Chapter 3
Environment–Mobility Interaction Mapping for Cognitive MANETs

Irene Macaluso, Timothy K. Forde, Oliver Holland, and Keith E. Nolan

Abstract Cognitive MANETs are likely to be complex radio systems. We already know that no single MANET solution can address all environments that may be encountered; such is the rationale of an ad hoc network that it must address the networking demands of unforeseen scenarios. Rather, a cognitive MANET should be viewed as a feature-rich radio system, i.e. one which has access to a range of radio and network components, each suited to different demands. Such a reconfigurable system requires cognitive functionality to self-architect the radios when they are deployed in addition to the cognitive functionality required for the various layers to self-organise. However, any cognitive decision-making process requires awareness of the world for which it is trying to optimise the system. This chapter introduces the concept of an *environment–mobility interaction* map, a persistent internal representation of the network which captures the presence of areas in the network's environment in which particular, sustained, mobility dynamics are observed. Such a self-generated map enables the cognitive MANET to plan a response to challenges brought about by these network dynamics.

3.1 Introduction

Cognitive mobile ad hoc networks (MANETs) will have an increasing role in the wireless communications realm as there is a strong emerging general trend that sees the world moving away from predominantly centrally pre-planned structures to more 'Wifi-like' approaches in which nodes are deployed randomly and have to 'fit in' to the environment in which they are deployed. This points to a self-planning or self-architecting wireless system consisting of a set of nodes that can form dense small cell networks, provide sparse regional area network coverage as well as form distributed structures. Nodes in such networks will need to be highly cognitive and hence capable of being *persistently aware of environmental constraints* through the many observations they can make.

In this chapter we attempt to ascertain if there is a way for a network to create a view of long-lasting network-wide mobility dynamics in spite of the fact that

I. Macaluso (✉)
CTVR, Trinity College, Dublin, Ireland
e-mail: macalusi@cs.tcd.ie

F.R. Yu (ed.), *Cognitive Radio Mobile Ad Hoc Networks*,
DOI 10.1007/978-1-4419-6172-3_3,

the cognitive MANET is transient and individual nodes are just *passing through*. In order to plan strategically, nodes (and the network) need access to information that tells them something about their likely future experiences. Otherwise they can only react to what they currently experience – and in the case of a MANET the local observations of a node are likely to be quite chaotic and random. Any sense of order or patterns can only be seen in a MANET by abstracting features of the network away from individual nodes, rather focussing on *all and any* nodes that might experience the same *persisting* and *orderly pattern* of events.

We explore the potential for a cognitive MANET to create a network-wide view of persistent features of the mobility dynamics that are experienced in various areas of the network, e.g. cross-paths, congregation areas, pinch-points and pathways. If each node, and thereby the network, can ascertain some understanding of the behaviour of a node's mobility in different areas, it may be able to plan the network in a better way, rather than each node simply reacting naively in each instance in ignorance of the behaviour having occurred persistently in the area heretofore. This chapter builds on some of the concepts presented by the authors [1].

The next section describes some pertinent features of MANETs and cognitive networks, drawing attention to the fact that cognition already exists in MANETs, although it is rarely labelled as such. Section 3.3 then looks at how mobility affects the operation of a MANET. In Section 3.4 we discuss the process of planning in a MANET, looking at how MANETs have coped with self-organisation heretofore and develop the concept of an *environment–mobility interaction* map. In Section 3.5, we present the details of our simulation of the *environment–mobility interaction* map concept. Section 3.6 concludes the chapter.

3.2 The MANET as a Cognitive Network

In this chapter we focus on the effects of mobility on a cognitive MANET and look to ways in which we can improve the network's ability to plan for mobility dynamics experienced in a given environment. Before exploring how mobility effects the operation of a cognitive MANET, we should understand what makes a cognitive MANET different to any other cognitive wireless network, and in understanding these differences we will see that such a network will require more self-generated and enhanced awareness of the world in which it operates.

MANETs are essentially distributed, peer-to-peer systems. They were initially proposed for situations in which the existing infrastructure-based networks either failed or did not exist. As such, the MANET is designed to be a robust, independent, relief network, resistant to failure [2, 3]. Decision making of any kind in a MANET is hard if not impossible; the Fischer–Lynch–Patterson impossibility result clearly delineates the limits of deterministic decision making in systems of the kind characterised by open mobile ad hoc networks [4].

All of the nodes in a MANET are autonomous with regard to their mobility. As such, no entity controls the mobility of any node other than the node itself. This autonomy makes the mobility of nodes somewhat unpredictable; any given node's mobility or immobility is at the whim of the entity hosting the radio, whether human, machine or other. The absence of any stationary or fixed network entities, as exist in most other network architectures, increases the complexity of organisation; fixed nodes act as natural cluster heads but their presence cannot be guaranteed in a MANET.

All nodes deal with the challenge of end-to-end network planning, e.g. multihop routing from source nodes to destination nodes via intermediate nodes. As such, a MANET requires more than the ability to create and maintain ad hoc links between adjacent nodes; it requires the ability to organise and maintain logical and physical connections across multiple nodes, at multiple layers of the stack, which may not have direct connectivity with, or awareness of, each other.

