Enabling Emergent Mobile Systems in the IoT: from Middleware-layer Communication Interoperability to Associated QoS Analysis

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PhD Defense
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1 August 2017
Emergent mobile systems in the IoT

➢ Traffic Information Management (TIM) system:

Heterogeneous

Dynamic
IoT heterogeneity at multiple layers

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Middleware protocols in the mobile IoT

DPWS  CoAP  MQTT  ZeroMQ  WebSockets  ....

Client-server  Pub/sub  Streaming  ....

reliable/unreliable  mobile connectivity  ....
Heterogeneous interconnections in the mobile IoT

- How to enable interconnections in the mobile IoT?
- What is the end-to-end QoS of the interconnection?

- Providing common API abstractions
- Convergence to a service bus
- Providing common API abstractions

- Evaluation of specific protocols and their interconnections
- Formal analysis of coupling in distributed architectures
- Performance evaluation in pub/sub systems

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"Enabling heterogeneous interactions in the mobile IoT calls for automated synthesis of interoperability artifacts as well as evaluation of the interoperability effectiveness in terms of end-to-end QoS"
Overview of contributions

1. Automated synthesis of interoperability artifacts
   - Functional semantics
   - VSB
   - Artifacts

2. Formal timed analysis
   - Timing semantics
   - Formal conditions

3. Performance evaluation
   - QoS semantics
   - Analytical models
   - Statistical Analysis
   - Simulated models
Automated synthesis of interoperability artifacts

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Models for core communication styles

**Client–Service (CS)**
- **Tight Time & Space Coupling**

**Publish-Subscribe (PS)**
- **Time & Space Decoupling**

**Data Streaming (DS)**
- **Tight Time & Space Coupling**

**Tuple Space (TS)**
- **Time & Space Decoupling**
Our generic connector defines 4 basic interaction types:

- one-way
- two-way async
- two-way sync
- two-way stream

Each interaction is represented as a combination of `post` and `get` primitives.

We rely on the GM abstraction to introduce our middleware protocol interoperability solution.
Our middleware protocol interoperability solution

- eVolution Service Bus (VSB)\(^1\)

- BC architecture: relies on GM for automated BC synthesis
- Primitives & data conversion between the bus protocol and the Things’ protocols
- A universal way to describe the Things’ I/O required

\(^1\) G. Bouloukakis et al., ICSOC, 2016
Automated BC synthesis

Generic Interface Description Language (GIDL) & Generic BC

Generic BC

- Generic BC logic
- GM API
- GM API
- GM connector X
- GM connector Y

BC synthesizer

Concrete BC

- Concrete BC logic
- GM for Bus protocol
- GM for Protocol Y
- Bus protocol
- Protocol Y

Protocol Pool

- Protocol X
- Protocol Y
- Protocol Z
- ...

Example GM:

```json
{
  "protocol": "Protocol Y",
  "operations": {
    "operation_1": {
      "type": "stream",
      "role": "consumer",
      "scope": "location",
      "input_data": "lon,lat"
    }
  }
}
```
VSB novelty

- Lightweight bus
- Any bus protocol
- BCs employed only when necessary
- Support for any protocol classified under CS, PS, DS & TS
- Automated BC synthesis
- 75-96% person-hours reduction when using VSB
- Evolution support
- QoS awareness
Formal timed analysis
We introduce a unifying timing model for IoT interactions by relying on GM.

GM one-way timing model:

- always connected
- limited data lifetime
- connection/disconnection
GM one-way timing analysis

GM sender automaton

\[ \delta_{\text{post}} \leq \text{max}_{\text{delta_post}} \]

\( t_{\text{post}} \)

\( t'_{\text{post}} \)

\( \text{lifetime} \)

\( \text{lifetime} \)

\( \text{post} \)

\( \text{delta_post} := 0 \)

\( \text{post_off} \)

\( \text{post_on} \)

\( \text{post_end} ? \)

\( \text{delta_post} := \text{lifetime} \)

\( \text{delta_post} \leq \text{max}_{\text{delta_post}} \)

GM receiver automaton

\[ \delta_{\text{get}} \]

\( \text{time_on} \)

\( \text{time_off} \)

\( \text{time_on} \)

\( t_{\text{get}} \)

\( t_{\text{get-return}} \)

\( t'_{\text{get}} \)

