On the Application of Mobility Predictions to Multipoint Relaying in MANETs: Kinetic Multipoint Relays*

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Abstract. In this paper, we discuss the improvements multipoint relays may experience by the use of mobility predictions. Multipoint Relaying (MPR) is a technique to reduce the number of redundant retransmissions while diffusing a broadcast message in the network. The algorithm creates a dominating set where only selected nodes are allowed to forward packets. Yet, the election criteria is solely based on instantaneous nodes' degrees. The network global state is then kept coherent through periodic exchanges of messages. We propose in this paper a novel heuristic to select kinetic multipoint relays based on nodes' overall predicted degree in the absence of trajectory changes. Consequently, these exchanges of message may be limited to the instant when unpredicted topology changes happen. Significant reduction in the number of messages are then experienced, yet still keeping a coherent and fully connected multipoint relaying network. Finally, we present some simulation results to illustrate that our approach is similar to the MPR algorithm in terms of network coverage, number of multipoint relays, or flooding capacity, yet with a drastic reduction in the number of messages exchanged during the process.

1 Introduction

Mobile Ad Hoc Networks (MANETs) is an emergent concept in view for infrastructureless communication. These networks rely on radio transmissions, but with the lack of infrastructures, flooding (distributing information to each and every node in the network in an uncontrolled way) happens to be a key part of information dissemination. In wireless networks and particularly when the network is dense, the overhead due to this kind of information dissemination may become prohibitive. Despite its simplicity, flooding is very inefficient and can result in high redundancy, contention and collision. This is the main motivation for many research teams that have proposed more efficient flooding techniques whose goal is to minimize the number of retransmissions while attempting to deliver packets to each node in the network. Different approaches of flooding techniques and broadcasting control protocols exist and are listed in [1, 2]. Multipoint relaying (MPR, [3]) provide a localized way of flooding reduction in a mobile ad hoc

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network. Using 2-hops neighborhood information, each node determines a small set of forward neighbors for message relaying, which avoids multiple retransmissions and blind flooding. MPR has been designed to be part of OLSR to specifically reduce the flooding of TC messages sent by OLSR to create optimal routes. Yet, the election criteria is solely based on instantaneous nodes' degrees. The network global state is then kept coherent through periodic exchanges of messages. Some studies showed the impact of periodic beacons, which could be compared to increasing the probability of transmission, in 802.11 performances [4], or the effects of beaconing on the battery life [5]. This denotes that these approaches have major drawbacks in terms of reliability, scalability and energy consumptions. The next step to their evolution should therefore be designed to improve the channel occupation and the energy consumption.

In this paper, we propose to improve the MPR protocol by using mobility predictions. We introduce the *Kinetic Multipoint Relaying (KMPR)* protocol which heuristic selects kinetic relays based on nodes actual and future predicted nodal degrees. Based on this, periodic topology maintenance may be limited to the instant when a change in the neighborhood actually occurs. Our objective is to show that this approach is able to significantly reduce the number of messages needed to maintain the backbone's consistency, thus saving network resources, yet with similar flooding properties as the regular MPR.

The rest of the paper is organized as follows. In Section 2, we shortly define our motivation for using mobility prediction with MPR. Section 3 describes the heuristic used in order to compute nodes' kinetic degrees. In Section 4, we formally describe our KMPR protocol, and in Section 5, we propose an aperiodic neighborhood maintenance strategy. Finally, Section 6 provides simulation results justifying our approach, while Section 7 draws some concluding remarks and describes some future works.

2 Preliminaries

In this section, we give a short description of mobility predictions and our motivation for using this concept in MANETs. Finally, we provide some related work on this field.

2.1 Mobility Predictions in MANETs

In mobility predictions, a mobile samples its own location continuously or periodically and constructs a model of its own movement. The model can be first order, which provides nodes' velocities, but higher and more complex models providing nodes' accelerations are also possible. The node disseminates its current model's parameters[1] in the network. Any changes to the model's parameters is reactively announced by the respective nodes. Every other node uses this information to track the location of this node. Very little location update cost is incurred if the model's prediction is accurate. For example, in Fig. 1, we compare the number of location updates needed with or without mobility predictions when using a linear first order mobility model.