Given these challenges, the MANET is an inherently self-organising system, reliant on the ability of its distributed, autonomous, mobile nodes to support communication from end-to-end and from link-to-link in an adaptive and dynamic manner. That self-organisation can range from immediate, reactionary adaptions and fine-tuning, such as PHY-level transmit-power-control changes, to more involved, considered and longer-term network planning, such as multihop routing and traffic loading.

Cognition, whether using the definition used in the cognitive radio field [5] or definitions derived from the artificial intelligence community [6], implies that a radio or network can learn about its environment and make decisions based on what it learns and then act on these decisions. MANETs are already performing these actions in the form of multi-hop routing protocols which *learn* routes, then *plan* an end-to-end route and finally route date from end-to-end. In essence, the MANET already contains cognitive entities, although they are rarely labelled as such.

However, within the wireless networking domain we suggest that a cognitive network will exhibit a number of additional features that distinguish it from other wireless networks. A cognitive network, and its component nodes, should be feature-rich, i.e. the nodes should have access to a suite of components so that they can make choices about what techniques to use and when to use them. A cognitive MANET node should be able to reconfigure its various layers, the components within those layers and the parameters of those components. Software-defined radios are often cited as ideal platforms for cognitive radios as it is relatively easy to manipulate and reconfigure a complex radio system in software [7]. Choices, options and decisions arise *everywhere* in a cognitive MANET; at every layer of the conceptual communication stack and, if the cognitive MANET is also a dynamic spectrum access system, in the organisation of access to spectrum. At the network layer choices concern the appropriate routing and group management protocols. At the medium access and physical layer choices are even more complex and interconnected; everything from modulation to FEC, multiplexing, etc., is up for grabs. Then in the dynamic spectrum domain, choices may range between licenced and unlicenced spectrum, channelisation of said spectrum and tolerable adjacent channel interference levels.

Such a reconfigurable network both necessitates the use of cognitive functionality and motivates its exploration and development. Furthermore, when less structure, whether in the form of lighter radio standards or more technical and service neutral spectrum policy or etiquette is imposed on the network, then the network will have more degrees of freedom. In the absence of cognitive functionality to impose order, such freedom would likely lead to *chaos*, i.e. an environment in which radios fail to converge to a state that allows for communication between them.

To elaborate the point, we can look to the choices that a cognitive MANET could make if operating an IEEE 802.16-*like* MAC and PHY. We say *like* as IEEE 802.16 itself is not a cognitive radio standard [8]. IEEE 802.16 has many variants, both approved; IEEE 802.16, 802.16a, 802.16d and 802.16e, and pending approval or in development; IEEE 802.16h and IEEE 802.16j. Each of these variants represents a different component or building block of a radio system. IEEE 802.16 introduced a single carrier-based PHY. IEEE 802.16a introduced OFDM to the PHY. IEEE 802.16d introduced Fixed Mesh MAC capabilities in addition to the PMP MAC of 802.16. IEEE 802.16e introduced mobility to the PMP MAC and OFMDA at the PHY. Additionally, new enhancements for the IEEE 802.16 family of standards are under development. 802.16h addresses the use of WiMAX systems in unlicenced spectrum and, as such, investigates co-existence mechanisms for adjacent independent systems. Of more interesting note to the development of MANETs, 802.16j addresses the creation of so-called mobile multi-hop relay (MMR) systems. These networks would consist of basestation couple with fixed, nomadic and/or mobile relay stations.

Taken together, as a suite of components, these enhancements would give a network of enabled cognitive radios the capability to address the needs of a wide array of topologies that may be formed by a MANET; from fixed to nomadic to mobile, from licenced to unlicenced, from best effort traffic support to real-time support. But while vendors currently sell radio solutions that offer one solution (IEEE 802.16e) or another (IEEE 802.16d) as distinct products, a cognitive self-architecting ad hoc system would assemble the required radio components to address the challenges of a given deployment scenario.

So, from our perspective there are two broad categories of cognition within a MANET; cognition at the layer/component level and cognition at the system level. While all cognition in the network is concerned with making decisions, the timescale on which decision are made varies from immediate, and often unilateral, node-specific internal adaptations to longer-term network-wide decisions that require multilateral negotiation, consent and execution. Some decisions are internal to the radio, perhaps optimising the way it uses its computational resources, while others are external to the radio, optimising the way that it interacts with other radios. These decisions, which involve interaction with, and consideration of, other radios in the network can be classified as self-organising or self-architecting decisions.

We distinguish self-organising decisions as cognition manifesting itself at the layer/component level. Here, components or layers plan on a node-to-node link-level (PHY), neighbourhood level (MAC) and network level using the same protocols or algorithms to achieve their objectives.

