^{(p,2)} + T_{ki}^{(p,3)} + T_p^{(\text{tr})}, \quad (12)$$

where $T_{ab}^{(p,u)} = \frac{d_{S_a S_b}^{(p,u)}}{c}$ is the transmission delay between node (S_a) and node (S_b) during the step u of the transmission sequence (or simply the sequence) p. Note that the transmission sequence corresponds to a complete cycle of the relaying technique. $d_{S_a S_b}^{(p,u)}$ is the distance between (S_a) and (S_b) during the step u of the sequence p, and $c = 3 \times 10^8$m/s is the speed of the signal in the communication medium.

B. Network Coding relaying

The key underlying NC [11] is that intermediate nodes send out a linear combination of their packets, instead of the packets themselves. Applied to the three-node network, the NC is a three-step relaying technique (Fig. 3). Similar to the TR, the sinks transmit their messages in the first two time slots. However, the two last time slots of the TR are merged into a single one, where the relay node transmits a linear combination of the sinks messages. In this case, the delay between two

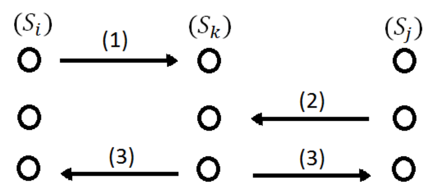

Fig. 3. NC-based relaying.

consecutive receptions at the node (S_i), $\tau_i^{(\text{nc})}$, is given by

$$\tau_i^{(\text{nc})} = T_{ik}^{(p,1)} + T_{jk}^{(p,2)} + T_{ki}^{(p,3)} + T_p^{(\text{nc})}, \quad (13)$$

where, $T_p^{(\text{nc})}$ is the sum of the processing times at the nodes in the case of NC technique.

C. Physical-layer Network Coding relaying

When PLNC is used, only two time slots are required. In this first time slot, the sinks transmit simultaneously their messages to the relay node, which forwards the coded packet (interference) to the sinks during the second time slot. The different steps are shown in Fig. 4. The delay between two

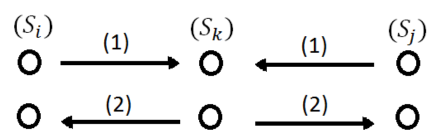

Fig. 4. PLNC-based relaying.

consecutive receptions at the node (S_i), $\tau_i^{(\text{plnc})}$, is given by

$$\tau_i^{(\text{plnc})} = T_{ik}^{(p,1)} + T_{ki}^{(p,2)} + T_p^{(\text{plnc})}, \quad (14)$$

with, $T_p^{(\text{plnc})}$ being the sum of the processing times at the nodes in the case of PLNC technique.

Considering (12)−(14), and assuming that transmission delays between node (S_a) and node (S_b) during the u-th step of the p-th transmission sequence are the same whatever the relaying technique used, we have

$$\tau_i^{(\text{tr})} - \tau_i^{(\text{nc})} = T_{kj}^{(p-1,4)} + \left(T_p^{(\text{tr})} - T_p^{(\text{nc})}\right). \quad (15)$$

$$\tau_i^{(\text{tr})} - \tau_i^{(\text{plnc})} = T_{kj}^{(p-1,4)} + T_{ki}^{(p,3)} + \left(T_{jk}^{(p,2)} - T_{ki}^{(p,2)}\right) + \left(T_p^{(\text{tr})} - T_p^{(\text{plnc})}\right). \quad (16)$$

$$\tau_i^{(\text{nc})} - \tau_i^{(\text{plnc})} = \left(T_{jk}^{(p,2)} - T_{ki}^{(p,2)}\right) + T_{ki}^{(p,3)} + \left(T_p^{(\text{nc})} - T_p^{(\text{plnc})}\right). \quad (17)$$

Note that PLNC only performs simple operations at the physical layer, thus reducing the processing time, on the contrary to NC. Therefore, a straightforward analysis of the expressions of the difference of time difference in the cases of TR, NC and PLNC relaying techniques in (15)−(17) shows that, in general,

$$\tau_i^{(\text{plnc})} < \tau_i^{(\text{nc})} < \tau_i^{(\text{tr})}. \quad (18)$$

For consistency of notation and nomenclature, $\tau_i^{(\text{X})}$ and $\Delta t = t - t_0$ represent the same metric in the rest of the paper. In this case, t_0 and t are the time at which the node receives the packet of interest in the previous and current sequence of transmission, respectively, and $X \in \{\text{tr}, \text{nc}, \text{plnc}\}$.

