PICO-MP: De-Centralised Macro-Programming for Wireless Sensor and Actuator Networks

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Abstract—Macro-programming advocates the use of high-level abstractions to specify distributed systems as a whole. However, macro-programming implementations are often centralised. In this paper we present PICO-MP, the first fully decentralised macro-programming middleware for wireless sensor and actuator network (WSAN) applications. PICO-MP incorporates a novel publish-subscribe service that can correlate events scattered across a WSAN using global formulae specifications that are automatically checked in a distributed fashion. PICO-MP has been implemented for the TinyOS operating system and validated on a case study that uses global formulae to improve energy efficiency (lifetime) of the implementation.

Index Terms—Wireless Sensor and Actuator Networks; Distributed Computation; Macro-programming; Publish / Subscribe Paradigm; Energy Efficiency.

I. INTRODUCTION

In order to build dependable WSAN applications, many aspects need to be addressed including the inherent challenges of distributed systems. For example, timing, communication and failure assumptions, security, the constraints of devices (cpu/memory/bandwidth/battery capacity), as well as the problems of the physical environment such as radio interference, bad weather, physical access. Having good software engineering tools for designing, reasoning, programming, testing/simulating, deploying, evolving and managing WSAN applications is also crucial.

In this paper we present a new approach for writing WSAN applications based on macro-programming (like Kairos [5], SOSNA [8], or [1]).

In our macro-programming system (PICO-MP) we define the global behaviour of an application using a novel and expressive first order filtering language that correlates distributed sensing and acting events. Global formulae in this language are checked in a distributed fashion by a network of brokers. Each broker uses the global formula to calculate a local sub-formula (called projection) which can be locally verified. PICO-MP ensures that the distributed checking of projections produces the same results as the corresponding global formula. One major advantage of distributed checking is that it leads to provide opportunities to optimise the energy efficiency (lifetime) of WSAN applications. To the best of our knowledge, PICO-MP is the first macro-programming system for WSANs with a de-centralised implementation and optimisations for energy efficiency.

The remainder of the paper is structured as follows: Section II presents the related work. Section III introduces an example of a smart house system which will be used to describe our approach. Section IV provides an overview of our middleware. Section V explains the PICO-MP type-based data model, and Section VI details the PICO-MP subscription language. Section VII discusses the projection of a global formula and its distributed checking by the network of brokers. Section VIII provides an analytical model which compares the performance of PICO-MP decentralised checking against a centralised solution. Finally, Section IX provides conclusions.

II. STATE OF ART

In this section we present some macroprogramming frameworks and middlewares based on the pub/sub paradigm, and their main features. As a matter of fact, the high decoupling between information producers and consumers provided by the pub/sub paradigm is a key factor in WSAN application development, where nodes can be added, removed, or can simply switch off their radio. Pub/sub systems can be categorised as topic-based and content/filter-based ([3]).

MQTTs is a topic-based pub/sub that has been proposed by IBM [12]. This is an adaptation of MQTT, their famous pub/sub based middleware. MQTTs aims at coping with issues such as unstable connections, low energy and limited resources; its main advantage is the aggregation mechanism for notifications provided in order to save energy at network gateways. Although it guarantees three levels of quality of service, it lacks, by nature, in performance and flexibility: the real computation can only happen into a full MQTT broker, outside the WSAN, after a translation process from MQTTs.

Another topic-based pub/sub middleware is PS-QUASAR [2]. This is a lightweight middleware composed of a network maintenance protocol, a simple API, and a routing protocol. This last component is the most important part in its functioning: it performs an intelligent multicast message passing between publishers and subscribers using the information provided by the maintenance protocol. This middleware generates good results in terms of energy consumption, and
it also provides advanced quality of service mechanisms. Unfortunately, it is limited to topic-based routing.

TinyCOPS [6] is a component-based middleware that supports both content and topic based pub/sub routing. Its main feature consists in its vast customisation possibility. This framework decouples the communication mechanism from the pub/sub broker functionalities, and it allows the addition of customised notifications and subscription paths; it also gives the chance to add service extensions. TinyCOPS uses a very expressive attribute-based naming scheme, giving a fine grained control over the pub/sub mechanism. Performance considerations must be done according to the selected components; however, TinyCOPS remains a very general-purpose middleware which is not so focused on energy efficiency.

