Topology-based Mobility Models for Wireless Networks

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Abstract. The performance and reliability of wireless network protocols heavily depend on the network and its environment. In wireless networks node mobility can affect the overall performance up to a point where, e.g. route discovery and route establishment fail. As a consequence any formal technique for performance analysis of wireless network protocols should take node mobility into account. In this paper we propose a topology-based mobility model, that abstracts from physical behaviour, and models mobility as probabilistic changes in the topology. We demonstrate how this model can be instantiated to cover the main aspects of the random walk and the random waypoint mobility model. The model is not a stand-alone model, but intended to be used in combination with protocol models. We illustrate this by two application examples: first we show a brief analysis of the Ad-hoc On demand Distance Vector (AODV) routing protocol, and second we combine the mobility model with the Lightweight Medium Access Control (LMAC).

1 Introduction

The performance and reliability of network protocols heavily depend on the network and its environment. In wireless networks node mobility can affect the overall performance up to a point where e.g. route discovery and route establishment fail. As a consequence any formal technique for analysis of wireless network protocols should take node mobility into account.

Traditional network simulators and test-bed approaches usually use a detailed description of the physical behaviour of a node: models include e.g. the location, the velocity and the direction of the mobile nodes. In particular changes in one of these variables are mimicked by the mobility model. It is common for network simulators to use *synthetic models* for protocol analysis [15]. In this class of models, a mobile node randomly chooses a direction and speed to travel from its current location to a new location. As soon as the node reaches the

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new location, it randomly chooses the next direction. Although these models abstract from certain characteristics such as acceleration, they still cover most of the physical attributes of the mobile node. Two well-known synthetic mobility models are the *random walk* (e.g. [1]) and the *random waypoint model* (e.g. [2]).

However, a physical mobility model is often incompatible with models of protocols, in particular protocols in the data link and network layers, due to limitations of the used modeling language and analysis tools. Even if it could be included, it would add a high complexity and make automatic analysis infeasible. From the point of view of the protocol it is often sufficient to model changes on the topology (connectivity matrix) rather than all physical behaviour.

In this paper we propose a topology-based mobility model that abstracts from physical behaviour, and models mobility as probabilistic changes in the topology. The main idea is to identify the position of a node with its current set of neighbours and determine changes in the connectivity matrix by adding or deleting nodes probabilistically to this set. The probabilities are distilled from the random walk or the random waypoint model. The resulting model is not meant to be a stand-alone model, but to be used in combination with protocol models. For this, we provide an Uppaal template for our model, which can easily be added to existing protocol models. The paper illustrates the flexibility of our model by two application examples: the first analyses quantitative aspects of the Ad hoc On-Demand Distance Vector (AODV) protocol [14], a widely used routing protocol, particularly tailored for wireless networks; the second example presents an analysis of the Lightweight Media Access Control (LMAC) [12], a protocol designed for sensor networks to schedule communication, and targeted for distributed self-configuration, collision avoidance and energy efficiency.

The rest of the paper is organised as follows: after a short overview of related work (Sect. 2), we develop the topology-based mobility model in Sect. 3. In Sect. 4 we present a simulator that is used to compute the transition probabilities for two common mobility models. In Sect. 5, we combine the distilled probabilities with our topology-based model to create an Uppaal model. Before concluding in Sect. 7, we illustrate how the model can be used in conjunction with protocol models. More precisely we present a short analysis of AODV and LMAC.

2 Related Work

Mobility models are part of most network simulators such as ns-2. In contrast to this, formal models used for verification or performance analysis usually assume a static topology, or consider a few scenarios with changing topology only. For the purpose of this section, we distinguish two research areas: mobility models for network simulators and models for formal verification methods.

Mobility models for network simulators either replay traces obtained from real world, or they use synthetic models, which abstract from some details and generate mobility scenarios. There are roughly two dozen different synthetic models (see [15, 4] for an overview), starting from well-known models such as the *random walk model* (e.g. [1]) and the *random way point model* (e.g. [2]), via *(partially) deterministic models* and *Manhattan models* to *Gauss-Markov* and *gravity mobility models*. All these models are based on the physical behaviour of mobile nodes, i.e. each node has a physical location (in 2D or 3D[1]), a current speed and a direction it is heading to. As these models cover most of the physical behaviour, they are most often very complex (e.g. [13, 10]) and include for example mathematics for Brownian motion. Due to this complexity these models cannot be incorporated directly into formal models for model-checking. This paper describes how two of these models, the random waypoint, and the random walk model, can be used to distill transition probabilities for a mobility model, which can easily be combined with formal protocol models.

Including mobility into a model for formal verification is not as common as it is for network simulators. If they are included, then typically in the protocol specification and therefore can rarely be reused for the analysis of different protocols. Moreover, formal verification often abstracts entirely from the underlying mobility model and allows arbitrary topology changes [9, 5, 8]. Other approaches allow only random, but very limited changes in the topology, often in the form of a scenario that involves deletion or creation of links [6, 18, 17]. Song and Godskesen propose in [16] a framework for modelling mobility; it models connectivity by distributions and propose a probabilistic mobility function to model mobility, without any specifics. This paper takes a similar approach, but adjacency matrices to model connectivity, and works out and analyses the transition probabilities obtained for two mobility models.