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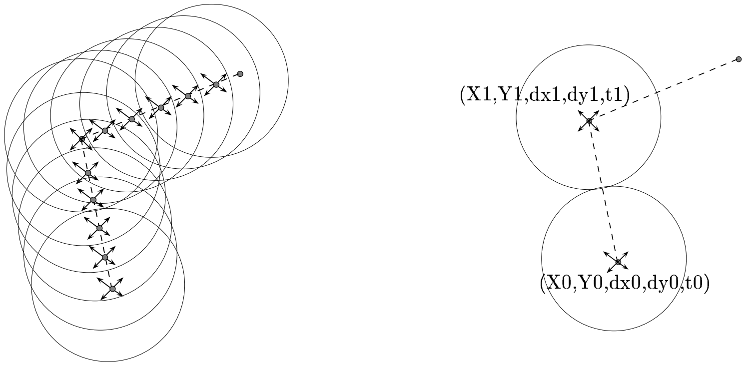
[1] The model's parameters are assumed to be valid over a relative short period of time depending on the model's complexity



(a) 1 message sent per second ⇒ A total of 12 messages in 12 seconds.

(b) 1 message sent upon any trajectory change ⇒ A total of 2 messages in 12 seconds.

Fig. 1. Illustration of the influence of mobility predictions on the number of location updates

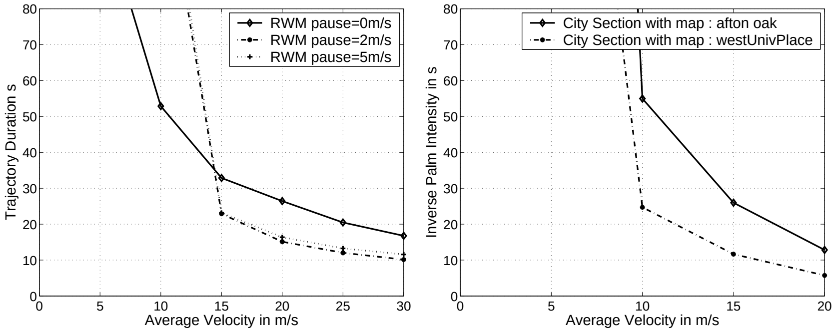
2.2 Average Linear Trajectory Durations in Ad Hoc Networks

A basic assumption in mobility prediction-based techniques is to assume that nodes move following a linear trajectory, then predict to update the neighborhood information when a trajectory change occurs. Therefore, scalability is highly dependent to the number of trajectory changes (or transitions) per unit of time, thereafter called β.

Part of the results obtained in [9] are reproduced in Fig. 2. It shows that even with an average velocity of 20m/s, nodes have an average trajectory duration of $22s$ (Fig. 2(a)) for the Random Waypoint model and $10s$ (Fig. 2(b)) for the City Section model. Figure 2 therefore provides a lower bound on the average trajectory duration, that is $\frac{1}{\beta} \approx 10s$ using extreme values for the configuration parameters of the mobility models. In more realistic situations, this value is rather $\frac{1}{\beta} \approx 30s$. Accordingly, it becomes conceivable to consider predictions to improve ad-hoc protocol the way we will do in this paper.

2.3 Related Work

Prediction-based protocols are a straight evolution of position-based methods. Indeed, this approach evolved from simple positions, to position and velocity, and finally to trajectory models. The first definition of such protocols has been done under the name *predictive distance-based* protocol [11], and has been cited in possible developments in the terminode project [10]. Almost at the same time, another study has been performed [12] which illustrated the benefits early unicast and multicast protocols could experience from mobility predictions. It is, however, only in recent months that this model started to get seriously studied. To our knowledge, the authors of [6] have been



(a) RWM with different pause times

(b) City Section with two suburban maps

Fig. 2. Average nodes' trajectory duration ($\frac{1}{\beta}$) under the Random Waypoint mobility model and the City Section

the first team to analyze it in their proposition of *Kinetic spanning trees* for ad hoc sensor networks. The authors managed to create an auto adaptive shortest path spanning tree to a sink node that was getting rid of periodic beacons inherited from the Bellman-Ford algorithm.