PADRES [9] shares some interesting features with our proposal. PADRES is a distributed pub/sub content based middleware that has two main innovative features: the first one is the differentiation between atomic and composite events. Subscribing to a composite event means that the overlay network of brokers will only deliver information when a set of different events are matched together. Then, the other important feature is the distribution of the subscription checking task among many brokers in the network, in order to further decrease useless messaging. However, PADRES is implemented as a Java middleware which uses RMI and other powerful full-desktop tools, making it not suitable for lightweight IoT implementations. MERC [7] proposes an interesting decoupling technique of event matching and event routing. Its main goal is the optimisation of throughout and latency in full desktop environments. The authors in [10], [11] propose a middleware that automatically distribute global state machines. These define policies that can correlate data related to distributed sensors. While the approach can run on small battery powered sensor nodes the state machine language is less expressive when compared to the PICO-MP first order filtering language.

Our main goal is energy efficiency, that is why PICO-MP introduces a distributed event matching to reduce the dissemination (and the routing) of events. Subscribers can also be notified only about the truth value of properties they request, thus reducing messaging and improving energy efficiency.

III. Case study

Monitoring and automatic control of a building environment ([13], [4]) can include the following functionalities: (i) heating, ventilation, and air conditioning (HVAC) systems; (ii) fire alarms; (iii) centralised lighting control; and (iv) other systems, to provide comfort, energy efficiency and security. In order to demonstrate macro-programming for WSANs we will use a simplified home-automation case study with 2 applications, a fire alarm system and a home heating system.

The fire alarm system is composed of temperature sensors, smoke detectors and sprinkler actuators. When a temperature sensor reads a value that exceeds a specified threshold (e.g., 50C) and a smoke sensor detects smoke, all the sprinklers are activated.

The automatic heating application is composed of different temperature sensors and various heaters. We provide the following automatic heating application:

- if all temperature sensors are greater than the maximum temperature $T_{max}$ (e.g., 24C), the central heating system turns off.
- if all temperature sensors are less than the minimum temperature $T_{min}$ (e.g., 16C), the central heating system turns on.

We use the home automation scenario of Figure 1 (which is mapped onto the PICO-MP deployment network of figure 2). The house is composed of the following four rooms: (i) the bathroom; (ii) a reception/kitchen; (iii) a bedroom; and (iv) a corridor. We have deployed one temperature sensor in each room. Sprinklers and smoke detectors are deployed in the bedroom and in the kitchen. The base station is in the corridor and the boiler inside a dedicated room. We assume sensors and actuators have some memory and processing capabilities (i.e., they can locally run some C code).

IV. Overview

PICO-MP is a type-based pub/sub system [3]. In a type-based subscription the declaration of a desired type is the main discriminating attribute by giving a coarse-grained structure on events (like in topic-based) on which fine-grained constraints can be expressed over attributes (like in content-based). Type-based pub/sub in this sense resembles the filtered topic model. Publishers periodically send information to the PICO-MP infrastructure in the form of typed events. Subscribers express their interests in the form of first order logic formulae which predicate over sets of events. Each set is composed of events of the same type. Notifications are sent to subscribers whenever a formula becomes true or false. PICO-MP minimises the size of the notifications since subscribers only get a true/false notification; subscribers with particular needs can request, together with the notification, the set of events that triggered the notification.
PICO-MP brokers are organised in a tree overlay network. Publishers and subscribers connect to exactly one broker. Brokers cooperate in order to manage subscriptions, events and distributed formula checking. Brokers ensure that all subscriptions flow up till the root node. A broker can prevent a subscription to reach the root when an equivalent subscription was already sent. This optimisation process can reduce the number of subscriptions that flow into the notification service.

The root forwards the global formulae down to the network of brokers in order to perform their truth check as close as possible to the event sources (i.e., the publishers). More precisely, each broker receives the global formula and generates a local projection of it. This contains parts of the global formula whose truth can be locally verified at the broker. The projection generation process assures that if a projection truth does not change, then the truth of the originating formula does not change too. When a projection switches its truth value the broker sends a message to its father, communicating which change too. When a projection switches its truth value the change, then the truth of the originating formula does not.