Our contribution is the following: we take the idea that the position of a mobile node can be characterised by a set of neighbours, which determines the topology, and we then define mobility as transitions between these sets. We then analyse the geometry of mobile nodes in a grid and determine which parameters actually influence the transition probabilities. In fact we found that some parameters, such as the step size of the random walk model have no influence on the transition probabilities. Based on this observation we build a topology-based mobility model which can easily be combined with protocol models.

3 Topology-based Mobility Model

Our model takes up the position of the protocol: for a protocol it only matters whether data packets can be sent to a node, i.e. whether the node is within transmission range. The speed, the direction and other physical attributes are unimportant and irrelevant for the protocol. Hence the topology-based mobility model we introduce abstracts from all physical description of a node, and also largely abstracts from time. It models the node as a set of one-hop neighbours, i.e. nodes that are within transmission range of the node. Movement is modelled as a transition from one set of neighbours to another.

We assume that the node to be modelled moves within a quadratic $N \times N$-grid of stationary nodes. For simplicity we assume that nodes in the grid have a

[1] 3D is required when nodes model aerospace vehicles, such as UAVs.

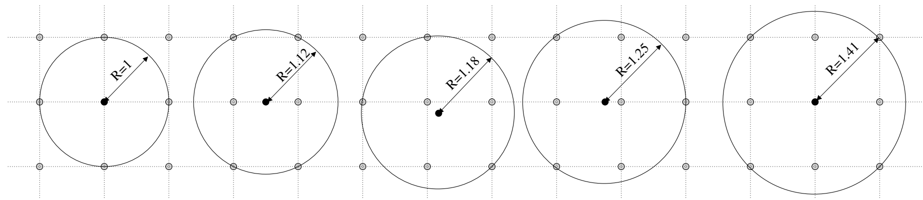

Fig. 1. Transmission ranges 1, $\frac{\sqrt{5}}{2} \approx 1.12$, $\frac{5}{6}\sqrt{2} \approx 1.18$, 1.25 and $\sqrt{2} \approx 1.41$.

distance of 1, and that both the stationary and the mobile node have the same transmission range R. Obviously, the model depends on the grid size and the transmission range. We further assume that the transition range R is larger than 1 and strictly smaller than $\sqrt{2}$. If it were smaller than 1 nodes in the grid would be outside of the range of all neighbours, if it were larger than $\sqrt{2}$ nodes could communicate diagonally in the grid.

The network topology of all nodes, including the mobile node, can be represented by an adjacency or *connectivity matrix* A with

$$A_{i,j} = \begin{cases} 1 & \text{if } D(i,j) \leq R \\ 0 & \text{otherwise} \end{cases},$$

where $D(i,j)$ is the distance between the nodes i and j using some kind of metric, such as the Euclidean distance. While the connectivity matrix has theoretically 2^{N^2} possible configurations, with N the number of nodes, a network with one mobile node will only reach a small fraction of those. First, the matrix is symmetric. Second, all nodes, except for one, are assumed static, and the connectivity $A_{i,j}$ between two static nodes i and j will be constant. Third, due to the geometry of the plane, even the mobile node can only have a limited number of configurations. For example, neither a completely connected node, nor a completely disconnected node is possible given the transmission range.

The possible topologies depend on the transmission range: the larger the range the larger the number of possible nodes that can be connected to the mobile node. Within the right-open interval $[1, \sqrt{2})$, the set of possible topologies changes at values $\frac{\sqrt{5}}{2}$, $\frac{5}{6}\sqrt{2}$ and 1.25. These values can be computed with basic trigonometry. Fig. 1 illustrates which topologies become possible at those transmission ranges.

By considering the transmission range of the stationary nodes, one can partition the plane into regions in which mobile nodes will have the same set of neighbours. The boundaries of these regions are defined by circles with radius R around the stationary nodes. Fig. 2 depicts three possible regions and a transmission range $R = 1.25$; stationary nodes that are connected to the mobile node (located somewhere in the coloured area) are highlighted. As convention we will number nodes from the top left corner, starting with node 0. This partitioning abstracts from the exact location of the mobile node. Mobility can now be expressed as a change from one region to the next. The topology-based model will capture the changing topology as a Markovian transition function, that assigns to a pair of topologies a transition probability.

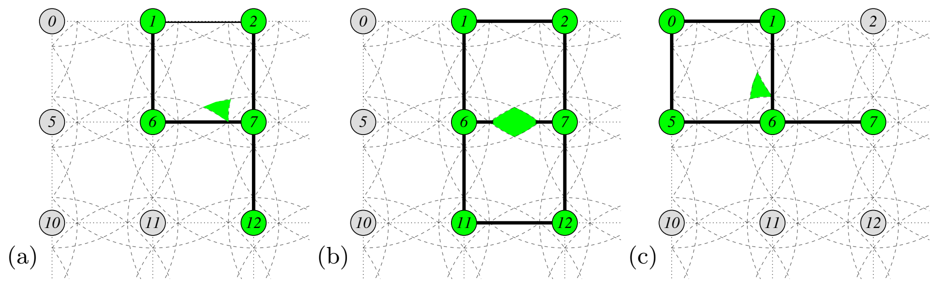

Fig. 2. Three regions and the corresponding set of neighbours for range $R = 1.25$.

