Modelling and Analysing Dynamic Decentralised Systems:
Application to Mobile Ad-hoc Network

Christian Attiogbé
LINA UMR CNRS 6241 - University of Nantes, France
Christian.Attiogbe@univ-nantes.fr

Abstract

We introduce a method to specify and analyse decentralised dynamic systems; the method is based on the combination of an event-based multi-process system specification approach with a multi-facet analysis approach that considers a reference abstract model and several specific ones derived from the abstract model in order to support facet-wise analysis. The method is illustrated with the modelling and the analysis of a mobile ad-hoc network. The Event-B framework and its related tools B4free and ProB are used to conduct the experiments.

1. Introduction

Distributed systems still pose challenging specification and analysis difficulties that needs specific languages, methods and tools. The structure of a classical centralised software system is based on the composition of several subsystems or processes. They are often parallely composed to enable synchronisation and communication. Unlikely, decentralised distributed systems with dynamically evolving architecture have unfixed but varying structure. They cannot be structured with parallel operators that compose a fixed number of processes; they have an ad-hoc structure related to the number of involved processes. Here, interaction is supported by communication and synchronisation between a group of processes currently involved in the cooperation to achieve given goals (the ones defined at the global system level). A group communication is then needed for systems with dynamic architecture.

In this article we introduce a method for the systematic specification and analysis of these systems with evolving structure. The proposed method extends and generalises a preliminary work [6] where a particular approach was used. We combine a multi-facet analysis method and a multi-process system specification method that we developed before [5], [7]. A multi-facet analysis method [4], [5], [7] consists in studying a system according its various facets both at specification level and verification level. Indeed, it is often the case that a global system is well tackled by combining appropriate languages and techniques that are well-suited for the considered facets of the system. A multi-process system [5] is the one in which several subsystems (the processes) are involved, but without a strong composition link between them; thus the architecture of the system is not static, it evolves dynamically according to the existence and the state of the processes.

The contribution of this work is: a seamless method to globally specify a multi-process system with dynamic architecture by considering an event-based abstract model to guide the specification and by considering several facets during the analysis.

The article is organised as follows: in Section 2 we illustrate the features of a decentralised system (MANET) considered as the support of the presentation. In Section 3 we describe the proposed general modelling and analysis method. Section 4 presents the application of the proposed method to the MANET system, from the modelling to the formal analysis. Finally Section 5 concludes the article.

2. Decentralised Dynamic System

A Mobile Ad-hoc Network (MANET) system is a typical example of a dynamic decentralised system. A Mobile Ad-hoc Network [10] is a network formed with wireless mobile nodes (called ad-hoc nodes) which are the user equipments or devices. A MANET has no dedicated network infrastructure, but each node serves as a part of the network and acts a router to forward messages or packets since there is no router dedicated to that task.

A mobile ad-hoc network is formed only when a group of users put together their resources to enable and perform communications; hence a mobile ad-hoc network is dynamically created and may also disappear quickly.

In a MANET, the nodes communicate either by exchanging directly or via intermediate nodes. Technically they use ISM band1 and more generally Wireless LAN technologies. Each node is equipped with one or more radio interfaces with specific transmission features. The transmission range of a node is the transmission area accessible from this node. All the nodes in this range are accessible directly (one hop); they are called the neighbours. To address a known node which is not in its transmission range, the sender node sends

1. they are radio system frequencies initially dedicated to industrial, scientific and medical usage.
its packet to one of the neighbour nodes which is closer to the destination node (according to the transmission ranges). Each node may communicate directly or indirectly using relay nodes (multi-hop), with other nodes that are outside the sender range.

**Dynamic Aspect.** One of the main features of a MANET is its dynamic aspect: the structure or topology of the network is frequently changing. A node may join or leave the net at any time, changing the net topology. The structure or topology of the net is then highly dynamic.

**Mobility Aspect.** The ad-hoc nodes may move at any time and very frequently due to their mobile nature; consequently this impacts not only on the net topology but also on its quality; there may be route changes, information loss, partitions of the network into different networks, etc. As far as routing is concerned, in classical infrastructure-based network, there are one or several nodes called routers that are in charge of routing packets between nodes. For this purpose the routers and the nodes are equipped with a routing table where there is the information about how to join a given destination node or a network identified with an Internet Address (IP address).