Eventually, we use structure as synonymous of type. The set of all possible structures; \( \{e_1, \ldots, e_n\} \) and \( \{E_1, \ldots, E_{2^n}\} \) are elements in \( \mathcal{E} \) and \( \mathcal{P}(\mathcal{E}) \). An event \( e \) is an n-tuple \( e(v_1, \ldots, v_n) \) that is an instance of a type \( t = (a_1 : \text{type}_1, \ldots, a_n : \text{type}_n) \) where each \( v_i \) is the value of the attribute \( a_i \). We can define a function \( t_e : \mathcal{E} \to \mathcal{T} \) that assigns to each event \( e \) its type \( t \), i.e., \( t_e(e) = t \). In order to ease the notation we use \( t_e \) to denote the application of the function to the event \( e \).

We generalise this mapping to sets of events and types. We can define the function \( T_E : \mathcal{P}(\mathcal{E}) \to \mathcal{P}(\mathcal{T}) \) that assigns to a set of events \( E = \{e_1, \ldots, e_k\} \) the set of types \( T_E(E) = T \) with \( T = \bigcup_{i=1}^k t_e(e) \). We use the notation \( T_E \) to denote the application of the function to the set of events \( E \). The set \( \mathcal{PUB} \) denotes the set of all possible publishers; \( \{pub_1, \ldots, pub_n\} \) and \( \{PUB_1, \ldots, PUB_n\} \) are elements in \( \mathcal{PUB} \) and \( \mathcal{P}(\mathcal{PUB}) \).

A publisher \( pub \) always generates events of the same type. We use \( t_{pub} \) to denote that \( pub \) generates events of the type \( t \). Let \( PbU B \) be a set of publishers \( \{pub_1, \ldots, pub_k\} \) we use \( T_{PUB} = \bigcup_{i=1}^k t_{pub} \) to assign a set of types to the set of publishers \( PbU B \).

V. PICO-MP DATA MODEL

Our projection process requires to assign a type and a state to events, publishers, predicates and formulae. This is described in this section.

A PICO-MP event (i.e., a publication) is an instance of a structure that encapsulates various attributes of a primitive type. These include numeric (byte, short, int, long, double), boolean and string types. More precisely, a structure \( t \) is a tuple \( t = (a_1 : \text{type}_1, \ldots, a_n : \text{type}_n) \) where each \( a_i \) is an attribute of a primitive type \( \text{type}_i \). The set \( \mathcal{T} \) denotes the set of all possible structures; \( \{t_1, \ldots, t_n\} \) and \( \{T_1, \ldots, T_n\} \) are elements in \( \mathcal{T} \) and the power set \( \mathcal{P}(\mathcal{T}) \). In the rest of the paper we use structure as synonymous of type. The set \( \mathcal{E} \) denotes the set of all possible events; \( \{e_1, \ldots, e_n\} \) and \( \{E_1, \ldots, E_{2^n}\} \) are elements in \( \mathcal{E} \) and \( \mathcal{P}(\mathcal{E}) \).

We use \( \mathcal{T} \) as the type \( \text{t} \) in the tuple \( \text{t} = (a_1 : \text{type}_1, \ldots, a_n : \text{type}_n) \) where each \( a_i \) is an attribute of a primitive type \( \text{type}_i \). The set \( \mathcal{T} \) denotes the set of all possible structures; \( \{t_1, \ldots, t_n\} \) and \( \{T_1, \ldots, T_n\} \) are elements in \( \mathcal{T} \) and the power set \( \mathcal{P}(\mathcal{T}) \). In the rest of the paper we use structure as synonymous of type. The set \( \mathcal{E} \) denotes the set of all possible events; \( \{e_1, \ldots, e_n\} \) and \( \{E_1, \ldots, E_{2^n}\} \) are elements in \( \mathcal{E} \) and \( \mathcal{P}(\mathcal{E}) \). An event \( e \) is an n-tuple \( e(v_1, \ldots, v_n) \) that is an instance of a type \( t = (a_1 : \text{type}_1, \ldots, a_n : \text{type}_n) \) where each \( v_i \) is the value of the attribute \( a_i \). We can define a function \( t_e : \mathcal{E} \to \mathcal{T} \) that assigns to each event \( e \) its type \( t \), i.e., \( t_e(e) = t \). In order to ease the notation we use \( t_e \) to denote the application of the function to the event \( e \).

