Distributed Event-Based System — Addendum

Revision: 2327

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Septembre 2018
1 Formal specification of simple event-based system

1. Formal specification of simple event-based system
1.1 Formal background — Temporal logic
1.2 Changes of the state caused by interface operations (w/o advertisements)
1.3 Trace-based specification of simple event-based system (w/o advertisements)
1.4 Changes of the state caused by the adding advertisements
1.5 Safety specification of simple event system with advertisements
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2. Formal specification of distributed routing

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4. Content-based data and filter models
1.1 Formal background — Temporal logic

- **Trace:** a sequence of states: $\sigma = s_0, s_1, s_2, \ldots$
- **Subtrace:** $\sigma|_i$ is the trace $s_i, s_{i+1}, s_{i+2}, \ldots$
- Atomic predicate $P$ is true for every trace whose first state satisfies $P$
- Formula $\Psi$: $P$ with quantifiers ($\forall$, $\exists$) and logical operators ($\lor$, $\land$, $\Rightarrow$, $\neg$)
- **Temporal operators:**
  - $\square$ ("always")
    - $\square \Psi$ is true for traces $\sigma$ iff $\forall i \geq 0, \Psi$ is true for $\sigma|_i$
    - $\square P$ means $P$ always holds, i.e. for all subtraces
  - $\Diamond$ ("eventually")
    - $\Diamond \Psi$ is true for traces $\sigma$ iff $\exists i \geq 0 : \Psi$ is true for $\sigma|_i$
    - $\Diamond P$ means $P$ will hold eventually, i.e. there is a subtrace for which $P$ holds
  - $\circ$ ("next")
    - $\circ \Psi$ is true for traces $\sigma$ iff $\Psi$ is true for $\sigma|_1$
    - $\circ P$ means $P$ holds for the subtrace starting at the second place of the trace
1.1.1 Exercise

\[ \square \Diamond P \]

\[ \Diamond \Box P \]

\[ \square [P \implies \square P] \]

\[ \square [P \implies \Diamond Q] \]

\[ \square [P \implies \Diamond \Box P] \]

\[ P \implies \Diamond \Box Q \]

\[ \square \neg P \lor \square \neg Q \equiv \neg (\Diamond P \land \Diamond Q) \]
1.2 Changes of the state caused by interface operations (w/o advertisements)

- $X$: a component of a system (being a producer and/or a consumer)
- $\mathcal{C}$: the set of all the components
- $S_X$: a set of active subscriptions for component $X$
- $P_X$: a set of published notifications by component $X$
- $D_X$: a set of delivered notifications to component $X$
- $\mathcal{N}$: the set of all the notifications, $N \subseteq \mathcal{N}$: a set of notifications
  - $n \in N(S_X)$: $X$ has a subscription that matches $n \in \mathcal{N}$

<table>
<thead>
<tr>
<th>Operation</th>
<th>Description</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{sub}(X, F)$</td>
<td>Component $X$ subscribes to filter $F$</td>
<td>$S'_X = S_X \cup {F}$</td>
</tr>
<tr>
<td>$\text{unsub}(X, F)$</td>
<td>Component $X$ unsubscribes to filter $F$</td>
<td>$S'_X = S_X \setminus {F}$</td>
</tr>
<tr>
<td>$\text{pub}(X, n)$</td>
<td>Component $X$ publishes $n$</td>
<td>$P'_X = P_X \cup {n}$</td>
</tr>
<tr>
<td>$\text{notify}(X, n)$</td>
<td>Component $X$ is notified about $n$</td>
<td>$D'_X = D_X \cup {n}$</td>
</tr>
</tbody>
</table>

« ' » indicates the state of a variable after the execution of the interface operation
1.2.1 Exercise

? $\Diamond \text{notify}(X, n)$

? $\Box \neg \text{unsub}(X, F)$

? $\Box [\text{notify}(X, n) \implies \Diamond \Box \neg \text{notify}(X, n)]$

? $\Box [\text{notify}(X, n) \implies n \in N(S_X)]$

? $\Box [\text{notify}(Y, n) \implies n \in \bigcup_{X \in C} P_X]$
1.3 Trace-based specification of simple event-based system (w/o advertisements)

A component receives

(a) only notifications it is currently subscribed to
(b) only notifications that have previously been published
(c) a notification at most once
(d) all future notifications matching one of its active subscriptions

Safety: demands that “something irremediably bad” will never happen

\[ \Box \left[ \text{\texttt{notify}}(Y, n) \implies [n \in N(S_Y)] \right] \]  
\[ \land [n \in \bigcup_{X \in C} P_X] \]  
\[ \land [\Box \Box \neg \text{\texttt{notify}}(Y, n)] \]  

Liveness: requires that “something good” will eventually happen

\[ \Box \left[ \Box (F \in S_Y) \implies \Diamond \Diamond \left[ \text{\texttt{pub}}(X, n) \land n \in N(F) \implies \Diamond \text{\texttt{notify}}(Y, n) \right] \right] \]
1.4 Changes of the state caused by the adding advertisements