In the scope of MANET, efficient routing protocols development is a challenging concern. A message or packet sent to a node reaches it unless the net is partitioned. Concerning the time, it is assumed to be discrete and divided into frames. A node has a set of neighbour nodes during a frame. During a frame a node may be idle, it also may send messages, receive messages, forward the received messages. Before sending a message to a destination, a source node sn which does not have the destination node address, sends a route request to get this destination address. The request travels through the net possibly with multi-hop and reaches the destination which sends back its address. When the address is received by sn the latter can send its message to the right destination address.

The study of MANET is an active and challenging field as this type of network is rapidly growing and supporting small and medium size applications such as mobile services sharing, wireless peer-to-peer systems, etc. We chose the field of MANET for this work because it is a challenging field shared by the fields of computer networks and software engineering. From the software system point of view, the MANET system is a typical decentralised, asynchronous system with dynamically evolving architecture. Moreover, its properties (dynamicty, mobility, correctness, etc) need a combined use of several verification techniques (namely a multifacet analysis).

### 3. The Proposed Method

We propose a multi-facet analysis method to globally specify and analyse a given system using possibly several tools. The method is made of four steps as follows:

#### 3.1. Overview of the Method

Step 1. To build an abstract formal model from the system at hand and to state the desired global properties according to this formal model; it is the reference model; an abstract reference model may be event-based, state-based, process-based, algebraic, etc.

Step 2. To systematically derive or translate from this reference model, other formal models which are specific to various analysis techniques;

Step 3. To perform analysis (verification of properties) with the specific models or with their extensions, by adding specific properties to the global ones;

Step 4. To ensure the consistency between the reference model and the specific ones by propagating the feedback from the specific models study on the reference model and by updating consequently the other specific models. Then, the analysis of each facet via a specific model participates in the global system analysis.

The first step on building a reference model needs methods that are appropriate to the system at hand. In the current case of the decentralised system, we have a *multi-process* system. We detail this step.

#### 3.2. On Building an Event-based Reference Model

An event-based model is suitable for dynamic system. The approach [5] provides rigorous guidelines to help in discovering and expressing the desired behaviours of a multiprocess system with dynamic architecture. Our approach to build the reference model combines a process-oriented view (at low level, for elementary identified processes) and an event-based one (at global level, for composing processes). The method used to build the reference model is summarised as follows.

1) Structuring aspects: From the requirements, elementary *types of processes* are identified to describe behaviours. Several processes may have the same type. Each identified *type of process* $P_i$ that participates in the global system model is specified by considering its space state $S_i$ and the events $E_i$ with their description $Evt_i$ that lead its behaviour. $P_i \equiv \langle S_i, E_i, Evt_i \rangle$

The constituents $S_i$, $E_i$ and $Evt_i$ will be detailed latter on. To handle the dynamic architecture of global system, we impose that for each type of process, the events to *join* and *leave* the system be defined. Some
events may be common to several processes; they handle interaction and state sharing aspects.

2) Interaction aspects: Interaction involves communication. As far as communication is concerned we use guarded events, message-passing and ordering of event occurrences. The processes synchronise and communicate through the enabling/disabling of the guards of their events. Therefore, if an event is used to model a process which is waiting for a data, it may be blocked until the availability of the data (enabling the event guard), which is the effect produced by another process event. Consider for example the case of processes exchanging messages, one process waits for the message, hence there should be an event with a non-enabled guard, and another process sends the message via a behaviour of an event which guard is enabled. Communications are modelled with abstract channels. An abstract channel modelled as a set, is used to wait for a message or to deposit it. Hence the interaction between the processes is handled using common abstract channels. Therefore, the communication is achieved in a completely decoupled way to favour dynamic structuring.

3) Composition of the processes: All the described processes are (hierarchically) combined by a fusion operation (\(\{\}\)) that merges state spaces and the events of the processes into a single global system \(S\).

\[
S \equiv \biguplus_i P_i \equiv \biguplus_i (S_i, E_i, \text{Evt}_i)
\]

According to the fusion operator, when the processes are merged, a set is introduced to identify the merged processes. Each feature that is modelled with a variable, results in a function from the set of process identifiers to a set of values (of the feature). The events of the processes are now defined by considering the elements of the identifier set (if the set is empty there is no more process).