\( \text{get} ! \)

\( \text{delta_get} := 0 \)

\( \text{get_off} \)

\( \text{delta_get} \leq \text{time_on} \)

\( \text{delta_get} \geq \text{time_on} \)

\( \text{get_end} ! \)

\( \text{delta_get} \leq \text{time_on} \)

\( \text{delta_get} \text{ get_on} \)

\( \text{delta_get} \text{ get_return} ? \)
Glue automaton & Verification

Sender and Receiver automata interact via the Glue automaton

Safety (A[ϕ]) property verified using UPPAAL – necessary condition for failed interactions:

\[ A[\text{glue.trans_fail}] \implies (\text{sender.post_on} \land \text{receiver.get_off} \land \text{delta_post} = \text{lifetime} \land \text{delta_get} - \text{time_on} \geq \text{lifetime}) \]
3 Performance evaluation

1. Automated synthesis of interoperability artifacts
   - Functional semantics
   - VSB
   - Artifacts

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IoT Interactions across Multiple Layers

- We enrich our timing model with more realistic constraints found across multiple layers in the IoT

![Diagram showing constraints across APP, MDW, and NET layers]

- **APP**
  - connection/disconnection
  - limited data lifetime
  - finite capacity buffers

- **MDW**
  - reliable/unreliable protocols
  - mdw processing delay

- **NET**
  - transmission delay
  - disconnections

- **Connection/Disconnection**
  - app processing delay
  - interop. processing delay
  - finite capacity buffers
We model the end-to-end path of an IoT interaction by using a combination of different types of queueing models.

- **Continuous queue**
  - Input rate: \( \lambda_{in} \)
  - Output rate: \( \lambda_{out} \)

- **Intermittent (ON/OFF) queue\(^1,2\)**
  - Input rate: \( \lambda_{in} \)
  - Output rate: \( \lambda_{out} \)
  - ON/OFF period: \( T_{ON} / T_{OFF} \)

**Additional features:**

- **Finite capacity queue**
  - Input rate: \( \lambda_{in} \)
  - Output rate: \( \lambda_{out} \)
  - Buffer
  - Dropped message

- **Messages exp. queue**
  - Input rate: \( \lambda_{in} \)
  - Output rate: \( \lambda_{out} \)
  - Lifetime
  - Expired message
  - Valid message

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\(^1\) G. Bouloukakis et al., ICC, 2017

\(^2\) G. Bouloukakis et al., ICPE, 2017
DS QoS model for mobile IoT interactions

- We model **reliable** or **unreliable** interactions by using our queueing models

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**DS one-way (1W) interactions**

[Diagram showing the DS one-way (1W) interactions]
Performance modeling patterns

- **CS/DS-1w**
- **CS-2w async**
- **CS-2w sync**
- **PS-1w**
- **PS-2w stream**
- **DS-2w stream**
- **TS-1w**
- **TS-2w sync**

What about heterogeneous interactions?
One-way PS to DS interconnection

- **GPS**
  - vehicle-device
  - PS protocol X

- **Binding Component 1**

- **Bus protocol**

- **Binding Component 2**

  - mobile app
  - DS protocol Y

- **PS one-way**
  - PS-1w reliable

- **CS one-way**
  - CS-1w unreliable

- **DS one-way**
  - DS-1w reliable
Evaluation Results

1. ON/OFF queueing model validation
2. One-way PS to DS end-to-end performance evaluation

➢ We validate the ON/OFF QM validation through:
  - probability distributions
  - arrival rates extracted from the Orange CDR dataset over Senegal\(^1\)
  - ON/OFF connectivity traces collected in the metro of Paris\(^2\)

\(^1\) G. Bouloukakis et al., WiMob, 2015
\(^2\) G. Bouloukakis et al., ICPE, 2017
Connectivity Analysis

1. ON/OFF queueing model validation
2. One-way PS to DS end-to-end performance evaluation

➢ We validate the ON/OFF QM validation through:
  ▪ probability distributions
  ▪ arrival rates extracted from the Orange CDR dataset over Senegal\(^1\)
  ▪ ON/OFF connectivity traces collected in the metro of Paris\(^2\)

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\(^2\) G. Bouloukakis et al., ICPE, 2017
ON/OFF QM Validation using Connectivity traces (1)

1. *Cité Universitaire → Dugommier*: journeys: 34; total duration: 15.18 hours; average duration journey: 26.8 min; $T_{ON} = 2.43$ min and $T_{OFF} = 1.6$ min.

