Modelling ambulance deployment with CARMA

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Outline

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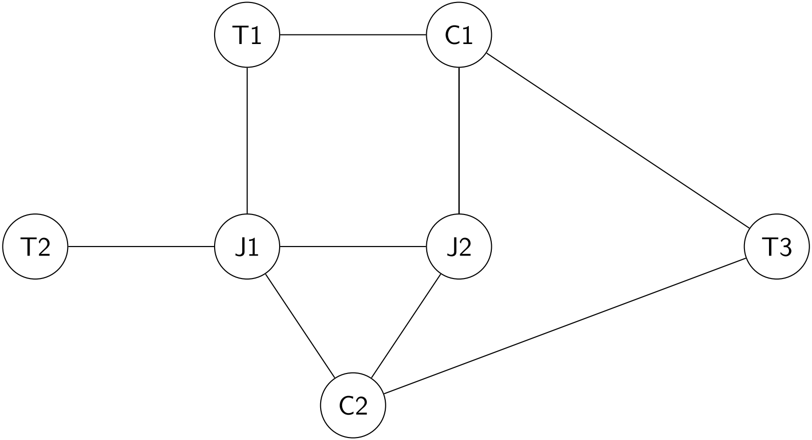
Introduction and motivation

- modelling of collective adaptive systems
  - collective: multiple agents interacting to achieve goals
  - adaptive: change behaviour in response to changing environment
- CARMA: language developed for modelling these systems
- ambulance deployment
  - case study
  - network of places and roads
  - heuristic to decide waiting place of idle ambulance
- experimentation through modelling
- exploration of CARMA and heuristic

Ambulance deployment



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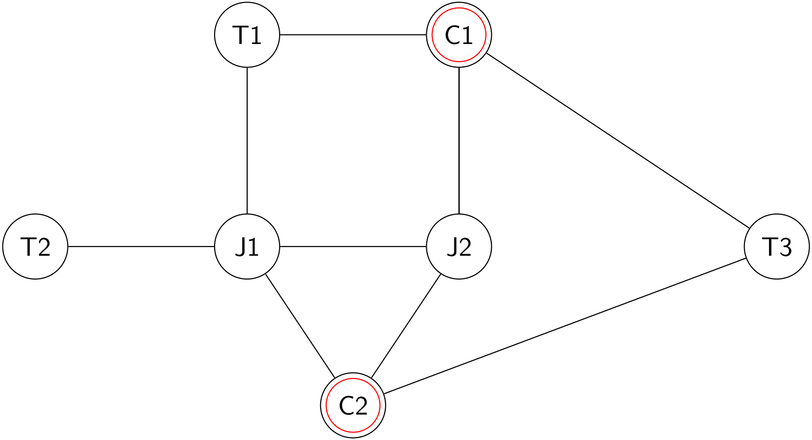

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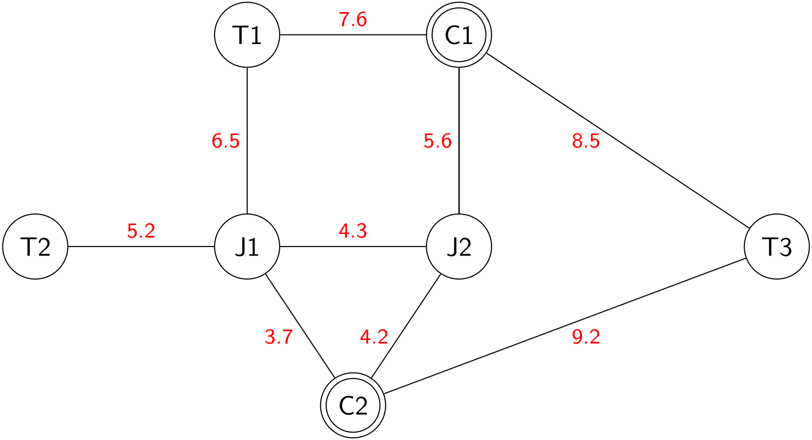

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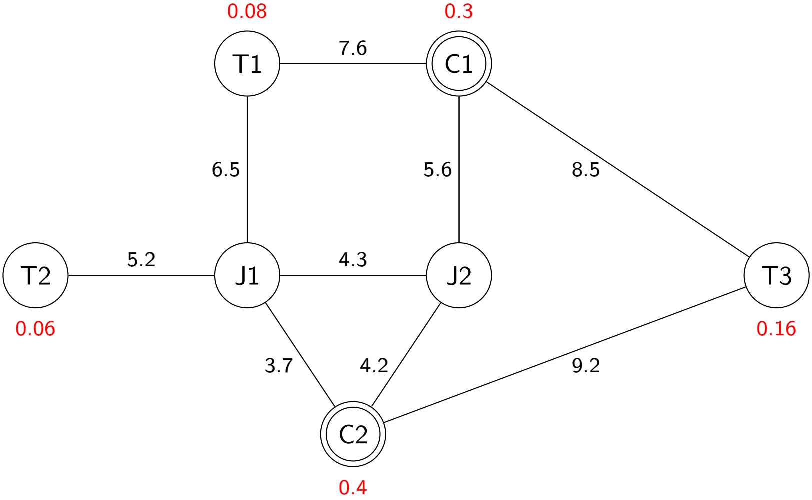