- $A_X$: set of all active advertisements of component $X$
- $n \in N(A_X)$: $X$ has an advertisement that matches $n \in \mathcal{N}$

<table>
<thead>
<tr>
<th>$\text{adv}(X, F)$</th>
<th>Component $X$ advertises filter $F$</th>
<th>$A'_X = A_X \cup {F}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{unadv}(X, F)$</td>
<td>Component $X$ unadvertises filter $F$</td>
<td>$A'_X = A_X \setminus {F}$</td>
</tr>
</tbody>
</table>
1.5 Safety specification of simple event system with advertisements

(a) + (b) + (c) +

(e) If a notification is published that does not match any of the active advertisements of the publishing component, the notification should not be delivered to any component

\[ \square \left[ \text{notify}(Y, n) \implies \Box \Box \neg \text{notify}(Y, n) \right] \] \quad (=c)

\[ \wedge \left[ \text{notify}(Y, n) \implies n \in \bigcup_{X \in C} P_X \cap N(S_Y) \right] \] \quad (=b,a)

\[ \wedge \left[ \text{pub}(X, n) \wedge n \notin N(A_X) \implies \square \neg \text{notify}(Y, n) \right] \] \quad (=e)
1.6 Liveness specification of simple event system with advertisements

f1) If a client Y is always subscribed to F and a client X always advertises G

f2) then there exists a future time where a notification n published by X matches F and G

f3) will lead to the delivery of n to Y.

\[\square\left[\square(F \in S_Y) \land \square(G \in A_X)\right]\]
\[\implies \left[\lozenge \square\left(\text{pub}(X, n) \land n \in N(F) \cap N(G)\right)\right]\]
\[\implies \lozenge \text{notify}(Y, n)]]\]

(=f1) (=f2) (=f3)
2 Formal specification of distributed routing

1. Formal specification of simple event-based system

2. Formal specification of distributed routing
   2.1 Architecture of the distributed service
   2.2 Distributed system model for notification routing
   2.3 Notations for notification forwarding and delivery
   2.4 Valid routing
   2.5 Safety and liveness conditions of valid routing
   2.6 Monotone valid routing algorithms
   2.7 Safety and liveness conditions of monotone valid routing

3. Routing algorithm framework

4. Content-based data and filter models
2.1 Architecture of the distributed service

- The notification service forms an overlay network in the underlying system
- The overlay consists of event brokers that run as processes on nodes
  - Local brokers put the first message into the network
  - Border and inner brokers forward the message to neighbouring brokers according to filter-based routing tables and routing strategies
  - Messages are sent to local brokers
  - Local brokers deliver the message to the application components
2.2 Distributed system model for notification routing

- Each node runs one or more processes
- Processes interact by passing messages via links between them
- A link connects a pair of processes and transmits messages asynchronously
- A FIFO ordering of messages is applied
- Acyclic connected topologies

- The topology of the overlay network of brokers is static
- Clients are stationary
- Communication channels are reliable and respect FIFO message ordering
- Message delay is unknown but finite, and system is not overloaded and fault-free
- System without advertisements
2.3 Notations for notification forwarding and delivery

- $T^D_B$: set of filters of the routing table of broker $B$ regarding single destination $D$
  \[ T^D_B = \{ F | \exists (F, D) \in T_B \} \]

- $T^D_B$: set of filters regarding all but single destination $D$
  \[ T^D_B = \{ F | \exists (F, E) \in T_B \land E \neq D \} \]

- $N(T^D_B)$: set of notifications that match $T^D_B$

- $N_B$: set of neighbouring brokers
2.4 Valid routing

- Valid routing algorithm = adapts the routing configuration by preserving the safety and liveness properties of the DEBS

- Additional notations:
  - $\theta(Y)$: identity of the broker that manages consumer $Y$
  - Simple directed path connecting a broker with $\theta(Y)$—i.e., the access broker
    - $B_1, \ldots, B_j$ simple path in the network of brokers
    - $\gamma(B_1, \ldots, B_j)$: set of notifications such that if a notification is published at $B_j$ and stays in this set, it reaches $B_1$ over this path
      - $\gamma(B_1, \ldots, B_j) = \bigcap_{1 < k \leq j} N(T_{B_{k-1}}^{B_k})$
2.5 Safety and liveness conditions of valid routing

- To guarantee safety, the local routing configuration ensures that only matching notifications are delivered
  - Local subset validity
    \[
    \Box \left[ N(T_{\theta(Y)}^Y) \subseteq N(S_Y) \right] \quad (=r1)
    \]

- To guarantee liveness, when a consumer \( Y \) subscribes to a filter \( F \) and stays subscribed, then from some time, every notification that is published at any broker \( B \) and that matches \( F \) should be delivered to \( Y \)
  - Eventual super-set validity
    \[
    \Box \left( F \in S_Y \Rightarrow \Diamond \Box \left[ N(T_{\theta(Y)}^Y) \supseteq N(F) \right] \right) \quad (=r2: \text{From } \theta(Y) \text{ to } Y)
    \]
    \[
    \Box \left( F \in S_Y \land B \neq \theta(Y) \land n \in N(F) \right) \quad \Rightarrow \quad \Diamond \Box \left[ n \in \gamma(\theta(Y),...,B) \right] \quad (=r3: \text{From } B \text{ to } \theta(Y))
    \]
2.6 Monotone valid routing algorithms