We generalise this mapping to sets of events and types. We can define the function \( T_E : \mathcal{P}(\mathcal{E}) \to \mathcal{P}(\mathcal{T}) \) that assigns to a set of events \( E = \{e_1, \ldots, e_k\} \) the set of types \( T_E(E) = T \) with \( T = \bigcup_{i=1}^k t_e(e) \). We use the notation \( T_E \) to denote the application of the function to the set of events \( E \). The set \( \mathcal{PUB} \) denotes the set of all possible publishers; \( \{pub_1, \ldots, pub_n\} \) and \( \{PUB_1, \ldots, PUB_n\} \) are elements in \( \mathcal{PUB} \) and \( \mathcal{P}(\mathcal{PUB}) \).

A publisher \( pub \) always generates events of the same type. We use \( t_{pub} \) to denote that \( pub \) generates events of the type \( t \). Let \( PbU B \) be a set of publishers \( \{pub_1, \ldots, pub_k\} \) we use \( T_{PUB} = \bigcup_{i=1}^k t_{pub} \) to assign a set of types to the set of publishers \( PbU B \). The function \( T_{PUB} \) allows us to relate the following set of types to a broker \( b \):

- the registration type set \( T_{PUB} \) where \( PbU B \) is a set that contains all publishers that are directly registered at \( b \). For the sake of notation, we use \( T_1 \) to denote \( T_{PUB} \);
- the subtree type set \( T_{tree(b)} \) where \( tree(b) \) is a set that contains all publishers in the subtree rooted at \( b \) except the publishers in \( T_1 \), i.e. the ones which are directly connected to \( b \).

In our system, we say that each publisher \( pub \) has a state \( S_{pub} = e \) where \( e \) is the last event that has been generated by \( pub \). The set \( S \) denotes the state of the system; \( \{S_{pub_1}, \ldots, S_{pub_n}\} \) and \( \{S_1, \ldots, S_n\} \) are elements in \( S \) and \( \mathcal{P}(S) \). We can define a function \( S_t : \mathcal{T} \to \mathcal{S} \) that assigns to each type \( t \) a state \( S_t(t) = \{S_{t_{pub_1}}, \ldots, S_{t_{pub_n}}\} \) where \( \{S_{pub_1}, \ldots, S_{pub_n}\} \) are all the publishers of the type \( t \) in the system; we denote it with \( S_t \).

Let \( PbU B \) be a set of publishers \( PbU = \{pub_1, \ldots, pub_k\} \) we use \( S_{PUB} = \bigcup_{i=1}^k S_{pub} \) to denote the state of all publishers inside \( PbU \). In the rest of the paper we denote with \( S_b \) the state of the set of publishers which are directly connected to \( b \), and with \( S_{tree(b)} \) the state of the set of publishers which are connected to some broker in the subtree rooted at \( b \) (except for the publishers which are directly connected to \( b \)).

Finally, we define the function \( \text{filter} : \mathcal{P}(\mathcal{T}) \times \mathcal{P}(\mathcal{E}) \to \mathcal{P}(\mathcal{E}) \). Given a set of types \( T \) and a set of events \( E \), \( \text{filter}(T, E) \) is the subset of \( E \) that contains all events of the type \( t \in T \).

For instance, in our home automation case study (see Section III for details) we use the structure \( \text{temperature}(\text{value} : \text{int}, \text{unit} : \text{string}) \) in order to abstract all sensors of temperature type. The attributes \( \text{value} \) and \( \text{unit} \) define the value and the unit of measurement of a temperature event. The event \( e = (24, \text{"celsius"}) \) can be generated by a sensor \( pub \) detecting a temperature of 24 celsius degree. This is also the state of the publisher \( S_{pub} \). \( S_{\text{temperature}} \) will be composed of the event \( e \) plus the states of all publishers of the type.
Prenex formula := Prefix Matrix
Prefix :=
| Prefix QuantifiedVar | QuantifiedVar
QuantifiedVar :=
| Quantifier Var ∈ S_t
Quantifier := ∀ | ∃
Matrix := Matrix ‘∧’ Predicate | Predicate
Predicate :=
| Var’.Field relop Const
| Δ(Var’.Field), ‘>=’ Const
| PredicateName (‘TermsList’)’
| ‘ is PredicateName (‘TermsList’)’
TermsList :=
| ‘Var’.Field’
| Constant
| Constant ‘,’ TermsList
| ‘Var’.Field ‘,’ TermsList
relop := ’<’ | ’>’ | ’==’