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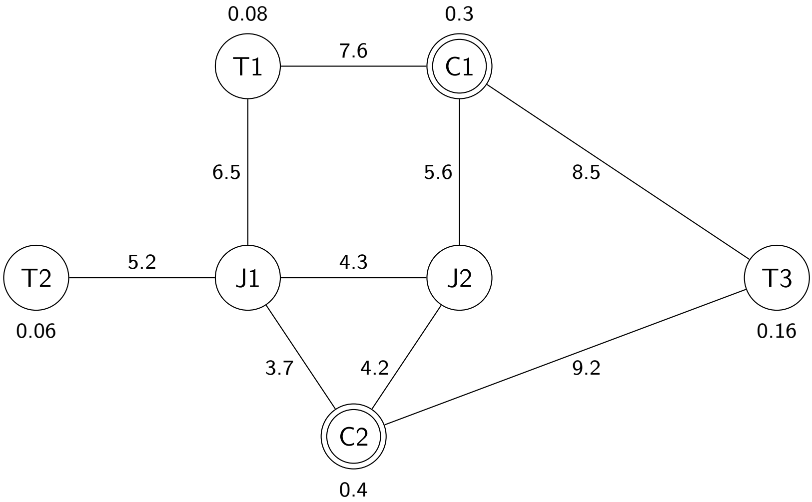

Ambulance protocol

1. An incident occurs and its level of severity is determined.
2. An idle ambulance is identified based on nearness to the incident.
3. The ambulance takes the shortest route using sirens and lights.
4. The ambulance treats the patient at the scene and then proceeds with item 7, or the ambulance uploads the patient.
5. The ambulance uses the shortest route to the hospital with sirens and lights.
6. The ambulance drops the patient off at the hospital.
7. The ambulance uses the shortest route without sirens and lights to return to a base location.

Ambulance base allocation

- static: each ambulance has a specific base
  - decided in advance of the operation of the system
  - based on simulation or other measures
- dynamic: when an ambulance has finished dealing with an incident, its base is determined by the locations of other idle ambulances
  - table-based approach: requires dispatchers to steer system to optimal states
  - using approximate dynamic programming and post-decision state is time-consuming, requires expert to implement
  - lightweight on-the-fly heuristic (Jagtenberg, Bhulai and van der Mei, 2015)

Performance evaluation

- assume set of ambulances A following protocol
- target of T minutes for an ambulance to reach incident from time of notification of incident
- classification of arrivals at incidents
  - **on-time**: T or fewer minutes to reach incident
  - **late**: more than T minutes to reach incident
- performance evaluated by proportion of late arrivals determined with respect to T

$$\text{late rate} = \frac{\text{late arrivals}}{\text{late arrivals} + \text{on-time arrivals}}$$

Definition of heuristic function

- $N = (V, E)$, $E \subseteq V \times V$: graph of places and roads
- $d(v) \in [0, 1]$: distribution of incidents
- $\rho(v, u) \in \mathbb{R}_{>0}$: deterministic time to get from vertex v to vertex u (with sirens and lights)
- $n_u(t)$: idle ambulances at or moving towards base $u \in B$

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- marginal coverage at vertex v for k ambulances that can arrive within T minutes: $E_k(v) - E_{k-1}(v) = d(v)(1 - q)q^{k-1}$
- the function returns a base giving maximum marginal coverage

$$\begin{aligned} p(N(t)) &= \underset{w \in B}{arg\ max} \sum_{v \in V} \mathbf{1}(\rho(w, v) \leq T) \cdot d(v)(1 - q)q^{c(v, N(t))} \\ c(v, N(t)) &= \sum_{u \in B} n_u(t) \cdot \mathbf{1}(\rho(u, v) \leq T) \end{aligned}$$

CARMA modelling language

- quantatitive modelling of collective adpative system
- focus on smart transport and smart grid
- define collectives of components that interact
- consider their behaviour within a specific environment defined separately
- CARMA features
  - local store in each component
  - unicast and broadcast communication
  - flexible modelling of discrete space
  - model behaviours described as time-inhomogeneous continuous-time Markov chains
- simulation using the CARMA Eclipse Plug-in

- set of CARMA *systems* SYS defined by

$$S \; ::= \; N \; \mathbf{in} \; \mathcal{E}$$

where N is a *collective* and $\mathcal{E}$ is an *environment*.

- set of collectives COL is defined by

$$N \quad ::= \quad C \;\; \Big| \;\; N \parallel N$$

- set of components COMP is defined by

$$C ::= \mathbf{0} \;\; \Big| \;\; (P, \gamma)$$

where $\mathbf{0}$ is the null component, P is a process and γ is its store

CARMA processes

$$
\begin{array}{rcll}
P, Q & ::= & \mathbf{nil} & \\
 & | & \mathbf{kill} & \\
 & | & act.P & \\
 & | & P + Q & \\
 & | & P \mid Q & \\
 & | & [\pi]P & \\
 & | & A & (A \stackrel{\mathrm{def}}{=} P)
\end{array}
$$

$$
\begin{array}{rcl}
act & ::= & \alpha^\star[\pi]\langle \overrightarrow{e} \rangle\sigma \\
 & | & \alpha[\pi]\langle \overrightarrow{e} \rangle\sigma \\
 & | & \alpha^\star[\pi](\overrightarrow{x})\sigma \\
 & | & \alpha[\pi](\overrightarrow{x})\sigma
\end{array}
$$

$$e ::= a \mid \mathrm{my}.a \mid x \mid v \mid \mathrm{now} \mid \cdots$$

$$\pi ::= \top \mid \bot \mid e_1 \bowtie e_2 \mid \neg\pi \mid \pi \wedge \pi \mid \cdots$$

four different action prefixes

- *broadcast output:* $\alpha^{\star}[\pi]\langle\overrightarrow{e}\rangle\sigma$,
- *broadcast input:* $\alpha^{\star}[\pi](\overrightarrow{x})\sigma$,
- *output:* $\alpha[\pi]\langle\overrightarrow{e}\rangle\sigma$,
- *input:* $\alpha[\pi](\overrightarrow{x})\sigma$,

where

- α: action type, π: predicate, x: variable, e: expression
- $\overrightarrow{\cdot}$ indicates a sequence of elements
- σ is an *update* mapping the current store to a distribution over stores
- $\alpha^{\star}[\perp]\langle\rangle$ is an action without communication