- **Drawbacks of valid routing**
  - Local subset validity does not require immediate delivery
  - Eventual super-set validity is a property of the routing configuration of the entire topology

- **Improvements**
  - Immediate delivery
    - Local consumer subscription followed by local publisher publication should imply local notification of the consumer
  - Set of notifications forwarded is monotonically increasing for any path
    - Notifications sent over $B_{i+1} \rightarrow B_i$ are sent over $B_{i+2} \rightarrow B_{i+1}$
      - Only depends on the routing configurations of neighbouring brokers
2.7 Safety and liveness conditions of monotone valid routing

- Reminder:
  - $T_B^D = \{ F | \exists (F, D) \in T_B \}$
  - $T_B^D = \{ F | \exists (F, E) \in T_B \land E \neq D \}$

- Local validity $\equiv$ immediate delivery

$$\Box [ N(T_{\theta(Y)}^Y) = N(S_Y) ]$$

(= merging of r1 and r2 + strengthness)

- Eventual monotone remote validity\(^1\)

$$\Box [ \Box [ n \in N(T_{B_i}^B) ] \implies \Diamond \Box [ n \in N(T_{B_j}^B) ] ]$$

1. If $n$ is forwarded to $B_k \neq B_j \in N_{B_i}$ then $n$ comes from $B_j$. 

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\(^1\) Local validity $\equiv$ immediate delivery
3 Routing algorithm framework

1. Formal specification of simple event-based system

2. Formal specification of distributed routing

3. Routing algorithm framework
   3.1 Generic algorithm
   3.2 Flooding
   3.3 Simple routing
   3.4 Identity-based routing

4. Content-based data and filter models
3.1 Generic algorithm

3.1.1 Main program
3.1.2 handleMessage procedure
3.1.3 handleNotification procedure
3.1.4 Preliminary words about the generic administer procedure
3.1.5 handleAdminMessage procedure
3.1.6 pub, sub and unsub procedures
3.1.1 Main program

The main program starts when the broker is created:

1. Initialise the routing table $T_B$ of the broker $B$
2. Initialise a delivery queue $Q_C$ for each local consumer $C$
3. Enter an infinite loop that dispatches messages arriving from neighbouring brokers to the `handleMessage` procedure

```
Program ContentBasedRouting()
initialise $T_B$
initialise $Q_C$ for all $C \in L_B$
loop
  wait until a message is available
  $m \leftarrow$ next selected message
  `handleMessage($m$)`
```
### 3.1.2 handleMessage procedure

- handleMessage dispatches a message based on message type
  - Two types of messages are exchanged among neighbouring brokers
    1. `forward(n)`: to disseminate a notification \( n \) in the network of brokers
    2. `admin(S, U)`: to propagate routing table updates
       - \( S \): set of subscriptions
       - \( U \): set of unsubscriptions
    3. `administer(S, U)`: to compute the admin messages to send
       - \( M_S \): set of pairs \((\text{filter}_{\text{sub}}, \text{destination})\) for sending admin messages
       - \( M_U \): set of pairs \((\text{filter}_{\text{unsub}}, \text{destination})\) for sending admin messages

```plaintext
1 procedure handleMessage(Message m)
2   if m is forward(n) from neighbour u then
3       handleNotification(u, n)
4   if m is admin(S, U) from neigh. u then
5     (M_S, M_U) ← administer(u, S, U)
6     handleAdminMessage(u, M_S, M_U)
```

![Diagram](attachment:diagram.png)
3.1.3 handleNotification procedure

- handleNotification sends forward messages to neighbouring brokers
- handleNotification notifies local consumers
  - notify is called by the broker to notify a local consumer about a notification
  - The notification is appended to the delivery queue $Q_Y$ of the consumer $Y$

```plaintext
1 procedure handleNotification(Neighbour $D$, Notification $n$)
2    send "forward($n$)" to all the neighbours $\in F_B(n) \setminus \{D\}$
3    forall local consumers $C \in F_B(n)$ do
4        notify($C, n$)
5 procedure notify(Consumer $Y$, Notification $n$)
6    $Q_Y \leftarrow \text{append}(Q_Y, n)$
```
3.1.4 Preliminary words about the generic administer procedure

- The code of *administer* is implemented by framework instantiations to realise a concrete routing algorithm
  - Flooding
  - Simple
  - Identity-based
  - Covering-based
  - Perfect merging
  - Imperfect merging

- *administer* returns two sets that are pairs: \((\text{filter}_{\text{sub}}, \text{destination})\) or \((\text{filter}_{\text{unsub}}, \text{destination})\)

- Send an admin message to *destination* for \(\text{filter}_{\text{sub}}\)
  - Sending done in handleAdminMessage, as explained in next slide
3.1.5 handleAdminMessage procedure