Fig. 3. PICO-MP subscription language BNF grammar

PICO-MP distributed checking procedure requires not only to have typed events but also to associate a type (or a set of
types) to each formula and each predicate call.

A predicate call of a formula \( f \) defines a set of types. This
includes the type of each variable that is used in the predicate
call; the total number of different variable types is referred to
as variety:

**Definition 1:** Let \( f \) be a formula \( q_1x_1 ∈ S_{t_1}, . . . q_mx_m ∈ 
S_{t_m} \) s.t. \( p_1 ∧ . . . ∧ p_n \) where \( q_h ∈ \{ ∀, ∃ \} \) is a quantified
variable of the type \( t_h \) (with \( 1 ≤ h ≤ m \)). \( p_1 . . . p_n \) are
predicate calls in the matrix of \( f \). Suppose that the \( i \)-th
predicate call of \( f \) is of the form \( p_i(x_k, a_k, . . . , x_q, a_q) \). The
set of types of the predicate call \( p_i \) in \( f \) is defined as

\[
T^f_{p_i} = \{ v^f_{i1}, . . . , v^f_{in} \}
\]

where \( x_k . . . x_q \) are all the variables in the predicate call \( p_i \)
of \( f \). The variety \( v^f_{i1} \) is equal to \( |T^f_{p_i}| \).

The definition of a predicate call type allows us to assign a
set of types to a formula \( f \). This is defined with \( T_f = \bigcup_{i=1}^n T^f_{p_i} \)
where \( \{ p_1, . . . , p_n \} \) are all the predicates in the matrix of \( f \).

VII. PICO-MP DISTRIBUTED NOTIFICATION SERVICE

In this section we discuss in details the flow of information
in our middleware, from publishers to subscribers.

A. Event publication and event type management

Each broker \( b \) (note that the root is only considered a particular
case of broker) implements the registration type set \( T_b \) and
the subtree type set \( T_{tree(b)} \) by using a publisherTable and
a brokerTable, respectively (see Figure 4). A broker
uses these tables in order to obtain a projection from a global
formula. A publisherTable of a broker \( b \) contains a tuple
\( (t, pub) \) when a publisher \( pub \) of the type \( t \) registered at \( b \). A
brokerTable of a broker \( b \) contains a tuple \( (t, b) \) when
one of its child broker \( b \) is the root of a subtree that contains
publishers of the type \( t \).

The publisherTable and brokerTable tables are kept updated by using the registration, unregistration, adver-
sisement and unadvertisement PICO-MP messages (as shown
in Figures 5 and 6). A publisher \( pub \) of the type \( t \), registers
to a broker \( b \) by using a registration \( (t, pub) \) message.
This registration is used by the publisher \( pub \) to declare the
type of events it generates (i.e., \( t \)). The broker \( b \) receives
the registration and adds \( (t, pub) \) to its publisherTable.
Effectively the broker recognises the publisher as its child
and keeps information about its address and the type of
events it generates. When the publisher \( pub \) exits the sys-
tem, it must send an unregistration \( (pub) \) message.
the broker \( b \). This message is received by \( b \) that deletes the entry \((t, pub)\) from its \texttt{publisherTable}. A broker \( b \) can send messages of the type \texttt{advertisement}(t, b) to its parent broker \( par(b) \). This uses the advertisements to keep its \texttt{brokerTable} updated. More precisely, when \( par(b) \) receives the message \texttt{advertisement}(t, b), it adds the entry \((t, b)\) to its \texttt{brokerTable}. A broker \( b \) can send an \texttt{unadvertisement}(t, b) message to its parent \( par(b) \) when it cannot receive anymore events of the type \( t \). This happens when all the publishers in \texttt{tree}(b) (of the type \( t \)) unregistered. When \( par(b) \) receives the message \texttt{unadvertisement}(t, b), it removes the entry \((t, b)\) from its \texttt{brokerTable}.