- γ_g: global store for global attributes
- $\langle \mu_p, \mu_r, \mu_u \rangle$: tuple of functions known as the *evaluation context*
  - $\mu_p(\gamma_s, \gamma_r, \alpha) \in [0,1]$ determines the probability that a component with store γ_r can receive a message from a component with store γ_s when α is executed
  - $\mu_r(\gamma, \alpha) \in \mathbb{R}_{\geq 0}$ determines the execution rate of action α executed at a component with store γ
  - $\mu_u(\gamma, \alpha)$ determines the updates on the environment (global store and collective) induced by the execution of action α at a component with store γ

CARMA model

- $|A|$ Ambulance components
- *Incident_Queue* component, *Closest_Idle_Ambulance* component
- other components are created when necessary: *Incident_Queue_Item*, *Incident_Handler*, *Route*, *Return_Handler*

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- functions embody knowledge of network
  - **IncidentLocation**(), **IncidentType**()
  - **HospitalLocation**(*loc*)
  - **MoveTime**(*nexts*, *nexte*, *dest*)
  - **NextHop**(*i*, *aloc*, *loc*), **RouteLength**(*aloc*, *loc*)
  - **GetBase**(*anum*, *aloc*, *N*)
  - **ClosestIdleAmbulance**(*iloc*, *N*)

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  - **GetBase**(*anum*, *aloc*, *N*)
  - **ClosestIdleAmbulance**(*iloc*, *N*)
- timing and probabilities
  - deterministic: time to move between vertices
  - stochastic: time for treatment, pick up, drop off
  - probabilistic: distribution of incidents and type of incident

Constants:

T	limit for response time
$timeout$	time to wait for a response for a request

Measures:

N	set containing the number of idle ambulances at each possible base

Initial collective:

$$\begin{aligned} EMS \stackrel{\text{def}}{=} \;& (Incident\_Queue, \{inum \mapsto 0, rnum \mapsto 1) \parallel \\ & (ClosestIdleAmbulance, \{dloc \mapsto nullLoc, iloc \mapsto nullLoc, t \mapsto 0)) \parallel \\ & (Ambulance, \{anum \mapsto 1, aloc \mapsto l_1, abase \mapsto l_1, idle \mapsto \top\}) \parallel \ldots \parallel \\ & (Ambulance, \{anum \mapsto n, aloc \mapsto l_n, abase \mapsto l_n, idle \mapsto \top\}) \end{aligned}$$

Global store:

ontime	number of ontime ambulances
late	number of late ambulances

Evolution rule functions:

$$\mu_p(\gamma_s, \gamma_r, \alpha) = 1$$

$$\mu_r(\gamma_s, \alpha) = \begin{cases} 1/r & \alpha = \text{incident}^\star \quad (r\text{: mean time between incidents}) \\ \lambda_p & \alpha = \text{pickup}^\star \\ \lambda_t & \alpha = \text{treat}^\star \\ \lambda_d & \alpha = \text{dropoff}^\star \\ 0 & \alpha = \text{pause}^\star \wedge \text{now} < \gamma_s(t) + \mathit{timeout} \\ \lambda_{fast} & \text{otherwise} \end{cases}$$

Updates on global store

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$$\mu_u(\gamma_s, \alpha) \quad = \quad \begin{cases} \{\mathit{ontime} \leftarrow \mathit{ontime} + 1\}, 0 \\ \qquad \alpha = \mathrm{timecheck}^\star \wedge \mathrm{now} <= \gamma_s(\mathit{itime}) + T \\ \\ \{\mathit{late} \leftarrow \mathit{late} + 1\}, 0 \\ \qquad \alpha = \mathrm{timecheck}^\star \wedge \mathrm{now} > \gamma_s(\mathit{itime}) + T \\ \qquad\qquad\qquad \vdots \end{cases}$$

Updates on collective

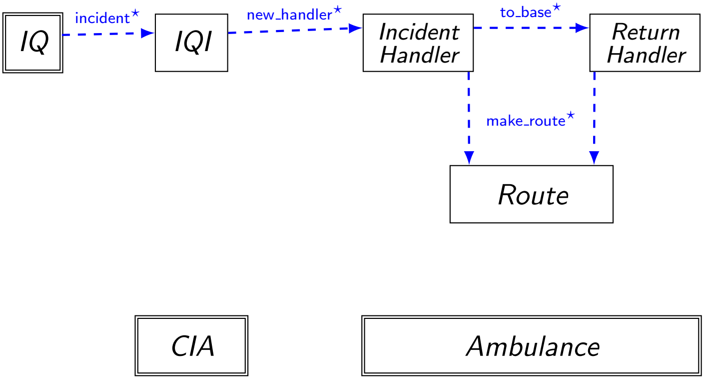
$$\mu_u(\gamma_s, \alpha) = \begin{cases} \vdots \\ \{\}, (\mathit{Incident\_Queue\_Item}, \{\mathit{qnum} \leftarrow \gamma_s(\mathit{num}), \mathit{itime} \leftarrow \text{now}\}) \\ \qquad \alpha = \text{incident}^\star \\ \\ \{\}, (\mathit{Incident\_Handler}, \{\mathit{loc} \leftarrow \textbf{IncidentLocation}(), \\ \qquad\qquad \mathit{dest} \leftarrow \textbf{IncidentType}(), \\ \qquad\qquad \mathit{itime} \leftarrow \gamma_s(\mathit{itime})\}) \\ \qquad \alpha = \text{new\_handler}^\star \\ \vdots \end{cases}$$