The number of possible transitions is also limited by the partition, as every region is bounded by a small number of arcs. If a mobile node transits an arc, a static node has to be added to or deleted from its set of neighbours. Consider, for example, the region that corresponds to set $\{1, 2, 6, 7, 12\}$ in Fig. 2(a). If the mobile node crosses the arc to the bottom left, node 11 will be added (Fig. 2(b)). The other two arcs of $\{1, 2, 6, 7, 12\}$ define the only two other transitions that are possible from this set.

We call a mobility model *locally defined* if congruent regions yield the same transition probabilities. Regions are congruent if they can be transformed into each other by rotation, reflection and translation. By extension we call transitions that correspond to congruent arcs in such regions also congruent. The movement of a node in a locally defined mobility model is independent from its exact position in the grid. The changes that can occur depend only on the topology of the current neighbours. For example, the congruent sets $\{1, 2, 6, 7, 12\}$ and $\{0, 1, 5, 6, 7\}$ in Fig. 2(a) and (c), would have the same transition probabilities.

In some cases this principle will uniquely determine the transition probability: the set $\{1, 2, 6, 7, 11, 12\}$ in Fig. 2(b) is bounded by 4 identical arcs. This means that all of them should correspond to a probability of $\frac{1}{4}$. For other regions the partition implies a relation/equation between some probabilities, but does not determine them completely. Considering only transition in a single cell of the grid yields just a few and very symmetric transitions between possible topologies. Fig. 3 depicts the transitions as transitions between topologies.

One way to assign probabilities is to require that they are proportional to the length of the arc. Alternatively, probabilities may be estimated by simulations of a moving node in the plane. Note, that the resulting probabilistic transition system will be memoryless, i.e. the probability of the next transition depends only on the current region (set of neighbours). In the next section, we will see that the common random waypoint model is not locally defined, i.e. the local topology is not sufficient to determine the transition probabilities.

4 Simulations of Two Mobility Models

In the previous section we proposed a topology-based mobility model, based on transition probabilities; the exact values for the probabilities, however, were

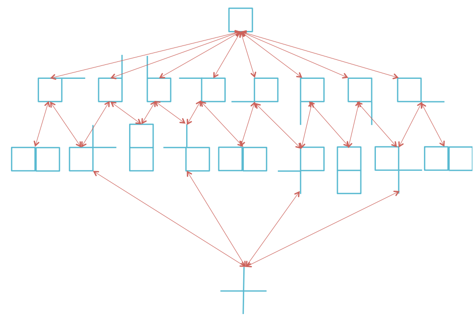

Fig. 3. Possible transitions within a single grid cell for $R = 1.25$.

not specified. In this section we use a simulator to compute it for two common mobility models, a random walk model, and a random waypoint model.

4.1 Simulator

The simulator considers a single mobile node in an $N \times N$ grid of stationary nodes. As before, we assume a distance of 1 between the nodes on the grid. The initial position (x_0, y_0) of the mobile node is determined by a uniform distribution over $[0, N-1] \times [0, N-1]$, i.e. $x_0 \sim \mathcal{U}([0, N-1])$ and $y_0 \sim \mathcal{U}([0, N-1])$. Depending on the mobility model chosen, the simulator then selects a finite number of waypoints $(x_1, y_1), \ldots, (x_n, y_n)$, and moves along a straight line from waypoint (x_i, y_i) to the next (x_{i+1}, y_{i+1}).

The *random waypoint* model uses a uniform distribution over the grid to select the next way point, i.e. for all x_i, we have y_i, $x_i \sim \mathcal{U}([0, N-1])$ and $y_i \sim \mathcal{U}([0, N-1])$. The choice of the next waypoint is independent of the previous waypoint. This model is the most common model of mobility for network simulators, even if its merits have been debated [19]. A consequence of the waypoint selection is that the direction of movement is not uniformly distributed; nodes tend to move more towards the centre of the square interval.

As an alternative we are using a simple *random walk* model. Given way point (x_i, y_i) the next way point is computed by $(x_i, y_i) + (x_\Delta, y_\Delta)$ where both x_Δ and x_Δ are drawn from a normal distribution $\mathcal{N}(0, \sigma)$. This also means that the Euclidean distance between waypoints $||(x_\Delta, y_\Delta)||$ has an expected value of σ, which defines the average step size in the random walk model. By this definition, the model is unbounded, i.e. the next waypoint may lie outside the grid. If this happens the simulator computes the intersection of the line segment with the grid's boundary and reflects the waypoint at that boundary. In this model the mobile node moves from the first waypoint to the boundary, and from there to the reflected waypoint. For the purposes of this paper the intersections with the boundary do not count as waypoints.