- The values returned by administer are used as input to handleAdminMessage
- handleAdminMessage sends admin messages to neighbouring brokers

```plaintext
procedure handleAdminMessage(Dest D, Set MS, Set MU)
  forall Bi ∈ NB\{D} 
  S' ← {F|(F, Bi) ∈ MS}
  U' ← {F|(F, Bi) ∈ MU}
  if S' ≠ ∅ ∨ U' ≠ ∅ then
    send "admin(S', U')" to Bi
```

3.1.6 pub, sub and unsub procedures

- pub is called by a local publisher to publish a notification
- sub is called by a local consumer to subscribe to a filter
- unsub is called by a local consumer to unsubscribe to a filter

```
procedure pub (Publisher X, Notification n)
  handleNotification(X, n)
procedure sub (Consumer Y, Filter F)
  (M_S, M_U) ← administer(Y, {F}, ∅)
  handleAdminMessage(Y, M_S, M_U)
procedure unsub (Consumer Y, Filter F)
  (M_S, M_U) ← administer(Y, ∅, {F})
  handleAdminMessage(Y, M_S, M_U)
```
3.2 Flooding

- Idea: a broker forwards a notification to all its neighbours
  - Each broker is initialised to the set \( \{(F_T, U) | U \in N_B\} \) with \( \forall n \in N, F_T(n) = true \)

- Each broker updates its routing table (RT) regarding its local consumers
  - If a consumer \( Y \) subscribes to a filter \( F \), the broker adds \((F, Y)\) to its RT
  - If a consumer \( Y \) unsubscribes to a filter \( F \), the broker deletes \((F, Y)\) from its RT

- Flooding does not require the remote routing configuration to be updated

```
1  procedure administer(Dest s, Set S, Set U)
2       T_B ← T_B ∪ \{(F, s) | F ∈ S\}
3       T_B ← T_B \ \{ (F, s) | F ∈ U\}
4       return (\emptyset, \emptyset);
```
3.3 Simple routing

- Idea: use filter forwarding to update the routing configuration in reaction to subscribing and unsubscribing consumers

- Initially, $\forall B, T_B = \emptyset$

```
procedure administer(Dest D, Set S, Set U)

1. $T_B \leftarrow T_B \cup \{(F, D) | F \in S\}$
2. $T_B \leftarrow T_B \setminus \{(F, D) | F \in U\}$
3. $M_S \leftarrow \{(F, H) | H \in N_B \setminus \{D\} \wedge F \in S\}$;
4. $M_U \leftarrow \{(F, H) | H \in N_B \setminus \{D\} \wedge F \in U\}$;
5. return ($M_S$, $M_U$);
```

Routing table of $B_1$

$\begin{array}{c}
\text{1. sub(F)} \\
\text{2. } (F, X1) \\
\text{3. admin({F},{})} \\
\text{4. } (F, B1)
\end{array}$
3.4 Identity-based routing

Reminder:

- \( T_B^D = \{ F | \exists (F, D) \in T_B \} \)
- \( T_B^\setminus D = \{ F | \exists (F, E) \in T_B \land E \neq D \} \)

Idea: a subscription (unsubscription) is only forwarded to a neighbour \( H \) if there is no identical subscription in the RT for a destination distinct from \( H \)

The superscript stands for Identical

- \( C_B^I(F, D) \) : set of routing entries in \( T_B \) of which the filter is identical to the filter \( F \) and of which the destination equals the destination \( D \)
  - \( C_B^I(F, D) = \{(G, D) | (G, D) \in T_B \land F \equiv G \} \)

- \( D_B^I(F) \) : set of neighbours \( H \) for which there is no routing entry \((G, D)\) in \( T_B \), where \( G \) is identical to \( F \) and \( D \) is distinct from \( H \)
  - \( D_B^I(F) = \{ H \in N_B | \nexists G \in T_B^\setminus H : F \equiv G \} \)
3.4.1 Algorithm

If a broker $B$ receives a(n) (un)subscription from a neighbour or a consumer $D$:

- $B$ updates its RT (lines 4-6):
  - If $D$ is a neighbour, $B$ removes $C_B^l(F, D)$ (line 5)
  - If $D$ is a local consumer, $B$ removes solely $(F, D)$ (line 6)
- $B$ forwards $F$ to all neighbours that are in $D_B^l(F)$ except $D$ (lines 7–10 and 13)
- If $F$ is a subscription, $B$ inserts a routing entry $(F, D)$ into its RT (line 11)

```
procedure administer(Dest D, Set S, Set U)
    MS ← ∅;
    MU ← ∅;
    forall F ∈ S ∪ U do
        if D ∈ NB then
            TB ← TB \ C_B^l(F, D);
        else
            TB ← TB \ (F, D);
        endif
    A ← {(F, H)|H ∈ D_B^l(F)\{D}};
    if F ∈ U then M_U ← MU ∪ A;
    else
        MS ← MS ∪ A;
        TB ← TB ∪ {(F, D)};
        endif
    return (MS, MU);
```
3.4.2 An example (1/3)
3.4.3 An example (2/3)
3.4.4 An example (3/3)

F' identical to F

1. sub(F')
   (F', S2)

2. admin({F'}, {})
   (F, S)
   (F, B1)
   (F, B1)