Updates on collective

$$\mu_u(\gamma_s, \alpha) = \begin{cases} \vdots \\ \{\}, (\mathit{Route}, \{\mathit{anum} \leftarrow \gamma_s(\mathit{anum}), \\ \qquad \mathit{dest} \leftarrow \gamma_s(\mathit{dest}), \\ \qquad \mathit{start} \leftarrow \gamma_s(\mathit{aloc}), \\ \qquad \mathit{end} \leftarrow \gamma_s(\mathit{loc}), \\ \qquad \mathit{nexts} \leftarrow \gamma_s(\mathit{aloc}), \\ \qquad \mathit{nexte} \leftarrow \textbf{NextHop}(1, \gamma_s(\mathit{aloc}), \gamma_s(\mathit{loc}), \\ \qquad h \leftarrow \textbf{RouteLength}(\gamma_s(\mathit{aloc}), \gamma_s(\mathit{loc})\})) & \alpha = \text{makeroute}^\star \\ \vdots \end{cases}$$

$$\mu_u(\gamma_s, \alpha) = \begin{cases} \vdots \\ \{\}, (\mathit{Return\_Handler}, \{\mathit{anum} \leftarrow \gamma_s(\mathit{anum}), \\ \qquad \mathit{aloc} \leftarrow \gamma_s(\mathit{aloc}), \\ \qquad \mathit{dest} \leftarrow \gamma_s(\mathit{dest}), \\ \qquad \mathit{loc} \leftarrow \mathbf{GetBase}(\gamma_s(\mathit{anum}), \gamma_s(\mathit{aloc}), N)\}) \\ \quad \alpha = \text{tobase}^\star \\ \{\}, 0 \qquad \text{otherwise} \end{cases}$$

Interaction between components



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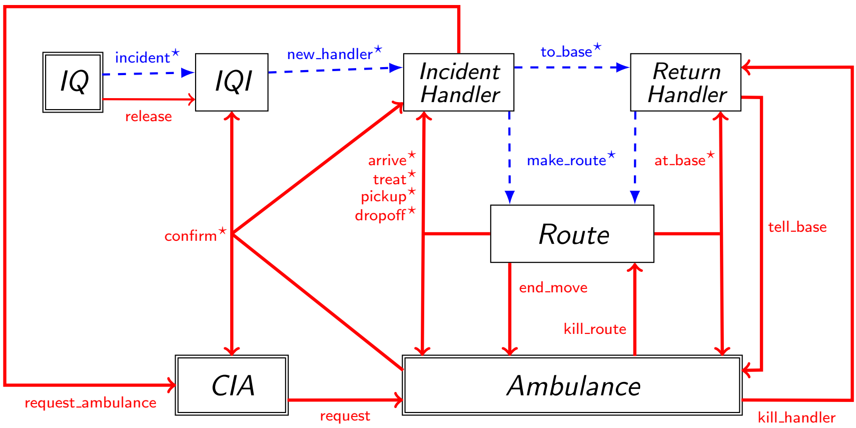

Store of *Ambulance* component:

anum	ambulance id
aloc	current location of ambulance
abase	current base of ambulance
idle	whether ambulance is idle or not

Initial state of *Ambulance* component: *Idle*

Behaviour of *Ambulance* component:

$$
\begin{array}{rcl}
\mathit{Idle} & \stackrel{\text{def}}{=} & \mathsf{request}[\mathit{al} == \mathsf{my}.\mathit{aloc}](\mathit{al})\{\mathit{idle} \leftarrow \bot\}.\mathit{Respond} \\
\mathit{Respond} & \stackrel{\text{def}}{=} & \mathsf{confirm}^{\star}[\top]\langle \mathit{anum}, \mathit{aloc}\rangle.\mathit{Busy} \\
\mathit{Busy} & \stackrel{\text{def}}{=} & \mathsf{end\_move}[\mathit{an} == \mathsf{my}.\mathit{anum} \wedge \mathsf{now} >= t + d](\mathit{an}, \mathit{al}, t, d) \\
 & & \qquad \{\mathit{aloc} \leftarrow \mathit{al}\}.\mathit{Busy} + \\
 & & \mathsf{arrive}^{\star}[\mathit{an} == \mathsf{my}.\mathit{anum}](\mathit{an}).\mathit{AtScene} + \\
 & & \mathsf{drop\_off}^{\star}[\mathit{an} == \mathsf{my}.\mathit{anum}](\mathit{an})\{\mathit{idle} \leftarrow \top\}.\mathit{AskBase} \\
\mathit{AtScene} & \stackrel{\text{def}}{=} & \mathsf{pickup}^{\star}[\mathit{an} == \mathsf{my}.\mathit{anum}](\mathit{an}).\mathit{Busy} + \\
 & & \mathsf{treat}^{\star}[\mathit{an} == \mathsf{my}.\mathit{anum}](\mathit{an})\{\mathit{idle} \leftarrow \top\}.\mathit{AskBase} \\
\mathit{AskBase} & \stackrel{\text{def}}{=} & \mathsf{tell\_base}[\mathit{an} == \mathsf{my}.\mathit{anum}](\mathit{an}, \mathit{ab})\{\mathit{abase} \leftarrow \mathit{ab}\}.\mathit{GoToBase} \\
\mathit{GoToBase} & \stackrel{\text{def}}{=} & \mathsf{end\_move}[\mathit{an} == \mathsf{my}.\mathit{anum} \wedge \mathsf{now} >= t + d](\mathit{an}, \mathit{al}, t, d) \\
 & & \qquad \{\mathit{aloc} \leftarrow \mathit{al}\}.\mathit{GoToBase} + \\
 & & \mathsf{atbase}^{\star}[\mathit{an} == \mathsf{my}.\mathit{anum}](\mathit{an}).\mathit{Idle} + \\
 & & \mathsf{request}[\mathit{an} == \mathsf{my}.\mathit{anum}](\mathit{an}).\mathit{CleanUp1} \\
\mathit{CleanUp1} & \stackrel{\text{def}}{=} & \mathsf{kill\_handler}^{\star}[\top]\langle \mathit{anum}\rangle.\mathit{CleanUp2} \\
\mathit{CleanUp2} & \stackrel{\text{def}}{=} & \mathsf{kill\_route}^{\star}[\top]\langle \mathit{anum}\rangle.\mathit{Respond}
\end{array}
$$