Later, another team studied, under the name *dead-reckoning*, the benefits of predictions for mobile ad hoc networks [15]. They showed that this model was able to deliver superior routing performances than DSR or AODV. They then extended their studies to location services [16]. They conclusions were quite similar, by noticing that the diffusion of predicted future locations of nodes in the network could improve the performances of location services. Recently, the authors in [13] proposed a paper that was analyzing the effect of trajectory predictions on topology management. By they intrinsic behavior, topology control protocols are usually considered as proactive, since they need to maintain a structure between moving nodes. However, the authors managed to show that, by using stochastic prediction-based trajectories, they could create the first totally reactive topology control protocol, in a sense that after an initial organization, the topology is maintained in an event-driven manner, without the need of periodic beacons.

Finally, in recent months many interesting papers has been presented that deal with prediction-based routing protocols. [18] presents an approach that reduces mobility-induced location errors on geographical routing using mobility predictions. [17] in other hand, make use of mobility prediction in order to improve routing protocols. This global interest in mobility predictions greatly justified the motivation we have to dig into that direction, since we firmly believe that such approach would improve any protocol under any configuration.

In this paper, our objective will be to develop a predicted model adapted to the MPR protocol by modeling nodes predicted degrees, also called *kinetic degree*.

3 Kinetic Nodal Degree in MANETs

We explain in this section the method for modeling kinetic degrees in MANETs. We model nodes' positions as a piece-wise linear trajectory and, as we showed in Section 2.2, the corresponding trajectory durations are lengthy enough to become a valuable cost for using kinetic degrees.

The term ”Kinetic” in KMPR reflects the motion aspect of our algorithm, which computes a node's trajectory based on its Location Information [6]. Such location information may be provided by the Global Positioning System (GPS) or other solutions exposed in [7] or [8]. Velocity may be derived through successive location samples at close time instants. Therefore, we assume a global time synchronization between nodes in the network and define x, y, dx, dy as the four parameters describing a node's position and instant velocity [2], thereafter called *mobility*.

Over a relatively short period of time [3], one can assume that each such node, say i, follows a linear trajectory. Its position as a function of time is then described by

$$\mathbf{Pos}_i(t) = \begin{bmatrix} x_i + dx_i \ \cdot \ t \\ y_i + dy_i \ \cdot \ t \end{bmatrix}, \tag{1}$$

where $Pos_i(t)$ represents the position of node i at time t, the vector $[x_i,\ y_i]^T$ denotes the initial position of node i, and vector $[dx_i,\ dy_i]^T$ its initial instantaneous velocity. Let us consider node j as a neighbor of i. In order to let node i compute node j's trajectory, let us define the squared distance between nodes i and j as

$$\begin{aligned} D^2_{ij}(t) = D^2_{ji}(t) &= \|\mathbf{Pos}_j(t) - \mathbf{Pos}_i(t)\|^2_2 \\ &= \left(\begin{bmatrix} x_j - x_i \\ y_j - y_i \end{bmatrix} + \begin{bmatrix} dx_j - dx_i \\ dy_j - dy_i \end{bmatrix} \ \cdot \ t \right)^2 \\ &= a_{ij}t^2 + b_{ij}t + c_{ij}, \end{aligned} \tag{2}$$

where $a_{ij} \geq 0$, $c_{ij} \geq 0$. Consequently, a_{ij}, b_{ij}, c_{ij} are defined as the three parameters describing nodes i and j mutual trajectories, and $D^2_{ij}(t) = a_{ij}t^2 + b_{ij}t + c_{ij}$, representing j's relative distance to node i, is denoted as j's linear relative trajectory to i. Consequently, thanks to Eq. 1, a node is able to compute the future position of its neighbors, and by using Eq. 2, it is able to extract any neighboring nodes' future relative distance.

Considering r as nodes maximum transmission range, as long as $D^2_{ij}(t) \leq r^2$, nodes i and j are neighbors. Therefore, solving

$$\begin{aligned} D^2_{ij}(t) - r^2 = 0 \\ a_{ij}t^2 + b_{ij}t + c_{ij} - r^2 = 0, \end{aligned} \tag{3}$$

gives t^{from}_{ij} and t^{to}_{ij} as the time intervals during which nodes i and j remain neighbors. Consequently, we can model nodes' kinetic degree as two successive sigmoid

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[2] We are considered moving in a two-dimensional plane.

[3] The time required to transmit a data packet is orders of magnitude shorter than the time the node is moving along a fixed trajectory.

functions, where the first one jumps to one when a node enters another node's neighborhood, and the second one drops to zero when that node effectively leaves that neighborhood (see Fig. 3).