Since the topology-based mobility model introduced in Sect. 3 abstracts from acceleration and speed, these aspects are not included in the simulation either. The simulator checks algebraically for every line segment from (x_i, y_i) to

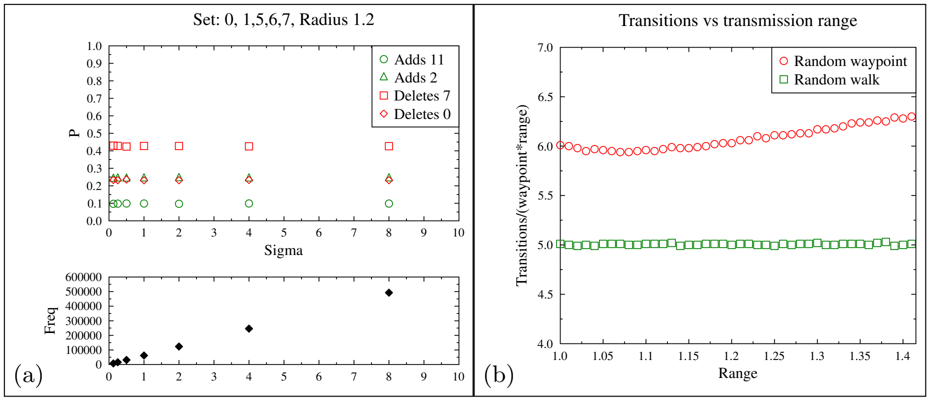

Fig. 4. (a) Transition probabilities and occurrences of set $\{0, 1, 5, 6, 7\}$. (b) The relation between number of transitions, the number of waypoints, and the transmission range.

(x_{i+1}, y_{i+1}) if it intersects with a node's transmission range R (given by a circle with radius R and the node in its centre). The simulator sorts all the events of nodes entering and leaving the transmission range and computes a sequence of sets of neighbours. This sequence is then used to count occurrences of transitions between these sets that are used to compute relative transition probabilities.

4.2 Simulation Results

The simulator is implemented in `C++`, and used to generate transition probabilities for the topology-based mobility model of Section 3. The simulator allows also a more detailed analysis of these two mobility models, in particular how the choice of parameters (grid size, transmission range, and standard deviation of the normal distribution σ) affects the transition probabilities. In this section we discuss some results for scenarios with a single mobile node on a 5×5 grid.

The simulation of the random walk model demonstrates a few important invariants. One observation is that the transition probabilities do not depend on the size of σ. This fact is illustrated by Fig. 4(a). The top part of this figure shows the probabilities that certain nodes are added or deleted from the set $\{0, 1, 5, 6, 7\}$. While σ ranges from $\frac{1}{8}$ to 8 the probabilities remain constant. The bottom part of the figure depicts the frequency with which the set occurs. Here there is a linear relation between σ and the total number of times that the set is visited. This is explained by the fact that σ is also the average step size, and doubling it means that twice as many transitions should be taken along the path.

Another linear relation exists between the total number of transitions along a path and the transmission range (cf. Fig. 4(b)). This relation is explained by the fact that the length of the boundary of each transmission area is linear to the range. For $\sigma = 1$, and $R = 1$, approximately 5 transitions will occur between any two waypoints. The ratio transition/range is constant for an increasing range. Note, that this number is independent of the grid size, and grows linearly with σ.