This contrasts with self-architecting decisions which involve system-level cognition where the MANET network, through its nodes, is able to choose the right combination of building blocks, i.e. layers, components, protocols, algorithms, to make a functioning MANET. In this chapter we are interested in developing the awareness of a cognitive MANET towards enabling it to plan its architecture. Awareness of the world in which the reconfigurable cognitive MANET operates is a prerequisite to it being able to adapt itself.

3.3 Mobility Perturbs the MANET

Regardless of where the cognition lies in a MANET, whether at the PHY or the network-layer, one of the biggest hurdles that the cognitive MANET must overcome is the disruption caused by autonomous network mobility. The inherent autonomous mobility of a MANET clearly necessitates an ability to deal with unforeseen and changing network topologies by creating ad hoc networks that deal with ad hoc scenarios. Mobility and MANETs go hand-in-hand, the former necessitating the later. Whenever the MANET has reached a steady state, mobility has the effect of perturbing the network out of that steady state; the state of a wireless network is represented by both the internal state of the nodes and the state of the local links. A self-correcting, self-organising and self-architecting MANET has to overcome the various degrees of state perturbance caused by mobility.

The principle way in which node and network mobility upsets the network is that it causes changes in the link stability and link density characteristics of a network. Link stability describes the stability of links established between a given node and its immediate one-hop neighbours. Stability can be measured by the average duration for which a node-to-node link lasts or the quality of that link over time - a link may exist but the SNR experienced over it may change the capacity of the link. Neighbourhood links are the basic building block of a MANET. Without connection to neighbouring nodes, a node is not connected to the broader MANET network. When it comes to self-organising end-to-end protocols at the higher layers, i.e. the network, transport, session and application layers, neighbourhood link stability is a prerequisite. A lack of stability at the link-level inhibits certain types of higher layer transactions; if the MAC is constantly trying to establish links with new neighbours the creation of communication paths beyond the immediate neighbourhood, i.e. distant, multihop communication, is impossible. One of the factors affecting link stability is the speed of nodes relative to each other; if nodes are passing in and out of each others communication ranges at speed then a link will not endure.

Node density, or node degree, describes the number of one-hop neighbours that a node has or is aware of. The presence of neighbours can be established at the PHY layer, the MAC or the network layer. High-node densities and low-node densities characterise dense and sparsely connected networks; there are pros and cons to each. A dense network means that each node has many immediate one-hop neighbours and, if each of these neighbours is relatively stable, then the node has a more robust connection to the network and more redundancy and options when it comes to how it communicates with other nodes. On the other hand, unless the protocols and algorithms in use have been designed for a dense network, such that message flooding or broadcasting and relaying is managed to reduce duplicated transmissions within the same area, then the local links will become very congested and the network will not converge. A sparse network, whilst not suffering from problems of network congestion, will suffer from a paucity of local links which gives the network little choice in managing traffic load balancing and having alternative options in the case of failing routes.

So, a large array of ad hoc network topologies may be formed. The transience of these topologies will vary from place to place and from time to time. The cognitive MANET topology patterns which emerge may mimic known, or previously planned for, *standard* topologies, e.g. a topology may arise with a stationary node (basestation) and a group of mobile nodes that operate within its transmission radius (mobile subscribers). For such a network topology there are many proven ways to organise the PHY, the MAC and the upper layers. Cognitive protocols and algorithms within the network impose order and bring about a stable system in spite of mobility.

Given that mobility affects the operation of a MANET at such a basic level, through the effect it has on node-to-node links, mobility models are extensively used in the domain to develop and stress test novel network protocols and algorithms. The standard method of evaluation for MANET technologies is to impose a number of mobility models on a simulated MANET network in order to benchmark the efficiency or efficacy of these techniques. Mobility models range from random-waypoint models and group mobility models [9, 10] to more realistic models such as Manhattan models [11]. However, while mobility models are *useful* in development, they are *useless* in practice unless the network itself can create a representation (i.e. model) of the mobility dynamics it experiences.

But, when the mobility characteristics of a network change beyond the design scope of a particular radio or network component, then the system requires recalibration. MANET routing protocols in particular have been shown to have optimal ranges of operation with regard to the mobility characteristics and topologies of the underlying networks [1, 12]. In [1] the authors developed a system that enabled nodes to detect certain network dynamics and relate these observations to prior knowledge that was made available to each node such that it could begin a decision-making process regarding reconfiguration of the routing protocol. The process in [1] was a recognition-triggered decision-making process; once a node recognised the type of dynamics it was experiencing it triggered the decision-making process locally at that node. Nodes had no representation of the network environment, and no way to tell in what part of the network they were since no location-based services were used, so that if a node moved back and forth between two areas dominated by distinct and different network dynamics it acted as though it was encountering these dynamics for the first time. In [1] each node created an internal representation of its local world, i.e. the dynamics it observed and those of its neighbours. However, as this system did not use location-based services such as GPS, it could not detect its own movement from one area to another; a node could simply observe that its neighbours changed but that is not enough to infer whether it has moved to a new area or the other nodes have moved away. The node's internal representation of its world moved with it and could not be shared with nodes that came to the same area of the network after it had left.