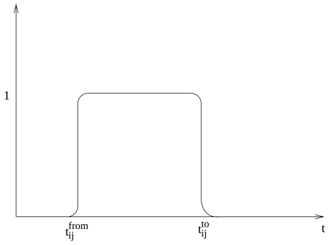
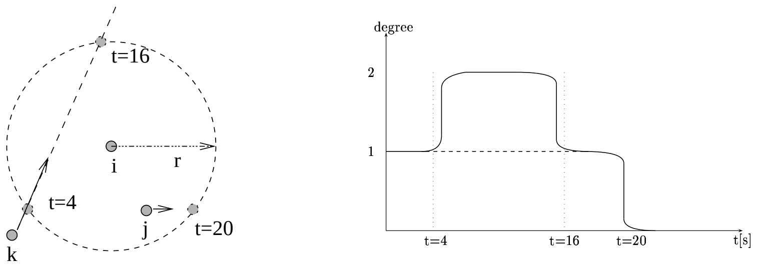


Fig. 3. Double sigmoid function modeling a link lifetime between node i and node j

Considering $nbrs_i$ as the total number of neighbors detected in node i's neighborhood at time t, we define

$$Deg_i(t) = \sum_{k=0}^{nbrs_i} \left(\frac{1}{1+\exp(-a \cdot (t - t_k^{from}))} \cdot \frac{1}{1+\exp(a \cdot (t - t_k^{to}))} \right) \tag{4}$$

as node i's kinetic degree function, where t_k^{from} and t_k^{to} represent respectively the time a node k enters and leaves i's neighborhood. Thanks to Eq. 4, each node is able to predict its actual and future degree and thus is able to proactively adapt its coverage capacity. Figure 4(a) illustrates the situation for three nodes. Node k enters i's neighborhood at time $t = 4s$ and leave it at time $t = 16s$. Meanwhile, node j leaves i's neighborhood at time $t = 20s$. Consequently, Fig. 4(b) illustrates the evolution of the kinetic degree function over t.



(a) Node i kinetic neighborhood

(b) Node i kinetic nodal degree

Fig. 4. Illustration of nodes kinetic degrees

Finally, the kinetic degree is obtained by integrating Eq. 4

$$\widehat{Deg}_i(t) = \int_t^{\infty} \left(\sum_{k=0}^{k=nbrs_i} \left(\frac{1}{1+\exp(-a \cdot (t - t_k^{from}))} \cdot \frac{1}{1+\exp(a \cdot (t - t_k^{to}))} \right) \right) \tag{5}$$

For example, in Fig. 4(b), node i kinetic degree is ≈ 32.

4 Kinetic Multipoint Relays

In this section, we describe our Kinetic Multipoint Relaying (KMPR) protocol. It is mainly extracted from the regular MPR protocol. Yet, we adapt it to deal with kinetic degrees.

To select the kinetic multipoint relays for node i, let us call the set of 1-hop neighbors of node i as $N(i)$, and the set of its 2-hops neighbors as $N^2(i)$. We first start by giving some definitions.

Definition 1 (Covering Interval). *The covering interval is a time interval during which a node in $N^2(i)$ is covered by a node in $N(i)$. Each node in $N^2(i)$ has a covering interval per node i, which is initially equal to the connection interval between its covering node in $N(i)$ and node i. Then, each time a node in $N^2(i)$ is covered by a node in $N(i)$ during a given time interval, this covering interval is properly reduced. When the covering interval is reduced to $\emptyset$, we say that the node is fully covered.*

Definition 2 (Logical Kinetic Degree). *The logical kinetic degree is the nodal degree obtained with Eq. 5 but considering covering intervals instead of connection intervals. In that case, t_k^{from} and t_k^{to} will then represent the time interval during which a node $k \in N^2(i)$ starts and stops being covered by some node in $N(i)$.*

The basic difference between MPR and KMPR is that unlike MPR, KMPR does not work on time instants but on time intervals. Therefore, a node is not periodically elected, but is instead designated KMPR for a time interval. During this interval, we say that the KMPR node is active and the time interval is called its activation.

The KMPR protocol elects a node as KMPR a node in $N(i)$ with the largest logical kinetic degree. The activation of this KMPR node is the largest covering interval of its nodes in $N^2(i)$.