IV. Numerical Results and Discussion

In this section, we analyze and compare the performance of the neighborhood prediction using PLNC. The prediction scheme proposed is based on the computation of the link availability probability expressed as the CDF in (9). Each node computes the probability that its relative distance to any other node is less than the transmission range R. Any node records its real mobility such that once it gets information such as the position, and the corresponding time of a specific node in the past, it can compute the probability that a given node would be in its neighborhood at a certain time. We consider different scenarios in which we vary the average length of the epoch, and the past relative distance d_0 between two nodes. For these different scenarios, we evaluate both the accuracy and the probability that the two nodes are neighbor after two consecutive receptions of the packet of interest. The numerical results are shown in Fig. 5−Fig. 9. In Fig. 5 (resp. Fig. 6), we assume the last relative distance between two nodes is known, and we set it to $d_0 = 3u$ (resp. $d_0 = 5u$), and the transmission range of the nodes is set to $R = 4u$, u being a length unit. In the rest of the paper, we simply denote $d_0 = 3$, $d_0 = 5$, $R = 4$, etc. The two cases of d_0 are considered to see how vary the CDF with respect to the time difference for different values of the average duration λ of the epoch, and for $R - d_0 < 0$ or $R - d_0 > 0$. We observe the opposite behavior of the CDF whether $R - d_0 < 0$ or $R - d_0 > 0$. A similar behavior is observed in Fig. 7; the CDF evolves symmetrically around the axis (CDF= 0.5) corresponding to the case $R = d_0$. In Fig. 7, we also make the observation that the probability that two nodes will be neighbors in the future increases as the relative distance between them in a close past decreases. We also notice that for $\Delta t \to \infty$, the CDF tends to be constant, and corresponds to the case $R = d_0$. Both in Fig. 5 and Fig. 7, we observe that for $\Delta t \to 0$, the CDF$\to 1$. However, the CDF increases much faster as $R - d_0 \to \max_{d_0}\{R - d_0\}$, with $(R - d_0) > 0$. Given such observations in one hand, and considering the result in (18) in the other hand, one may conclude that PLNC provides the best prediction compared to

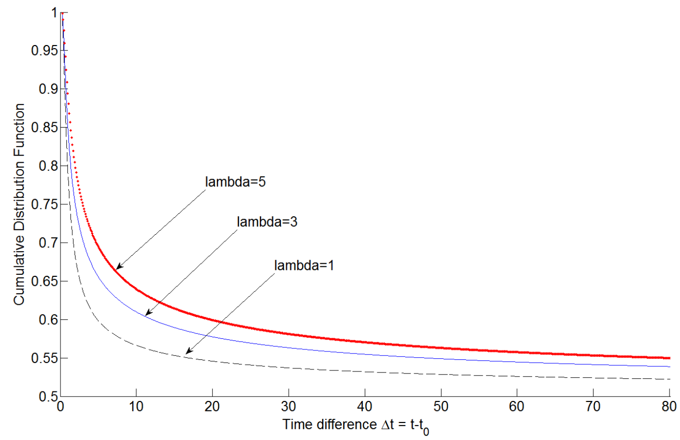

Fig. 5. Cumulative Distribution Function with respect to the time difference $\Delta t = t - t_0$ for different values of λ. The transmission range is fixed at $R = 4$, and the relative distance at t_0 is $d_0 = 3$.

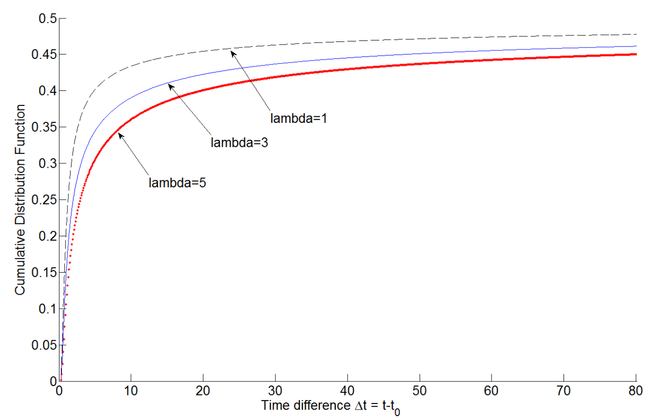

Fig. 6. Cumulative Distribution Function with respect to the time difference $\Delta t = t - t_0$ for different values of λ. The transmission range is fixed at $R = 4$, and the relative distance at t_0 is $d_0 = 5$.