In this regard, deliberative planning of changes to the network was not possible as each node could only act on immediate local and neighbourhood knowledge, knowledge which could appear to each node to oscillate without recognisable pattern as it passed from one area to another.

In this chapter, we relax the assumption in [1] that the network has no access to a system such as GPS, and advance that work by developing an internal representation of the network at each node that captures the persistence of certain mobility dynamics as they occur across a given environment. Using this approach, it does not matter that each node may observe different dynamics as it passes through the environment as it adds these observations to a representation that is shared by the network. When a node moves into a new area of the networking environment, it knows which part of the map represents that area, if the map has been created already, and the node can then update the map for the area while it too is present. With access to a map, nodes can see beyond local oscillations in observations allowing for decision-making techniques, such as those used in [1], to be used with greater certainty and for greater changes to the network architecture. When a network has a better internal representation of its world it can plan for change by weighing the cost of disruption caused by change against the benefits of using more suitable components, algorithms etc.

3.4 MANET Planning In Spite of Mobility

Looking back to the example of IEEE 802.16, a significant challenge for each of the IEEE 802.16 variants is the organisation of the schedule for the TDMA MAC; a task that can be approached using either centralised or distributed techniques [13]. In 802.16j the challenge is to develop an efficient MAC that allows for much more dynamic network topology changes and the timely organisation of schedules for the five classes of traffic supported by the standard which range from best-effort to real-time. The 802.16j MAC addresses the challenges of a TDMA MAC for an actively mobile MANET. So, given a particular networking environment, i.e. as characterised by the physical layout of the space, the spatial distribution of the nodes, their mobility characteristics and the spectrum in use, certain networking choices, e.g. choices within the IEEE 802.16 suite of standards, are more effective than others. But for a cognitive MANET, using an IEEE 802.16-*like* MAC/PHY, to plan the appropriate radio system for the network, it must be able to create a representation of those aspects of the networking environment that influence the efficient operation of its candidate MAC and PHY options.

Oftentimes in an ad hoc network mobility-related events happen too fast for any entity, whether at the local radio level or at the broader network level, to analyse the situation and plan an optimal response. More often than not the network simply reacts to changing events according to predetermined triggers, e.g. if the SNR experienced at the PHY deteriorates beyond a threshold then a lower-order modulation scheme is adopted. Such an immediate change requires no *thought*, no deliberation, simply reaction. To a MANET radio, constant, locally perceived change can seem quite random.

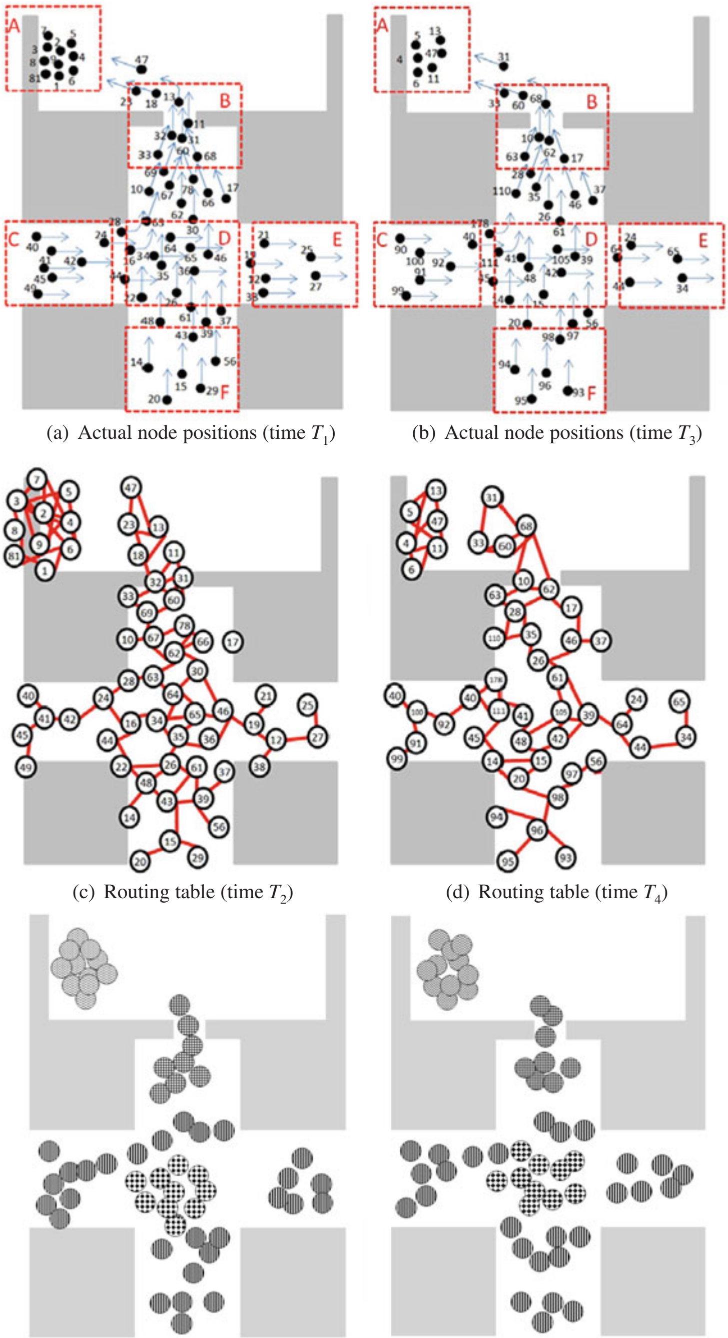
However, from a higher perspective, the network may have more order, i.e. there may be patterns of network behaviour or patterns in the underlying physical environment that, while undetectable locally by myopic nodes on their own, can be seen by stitching together local views to form a larger picture of the network's behaviour.