F' identical to F

3. a
   (F, B1) → (F', S2)

3.b.
   (F, S) → (F', B4)

3.a
   (F, B1) → (F', S2)

2. admin({F'}, {})
   (F, B1)

1. sub(F')
   (F, B4)

S2
3.4.5 Exercise

F3 not identical to F
F3 not identical to F’
F4 identical to F3

? Execute the algorithm for the new subscription $F_3$ of $S_3$ and then the new subscription $F_4$ of $S_4$
4 Content-based data and filter models

1. Formal specification of simple event-based system

2. Formal specification of distributed routing

3. Routing algorithm framework

4. Content-based data and filter models
   4.1 Data model and Filter model
   4.2 Tuples
   4.3 Structured records
   4.4 Semi-structured records
   4.5 Objects
4.1 Data model and Filter model

- **Data model**: how the content of notifications is structured

- **Filter model**: how subscriptions can be specified
  - How notifications can be selected by applying filters that evaluate predicates over the content of notifications
4.2 Tuples

- **Data model:**
  - A notification is a tuple: an ordered set of attributes

- **Filter model:**
  - A subscription is defined as a template
  - The attributes of notifications and templates are matched to each other according to their position

- **Example:** the notification (StockQuote, "Foo Inc", 45) is matched by the subscription template (StockQuote, "Foo Inc", *)
  - Tuples with templates provide a simple model that is not flexible
  - Because attributes cannot be optional
4.3 Structured records

4.3.1 Data model
4.3.2 Filter model
4.3.3 Identity, overlapping, covering of attribute filters
4.3.4 Routing optimisations with identity
4.3.5 Routing optimisations with covering
4.3.6 Covering with types and comparison
4.3.7 Covering with intervals and strings
4.3.8 Covering with sets
4.3.9 Routing optimisations with overlapping
4.3.10 Routing optimisations with merging
4.3.1 Data model

- A notification $n$ is a nonempty set of attributes $\{a_1, ..., a_n\}$
- $a_i$ is a (name,value) pair: $(n_i, v_i)$
- Attribute names are unique: $i \neq j \Rightarrow n_i \neq n_j$
- Example of notification: $\{(\text{type}, \text{StockQuote}), (\text{name,“Infineon”}), (\text{price, 45.0})\}$

- More powerful than tuples since attributes can be optional in subscriptions and notifications
4.3.2 Filter model

- Attribute filter: triple \( A_i = (n_i, Op_i, C_i) \) with \( n_i \) = attribute name, \( Op_i \) = test operator, \( C_i \) = value for the test

- \( L_A(A_i) \) = set of values \( v_i \) that cause an attribute filter to match attribute \( n_i \)
  - \( L_A(A_i) = \{ v_i | Op_i(v_i, C_i) = true \} \)
  - Usually \( L_A(A_i) \neq \emptyset \)

- Filter \( F \) = boolean function applied to a notification \( n \): \( F(n) \rightarrow \{true, false\} \)

- The set of matching notifications \( N(F) = \{ n | F(n) = true \} \subseteq N \)

- Simple filter = filter consisting of a single atomic predicate

- Compound filter = conjunction of simple filters: \( F = A_1 \land ... \land A_n \)
  - E.g., \( (type = \text{StockQuote}) \land (name = \text{“Foo Inc”}) \land (price \notin [30, 40]) \)

- A notification \( n \) matches a filter \( F \) iff it satisfies all the attributes filters of \( F \)

  + Attributes can be optional in the notification

  + New attributes can be added without affecting existing filters
4.3.3 Identity, overlapping, covering of attribute filters

- **Identity:**
  
  \[ A_1 \equiv A_2 \iff n_1 = n_2 \land L_A(A_1) = L_A(A_2) \]
  
  *E.g.*, \((\text{price} \in \{20, 21, 22, 23, 24, 25\})\) is identical to \((\text{price} \in [20, 25])\)

- **Overlapping:**
  
  \[ A_1 \cap A_2 \iff n_1 = n_2 \land L_A(A_1) \cap L_A(A_2) \neq \emptyset \]
  
  *E.g.*, \((\text{price} > 25)\) overlaps \((\text{price} \in [20, 30])\)

- **Covering:**
  
  \[ A_1 \sqsupseteq A_2 \iff n_1 = n_2 \land L_A(A_1) \supseteq L_A(A_2) \]
  
  *E.g.*, \(A_1 = (\text{price} > 10)\) covers \(A_2 = (\text{price} \in [20, 30])\)

- **Disjoint**
  
  \[ A_1 \n préc À 2 \iff n_1 = n_2 \land L_A(A_1) \cap L_A(A_2) = \emptyset \]
  
  \{\text{price} < 10\} and \{\text{price} > 20\} are disjoint
4.3.4 Routing optimisations with identity

- An identity test among filters is necessary to implement identity-based routing to avoid redundant routing entries and unnecessary forwarding of (un)subscriptions.

- Given two filters $F_1 = A_1^1 \land ... \land A_n^1$ and $F_2 = A_1^2 \land ... \land A_m^2$ that are conjunctions of attribute filters with at most one attribute filter per attribute, $F_1 \equiv F_2$ iff they contain the same number of attributes filters $\land (\forall i, \exists j : A_i^1 \equiv A_j^2)$.