Route

Store of *Route* component:

anum	number of ambulance
dest	current destination type and incident type
start	start of route
end	end of route
nexts	start of next hop
nexte	end of next hop
h	number of hops in route
i	hop counter
t	timer variable for deterministic movement

Initial state of *Route* component: $R \mid KR$

Behaviour of *Route* component:

$$
\begin{aligned}
R \;&\stackrel{\text{def}}{=}\; [i < h]\mathrm{start\_move}^{\star}[\bot]\langle\rangle\{i \leftarrow i+1, t \leftarrow \mathrm{now}\}.RC \;+ \\
&\quad [i = h \wedge (\mathrm{my}.dest == ToSevere \vee \mathrm{my}.dest == ToMinor)] \\
&\qquad\qquad \mathrm{arrive}^{\star}[\top]\langle anum\rangle.RS \;+ \\
&\quad [i = h \wedge \mathrm{my}.dest == ToHosp]\mathrm{dropoff}^{\star}[\top]\langle anum\rangle.\mathbf{kill} \;+ \\
&\quad [i = h \wedge \mathrm{my}.dest == ToBase]\mathrm{atbase}^{\star}[\top]\langle anum\rangle.\mathbf{kill} \\[1em]
RS \;&\stackrel{\text{def}}{=}\; [i = h \wedge \mathrm{my}.dest == ToSevere]\mathrm{pickup}^{\star}[\top]\langle anum\rangle.\mathbf{kill} \;+ \\
&\quad [i = h \wedge \mathrm{my}.dest == ToMinor]\mathrm{treat}^{\star}[\top]\langle anum\rangle.\mathbf{kill} \\[1em]
RC \;&\stackrel{\text{def}}{=}\; \mathrm{end\_move}[\top]\langle anum, nexte, t, \mathbf{MoveTime}(nexts, nexte, dest)\rangle \\
&\quad \{nexts \leftarrow \mathrm{my}.nexte, nexte \leftarrow \mathbf{NextHop}(i, \mathrm{my}.start, \mathrm{my}.end)\}.R \\[1em]
KR \;&=\; \mathrm{kill\_route}^{\star}[\mathrm{my}.anum == an](an).\mathbf{kill}
\end{aligned}
$$

Store of *Incident_Handler* component:

loc	location of incident or hospital
anum	id of ambulance assigned to incident
aloc	current location of ambulance assigned to incident
dest	current destination type and incident type
itime	time of incident
atime	arrival time at incident

Initial state of *Incident_Handler* component: *IH*

Incident handler

Behaviour of *Incident_Handler* **component:**

$$
\begin{aligned}
IH &\stackrel{\text{def}}{=} \mathsf{request\_ambulance}^{\star}[\top]\langle loc\rangle.IH_C \\
IH_C &\stackrel{\text{def}}{=} \mathsf{confirm}^{\star}[an, al](\{anum \leftarrow an, aloc \leftarrow al\}).IH_I \\
IH_I &\stackrel{\text{def}}{=} \mathsf{makeroute}^{\star}[\bot]\langle\rangle.IH_S \\
IH_S &\stackrel{\text{def}}{=} \mathsf{arrive}^{\star}[an == \mathsf{my}.anum](an).IH_T \\
IH_T &\stackrel{\text{def}}{=} \mathsf{timecheck}^{\star}[\bot]\langle\rangle\{atime \leftarrow \mathsf{now}\}.IH_P \\
IH_P &\stackrel{\text{def}}{=} \mathsf{pickup}^{\star}[an == \mathsf{my}.anum](an)\{aloc \leftarrow \mathsf{my}.loc, \\
&\qquad\qquad loc \leftarrow \mathbf{HospitalLocation}(\mathsf{my}.loc), dest \leftarrow ToHosp\}.IH_H + \\
&\quad\ \mathsf{treat}^{\star}[an == \mathsf{my}.anum](an)\{aloc \leftarrow \mathsf{my}.loc, dest \leftarrow ToBase\}.IH_F \\
IH_H &\stackrel{\text{def}}{=} \mathsf{makeroute}^{\star}[\bot]\langle\rangle.IH_D \\
IH_D &\stackrel{\text{def}}{=} \mathsf{dropoff}^{\star}[an == \mathsf{my}.anum](an)\{aloc \leftarrow \mathsf{my}.loc, dest \leftarrow ToBase\}.IH_F \\
IH_F &\stackrel{\text{def}}{=} \mathsf{tobase}^{\star}[\bot]\langle\rangle.\mathbf{kill}
\end{aligned}
$$

Return handler

Store of *Return_Handler* component:

anum	id of ambulance assigned
aloc	current location of ambulance
dest	current destination and incident type
loc	location of base of ambulance

Initial state of *Return_Handler* component: RH

Behaviour of *Return_Handler* component:

$$
\begin{array}{rcl}
RH & \stackrel{\mathrm{def}}{=} & \mathsf{tell\_base}[\top]\langle loc\rangle.RH' \\
RH' & \stackrel{\mathrm{def}}{=} & \mathsf{makeroute}^{\star}[\bot]\langle\rangle.RH'' + \mathsf{kill\_handler}^{\star}[\mathsf{my}.anum == an](an).\mathbf{kill} \\
RH'' & \stackrel{\mathrm{def}}{=} & \mathsf{atbase}^{\star}[\mathsf{my}.anum == an](an).\mathbf{kill} + \\
 & & \mathsf{kill\_handler}^{\star}[\mathsf{my}.anum == an](an).\mathbf{kill}
\end{array}
$$

Store of *Incident_Queue* **component:**

inum	number of incidents generated
rnum	next incident to be dealt with

Initial state of *Incident_Queue* **component:** $IG \mid RN$

Behaviour of *Incident_Queue* **component:**

$$IG \stackrel{\text{def}}{=} \text{incident}^{\star}[\bot]\langle\rangle\{inum \leftarrow inum + 1\}.IG$$

$$RN \stackrel{\text{def}}{=} \text{release}[\top]\langle rnum\rangle.RN'$$

$$RN' \stackrel{\text{def}}{=} \text{confirm}^{\star}[\top](an, al)\{rnum \leftarrow rnum + 1\}.RN$$