As we mentioned in Section 3.2, MANETs *do* exist already and *do* manage to function and organise themselves to some degree, notably at the network layer by use of advanced multi-hop routing protocols. These protocols allow multihop-distant, distributed, mobile nodes to communicate in such a way that they collectively build up a view of the logical links that exist throughout the network. But the routing information itself is as transient as the nodes are, and routing protocols are constantly reacting to the topology in a *just-in-time* fashion. The view that they assemble is almost always incomplete and its validity is immediately decaying, eventually being deleted from a node's memory if not refreshed. It should be noted that many routing protocols have been proposed for MANETs taking many forms; reactive source-routed [14], table-driven [15], GPS-assisted [16, 17]. Other routing protocols use cognitive techniques in terms of link management, e.g. OLSR link hysteresis [18] and others [19], while some use location data to predict the stability of links and routes [20].

Regardless of the actual method, routing protocols enable the network's radios to build an internal representation of their external world. From this representation an individual node is able to plan; to choose the best multihop route available to its destination based on its internalised understanding of the world beyond.

Referring to Fig. 3.1a, a network of nodes is depicted operating within a space; the gray blocks represent physical barriers. Corresponding to the actual distribution of nodes at time T_1 is a routing table, Fig. 3.1c created sometime thereafter at time T_2 ($>T_1$). As this is a MANET, by time T_3 ($>T_2$) the distribution of individual nodes may have changed, Fig. 3.1b, resulting in the routing table created at time T_2 being partially or completely out-of-date. But by time T_4 ($>T_2$) an updated routing table, as shown in Fig. 3.1d, is created.

But in spite of the fact that for any given physical environment nodes are *transient* and the routing information is *perishable*, underlying pertinent network characteristics, which are a function of the network's mobility and the environment it inhabits, may *persist*. Even though mobility is autonomous, the mobility actions taken by nodes are both constrained and induced by the environment in which the node operates. Physical barriers, e.g. walls, buildings, rivers, limit the range of movement of a node/network. Referring to Fig. 3.1a, it can be seen that the nodes are outside the buildings. Also, depending on the characteristics of the radio host, i.e. whether it is human-held, vehicle mounted or embedded in a stationary object, the environment will also promote or induce certain behaviours. Generally, humans walk on pavements and pass through doorways whereas cars travel along streets. The interaction of mobile nodes and their physical environment has a significant effect on the ability of a given algorithm (e.g. a PHY FEC scheme) or protocol (e.g. an IEEE 802.16



(a) Actual node positions (time T_1)

(b) Actual node positions (time T_3)

(c) Routing table (time T_2)

(d) Routing table (time T_4)

(e) Map (time $> T_3$)

(f) Map (time $> T_4$)

Fig. 3.1 A network as viewed over time from 3 perspectives; actual node positions **(a)**, **(b)**; corresponding routing tables **(c)**, **(d)**; maps of pertinent features **(e)**, **(f)**

MAC) to operate efficiently, if at all. Notably, it has an impact on the node degree and the link stability experienced by a node. Capturing a representation of these persistent features, which we term *environment–mobility interactions*, can further enable a cognitive MANET to plan.

The question arises as to whether it is possible to abstract from the world as it is, i.e. from the actual unknown (from a network point-of-view) reality of individual nodes locations, to a fairly transient representation of the world in terms of routes through the creation of routing tables which capture a perishable, but detailed, snapshot of logical links, to a more persistent representation of the world in the form of a map of perceived and pertinent *environment–mobility interactions*.

Unlike the information that is captured in a routing table, i.e. precise node- and link-specific information, the information that we want to represent is specific to activity that occurs in an area. As noted, the physical environment drives a node's mobility behaviour by creating paths, plains, pinch-points, landmarks and other features which induce node movements, thereby actually limiting the real autonomy of the nodes. In short, nodes can't walk through walls. In any given area these features, e.g. doors, walls, roads, are likely to be permanent or at least their presence is likely to significantly outlast that of a transient cognitive MANET. However, they are only of interest to a cognitive MANET, and detectable by it, when the cognitive MANET exists in that area and its mobile nodes' interactions are influenced by those features.