- E.g., $F_1 = \{x = 4\} \land \{y > 5\}$ not identical to $F_2 = \{x = 4\} \land \{y > 5\} \land \{z \in [3, 5]\}$.
4.3.5 Routing optimisations with covering

- A covering test among filters is necessary to implement covering-based routing to avoid redundant routing entries and unnecessary forwarding of (un)subscriptions ∧ to get rid of the obsolete² routing entries.

- Given Two filters $F_1 = A_1^1 \land \ldots \land A_n^1$ and $F_2 = A_1^2 \land \ldots \land A_m^2$ that are conjunctions of attribute filters with at most one attribute filter per attribute, $F_1 \sqsupseteq F_2$ iff $\forall i, \exists j : A_i^1 \sqsupseteq A_j^2$

- E.g., $F_1 = \{x = 4\} \land \{y > 5\}$ covers $F_2 = \{x = 4\} \land \{y > 5\} \land \{z \in [3, 5]\}$

- E.g., $F_3 = \{x \geq 2\} \land \{y > 5\}$ covers $F_4 = \{x = 4\} \land \{y = 7\} \land \{z \in [3, 5]\}$

---

2. A routing entry covers another routing entry, which becomes obsolete
4.3.6 Covering with types and comparison

- $n_1 = n_2$

- Covering among notification types
  
  - A notification $n$ is an instance of Type $T$: $n$ instanceof $T$

<table>
<thead>
<tr>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_1 \sqsupseteq A_2$ iff</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$ instanceof $T_1$</td>
<td>$n$ instanceof $T_2$</td>
<td>$T_1 = T_2 \lor T_1$ supertypeof $T_2$</td>
</tr>
</tbody>
</table>

- Covering among comparison constraints on simple values

<table>
<thead>
<tr>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_1 \sqsupseteq A_2$ iff</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x \neq c_1$</td>
<td>$x &lt; c_2$</td>
<td>$c_1 \geq c_2$</td>
</tr>
<tr>
<td>$x &gt; c_1$</td>
<td>$x &gt; c_2$</td>
<td>$c_1 \leq c_2$</td>
</tr>
</tbody>
</table>

- E.g., $A_1 = (x \neq 15)$ and $A_2 = (x < 10) \implies A_1 \sqsupseteq A_2$
- E.g., $A_1 = (x > 10)$ and $A_2 = (x > 20) \implies A_1 \sqsubseteq A_2$
4.3.7 Covering with intervals and strings

- \( n_1 = n_2 \)

- Covering among interval constraints on simple values

<table>
<thead>
<tr>
<th>( A_1 )</th>
<th>( A_2 )</th>
<th>( A_1 \trianglelefteq A_2 ) iff</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x \in I_1 )</td>
<td>( x \in I_2 )</td>
<td>( I_1 \supseteq I_2 )</td>
</tr>
<tr>
<td>( x \notin I_1 )</td>
<td>( x \notin I_2 )</td>
<td>( I_1 \subseteq I_2 )</td>
</tr>
</tbody>
</table>

- E.g. \( A_1 = (x \in [3, 10]) \) and \( A_2 = (x \in [4, 6]) \) \( \Rightarrow \ A_1 \trianglelefteq A_2 \)

- Covering among constraints on strings

<table>
<thead>
<tr>
<th>( A_1 )</th>
<th>( A_2 )</th>
<th>( A_1 \trianglelefteq A_2 ) iff</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s \ hasPrefix \ S_1 )</td>
<td>( s \ hasPrefix \ S_2 )</td>
<td>( S_2 \ hasPrefix \ S_1 )</td>
</tr>
<tr>
<td>( s \ hasPostfix \ S_1 )</td>
<td>( s \ hasPostfix \ S_2 )</td>
<td>( S_2 \ hasPostfix \ S_1 )</td>
</tr>
<tr>
<td>( s \ hasSubstring \ S_1 )</td>
<td>( s \ hasSubstring \ S_2 )</td>
<td>( S_2 \ hasSubstring \ S_1 )</td>
</tr>
</tbody>
</table>

- E.g. \( A_1 = (s \ hasPrefix \ "abc") \) and \( A_2 = (s \ hasPrefix \ "abcd") \) \( \Rightarrow \ A_1 \trianglerighteq A_2 \)
4.3.8 Covering with sets

- \( n_1 = n_2 \)

- Covering among set constraints on simple values

<table>
<thead>
<tr>
<th>( A_1 )</th>
<th>( A_2 )</th>
<th>( A_1 \supseteq A_2 ) iff</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x \in M_1 )</td>
<td>( x \in M_2 )</td>
<td>( M_1 \supseteq M_2 )</td>
</tr>
<tr>
<td>( x \notin M_1 )</td>
<td>( x \notin M_2 )</td>
<td>( M_1 \subseteq M_2 )</td>
</tr>
</tbody>
</table>