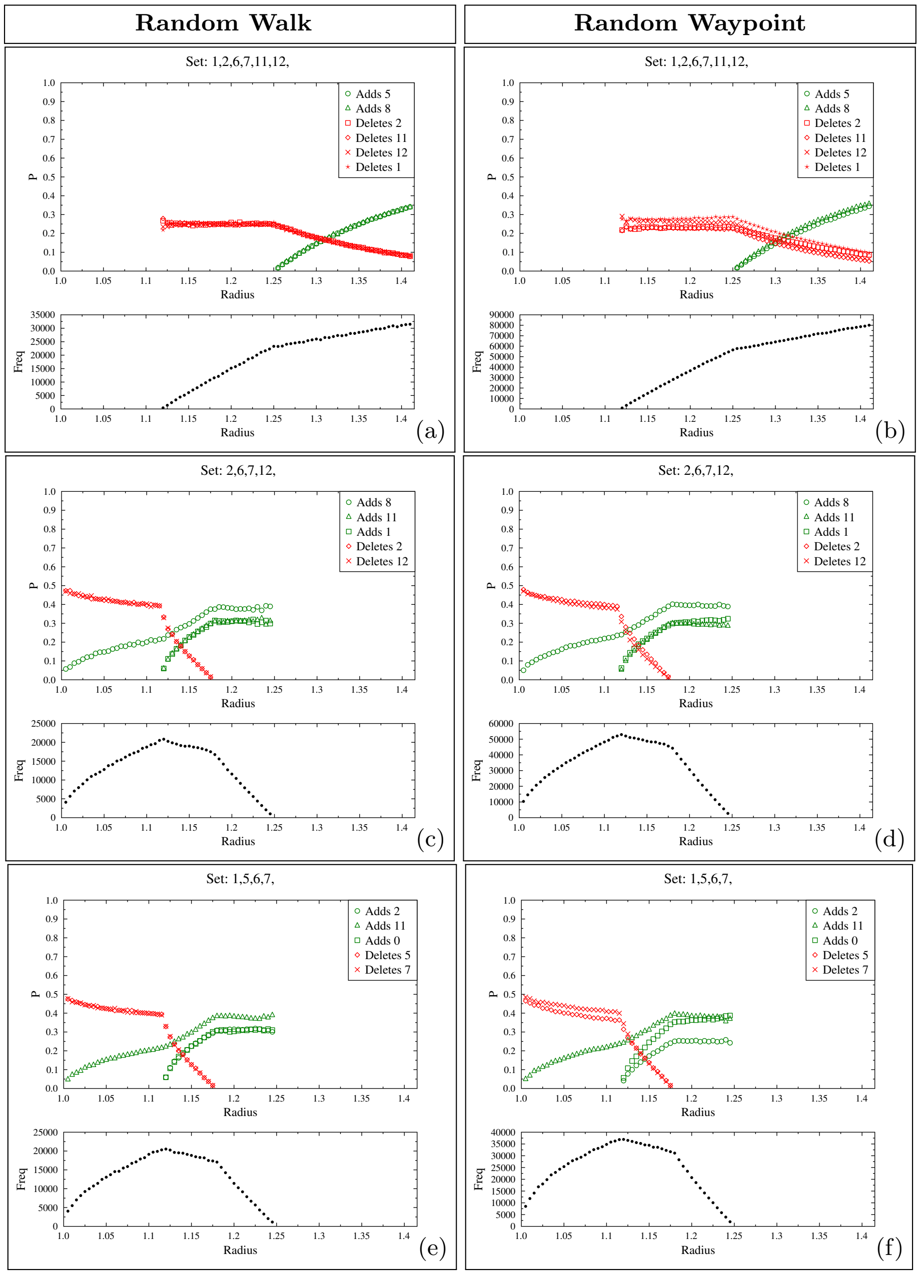

Fig. 5. Selected simulation results of the random walk and the random waypoint model.

These invariants do not hold for the random waypoint model. The ratio of transitions to range is not constant, as illustrated in Fig. 4(b). This is because transitions are not evenly distributed but cluster towards the center of the grid. The ratio is also dependent on the size of the grid. In a larger grid the distance between waypoints will be larger, and more transitions occur per waypoint.

For the random walk model we found that the step size σ has no effect on the actual transition probabilities. The effect of the transmission range on the transition probabilities is less trivial. Fig. 5 shows a few illustrative examples. Similar result were obtained for all possible sets of neighbours.

Fig. 5(a) depicts the results for $\{1, 2, 6, 7, 11, 12\}$, a set of six nodes that form a rectangle. This set cannot occur if the transmission ranges are smaller than $\frac{\sqrt{5}}{2}$ (cf. Sect. 3). For transmission ranges $R \in [\frac{\sqrt{5}}{2}, 1.25]$ the only possible transitions are to delete one of the four vertices located at the corners of the rectangle. In the random walk model the probability for these four transitions is $\frac{1}{4}$. Fig. 5(a) also illustrates that for transmission ranges $R \geq 1.25$, it is possible to add one additional node (either 5 or 8), reaching a set with 7 one-hop neighbours. As the range increases, the probability of this happening increases. At the same time the probability of deleting a vertex decreases.

Fig. 5(b) consider the same set of neighbours as Fig. 5(a), but under the random waypoint model. It demonstrates that this model is not locally defined, as congruent transitions, e.g. deleting vertices, do not have the same probability. The probability also depends of the distance of a node to the centre of the grid.

Fig. 5(c–f) show the transition probabilities for sets of neighbours that occur only if $R \in [1, 1.25]$: if $R < 1$, the transmission range is too small to cover the sets $\{2, 6, 7, 12\}$ and $\{1, 5, 6, 7\}$, resp.; if $R > 1.25$ the transmission range of the mobile will always contain more than four nodes. The observation is that as the transmission range increases, the probability of deleting a node decreases, while the probability of adding nodes increases. The sets $\{2, 6, 7, 12\}$ and $\{1, 5, 6, 7\}$ have the same basic "⊤" shape; one is congruent to the other. Hence, for the random walk model both sets have essentially the same transition probability; but also the frequency with which the sets occur is the same. This confirms that the position or orientation in the grid does not matter.

For the random waypoint model this no longer holds. The transition probabilities of similarly shaped neighbourhoods are not similar, but also determined by the position relative to the centre: the closer the set is to the centre the often it occurs in paths. Note, Fig. 1(d) and (f) use different scales for the frequency.

To conclude this section, we summarise our findings:

Random walk model:

- The transition probabilities are independent of σ and the grid size;
- The number of transitions per waypoint path grows linear with the range;
- The transition probabilities of congruent transitions are the same;
- The probabilities depend only locally on the set of nodes within range.

Random waypoint model: None of the above observations hold.