In the following we illustrate the four steps of the method.

### 4. Application to the MANET System

The method is practically supported by tools.

#### 4.1. The Used Methods and Tools

##### 4.1.1. The Event-B Method

Within the Event-B framework, asynchronous systems may be developed and structured using abstract systems \[1], \[3]. Abstract systems are the basic structures of the so-called event-driven B. An abstract system \[1], \[3] describes a mathematical model of a system behaviour\(^2\). An abstract system is made mainly of a state description (constants, properties, variables and invariant) and several event descriptions. Abstract systems are comparable to Action Systems \[8]; they describe a nondeterministic evolution of a system through guarded actions. Dynamic constraints can be expressed within abstract systems to specify various liveness properties \[3], \[9]. The state of an abstract system is described by variables and constants linked by an invariant. Abstract systems may be refined to concrete ones like abstract machines \[9], \[2].

An event of a B abstract system is considered as the observation of one transition of the system. Events are spontaneous and show the way a system evolves. An event \(e\) is modelled as a guarded substitution: \(e \equiv eG \implies eB\) where \(eG\) is the event guard and \(eB\) the event body or action. The symbol \(\implies\) denotes the guard.

An event may occur or may be observed only when its guard holds. The action of an event describes, with generalised substitutions, how the system state evolves when this event occurs. Several events may have their guards hold simultaneously; in this case, only one of them occurs. The system makes internally a nondeterministic choice. If no guard is true the abstract system is blocking (deadlock).

#### 4.1.2. The B4free and ProB Tools

We use the theorem prover B4free\(^3\) and the ProB\(^4\) model checker.

**Overview of B4free.** B4free is one of the public domain theorem prover dedicated to Event-B. The prover originated from the industrial commercialised tool called AtelierB. It was developed together with an emacs front-end. It does

---

2. A system behaviour is the set of its possible transitions from state to state beginning from an initial state


4. www.stups.uni-duesseldorf.de/ProB/
not have the other modules such as code generator or document generator available in the AtelierB tool. However, the B4free tool is free and is convenient for experimentations with the B method: parsing and proving the obligation proofs related to the B method. A new public domain framework for B is now available: Rodin5.

Overview of ProB. The ProB tool [11], [12] is an animator and a model checker for B specifications. It supports automated consistency checking of B specifications (an abstract machine or a refinement with its state space, its initialisation and its operations). The consistency checking is performed on all the reachable states of the machine. ProB also provides a constraint-based checking; with this approach ProB does not explore the state space from the initialisation, it checks whether applying one of the operation can result in an invariant violation independently from the initialisation. ProB provides functionalities to show graphical views of automata. The functionalities of ProB are organised within three categories: Animation, Verification and Analysis. ProB tool is used in our study to help in discharging consistency proof obligations (invariant violation) and to check liveness properties.

4.2. Modelling and Analysing the System

We consider the four steps of the proposed method.

4.2.1. Step 1: Building an Abstract Reference Model. The Manet system is made of a set of nodes that communicate; they form a range; a node is identified as a process type.

Specifying a Node Process. Each node has an identifier, a location, an IP address, a connection relation that indicates its neighbours, etc. Accordingly we have the \( S_i \) part of the node as a set of typed variables that denote the features. A set of events \( (E_i) \) with the associated behaviours \( (Evt_i) \) define the process behaviours which lead the evolution of the system. As far as its behaviour is concerned, any node may initiate a message for a given destination, send a message, receive a message, forward a message, leave a net (a transmission range). The behaviour described by these events is observed only when a net exists; that means the net structuring events are related to those needed for the routing. Also we deal with the creation of a network by nodes which have a given range, other nodes may join or leave this range. Therefore, we link the range of a node with a given abstract network. The formal specification of a MANET is then a set of sequences of configurations of the considered nodes; that is their state variables, resulting from the fusion of the node state variables; the evolution is modelled through the enabling of events which possibly modify the state space.