- Covering among set constraints on multi values

<table>
<thead>
<tr>
<th>( A_1 )</th>
<th>( A_2 )</th>
<th>( A_1 \supseteq A_2 ) iff</th>
</tr>
</thead>
<tbody>
<tr>
<td>( X \subset M_1 )</td>
<td>( X \subset M_2 )</td>
<td>( M_1 \supseteq M_2 )</td>
</tr>
<tr>
<td>( X \text{ contains } a_1 )</td>
<td>( X \supseteq M_2 )</td>
<td>( a_1 \in M_2 )</td>
</tr>
<tr>
<td>( X \supseteq M_1 )</td>
<td>( X \supseteq M_2 )</td>
<td>( M_1 \subset M_2 )</td>
</tr>
<tr>
<td>( X \text{ notContains } a_1 )</td>
<td>( X \text{ disjunct } M_2 )</td>
<td>( a_1 \in M_2 )</td>
</tr>
<tr>
<td>( X \text{ disjunct } M_1 )</td>
<td>( X \text{ disjunct } M_2 )</td>
<td>( M_1 \subset M_2 )</td>
</tr>
<tr>
<td>( X \text{ overlaps } M_1 )</td>
<td>( X \text{ overlaps } M_2 )</td>
<td>( M_1 \supseteq M_2 )</td>
</tr>
</tbody>
</table>
4.3.9 Routing optimisations with overlapping

- An overlapping test among filters is necessary to use advertisements in subscription-based routing optimisations.

- Advertisement and subscription routing tables are used to route (un)subscriptions from consumers to producers.
  - A subscription can be served by an advertisement if both overlap.

- Given two filters $F_1 = A_1^1 \land \ldots \land A_n^1$ and $F_2 = A_1^2 \land \ldots \land A_m^2$ that are conjunctions of attribute filters with at most one attribute filter per attribute,
  - $F_1$ and $F_2$ are disjoint iff $\exists i,j : (n_i^1 = n_j^2) \land (L_A(A_i^1) \cap L_A(A_j^2) = \emptyset)$
    - E.g., $F_1 = \{x \geq 2\} \land \{y > 5\}$ and $F_2 = \{x < 1\} \land \{y < 7\}$ are disjoint because $\{x \geq 2\}$ and $\{x < 1\}$ are disjoint.
  - $F_1$ and $F_2$ overlap iff $\not\exists i,j : (n_i^1 = n_j^2) \land (L_A(A_i^1) \cap L_A(A_j^2) = \emptyset)$
    - E.g., $F_1 = \{x \geq 2\} \land \{y > 5\}$ and $F_2 = \{x < 5\} \land \{y < 7\}$ because $\{x \geq 2\}$ overlaps $\{x < 5\}$ and $\{y > 5\}$ overlaps $\{y < 7\}$.
4.3.10 Routing optimisations with merging

- Merging of conjunctive filters
  - A merging test among filters is necessary to implement merging-based routing to reduce the number of subscriptions and advertisements stored by brokers
  - Examples:
    - \( F_1 = \{x = 5\} \land \{y \in \{2, 3\}\} \) and \( F_2 = \{x = 5\} \land \{y \in \{4, 5\}\} \) can be merged to \( F = \{x = 5\} \land \{y \in \{2, 3, 4, 5\}\} \)
    - \( F_1 = \{y = 3\} \land \{x = 5\} \) and \( F_2 = \{y = 3\} \land \{x \neq 5\} \) can be merged to \( F = \{y = 3\} \)
  - Example of perfect merging rules for attribute filters

<table>
<thead>
<tr>
<th>( A_1 )</th>
<th>( A_2 )</th>
<th>Condition</th>
<th>( A_1 \cup A_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x \in M_1 )</td>
<td>( x \in M_2 )</td>
<td>-</td>
<td>( x \in M_1 \cup M_2 )</td>
</tr>
<tr>
<td>( x \notin M_1 )</td>
<td>( x \notin M_2 )</td>
<td>( M_1 \cap M_2 = \emptyset )</td>
<td>( \exists x ) (i.e., no att. filter)</td>
</tr>
<tr>
<td>( x \notin M_1 )</td>
<td>( x \notin M_2 )</td>
<td>( M_1 \cap M_2 \neq \emptyset )</td>
<td>( x \notin M_1 \cap M_2 )</td>
</tr>
<tr>
<td>( X ) overlaps ( M_1 )</td>
<td>( X ) overlaps ( M_2 )</td>
<td>-</td>
<td>( X ) overlaps ( M_1 \cup M_2 )</td>
</tr>
<tr>
<td>( X ) disjunct ( M_1 )</td>
<td>( X ) disjunct ( M_2 )</td>
<td>( M_1 \cap M_2 = \emptyset )</td>
<td>( \exists X ) (i.e., no att. filter)</td>
</tr>
</tbody>
</table>
4.4 Semi-structured records