Returning to Fig. 3.1a we see that the network can be divided, by visual inspection, into a number of zones exhibiting certain *environment–mobility interactions*. In zone A, a ticket-booth, or other such landmark, causes nodes to queue and cluster, i.e. good link stability, high node density. In zones B, C, E and F, nodes follow a path and in zone D the two paths intersect. A certain approach to MAC/PHY management may be appropriate in one zone, it may fail in another.

In Fig. 3.1b, the nodes have moved to new positions; continued down the path, finished or started queueing, etc. However, so long as more (new) network nodes populate the same environment, they too will be subjected to the same *environment–mobility interactions*. So, while individual nodes come and go, as reflected in the routing tables of Fig. 3.1e, f, a *environment–mobility interaction map* created by the network captures a persistent, if coarse, network view.

Of course, if no more nodes enter an environment then the ad hoc network ceases to exist in that space and the map is abandoned, or if the number of nodes increases or decreases then that network may take on a different characteristic changing the map.

3.5 Environment–Mobility Interaction Mapping

To elucidate the potential feasibility or intractability of this problem, we investigate how MANETs could identify pertinent network *environment–mobility interactions*.

The nodes' mobility pattern emerges from the interaction of a collection of radios and a man-made environment. As nodes' movements are constrained by the environment features, we classify radios according to the following definitions:

- *Way*: a radio that moves along with some of its neighbours in a certain direction.
- *Cross-way*: a mobile radio whose neighbours move in many different directions.
- *Passage*: a mobile radio that experiences an increase in the density of neighbours.
- *Landmark*: a static radio whose neighbours are also static.
- *Other*: a radio that does not belong to any of the previous definitions.

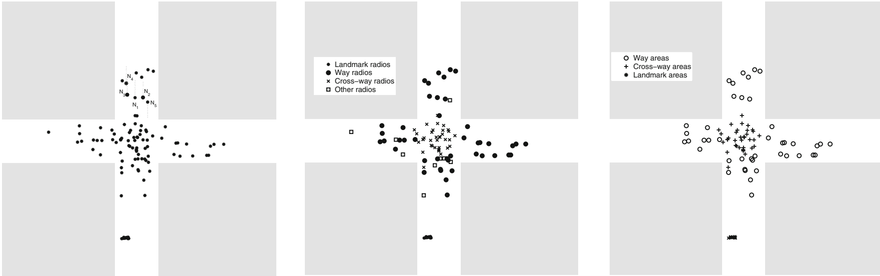
In the following we will describe the procedure to build a *environment–mobility interaction* map. Such representation should be flexible enough to account for sensing uncertainty, thus allowing it to be robustly modifiable as new information is added or the old one is updated. Furthermore the entire process should be autonomous and unsupervised. The problem of space representation has been the subject of research both in the robotics and in the cognitive science community [21]. Depending on the application, spatial knowledge can be represented at different levels, from a coarse topological map to a fine-grained metric map. Metric maps are usually accurate, but they do not scale well with the size of the environment. Topological maps represent the environment as a graph, where each node is an area or a place and the link between nodes implies a connection between places. Their structure allows them to naturally interface with symbolic planners [22]. As the accuracy provided by metric maps is not required in this context, the most suitable choice for our purposes is a topological map.

Radios are randomly distributed in a urban-like environment, which is composed by two orthogonal streets (see Fig. 3.1a). A congregation point, around which radios gather with a given probability, is also included. In order to build the *environment–mobility interaction* map, radios have to estimate their mobility state and communicate it to their neighbours: each radio periodically sends its position, its class (landmark, way, etc) and its direction of motion. Periodic beaconing is highly likely to already exist at some layer of the MANET, this data may piggy-back an existing beacon.

Each radio classifies itself based on its current direction of motion and its neighbors' direction of motion, according to the definition above. In the example in Fig. 3.2a, the radio highlighted as N1 moves in the same direction as the majority of its neighbours and it accordingly identifies itself as a way radio (cf. Fig. 3.2b). The movement information required to estimate the device's mobility state is provided by GPS measurements.

Several sources of error might hinder the self-identification process performance. For example, the GPS measurements are likely to be inaccurate or messages containing the neighbours' mobility state can be lost. However, we aim to get a representation which should not be precise at the level of a single radio, but that arises from the merging of the information provided by all the devices in the network. Therefore possible errors on the self-identification process are unlikely to deteriorate the pattern emerging from a set of radios.