Grid size	Transmission range					
	$[1, 1]$	$(1, 1.12)$	$(1.12, 1.18)$	$(1.18, 1.25)$	$[1.25, 1.25]$	$(1.25, 1.41)$
2×2	9	9	5	5	5	5
3×3	32	41	49	49	37	41
4×4	69	97	133	133	101	117
5×5	120	177	257	257	197	233
6×6	185	281	421	421	325	389
7×7	264	409	625	625	485	585
8×8	357	561	869	869	677	821
9×9	464	737	1153	1153	901	1097
10×10	585	937	1477	1477	1157	1413

Table 1. Number of possible topologies, in relation to the range and the grid size.[2]

5 Uppaal Model

This section describes an Uppaal model that implements the topology-based mobility model described in Sect. 3, and uses the transition probabilities obtained in Sect. 4. The model is not meant to be stand-alone, but meant to be used within other protocol models. It assumes that an adjacency matrix `bool topoloy[N][N]` is used. The constant `N` is the size of the grid plus the mobile node. Depending on whether the random walk or random waypoint model is used, the model includes parameters for grid size and transmission range.

The template provides a list of all possible sets of neighbours. Table 1 shows the numbers of possible sets depending on the size of the grid and the transmission range. The results show that even for relatively large grids the number of possible sets of neighbors of the mobile node is limited. They will increase the potential state space only by three order of magnitude. The reachable space may increase by more when a template for mobility is added, because the protocol might reach more states than it did for static topologies.

The Uppaal template of Fig. 6 implements a lookup table of transition probabilities. After initialisation the template loops through a transition that changes the topology probabilistically. It contains a clock `t`, a guard `t>=minframe` and an invariant `t<=maxframe` to ensure that the change happens once in the interval `[minframe,maxframe]`. The values of `minframe` and `maxframe` determine the frequency of topology changes, and hence simulate the speed of a node.

The lookup is implemented by functions `updatemapindex`, `changeprob` and `changenode`. After every topology change, the function `updatemapindex` maintains the index (`mapindex`); this index into the list of possible sets is used to look up transition probabilities for a smaller set of representative sets of neighbours. Every set of neighbours is congruent to one of these representative sets. This information is used by `changeprob` to look up for a given node i the probability that it will be added or deleted from the current set of neighbours. Function `changenode` implements that change.

[2] Results for the point intervals containing $\frac{\sqrt{5}}{2}$ and $\frac{5}{6}\sqrt{2}$ are omitted.

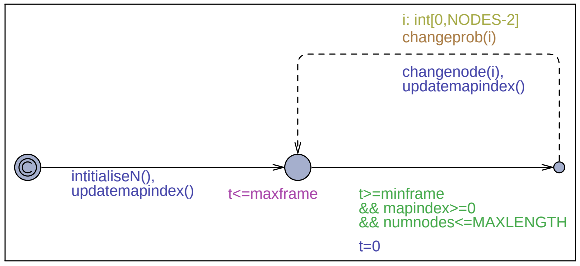

Fig. 6. Uppaal template for the mobility model.

6 Application Examples

In this section we illustrate how the topology-based model can be used in combination with protocol models: first we briefly present an analysis of the Ad-hoc On demand Distance Vector (AODV) routing protocol, and second we combine the mobility model with the Lightweight Medium Control (LMAC). A detailed study of these protocols is out of the scope of the paper; we only show the applicability and power of the introduced mobility model.

Since we are interested in quantitative properties of the protocols, we are not using "classical" Uppaal, but SMC-Uppaal, the statistical extension of Uppaal [3]. *Statistical Model Checking (SMC)* [20] combines ideas of model checking and simulation with the aim of supporting quantitative analysis as well as addressing the size barrier that currently prevents useful analysis of large models. SMC trades certainty for approximation, using Monte Carlo style sampling, and hypothesis testing to interpret the results. Parameters setting thresholds on the probability of false negatives and on probabilistic uncertainty can be used to specify the statistical confidence on the result. For this paper, we choose a confidence level of 95%.

6.1 The Ad-hoc On demand Distance Vector (AODV) Protocol

AODV is a reactive routing protocol, which means that routes are only established on demand. If a node S needs to send a data packet to node D, but currently does not know a route, it buffers the packet and initiates a route discovery process by broadcasting a route request message in the network. An intermediate node A that receives this message stores a route to S, and re-broadcasts the request. This is repeated until the message reaches D, or alternatively a node with a route to D. In both cases, the node replies to the route request by unicasting a route reply back to the source S, via the previously established route.