4.4.1 Data model
4.4.2 Filter model
4.4.1 Data model

- Notification = XML document = set of elements arranged in a tree
  - Element = set of attributes + subordinate child elements
    - Attributes = pairs \((name, value)\)
    - Sibling attributes can have same name \(\implies\) names address sets of attr.

```
1  <notification>
2    <auction endtime="05/18/02 22:17:42"
3      minprice="50">
4      <seller name="Smith" id="1234"/>
5    </item>
6    <item>
7      <board ... />
8    </item>
9    <item>
10      <cpu manufacturer="AMD"
11          type="Athlon" clock="800"/>
12    </item>
13  </auction>
14  </notification>
```
4.4.2 Filter model I

- A filter model uses a path expression (e.g., XPath)
  - Select a set of attributes and Impose constraints on the selected attributes
- A filter is a conjunction of path filters: \( F = \bigwedge_i P_i \)
- A path filter \( P = (S, C) \) consists of an element selector \( S \) and an element filter \( C \)
- An element selector selects a subset of the elements of a notification
  - An absolute path: e.g. `/notification/auction/item/cpu`
  - An abbreviated path: e.g. `//cpu`
- An element filter is a conjunction of a nonempty set of attribute filters: \( C = \bigwedge_i A_i \)
  - e.g. `[@manufacturer = “AMD” \& @clock \geq 700]`
- Example of path filter:
  `/notification/auction/item/cpu[@manufacturer = “AMD” \& @clock \geq 700]`
4.4.2 Filter model II

- \( L_A(A) \): set of all values that cause an attribute filter \( A \) to match an attribute

- \( A_1 = (n_1, Q_1) \) covers \( A_2 = (n_2, Q_2) \), \( A_1 \supseteq A_2 \) iff \( n_1 = n_2 \land L_A(A_1) \supseteq L_A(A_2) \)
  - Example: \([\text{clock} \geq 600]\) covers \([\text{clock} \geq 700]\)

- \( L_E(C) \): set of all elements that match an element filter \( C \)

- \( C_1 \) covers \( C_2 \), \( C_1 \supseteq C_2 \) iff \( L_E(C_1) \supseteq L_E(C_2) \)
  - Example: \([\text{clock} \geq 600]\) covers \([\text{manufacture} = \text{“AMD”} \land \text{clock} \geq 700]\)

- \( C_1 \) is disjoint with \( C_2 \) if there exists no attribute that is constrained in both element filters
  - Example: \([\text{minprice} \not< 100]\) is disjoint with \([\text{name} = \text{“Pu”}]\)

- \( L_S(S) \): set of all elements that are selected by an element selector \( S \)

- \( S_1 \) covers \( S_2 \), \( S_1 \supseteq S_2 \) iff \( L_S(S_1) \supseteq L_S(S_2) \)
4.4.2 Filter model III

- \( S_1 \) is disjoint with \( S_2 \) iff \( L_S(S_1) \cap L_S(S_2) = \emptyset \)
- An absolute path covers another absolute path iff both are identical
- An abbreviated path covers another (abbreviated/absolute) path iff the former is a suffix of the later
  - Example: \( //cpu \) covers \( //item/cpu \) because \( //cpu \) selects all elements named \( cpu \), \( //item/cpu \) only selects those elements named \( cpu \) which are a sub-element of an element \( item \)
- \( L_P(P) \): set of all elements that match a path filter \( P \)
- \( P_1 = (S_1, C_1) \) covers \( P_2 = (S_2, C_2) \), \( P_1 \supseteq P_2 \) iff \( L_P(P_1) \supseteq L_P(P_2) \)
  - Example: \( //cpu[@manufacturer = "AMD"] \) covers \( //cpu[@manufacturer = "AMD" \land @clock \geq 700] \)
- \( P_1 \) is disjoint with \( P_2 \) iff \( S_1 \) is disjoint with \( S_2 \) or \( C_1 \) is disjoint with \( C_2 \)
4.4.2 Filter model IV

- **Lemma:** Given two path filters $P_1 = (S_1, C_1)$ and $P_2 = (S_2, C_2)$:
  $P_1 \supseteq P_2$ iff $S_1 \supseteq S_2 \land C_1 \supseteq C_2$
  A filter $F_1$ covers $F_2$, $F_1 \supseteq F_2$ iff $N(F_1) \supseteq N(F_2)$

- **Lemma:** Given two filters $F_1 = P_1^1 \land ... \land P_n^1$ and $F_2 = P_1^2 \land ... \land P_m^2$:
  $F_1 \supseteq F_2$ iff $\forall i \exists j$ such that $P_i^1 \supseteq P_j^2$

- **Example:** the filter \{$//cpu[@type = "Athlon"]\$} covers \{$//seller[@name = "Pu"] \land //cpu[@type = "Athlon" \land @clock \geq 600]\$}
4.5 Objects

- Model notifications and filters as objects
- Calling methods on attribute objects
  - Methods can be invoked on the objects embedded in the notification
  - The return value of the method can be a boolean value that is interpreted as a result of the attribute filter or a value that is used to evaluate the constraint
  
  **Example:** An instance of a class *StockQuote* has been embedded in a notification
  - The object possesses an attribute with the name *quote*
  - \( A = (quote.id() = “IBM”) \)
  - \( A \) covers
    \( (quote.isRealTime()) \land (quote.id() = “IBM”) \land (quote.price() > 45.0) \)