2. *Dugommier → Cité Universitaire*: journeys: 28; total duration: 12.13 hours; average duration journey: 26 min; $T_{ON} = 2.5$ min and $T_{OFF} = 1.2$ min.
2\textsuperscript{nd} path: \textit{Dugommier} \rightarrow \textit{Cité Universitaire}

For high rates, there is a quite good match with maximum difference of about 10\%.
PS to DS performance evaluation: success rates

\[ T_{\text{ON}}^{\text{pub}} + T_{\text{OFF}}^{\text{pub}} = 80 \text{ sec} \]
\( \lambda_{\text{app}} = 2 \text{ msg/sec} \)

lifetime = 10, 20 and 30 sec

\[ T_{\text{ON}}^{\text{sub}} + T_{\text{OFF}}^{\text{sub}} = 30 \text{ sec} \]

- Success Rate 39%
- Success Rate 63%
- Success Rate 39% and Response Time within 5 sec. with Prob = 0.78
- Success Rate 63% and Response Time within 5 sec. with Prob = 0.45

Lower lifetime periods produce improved response time (but with lower success rates)
Conclusions & future work
Conclusions

- We introduce a platform that enables functional interoperability and QoS-related interoperability evaluation with focus on the mobile IoT

We enable system designers to:

1. Automatically map functional semantics of heterogeneous Things for integrating them into IoT applications
2. Formally analyze time semantics of heterogeneous IoT interactions for ensuring high success rates
3. Analyze realistic QoS semantics of heterogeneous IoT interactions for assessing end-to-end performance

- Our platform provides precise design-time modeling, analysis and software synthesis to ensure accurate runtime system behavior.
Future Work

- From design for interoperability and design-time evaluation to runtime adaptation:

1. Dynamic composition of heterogeneous Things in emergency scenarios:
   - face possible emergencies and ensure safety through the composition of Things

2. QoS-aware adaptation of IoT middleware protocols
   - detect performance degradation at runtime and decide appropriate actions

3. Ensure cross-layer resilience for heterogeneous IoT interactions
   - control the underlying IoT networking capabilities to improve and adapt IoT interactions

4. Explore large-scale IoT deployments
   - explore the deployment of our interoperability, resilience and adaptation solutions in large-scale IoT applications
Software artifacts and adoption

- VSB is used as a core component in H2020 CHOREvOLUTION project

- Download VSB:
  - [https://repository.ow2.org/nexus/content/repositories/releases](https://repository.ow2.org/nexus/content/repositories/releases)

- Download Eclipse plugin for defining Things’ GIDLs:
  - [http://nexus.disim.univaq.it/content/sites/chorevolution-modeling-notations](http://nexus.disim.univaq.it/content/sites/chorevolution-modeling-notations)

- VSB development and runtime demo:

- Download MobileJINQS:
  - [http://xsb.inria.fr/MobileJINQS.jar](http://xsb.inria.fr/MobileJINQS.jar)

- MetroCognition mobile app:
  - [https://play.google.com/apps/testing/edu.sarathi.metroCognition](https://play.google.com/apps/testing/edu.sarathi.metroCognition)
Publications (1/2)


- G. Bouloukakis, N. Georgantas, S. Dutta, V. Issarny, "Integration of Heterogeneous Services and Things into Choreographies", ICSOC, October 2016, Banff, Alberta, Canada

- V. Issarny, G. Bouloukakis, N. Georgantas, B. Billet, "Revisiting Service-oriented Architecture for the IoT: A Middleware Perspective", ICSOC, October 2016, Banff, Alberta, Canada

Publications (2/2)


- G. Bajaj, G. Bouloukakis, A. Pathak, S. Pushpendra, N. Georgantas, and V. Issarny, "Toward Enabling Convenient Urban Transit through Mobile Crowdsensing", ITSC, September 2015, Gran Canaria, Spain


- N. Georgantas, G. Bouloukakis, S. Beauche, V. Issarny, Service-oriented Distributed Applications in the Future Internet: The Case for Interaction Paradigm Interoperability, ESOCC, September 2013, Malaga, Spain
Thank you!

MiMove Project Team - https://mimove.inria.fr