Concerning the interaction within the MANET system, we consider the events of the nodes and also the common events related to the entire system network (including the ranges).

4.2.2. Step 2: Deriving an Event-B Specification. The derivation of an Event-B model from the abstract event-based model is quite straightforward. The state variables form the B invariant; the abstract events are translated as B events.

Resulting B specification of the MANET. The specification of the structure of a MANET is achieved using a set of state variables and an invariant that describes the nodes and their current configurations:

```
SYSTEM MANET
SETS NODE, RANGE, MSG /* abstract sets */
VARIABLES
  nodes, ranges, messages, Kg */ state variables*/
  rangNodes, reqMsg, inReqMsg, ... IN Variant /* state space predicate */
  nodes \subseteq NODE \land ranges \subseteq RANGE
  \land messages \subseteq MSG
  \land rangNodes \subseteq \text{nodes} \land ranges \subseteq \text{ranges}
  \land reqMsg \subseteq \text{nodes} \land messages
  \land inReqMsg \subseteq \text{nodes} \land messages
  \land waitReqMsg \subseteq \text{nodes} \land messages
  \land ...

INITIALISATION
  nodes, ranges, messages, rangNodes := \emptyset, \emptyset, \emptyset
```

Event-B uses the set notation. The standard operators are written as usually (\( \in, \cup, \cap, \{\ldots\} \)). The symbol \( A \leftrightarrow B \) denotes a relation between two sets.

The behaviour of the system depends on the set of events that define the nodes and the specific system events: the observation of a net creation (newRange); an existing net may disappear if there is no more connected nodes (rmvRange). Other events considered for the network are the following: joinRange: a node joins a range; leaveRange: a node leaves a net range; newNode: a new node appears; newMsg: a node initiates a message.

At this stage, the behaviour part (the set of events) is specified using Event-B as follows:

```
SYSTEM MANET (continued)
  ...
EVENTS
  newNODE \triangleq ...
  newRANGE \triangleq ...
  joinRange \triangleq ...
  leaveRange \triangleq ...
  newMsg \triangleq ...
END
```

The specification of the event joinRange is depicted in Fig. 2. The other events are specified in quite the same way.

In the B language, dom denotes the domain of a relation; if \( r \) is a relation and \( e \) an element of its domain, \( r[\{e\}] \)
denotes the images of $e$ with $r$. $a \mapsto b$ denotes the couple $(a, b)$.

As far as the routing aspect is concerned we consider one of the widely studied routing protocols of MANET: Ad-hoc On Demand Distance Vector (AODV) [10].

A part of the behaviour of our B specification is related to the structuring and another part is about the routing protocol. Therefore we complete the previous specification of the MANET system with the events related to the routing protocol. Within the AODV protocol, each node acts as a router, contributes to construct routes and to forward messages to other nodes. There are two phases of the protocol: route discovery and route maintenance. Route discovery is achieved by exchanging Route Request (RREQ) and Route Response (RREP) messages. The algorithm of the nodes is as follows: when a node desires to set up a route to a destination node, it broadcasts a RREQ message to its neighbours (the nodes in its range). The RREQ/RREP messages have the following main parameters: the source node Id, the destination node Id, the number of hops.

When a node $nd$ receives a RREQ message, $i)$ either $nd$ is itself a destination and $nd$ responds with a RREP or $nd$ is an active route to the searched destination node then $nd$ responds with a route information using the RREP message; $ii)$ otherwise $nd$ broadcasts the RREQ further with the hop count of RREQ increased by 1. The routing of messages is symmetric when a node receives a RREP message. The Event B specification is completed with all the events related to the routing protocol described above.

We give in the following (see Fig. 3) the specification of the sndRREQ event to illustrate the specification principle. Here, any node $(sn)$ may send a message $(msg)$ that it has already prepared $(msg \in reqMsg[\{sn\}])$ to all the nodes in its range $(otherNodesInRange)$. Exchanged messages are modelled using abstract channels $(inRepMsg, repMsg)$.

The expression $otherNodesInRange \ast \{msg\}$ denotes the Cartesian product of the elements in $otherNodesInRange$ with the singleton $\{msg\}$.