An Uppaal model of AODV is proposed in [6]. The analysis performed on this model was done for static topologies and for topologies with very few changes. This limits the scope of the performance analysis. Here, the mobility automaton is added to the model of AODV. Since the mobility automaton is an almost

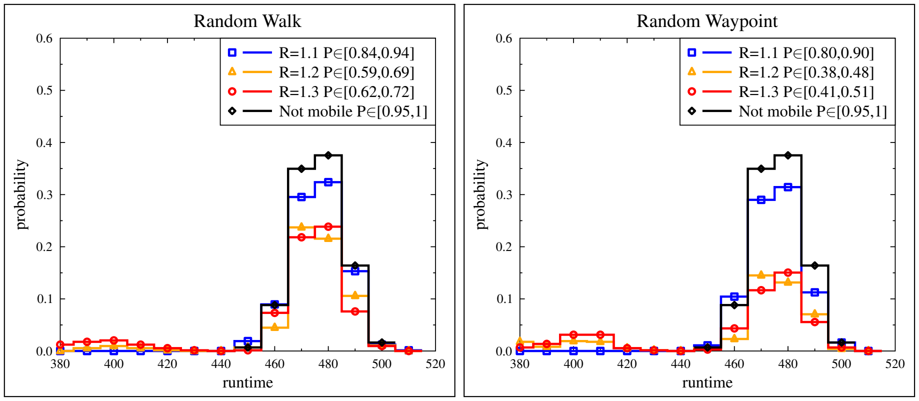

Fig. 7. AODV: probability of packet delivery within a certain time.

independent component, it can be easily integrated into any Uppaal model that model topologies by adjacency matrices.

Our experiments consider scenarios with a single mobile node moving within a 4×4 grid. A data packet destined for a randomly chosen stationary node is injected at a different stationary node. During route discovery the mobile node will receive and forward route requests and replies, as any other node will do.

The experiment determines the probability that the originator of the route request learns a route to the destination within 2000 time units. This time bound is chosen as a conservative upper bound to ensure that the analyser explores paths to a depth where the protocol is guaranteed to have terminated. In (SMC-)Uppaal syntax this property can be expressed as

$$\texttt{Pr[<=2000](<> node(OIP).rt[DIP].nhop!=0)}\ . \tag{1}$$

The variable `node(OIP).rt` denotes the routing table of the originator `OIP`, and the field `node(OIP).rt[DIP].nhop` represents the next hop on the stored route to the destination `DIP`. In case it is not `0`, a route to `DIP` was successfully established. The property was analysed for the random walk and the random waypoint model with three different transmission ranges R: 1.1, 1.2, and 1.3. SMC-Uppaal returns a probability interval for the property (1), as well as a histogram of the probabilities of the runtime needed until the property is satisfied.

The results are presented in Fig. 7. The legend contains, besides the name of the model, the probability interval. For example, the random walk model with $R = 1.1$ satisfies property (1) with a probability $P \in [0.84, 0.94]$. In contrast to that the probability of route establishment in a scenario without a mobile node is $[0.95, 1]$, which indicates that the property is always satisfied. The probability intervals show that all scenarios with a mobile node have a lower probability for route discovery, some dramatically so. The random waypoint model with $R = 1.2$ has a probability interval of $[0.38, 0.48]$, which means that more than half of all route discovery processes fail. It is also notable that the random walk models have better results than the corresponding random waypoint models. Finally, the mobility models with $R = 1.1$ have a significantly higher probability to succeed than the other four models with $R = 1.2$ and $R = 1.3$.

The histograms show another interesting finding. The time it takes for a route reply to be delivered, if it is delivered, can be shorter for the models with the mobile node. Apparently, the mobile node can function as a messenger between originator and destination; not just by forwarding messages, but also by physically creating shortcuts.

6.2 The Lightweight Medium Access Control (LMAC) Protocol

LMAC [11] is a lightweight time division medium access protocol designed for sensor networks to schedule communication, and targeted for distributed self-configuration, collision avoidance and energy efficiency. It assumes that time is divided into frames with a fixed number of time slots. The purpose of LMAC is to assign to every node a time slot different from its one- and two-hop neighbours. If it fails to do so, collisions may occur, i.e. a node receives messages from two neighbours at the same time. However, LMAC contains a mechanism to detect collisions and report them to the nodes involved, such that they choose (probabilistically) a new time slot.

A (non-probabilistic) Uppaal model for LMAC was developed in [7], where it was also used to study static topologies. Based on this model a probabilistic model was developed [11]. This model was then used to study the performance of LMAC for heuristically generated topologies with 10 nodes [3]. The model we use for this paper differs in one aspect from [3]: it uses a smaller frame, with only six time slots, rather than 20. The purpose of LMAC is to assign time slots such that collisions are avoided or resolved, even if the number of time slots is restricted. For a 3×3 grid, it is possible to find a suitable assignment with only five time slots; six time slots should therefore be sufficient to cover a network with 10 nodes (one mobile node), although it might be challenging.

We check the following two properties:

```
Pr[<=2000](<> forall (i: int[0,9]) slot_no[i]>=0)      (2)
Pr[collisions<=2000](<> time>=2000) .                   (3)
```

The first property holds if, at some time point (before time 2000), all nodes are able to select a time slot. While this does not guarantee the absence of collisions, it does guarantee that all nodes have been able to participate in the protocol. The second property checks whether it is possible to reach 2000 time units, with less than 2000 collisions. This property is true for all runs. It is used merely to obtain a histogram of the number of collisions.