B. Subscription management

A broker \( b \) and a root \( r \) use the \texttt{subTable} (see Figure 4) in order to keep information about subscriptions that originated in their sub-tree.

The \texttt{subTable} is kept updated by using the subscription and unsubscription PICO-MP messages (as shown in Figures 5 and 6). A subscriber \( c \) can send a subscription \((f, sub)\) message to a broker \( b \). When \( b \) receives the message subscription \((f, sub)\) its \texttt{subTable} (see Figure 4) is updated with the entry \((f, sub)\). Subscriptions are always propagated till the root (i.e., a broker always forwards the message subscription \((f, sub)\) to its parent).

A subscriber \( sub \) which is no longer interested in a certain formula \( f \) can send an unsubscription \((f, sub)\) message to its parent \( par(sub) \). When \( b \) receives this message it removes the entry \((f, sub)\) from its \texttt{subTable}. Unsubscriptions are always propagated till the root (i.e., a broker always forwards the message unsubscription \((f, sub)\) to its parent). An optimised version of PICO-MP can use equivalence amongst formulae in order to minimise the subscription flow. More precisely, a broker does not forward a subscription formula \( f_1 \) that is equivalent to a subscription \( f \) that was previously sent. When the broker receives a notification for the subscription formula \( f \) also produces a notification for the equivalent formula \( f_1 \).

C. Projection generation process

A root always forwards down to the broker tree each new subscription \( f \). When a broker \( b \) receives the formula \( f \), it can perform the projection procedure of Figure 7. This projection decomposes \( f \) into a set of local formulae, i.e., a \( f_v \) formula and an array \( f_3 \) of formulae. In the rest of the paper these formulae are referred to as projections. The \( f_v \) projection contains all predicates of \( f \) that have all universally quantified variables (lines 6-9) and have a type set contained in the type set of the broker \( b \) (condition of line 5). This last condition ensures that the truth of the \( f_v \) projection can be locally verified by the broker. A \( f_v \) projection has a \( f_v\text{-truth} \), a \( f_v\text{-children}\text{-number} \) and a \( f_v\text{-truth}\text{-counter} \) variables. The \( f_v\text{-truth} \) defines the truth of the \( f_v \) projection. \( f_v\text{-children}\text{-number} \) is the number of broker children which have a non empty \( f_v \) formula; these brokers are contained in \( \forall\text{-childrenSet} \). The \( f_v\text{-truth}\text{-counter} \) is the number of children which informed \( b \) that their \( f_v \) projection is true. Each element of the \( f_3 \) array contains a projection that has one predicate with all existentially quantified variables (lines 10-15). Each \( f_3\text{-truths}[i] \) defines the truth value of the \( f_3[i] \) projection. The \( f_3\text{-truth}\text{-counters}[i] \) is the number of children which informed \( b \) that their \( f_3[i] \) projection is true. The projection procedure forwards \( f \) to all children brokers that can generate at least a projection from \( f \) (lines 26-28).

D. Distributed event matching

A broker \( b \) performs the distributed event matching to check the truth of projections. This check reduces the number of pubs that are forwarded towards the root and allows a distributed computation of each global formula \( f \).

1) \( f_v \) projection checking: A broker \( b \) uses the \texttt{check}\_\texttt{truth}\_\( \forall \) procedure of Figure 8 for evaluating the truth of all universally quantified predicates inside a \( f_v \).
projection. This evaluation is performed on all publication events that can be locally observed at \( b \). This forwards synchronisation information (i.e., publications) only when all \( f_V \) predicates are true. In fact, local publications that falsify a universally quantified predicate of \( f_V \) are sufficient to falsify the truth of the global formula \( f \). In this case events are locally blocked. In the following we describe in details the check_truth_\( \forall \) procedure:

