Enabling Emergent Mobile Systems in the IoT: functional and QoS interoperability at the middleware layer

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Emergent mobile systems in the IoT

➢ Traffic Information Management (TIM) system:

Heterogeneous

TIM system

Dynamic
### IoT heterogeneity at multiple layers

<table>
<thead>
<tr>
<th>Application layer</th>
<th>Middleware layer</th>
<th>Transport Layer</th>
<th>Network layer</th>
<th>Data Link layer (MAC &amp; LLC)</th>
<th>Physical layer</th>
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- **Physical layer**
- **Data Link layer (MAC & LLC)**
- **Network layer**
- **Transport Layer**
- **Middleware layer**
- **Application layer**

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- **DPWS**
- **IP**

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Middleware protocols in the mobile IoT

DPWS, CoAP, MQTT, ZeroMQ, WebSockets, ...

Client-server, Pub/sub, Streaming, ...

reliable/unreliable, mobile connectivity, ...

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Heterogeneous interconnections in the mobile IoT

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

“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”
Platform for functional and QoS interoperability

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
- one-way
- two-way sync or async

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.

*post* and *get* primitives abstract CS, PS, DS and TS primitives.

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

- eVolution Service Bus (VSB)

- 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

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

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

<< Protocol Pool >>

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

Bus protocol
Protocol Y
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
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Formal timed analysis

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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_post <= max_delta_post
post_off

post !
delta_post := 0
post_on

post_end ?
delta_post := lifetime

GM receiver automaton

delta_get <= max_delta_get
get_off

get !
delta_get := 0
get_on

delta_get <= time_on
get_end !
delta_get >= time_on
delta_get <= time_on
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} \Rightarrow (\text{sender.post_on and receiver.get_off and delta_post==lifetime and delta_get – time_on} \geq \text{lifetime}) \]

\[ \text{delta_post_on := 0} \]

\[ \text{post ?} \]

\[ \text{get ?} \]

\[ \text{get_end ?} \]

\[ \text{get_return !} \]

\[ \text{post_end !} \]

\[ \text{trans_succe} \]

\[ \text{trans_fail} \]

\[ \text{delta_post_on <= lifetime} \]

\[ \text{get} \]

\[ \text{post} \]

\[ \text{get} \]

\[ \text{post} \]

\[ \text{lifetime} \]

\[ \text{time_on} \]

\[ \text{time_off} \]

\[ t_{\text{post}} \]

\[ t_{\text{get}} \]
Performance evaluation

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

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

- MDW
  - reliable/unreliable protocols
  - mdw processing delay

- NET
  - transmission delay
  - mdw processing delay
  - finite capacity buffers
  - disconnections
We model the end-to-end path of an IoT interaction by using a combination of different types of queueing models:

- **Continuous queue**
  - $\lambda_{in}$\rightarrow \text{buffer} \rightarrow \mu \rightarrow \lambda_{out}$

- **Intermittent (ON/OFF) queue**
  - $\lambda_{in}$\rightarrow \mu \rightarrow \begin{cases} T_{ON} & \text{ON} \\ T_{OFF} & \text{OFF} \end{cases}$

- **Finite capacity queue**
  - $\lambda_{in}$\rightarrow \text{buffer} \rightarrow \mu \rightarrow \lambda_{out}$
  - dropped message

- **Messages exp. queue**
  - $\lambda_{in}$\rightarrow \mu \rightarrow \lambda_{out}$
  - lifetime \rightarrow \text{valid message} \rightarrow \text{expired message}$

**Additional features:**

1. G. Bouloukakis et al., ICC, 2017
2. G. Bouloukakis et al., ICPE, 2017
We model **reliable** or **unreliable** interactions by using our queueing models.

**DS one-way (1W) interactions**
Performance modeling patterns

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

PS protocol X → Binding Component 1 (Bus protocol) → Binding Component 2 → DS protocol Y

- PS one-way
- CS one-way
- DS one-way

- PS-1w reliable
- CS-1w unreliable
- 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
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: Dugommier → Cité Universitaire

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

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

lifetime = 10, 20 and 30 sec

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

- Success Rate 39%
- Success Rate 63%
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

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

- VSB development and runtime demo:
  - https://youtu.be/UgfM3810RS8

- Download MobileJINQS:
  - http://xsb.inria.fr/MobileJINQS.jar

- MetroCognition mobile app:
  - https://play.google.com/apps/testing/edu.sarathi.metroCognition


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Thank you!

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