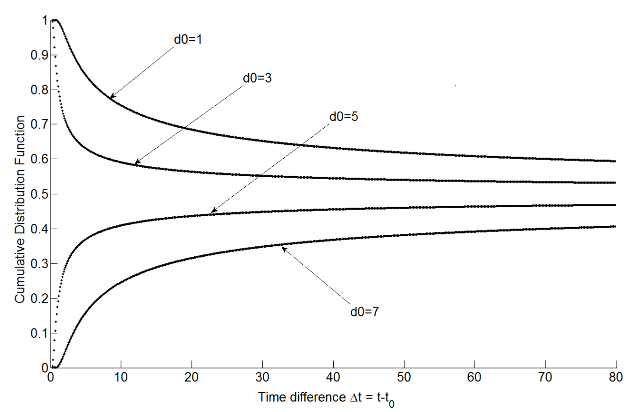

Fig. 7. Cumulative Distribution Function with respect to the time difference $\Delta t = t - t_0$ for different values of d_0. The transmission range is fixed at $R = 4$, and $\lambda = 2$.

TR and NC. Despite the fact that for $\Delta t \to 0$, CDF $\to 0$, a similar conclusion is done when considering Fig. 6. The worst performance for $R - d_0 < 0$ is due to the fact that we have considered in our analysis a unidirectional way scenario and a small variance for the velocity of the vehicles.

The variation of the accuracy of prediction with respect to relevant parameters of the analysis is shown in Figs. 8, 9. In Fig. 8, we set the transmission range R, we consider

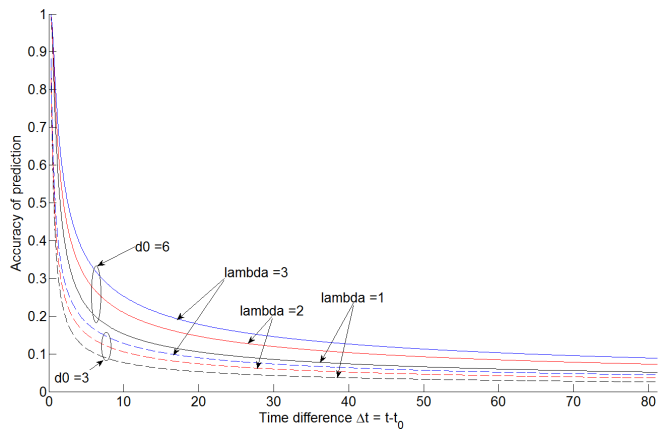

Fig. 8. Accuracy of prediction with respect to the time difference $\Delta t = t - t_0$ for different values of the relative distance d_0 and $\lambda = 2$. $\sigma^2 = 3$, and the transmission range is set to $R = 4$.

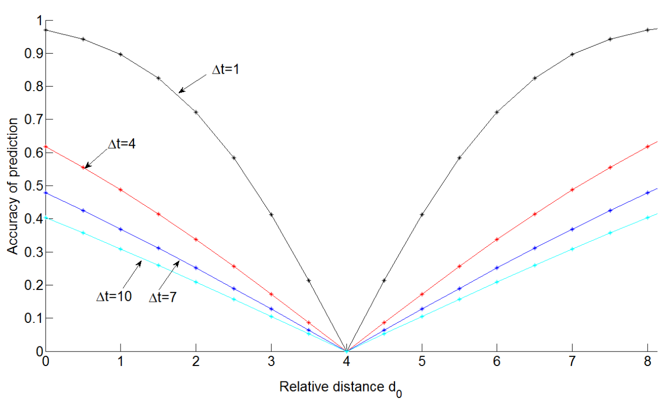

Fig. 9. Accuracy of prediction with respect to the relative distance d_0 for different values of Δt. $\lambda = 2$, $\sigma^2 = 3$, and the transmission range is set to $R = 4$.

different values of λ and d_0, and we analyze the accuracy of prediction with respect to the time difference Δt. Whatever the values of λ or Δt, one can observe that the prediction accuracy increases as the time difference decreases. This result implies that PLNC outperforms both TR-based and NC-based relaying techniques which have longer time difference compared to the PLNC-based relaying technique. In Fig. 9, we consider different time difference values, and we analyze the prediction accuracy with respect to the relative distance d_0. The results confirm those provided in Fig. 8 relaying techniques. PLNC provides shorter delay between two consecutive receptions, and provides a higher accuracy. However, additional results can be deduced. Indeed, we observe that the accuracy of prediction also varies considerably with respect to the previous relative distance d_0 for a given transmission range. It is shown that prediction accuracy increases as the absolute value of the difference between the past relative distance d_0 and the desired relative distance R (i.e. $|R - d_0|$) increases.

V. Conclusion

In this paper, we have studied the impact of using PLNC as a relaying mechanism of control messages on neighborhood accuracy prediction in vehicular networks. We compared the performance of PLNC with that of NC and TR relaying schemes. The results confirm that frequent updates of the neighborhood table lead to accurate location prediction, but using the PLNC-based relaying approach that we proposed alleviates the wasting of bandwidth resources by flooding the network with control messages. In fact, the PLNC-based neighborhood prediction approach does improve neighborhood prediction by the use of $p-$hops relaying.

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