Store of *Incident_Queue_Item* **component:**

qnum	number of incident
itime	time of incident

Initial state of *Incident_Queue_Item* **component:** IQI

Behaviour of *Incident_Queue_Item* **component:**

$$IQI \stackrel{\text{def}}{=} \text{release}[\text{my}.qnum == n](n).IQI'$$

$$IQI' \stackrel{\text{def}}{=} \text{new\_handler}^{\star}[\bot]\langle\rangle.\mathbf{kill}$$

Closest idle ambulance

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Store of *Closest_Idle_Ambulance* **component:**

iloc	location of incident
dloc	location of idle ambulances
t	timer variable for timeout

Initial state of *Closest_Idle_Ambulance* **component:** CIA

Behaviour of *Closest_Idle_Ambulance* **component:**

$$\begin{aligned}
CIA &\stackrel{\text{def}}{=} \text{request_ambulance}[\top](l)\{iloc \leftarrow l, \\
&\qquad dloc \leftarrow \mathbf{ClosestIdleLoc}(iloc, N), t \leftarrow \text{now}\}.CIA' \\
CIA' &\stackrel{\text{def}}{=} \text{request}[\top]\langle dloc\rangle.CIA'' + \\
&\qquad \text{pause}^{\star}[\bot]\langle\rangle\{dloc \leftarrow \mathbf{ClosestIdleLoc}(iloc, N), t \leftarrow \text{now}\}.CIA' \\
CIA'' &\stackrel{\text{def}}{=} \text{confirm}^{\star}[\top](an, al).CIA
\end{aligned}$$

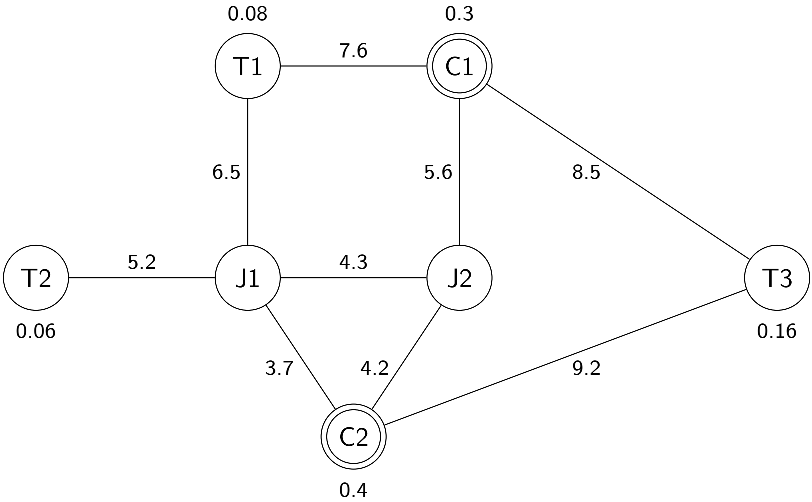
Experiments

- 3 ambulances
- parameters

λ_p	$1/12$	rate of pickup* action
λ_t	$1/12$	rate of treat* action
λ_d	$1/15$	rate of dropoff* action
λ_{fast}	100	all other actions
q	0.65	busy fraction
m	1	proportion of serious incidents
r	25	mean time between incidents

- 500 simulation runs of 20 hours of simulated time
- investigation of hospital location and availability
- investigation of behaviour of heuristic

Ambulance deployment

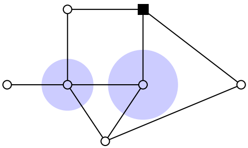
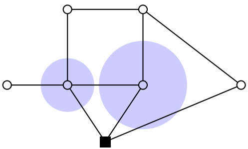
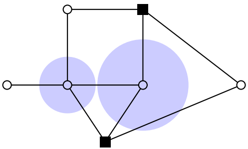
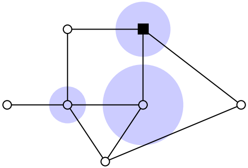
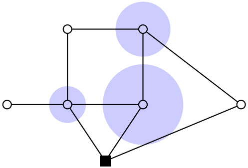
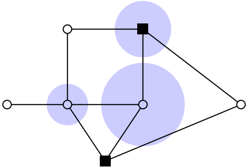


Results: time versus location

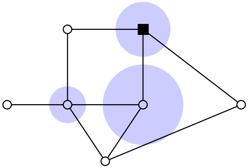
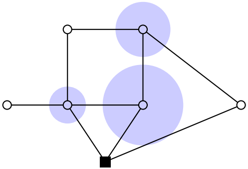
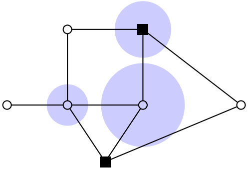
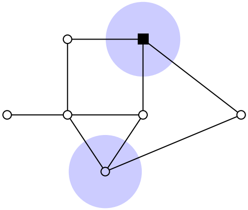
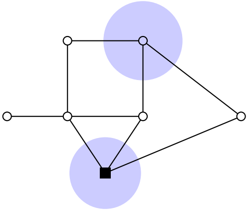
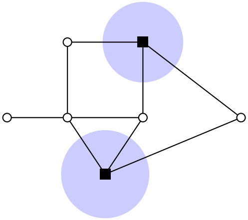
late rate

	hospital locations			base locations
	C1	C2	both	
7 min	0.53	0.46	0.46	C1 C2 J1 J2 T1 T2 T3
9 min	0.42	0.41	0.37	C1 C2 J1 J2 T1 T2 T3
10 min	0.30	0.30	0.26	C1 C2 J1 J2 T1 T2 T3
11 min	0.35	0.20	0.22	C1 C2 J1 J2 T1 T2 T3
13 min	0.44	0.35	0.35	C1 C2 J1 J2 T1 T2 T3