- the update state contains all events that are forwarded when the \( f_V \) projection of \( f \) is true (line 2).
- The check_truth_\( \forall \) procedure sets \( f_V \) as false when there is at least one children broker that has locally evaluated its \( f_V \) as false (lines 3-6).
- A broker \( b \) evaluates all \( f_V \) predicates with variety one (line 9) by considering the state of its directly connected publishers (line 10). When at least one of the \( f_V \) predicates is false the \( f_V \) projection is false.
- The truth of \( f_V \) predicates with variety more than one requires the broker local state and the state of all the children brokers to be considered (line 16). In fact, predicates that contain variables of different types must consider n-tuples that are defined across the state of all the children brokers. When a \( f_V \) predicate with variety more than 1 is true the state of its variable type is added to the state update variable to be returned. This state will be forwarded to the parent of \( b \).

2) \( f_Z \) projection checking: The check_truth_\( \exists \) procedure of Figure 9 is quite similar to the check_truth_\( \forall \) one. Each \( p_j \) of an existentially quantified projection inside the array \( f_Z \) is considered. When \( p_j \) is true in one of the children broker (lines 5-8) the projection is set to true for the local broker \( b \) as well. When \( p_j \) has variety one the truth is checked by using the local state of \( b \) (line 13) otherwise the state of the children brokers is used as well (line 116). The \( i \)th element of the array \( f_Z \) is true when the \( i \)th projection of the array \( f_Z \) is true at least in one of the children broker or in the local broker.

3) Projection checking: Figure 10 shows the check procedure that a broker \( b \) performs to evaluate all projections of a formula \( f \). These projections are created when they are not in the projection table (lines 3-5). The check procedure first checks the \( f_V \) projections of \( f \) by calling the check_truth_\( \forall \) procedure that is described in section VII-D1. When the \( f_V \) projection is evaluated to false the procedure exits and no publication event is forwarded to the parent broker. A particular case is when the \( f_V \) projection was previously true and becomes false. In this case the parent broker of \( b \) is informed by using a \( \forall \) synchronisation message (line 12). Symmetrically, when the \( f_V \) projection was false and becomes true the parent broker is informed (line 16). The \( f_Z \) projections are also checked when the \( f_V \) projection is true (line 19). The check procedure also forwards (if the

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**Fig. 7.** Projection procedure performed by a broker \( b \).

**Fig. 8.** Check \( \forall \) part of a projection.
for each predicate \( p \) in \( f \)

```c
for each predicate \( p \) in \( f \)
if (\( p \) has at least a universally and an existentially quantified variable)
TypeSet \( T = T_f \)
State \( S = S_b \)
update = update \( \cup \) filter\( (T, S) \)
return update
```

### Fig. 10. Checking procedure of formulae performed by a broker \( b \).

\( f_b \) projection is true) all publications events that are needed by the parent broker to check predicates that have at least a universally and an existentially quantified variable (line 25). These predicates are not checked at any broker but their truth is globally checked by the root by using the state forwarded by all brokers.

4) Parsing of messages: Figure 11 outlines how a broker \( b \) parses messages arriving from other brokers, publishers and subscribers. This procedures always sends any publication events produced (if any) at the end (line 34). When a new formula \( f \) is received the broker uses the check procedure to update its projection table (line 5) and checks the truth value of \( f \). The local subtree state of a broker can be synchronised upon the reception of a state synchronisation message (lines 7-10). This requires the checking of some formulae to be performed. The broker \( b \) can also receive updates on the \( f_b \) projections from its children brokers; in this case it updates the \( f_b \_truth \_counter \) (we recall this stores the number of children brokers which informed \( b \) that their \( f_b \) projection is true). The parent broker is notified with a \( V \) message \( false \) (lines 19-22) when the counter gets lower than \( f_b \_children \_number \). In fact, the parent needs to be updated when the \( f_b \) projection is not true in any of the children brokers that are evaluating it. When an \( \exists \) truth is received (line 29) the \( f_b \_truth \_counters \) array is updated and the check procedure is called.

#### E. Notification delivery

A root is a particular type of broker that has access to the entire state of the system. The root receives synchronisation messages from its children brokers and can calculate the truth of every global formula \( f \). This is done by procedures that are similar to the broker ones. Whenever the root detects a change in the truth of a subscription formula \( f \) it notifies its subscriber of it. To do this, each broker (starting with the root itself) uses its subTable to trace back the subscriber which submitted the subscription. In this way, a notification\( (f) \) message is sent to the subscriber of \( f \) and all equivalent formulae. At this point, subscribers can react to notifications with a customised callback procedure, which gives the programmer the power to define any possible behaviour.