Kinetic Multipoint Relaying (KMPR).
The KMPR protocol applied to an initiator node i is defined as follows:

- Begin with an empty KMPR set.
- First Step: Compute the logical kinetic degree of each node in $N(i)$.
- Second Step: Add in the KMPR set the node in $N(i)$ that has the maximum logical kinetic degree. Compute the activation of the KMPR node as the maximum covering interval this node can provide. Update all other covering intervals of nodes in $N^2(i)$ considering the activation of the elected KMPR, then recompute all logical kinetic degrees. Finally, repeat this step until all nodes in $N^2(i)$ are fully covered.

Then, each node having elected a node KMPR for some activations is then a KMPR Selector during the same activation. Finally, *KMPR flooding* is defines as follows:

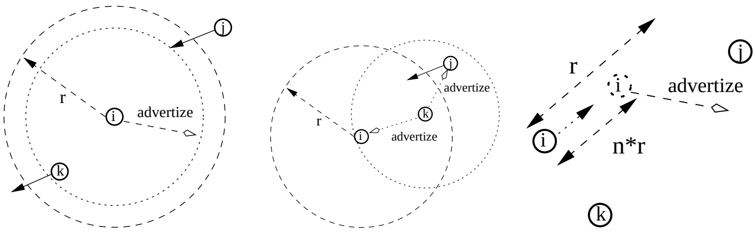
Definition 3 (KMPR flooding). *A node retransmits a packet only once after having received the packet the first time from an active KMPR selector.*

5 Adaptive Aperiodic Neighborhood Maintenance

A limitation in per-event maintenance strategies is the neighborhood maintenance. While mobility prediction allows to discard invalid links or unreachable neighbors, it remains impossible to passively acquire new neighbors reaching some other nodes' neighborhood. The lack of an appropriate method to tackle this issue would limit KMPR's ability to obtain up-to-date links and effective kinetic multipoint relays.

We developed several heuristics to help KMPR detecting nodes stealthily entering some other nodes transmission range in a non-periodic way.

- ***Constant Degree Detection—*** Every node tries to keep a constant neighbor degree. Therefore, when a node i detects that a neighbor actually left its neighborhood, it tries to acquire new neighbors by sending a small advertising message. (see Figure 5(a));
- ***Implicit Detection—*** A node j entering node i transmission range has a high probability to have a common neighbor with i. Considering the case depicted in Figure 5(b), node k is aware of both i and j's movement, thus is able to compute the moment at which either j or i enters each other's transmission range. Therefore, node k sends a notification message to both nodes. In that case, we say that node i implicitly detected node j and vice versa;
- ***Adaptive Coverage Detection—*** We require each node to send an advertising message when it has moved a distance equal to a part of its transmission range. An adjusting factor which vary between 0 and 1 depends on the node's degree and its velocity (see Figure 5(c));

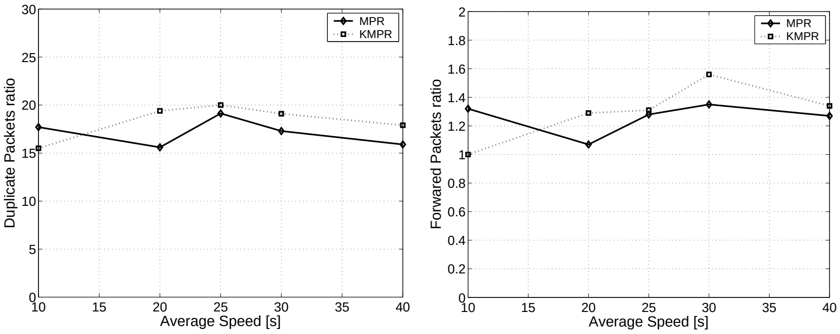


(a) Constant Degree Detection (b) Implicit Detection (c) Adaptive Coverage Detection

Fig. 5. Three heuristics to detect incoming neighbors in a per-event basis

6 Simulation Results

We implemented the KMPR protocol under ns-2 and used the NRL-MPR [19] implementation for comparison with KMPR. We measured several significant metrics for Manets: The effectiveness of flooding reduction, the delay before the network receives a broadcast packet, the number of duplicate packets and finally the routing overhead. The following metrics were obtained after the population of 20 nodes were uniformly distributed in a 1500×300 grid. Each node has a transmission range of $250m$. The mobility model we used is the standard Random Mobility Model where we made nodes average velocity vary from $5m/s$ to $30m/s$. Finally, we simulated the system for $100s$.