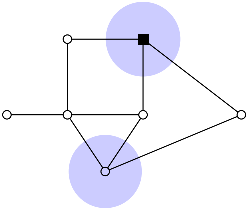
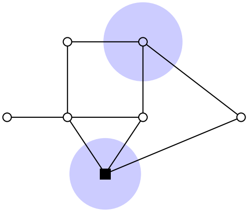
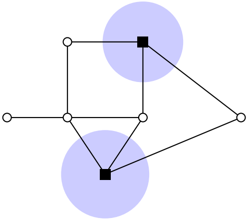
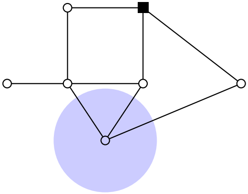
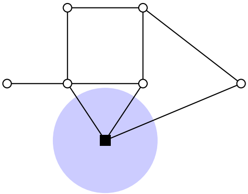
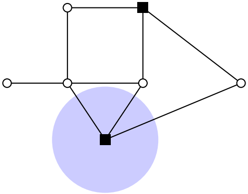
Results: 7 minutes and 9 minutes

Hospital at C1	Hospital at C2	Hospital at C1 and C2
 $T = 7$ min $lr = 0.53$	 $T = 7$ min $lr = 0.46$	 $T = 7$ min $lr = 0.46$
 $T = 9$ min $lr = 0.42$	 $T = 9$ min $lr = 0.41$	 $T = 9$ min $lr = 0.37$

Results: 9 minutes and 10 minutes

Hospital at C1	Hospital at C2	Hospital at C1 and C2
 $T = 9$ min $lr = 0.42$	 $T = 9$ min $lr = 0.41$	 $T = 9$ min $lr = 0.37$
 $T = 10$ min $lr = 0.30$	 $T = 10$ min $lr = 0.30$	 $T = 10$ min $lr = 0.26$

Results: 10 minutes and 11 minutes

Hospital at C1	Hospital at C2	Hospital at C1 and C2
 $T = 10$ min $lr = 0.30$	 $T = 10$ min $lr = 0.30$	 $T = 10$ min $lr = 0.26$
 $T = 11$ min $lr = 0.35$	 $T = 11$ min $lr = 0.20$	 $T = 11$ min $lr = 0.22$

Results: 11 minutes and 13 minutes

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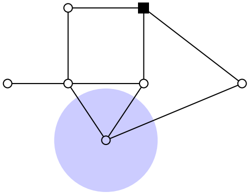
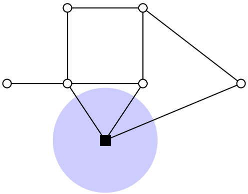
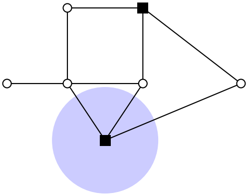
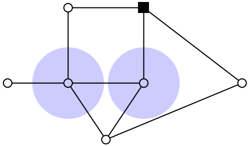
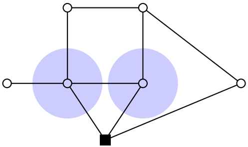
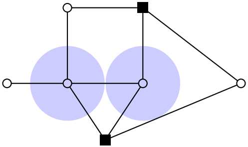
Hospital at C1	Hospital at C2	Hospital at C1 and C2
		
$T = 11$ min $lr = 0.35$	$T = 11$ min $lr = 0.20$	$T = 11$ min $lr = 0.22$
		
$T = 13$ min $lr = 0.44$	$T = 13$ min $lr = 0.35$	$T = 13$ min $lr = 0.35$

Further experimentation

- exploration of parameter space
- exploration of different road network graphs
- calculation of busy fraction during simulation
  - longer simulations required to achieve stable busy fraction
- variants of heuristic
  - include hospital locations explicitly
  - different targets for different levels of severity
- variants of protocol
  - switch to ambulance closer to incident if one becomes available
  - move ambulances between bases when an incident occurs to improve coverage

Conclusion

- quantitative modelling of an ambulance scenario
- CARMA: a language for modelling collective adaptive systems
- CARMA supports separation of concerns
  - environment distinct from collective
  - functions to capture network specifics
- exploration of heuristic which determines next base
- heuristic behaviour is not monotonic
- various options for further exploration

Conclusion

- quantitative modelling of an ambulance scenario
- CARMA: a language for modelling collective adaptive systems
- CARMA supports separation of concerns
  - environment distinct from collective
  - functions to capture network specifics
- exploration of heuristic which determines next base
- heuristic behaviour is not monotonic
- various options for further exploration

Thank you for your attention. Any questions?

Heuristic function

- the function returns a base using maximum marginal coverage

$$
\begin{aligned}
p(N(t)) &= \underset{w \in B}{arg\ max} \sum_{v \in V} \mathbf{1}(\rho(w,v) \leq T) \cdot d(v)(1-q)q^{k(v,w,N(t))-1} \\
k(v,w,N(t)) &= \mathbf{1}(\rho(w,v) \leq T) + \sum_{u \in B} n_u(t) \cdot \mathbf{1}(\rho(u,v) \leq T)
\end{aligned}
$$

$$
\text{where } \mathbf{1}(\phi) = \begin{cases} 1 & \text{if } \phi \text{ is true} \\ 0 & \text{if } \phi \text{ is false} \end{cases}
$$

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- the function returns a base using maximum marginal coverage

$$p(N(t)) = \arg\max_{w \in B} \sum_{v \in V} \mathbf{1}(\rho(w,v) \leq T) \cdot d(v)(1-q)q^{k(v,w,N(t))-1}$$

$$k(v,w,N(t)) = \mathbf{1}(\rho(w,v) \leq T) + \sum_{u \in B} n_u(t) \cdot \mathbf{1}(\rho(u,v) \leq T)$$

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Heuristic function

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Heuristic function

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$$p(N(t)) = \arg\max_{w \in B} \sum_{v \in V} \mathbf{1}(\rho(w,v) \leq T) \cdot d(v)(1-q)q^{k(v,w,N(t))-1}$$