We emphasise that that predicates with variety one are always computed in a distributed manner, i.e., the root wait for the truth of their children brokers and evaluate the truth in its local state. Predicates with variety more than one requires a state synchronisation from the children brokers in order to consider tuples which contain events that are observed by different brokers.

#### VIII. PICO-MP PERFORMANCE

In this section we discuss the energy efficiency of the PICO-MP middleware. To this ending we study the traffic generated inside the distributed notification service. We compare PICO-MP with an MQTT-like centralised implementation.

The following assumptions are made: (i) WSAN devices and brokers are arranged in a tree like structure (see Figure 5); (ii) the centralised implementation can only perform the event matching at the root of the tree (devices are not enough performant to run the broker); (iii) PICO-MP brokers run in all WSANs devices. In our study we do not consider subscription and notification messages since they flow in the same way in both centralised and PICO-MP implementation.
It is worth mentioning that PICO-MP can optimise the traffic generated by subscriptions and notifications. More precisely, a subscription does not reach the root when an equivalent one was already sent. Notification traffic can be reduced when subscribers only require changes in truth value of a formula and not the entire state.

The total amount of messages that are sent/received by a broker \( b \) (at the time \( t \)) can be summarised as follows:

\[
M_b(t) = M_{pub}(t) + M_{reg}(t) + M_{init}(t)
\]

where \( M_{pub}(t) \) and \( M_{reg}(t) \) is the total amount of publication and registration messages sent/received and \( M_{init}(t) \) all additional control messages that are sent/received by the broker.

The centralised implementation has no registration messages and no additional control messages thus the total amount of messages can be summarised as \( M_{centralised}(t) = M_{pub}(t) \).

The PICO-MP total amount of messages can be calculated as:

\[
M_p^{PICO}(t) = M_1(t) + M_2(F, t) + M_{pub}(F, t)
\]

where \( M_1(t) \) control messages that do not depend on the truth value of any formula (i.e., projections, registrations and unregistrations of publishers, advertisements and unadvertisements of brokers), \( M_2(F, t) \) are messages that are generated when one or more formulae change their truth value (i.e, \( \forall \) and \( \exists \) control messages). The \( M_{pub}(F, t) \) term identifies the publications that have been sent/received at time \( t \) (i.e., the state control messages). These are sent when the subscribers require the state that made the formulae truth changing.

We want to study the equation \( M_p^{PICO}(t) \leq M_{centralised}(t) \). This can be written as:

\[
M_1(t) + M_2(F, t) + M_{pub}(F, t) \leq M_{pub}(t)
\]

This equation states that PICO-MP performs worse than a centralised implementation when the formulae are always true and the subscribers always require the entire state to be sent. In this case PICO-MP adds to the publication messages the \( M_{pub}(F, t) = M_{pub}(t) \) the extra messages \( M_1(t) \) and \( M_2(F, t) \) for projections/registrations and formula truth notifications (i.e., \( \forall \) and \( \exists \)). PICO-MP performs much better when subscribers do not require the state (the term \( M_{pub}(F, t) \) is zero), the formulae do not change their truth often (i.e., \( M_2(F, t) \) is low) and subscriptions are not frequent (i.e., \( M_1(t) \) is low due to reduced control messages). For instance this is the case of home and building automation where subscriptions are usually related to actuators. Actuators are not added/removed frequently and an actuator policy is rarely changed.

IX. Conclusions

In this paper we present PICO-MP, a fully decentralised macro-programming middleware for WSANs. An expressive language that is based on first order logic is used to specify a global behaviour. This can correlate distributed sensing and actuating events. A broker can locally create a projection of a global formula. PICO-MP ensures that the distributed checking of all projections of all brokers produces the same results of their global formula checking. The use of PICO-MP can improve the WSAN life time when publishers plays a very dynamic role with a lot of activity, while subscribers do not change their subscriptions very often.

REFERENCES