(a) Duplicate reception

(b) Forwarding Nodes

Fig. 6. Illustration of the flooding reduction of MPR and KMPR

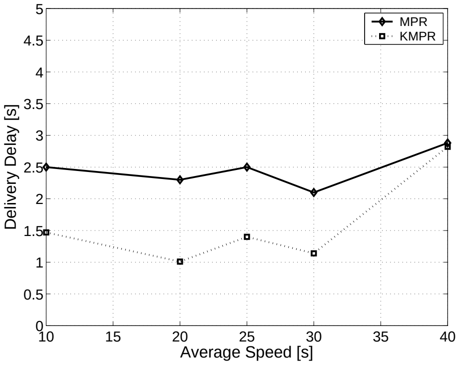
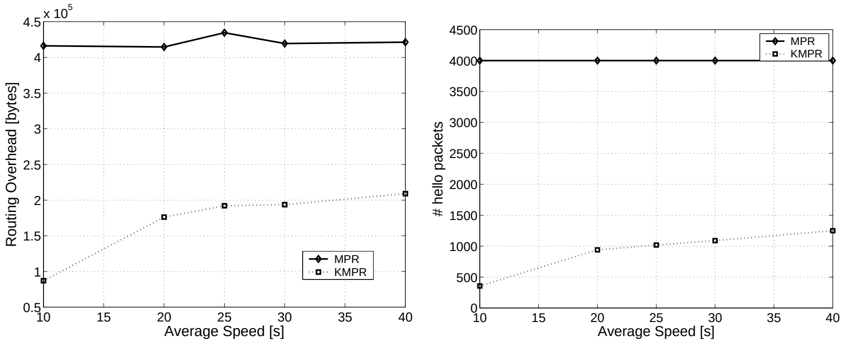


Fig. 7. Illustration of the broadcast efficiency of MPR and KMPR

Figure 6 illustrates the flooding reduction of MPR and KMPR. Although MPR is slightly more performing than KMPR, we can see that both protocols are close together and have a fairly good flooding reduction, both in terms of duplicate and forwarded packets. Note that the low fraction of relays in Fig 6(b) comes from the rectangular topology, where only a couple of MPRs are used as bridge in the center of the rectangle.

On Figure 7, we depicted the broadcast efficiency of MPR and KMPR. In the simulations we performed, we measured the broadcast efficiency as the time a packet takes before being correctly delivered to the entire network. As we can see, KMPR has a delivery time faster than MPR by 50%. This might comes from two properties of KMPR. Firstly, as described in [14], MPR suffers from message decoding issues. Indeed, MPR often discards correct neighborhood information based on wrong message decoding. It therefore relies on several iterations before being able to obtain correct information about nodes neighborhood. Since MPR nodes are periodically recomputed, the time before which MPR is operational also increases. In KMPR, since we do not rely on periodic retransmissions, we changed the decoding order as suggested in [14]. Secondly, as we will see in the next figure, KMPR's backbone maintenance is significantly less than MPR. Therefore, the channel access is faster and the probability of collisions is decreased.

In the two previous figures, we have shown that KMPR had similar properties than MPR in term of flooding reduction and delay. Now, in Figure 8, we illustrate the principal benefit of KMPR: its *low routing overhead*. Indeed, since KMPR uses mobility predictions and does not rely on periodic maintenance, the routing overhead may be reduced by 75% as it may be seen on Fig. 8(a). We also show on Fig. 8(b) the number of hello messages which drops dramatically with KMPR, yet still preserving the network's consistency.



(a) Routing overhead

(b) Number of Hello packets

Fig. 8. Illustration of the network load for MPR and KMPR

7 Conclusion and Future Works

In this paper, we presented a original approach for improving the well-known MPR protocol by using mobility predictions. We showed that the Kinetic Multipoint Relaying (KMPR) protocol was able to meet the flooding properties of MPR, and this by reducing the MPR channel access by 75% and MPR broadcast delay by 50%. We consequently illustrated that, after having been studied in other fields of mobile ad hoc networking, mobility predictions are also an interesting technique to improve broadcasting protocols.

In the final version of this paper, we intend to include simulations considering an increased number of nodes and a larger variety of scenarios on order to test KMPR scalability.

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