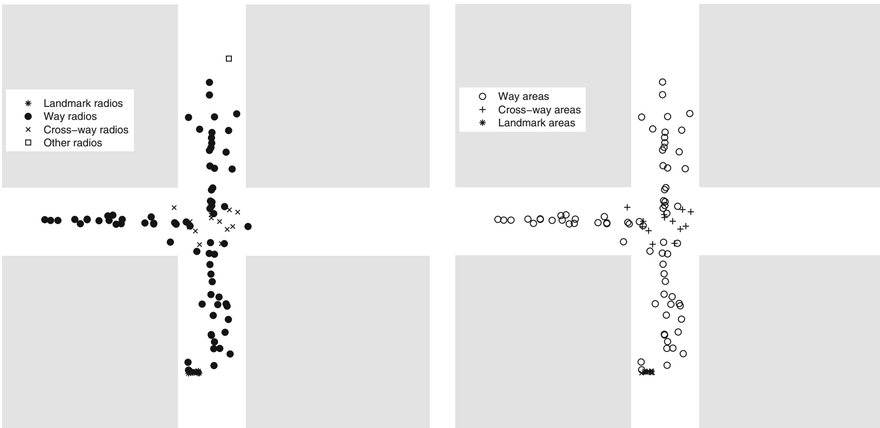
Each device uses the location and the identity of all the radios in the network to segment the environment into areas. Each area, i.e. a portion of the environment occupied by radios presenting the same mobility pattern, constitutes a node in the topological map, as illustrated in Fig. 3.2a, b. The segmentation of the



(a) (b) (c)

Fig. 3.2 **(a)** Radios in the simulated environment. Node N1 and the majority of its neigbours display the same mobility behaviour. The nearby N5 node moves in the opposite direction. **(b)** Nodes self-identification. Node N1 and nodes N2, N3 and N4 identify themselves as way radios; node N5 does not belong to any of the above definitions. **(c)** Segmentation of the environment into areas

environment in different areas takes into account the state of the nodes in the previous k periods and integrates all the observations performed during this temporal window. As soon as new information is available, the oldest one is discarded. This sliding window mechanism allows the representation to be robust to errors and adaptable to changes in the environment-radios situation. A link between two nodes i and j in the topological map exists if the radios previously located in the area corresponding to node i moved into the area corresponding to node j or vice versa. Each link may have a weight which depends on the number of devices that passed from node i to node j or vice versa.



(a) (b)

Fig. 3.3 **(a)** Nodes self-identification. **(b)** Segmentation of the environment into areas. The map is updated according to the radios operating in the environment: the area east of the intersection is removed (cf. Fig. 3.2c)

It should be highlighted that the map, or parts of it, is maintained as long as radios are operating on that environment, and it is eventually abandoned or altered according to the current situation. For example, a node is removed in the topological map shown in Fig. 3.3 as in the corresponding area radios are not longer operating.

3.6 Concluding Discussion

MANETs already exhibit some level of cognition. Nodes in a MANET are able to perceive and monitor their environment; to a certain extent they can plan activities to acquire additional knowledge; they are able to modify their behaviour in response to changes in the environment. For example, many different protocols have been proposed to estimate and update the network routing tables.

Currently, however, the MANETs use procedural knowledge to accomplish specific tasks. We believe that allowing a MANET to access different kinds of knowledge and to build a representation which is relatively stable over time is a key feature to extend its capabilities. This is the case when considering the self-configuration of single node or the self-architecting of the entire network. If *network maps* of the kind proposed in this chapter are developed for cognitive MANETs to address different aspects of the network environment then decision-making techniques, more deliberative than that described in [1], can be developed to manage a cognitive MANET. The environment–mobility interaction map discussed in the previous sections is to be considered as one example of the integration of different information into a single assessment of the environmental situation. Nonetheless, it exploits some cognitive capabilities [6], namely:

- Recognition of situations as instances of known patterns: radios recognize the mobility pattern displayed by themselves or other devices in the network. This process occurs in a single cycle and it operates on the output of the perceptual system and on the information conveyed by other agents.
- Categorization of situations: radios are able to assign the perceived situations (mobility patterns) to known categories (way, landmark, etc).
- Situation assessment: radios are able to combine the information coming from the perceptual system and the communication with other devices and create a model of the current environment-radios situation.

Although not explicitly addressed in the simulation, this representation also enables other cognitive capabilities, such as prediction and planning. Both functionalities require a model of the environment along with a model of the effects of the agent's actions.

Acknowledgments This material is based upon work supported by Science Foundation Ireland under Grant No. 03/CE3/I405.