The results are illustrated in the histogram of Fig. 8: for all models with a mobile node, the property (2) is satisfied (the probability interval is $[0.95, 1]$, by a confidence level of 95%). The detailed results show that all runs reach a state in which all nodes have chosen a time slot. For the model without a mobile node, the probability interval is $[0.80, 0.90]$. This means that in at least 10% of all cases LMAC is not able to assign a time slot to all nodes; the histogram shows runs with 80–90, 160–170, and 240–250 collisions. These are runs in which

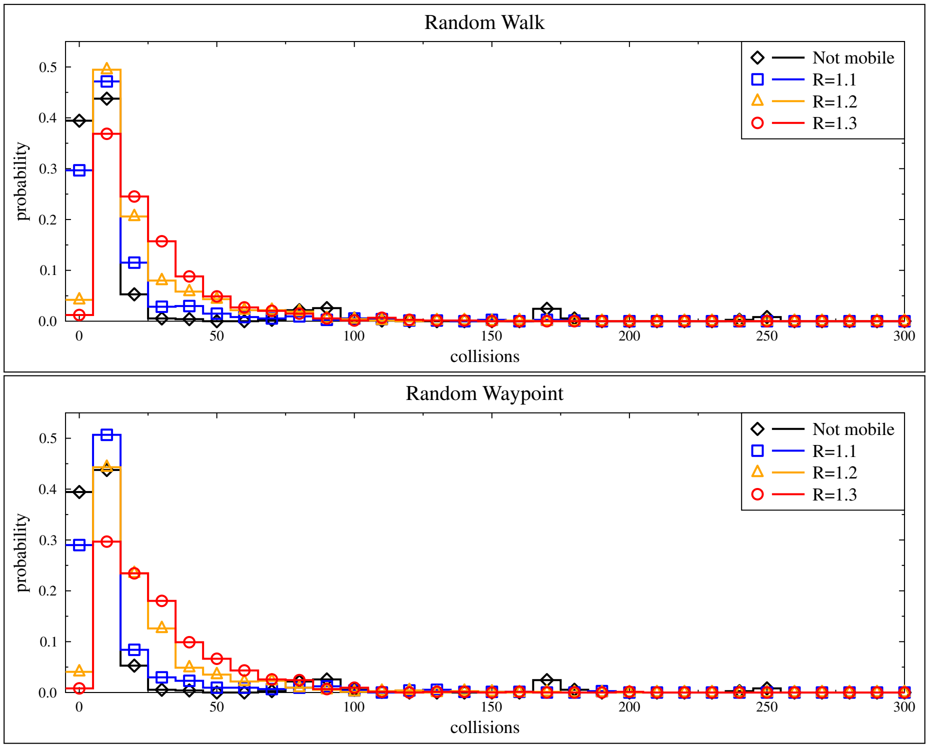

Fig. 8. LMAC: number of collisions within 2000 time units.

one, or more nodes are engaged in a perpetual collision. Interestingly, this type of perpetual collisions do not occur in models with a mobile node. The mobile node functions as an arbiter, which, as it moves around, detects and reports collisions that static nodes could not resolve.

The histograms reveal a few other interesting findings. In the model without mobility about 40% of the runs have no collisions. For both mobility models with transmission range $R = 1.1$ this drops to about 30%. For larger transmission ranges this drops even further to close to 0%, which means that almost all runs have at least some collisions. The differences between range $R = 1.1$, $R = 1.2$ and $R = 1.3$ is explained by the fact that the mobile node for $R = 1.1$ will have at most 5 neighbours, while for $R = 1.3$ it may be 7 neighbours. A larger neighbourhood makes choosing a good time slot more difficult. This is confirmed by another observation, namely that for $R = 1.1$ only a few runs have more than 20 collisions (approx. 12% of the runs, both random walk and random waypoint), while for a range of 1.2 and 1.3 it is in the range from 25% to 45%.

Both application examples show that introducing mobility can change the behaviour of network protocols significantly. As mentioned above, the purpose of these application examples was not to analyse these protocols in detail, but to show that the topology-based mobility models can be used to improve the scope of performance analyses of such protocols.

7 Conclusion

In this paper we have proposed an abstract, reusable, topology-based mobility model for wireless networks. The model abstracts from all physical aspects of a node as well as from time, and hence results in a simple probabilistic model. To choose a right level of abstraction, we have studied possible transitions and configurations of network topologies. To determine realistic transition probabilities regarding existing mobility models, we have performed simulation-based experiments. In particular, we have distilled probabilities for the random walk and the random waypoint model (using different transition ranges). We have then combined the topology-based model with the distilled probabilities and have created a (SMC-)Uppaal model[3]. The generated model is small and can easily be combined with other Uppaal models specifying arbitrary protocols. To illustrate this claim we have combined our model with a model of AODV and LMAC, resp. By this we were able to demonstrate that topology-based mobility models can be used to improve the scope of performance analysis of such protocols.

There are several possible directions for future work. First, we hope that our model is combined with a variety of protocols. Anybody who has some experience with the model checker Uppaal should be able to integrate our model easily. Second, we want to extend our mobility model to more than one mobile node. Having many mobile nodes will most likely increase the state space significantly, but statistical model checking should overcome this drawback. Last, but not least, we plan to use the mobility model to perform a thorough and detailed analysis of AODV and LMAC. In this paper we have only scratched the surface of the analysis; we expect to find unexpected behaviour in both protocols.

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