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Heuristic function

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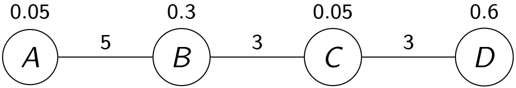
\end{aligned}
$$

$$
\text{where } \mathbf{1}(\phi) = \begin{cases} 1 & \text{if } \phi \text{ is true} \\ 0 & \text{if } \phi \text{ is false} \end{cases}
$$

- it can be simplified to

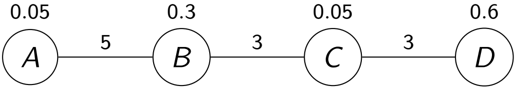
$$
\begin{aligned}
p(N(t)) &= \underset{w \in B}{arg\ max} \sum_{v \in V} \mathbf{1}(\rho(w,v) \leq T) \cdot d(v)(1-q)q^{c(v,N(t))} \\
c(v,N(t)) &= \sum_{u \in B} n_u(t) \cdot \mathbf{1}(\rho(u,v) \leq T)
\end{aligned}
$$

Calculation of heuristic



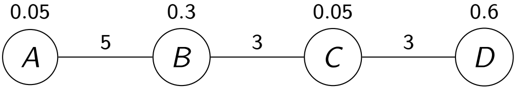
Calculation of heuristic

$T = 11$



Calculation of heuristic

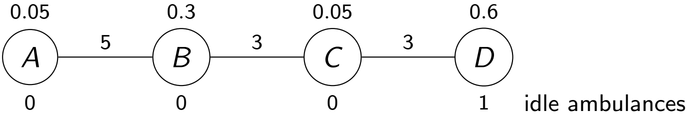
$$T = 11$$
$$q = 0.4$$



Calculation of heuristic

$T = 11$

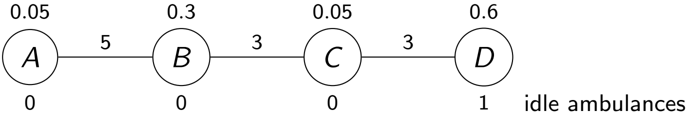
$q = 0.4$



Calculation of heuristic

$T = 11$

$q = 0.4$

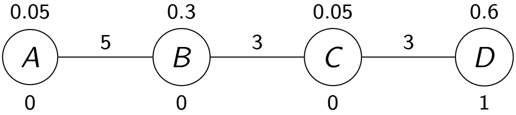


Base for return	A	B	C	D	
	Total idle ambulances in range when coverage increases				
A	2	2	2	2	
B	2	2	2	2	
C	2	2	2	2	
D	2	2	2	2	
	Increase in coverage				**Total**
A	0.01	0.07	0.01	0.14	0.24
B	0.01	0.07	0.01	0.14	0.24
C	0.01	0.07	0.01	0.14	0.24
D	0.01	0.07	0.01	0.14	0.24

Calculation of heuristic

T = 11

q = 0.8



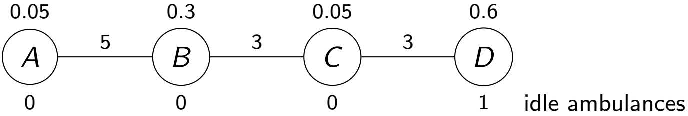
idle ambulances

Base for return	A	B	C	D	
	Total idle ambulances in range when coverage increases				
A	2	2	2	2	
B	2	2	2	2	
C	2	2	2	2	
D	2	2	2	2	
	Increase in coverage				**Total**
A	0.01	0.05	0.01	0.10	0.16
B	0.01	0.05	0.01	0.10	0.16
C	0.01	0.05	0.01	0.10	0.16
D	0.01	0.05	0.01	0.10	0.16

Calculation of heuristic

$T = 11$

$q = 0.4$

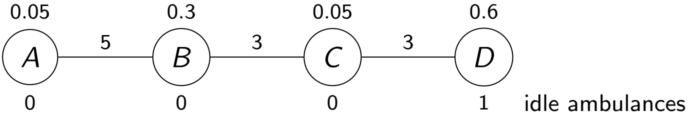


Base for return	*A*	*B*	*C*	*D*	
	Total idle ambulances in range when coverage increases				
A	2	2	2	2	
B	2	2	2	2	
C	2	2	2	2	
D	2	2	2	2	
	Increase in coverage				**Total**
A	0.01	0.07	0.01	0.14	0.24
B	0.01	0.07	0.01	0.14	0.24
C	0.01	0.07	0.01	0.14	0.24
D	0.01	0.07	0.01	0.14	0.24

Calculation of heuristic

T = 7

q = 0.4

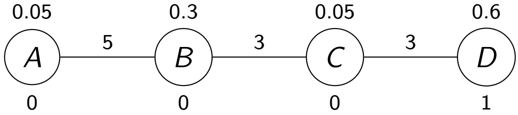


Base for return	*A*	*B*	*C*	*D*	
	Total idle ambulances in range when coverage increases				
A	1	2	-	-	
B	1	2	2	2	
C	-	2	2	2	
D	-	2	2	2	
	Increase in coverage				**Total**
A	0.03	0.07			0.10
B	0.03	0.07	0.01	0.14	0.26
C		0.07	0.01	0.14	0.23
D		0.07	0.01	0.14	0.23

Calculation of heuristic

T $= 5$

q $= 0.4$



idle ambulances

Base for return	*A*	*B*	*C*	*D*	
	Total idle ambulances in range when coverage increases				
A	1	1	-	-	
B	1	1	2	-	
C	-	1	2	2	
D	-	-	2	2	
	Increase in coverage				**Total**
A	0.03	0.18			0.21
B	0.03	0.18	0.01		0.22
C		0.18	0.01	0.14	0.34
D			0.01	0.14	0.16