References

1. Forde, T.K., Doyle, L.E., O'Mahony, D., "Ad hoc innovation: Distributed decision making in ad hoc networks", DOI: 10.1109/MCOM.2006.1632660, 2006, pp: 131–137.
2. Burbank, J.L., Chimento, P.F., Haberman, B.K., Kasch, W.T., "Challenges of military tactical networking and the elusive promise of MANET technology", Communications Magazine, IEEE, Vol. 44, No. 11 DOI: 10.1109/COMM.2006.248156, 2006, pp: 39–45.
3. Tsunemine, T., Kadokawa, E., Ueda, Y., Fukumoto, J., Wada, T., Ohtsuki, K., Okada, H., "Emergency urgent communications for searching evacuation route in a local disaster", Consumer Communications and Networking Conference, 2008. CCNC 2008. 5th IEEE, DOI: 10.1109/ccnc08.2007.267, 2008, pp: 1196–1200.
4. Fischer, M.J., Lynch, N.A., and Paterson, M.S., "Impossibility of distributed consensus with one faulty process," *Journal of the ACM*, Vol. 32, No. 2, Apr. 1985, pp. 374–82.
5. Doyle, L.E., "Essentials of Cognitive Radio (The Cambridge Wireless Essentials Series)", Cambridge University Press; 1 edition, 30 April 2009.
6. Langley, P., Laird, J., and Rogers, S., "Cognitive architectures: Research issues and challenges," Cognitive Systems Research, Vol. 10, no. 2, 2009, pp. 141–160.
7. Nolan, K.E., Sutton, P.D., Doyle, L.E., Rondeau, T.W., Le, B., Bostian, C.W., "Dynamic spectrum access and coexistence experiences involving two independently developed cognitive radio testbeds", New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on, DOI: 10.1109/DYSPAN.2007.43, 2007, pp: 270–275.
8. Hossain, E., "IEEE802.16/WiMAX-based broadband wireless networks: Protocol engineering, applications, and services", Communication Networks and Services Research, 2007. CNSR '07. Fifth Annual Conference on, DOI: 10.1109/CNSR.2007.37, 2007, pp: 3–4.
9. Ariyakhajorn, J., Wannawilai, P., Sathitwiriyawong, C., "A comparative study of random waypoint and Gauss-Markov mobility models in the performance evaluation of MANET", Communications and Information Technologies, 2006. ISCIT '06. International Symposium on, DOI: 10.1109/ISCIT.2006.339866, 2006, pp: 894–899.
10. Biradar, S.R., Sarma, H.H.D., Sharma, K., Sarkar, S.K., Puttamadappa, C., "Performance comparison of reactive routing protocols of MANETs using group mobility model", 2009 International Conference on Signal Processing Systems, DOI: 10.1109/ICSPS.2009.56, 2009, pp: 192–195.
11. Gowrishankar, S., Sarkar, S., Basavaraju, T.G., "Simulation based performance comparison of community model, GFMM, RPGM, Manhattan Model and RWP-SS mobility models in MANET", Networks and Communications, 2009. NETCOM '09. First International Conference on, DOI: 10.1109/NetCoM.2009.31, 2009, pp: 408–413.
12. Doyle, L.E., Kokaram, A.C., Doyle, S.J., Forde, T.K., "Ad hoc networking, Markov random fields, and decision making", Signal Processing Magazine, IEEE, Vol. 23, No. 5, 2006 , pp: 63–73.
13. Abu Ali, N.A., Taha, A.-E.M., Hassanein, H.S., Mouftah, H.T., "IEEE 802.16 Mesh Schedulers: Issues and design challenges", Network, IEEE, Vol. 22, No. 1, DOI: 10.1109/MNET.2008.4435904, 2008, pp: 58–65.
14. Ahmad, S., Awan, I., Waqqas, A., Ahmad, B., "Performance analysis of DSR & extended DSR protocols", Modeling & Simulation, 2008. AICMS 08. Second Asia International Conference on, DOI: 10.1109/AMS.2008.72, 2008, pp: 191–196.
15. Rasheed, T., Javaid, U., Jerbi, M., Al Agha, K., "Scalable multi-hop ad hoc routing using modified OLSR routing protocol", Personal, Indoor and Mobile Radio Communications, 2007. PIMRC 2007. IEEE 18th International Symposium on, DOI: 10.1109/PIMRC.2007.4394079, 2007, pp: 1–6.
16. Blazevic, L., Le Boudec, J.-Y., Giordano, S., "A location-based routing method for mobile ad hoc networks", Mobile Computing, IEEE Transactions on, Vol. 4, No. 2, DOI: 10.1109/TMC.2005.16, 2005, pp: 97–110.

17. Blazevic, L., Buttyan, L., Capkun, S., Giordano, S., Hubaux, J.-P., Le Boudec, J.-Y., "Self organization in mobile ad hoc networks: the approach of Terminodes", Communications Magazine, IEEE, Vol. 39, No. 6, DOI: 10.1109/35.925685, 2001, pp: 166–174.
18. Ali, H.M., Busson, A., Veque, V., "Network layer link management using signal strength for ad-hoc networks", Computers and Communications, 2009. ISCC 2009. IEEE Symposium on, DOI:10.1109/ISCC.2009.5202353, 2009, pp: 141–146.
19. Hua, E.Y., Haas, Z.J., "An algorithm for prediction of link lifetime in MANET based on unscented kalman filter", Communications Letters, IEEE, Vol. 13, No. 10, DOI: 10.1109/LCOMM.2009.090974, 2009, pp: 782–784.
20. Nen-Chung Wang, Yu-Li Su, "A power-aware multicast routing protocol for mobile ad hoc networks with mobility prediction", Local Computer Networks, 2005. 30th Anniversary. The IEEE Conference on, DOI: 10.1109/LCN.2005.15, 2005.
21. Kuipers, B., "The spatial semantic hierarchy," Artificial Intelligence, Vol. 119, No. 1–2, 2000, pp: 191–233.
22. Thrun, S., "Learning metric-topological maps for indoor mobile robot navigation* 1," Artificial Intelligence, Vol. 99, No. 1, 1998, pp: 21–71.