The dynamic aspect of the system architecture is based on the fact that the event guards depend on the variables $nodes, messages, \cdots$ which themselves depend on the current event. That means in an event guard, we can consider any event from $nodes$ or any messages from $messages$, etc.

This is illustrated by the non-deterministic form of the event specifications:

\begin{align*}
\text{event} & \equiv \text{ANY } sn \text{ WHERE } sn \in nodes \text{ THEN ... END} \\
\text{sndRREQ} & \equiv /\ast \text{ route request from sn to dn } /\ast
\end{align*}

The Event-B specification which is the specific model for the study of the MANET is then an abstract system equipped with all the events described before: structuring and routing events.

4.2.3. Step 3: Analysis of the Specific Model. A multi-facet analysis of the specific Event-B model of the MANET system is performed. For this purpose two different tools are used but they cover different facets of the analysis: B4free and ProB.

**Consistency and Refinement of the System.** The previously described B abstract system is proved consistent using the B4free tool. Then it is refined; more details are added to the state space and the event specifications; for instance we consider the management of the IP addresses of the nodes and exchanged messages. Unlike in the abstract system where a packet destination is nondeterministically selected, in the refinement the nodes and the messages have IP addresses, therefore, the receiver node is checked against the destination IP address. The resulting refined system is also proved correct with respect to consistency using the B4free tool. However to accomplish the proofs, we combine the use of B4free and ProB. That is, when a proof obligation is not discharged by B4free, we model-check the specification and discover possible errors by displaying and analysing the displayed error state. Accordingly the feedback is propagated in the reference model and we iterate.

**Liveness Properties Analysis.** Many properties of the MANET routing protocol are well-expressed using LTL (Linear Temporal Logic) formula which is not supported by the B4free tool. We express these liveness properties with the ProB LTL formalism. Then we extend the Event-B abstract system with these LTL properties; for example

\begin{align*}
\text{joinRange} & \equiv /* a node joins a range */ \\
\text{sndRREQ} & \equiv /* route request from sn to dn */
\end{align*}
P1. A route request is always followed by a response: 
\[ G(e(sndRREQ) \Rightarrow F(e(sndRREP))) \]

The resulting specification is model-checked using ProB. After that we come to the conclusion that our model extended with the stated properties, is correct with respect to these properties.

4.2.4. Step 4: Feedback to the Reference Model. Using the multi-facet approach, with B4free and ProB helps us to perform a complete analysis. For illustration, in experiments with ProB, when a deadlock is detected after the exploration of nodes and transitions that cover all the operations (the B events), the state corresponding to the deadlock is carefully analysed. In one case we discover that it corresponds to a situation (net partitioning) where there are nodes with some packets to be transmitted but no node in the current net range. This corresponds to a real-life situation which is due to the dynamic aspect of the MANET and the mobility of nodes. A feedback is then propagated first in the Event-B specification. The model is corrected by strengthening the guard of message initiation by the hypothesis of non-emptiness of the net range. Thus the analysis of the model runs without errors.

5. Discussion and Conclusion

We proposed a method that combines two main techniques to model and analyse dynamic decentralised systems: a multi-facet analysis technique and an event-based technique. As illustration the MANET system was modelled and analysed using Event-B tools for experimentations.

The proposed method is to be contrasted with classical approaches (Transition Systems, Process Algebra) where the dynamic aspect of the system is not taken into account; most of them use a process-algebra oriented approach, they focus on the changes on defined architectures and (pre)define rules to perform reconfiguration of the architecture. Our event-based approach overcomes these limitations of the classical approaches; it considers distribution and mobility of processes and no predefined reconfiguration rules are needed, instead we use the behaviour of process types and the composition of events with related guards that depend, at the abstract level, on shared state information. The π-calculus [13] permits the description of evolving structures of processes but new processes are generated from existing ones with the name passing mechanisms; the π-calculus is also not yet well supported by tools.

Ongoing works are about the scalability of our approach; we also plan a refinement of the specification until simulation (that will replace code level). Currently, to tackle the scalability we consider the strengthening of message passing aspects during the refinement of our specifications; indeed message passing is the standard way to deal with asynchronous communication. It will be very interesting to get an abstract specification level where these communications are expressed with very simple schemas.

References