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A Fog Computing Service Placement for Smart Cities based on Genetic Algorithms

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Background and motivation

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Cyber-physical environments driven by geographically distributed sensors

- Increasing amount of information to be filtered and processed

Excessive delay and scalability issues for some applications:

- Applications requiring very low and predictable latency (traffic control, support for autonomous driving)
- Geo-distributed applications (pipeline monitoring, sensor networks to monitor the environment)
- Fast mobile applications (smart connected vehicle, connected rail)
- Large-scale distributed control systems (smart grid, smart traffic monitoring)

Fog Computing

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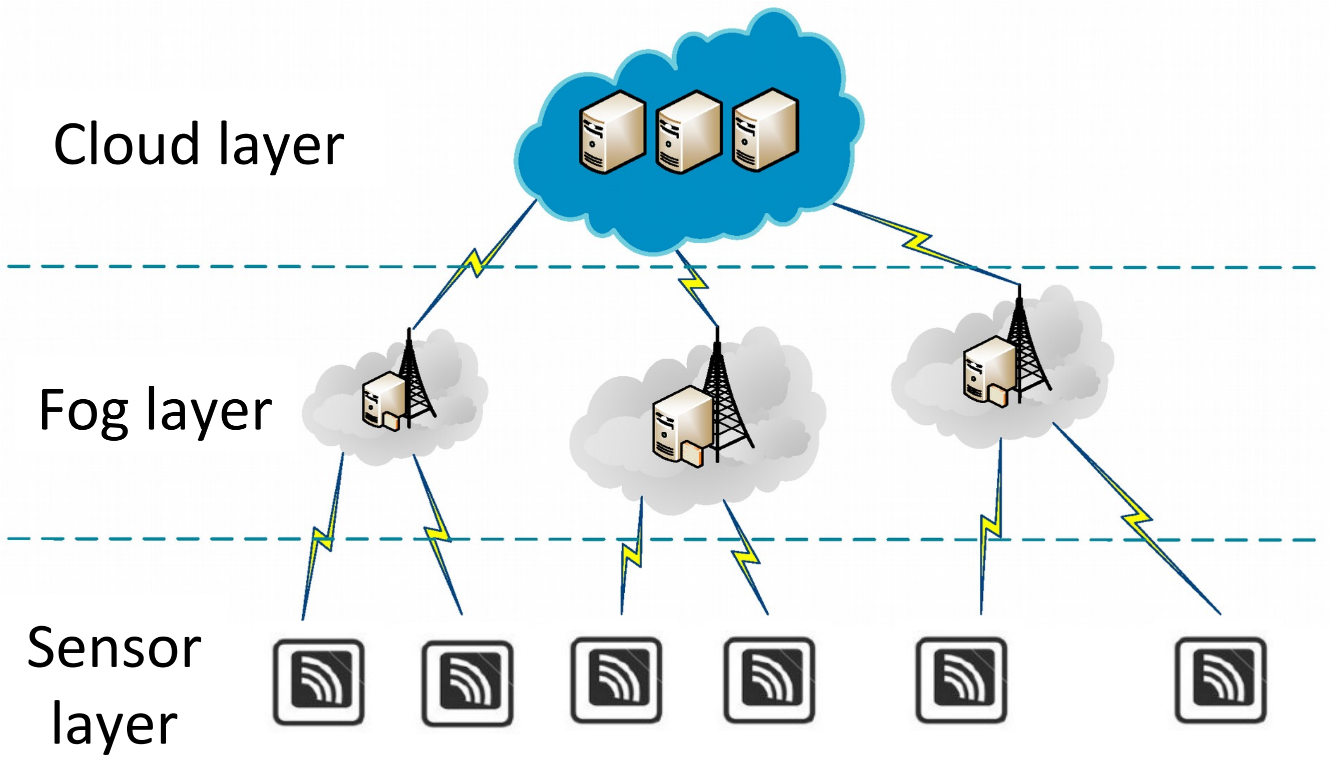
- Intermediate layer of fog nodes close to the sensors
- Services moved to the edge of the network: filtering, aggregation and/or latency critical tasks

Goal: improve latency and scalability



State of the art

- New challenges
- Existing studies:
  - Focus on the level between Fog and Cloud layers
  - Optimizing allocation of processing tasks on cloud infrastructure
  - Solutions exploiting fog-to-fog nodes communication
- Less covered issue

  Mapping sensor data flows over fog nodes
- Common assumption:
  - Fog nodes directly communicate with sensors - single-hop wireless connections
- Critical task to reduce global latency and processing time for high QoS in terms of response time

Problem definition

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- Smart city scenario:
  - City monitoring application (e.g., traffic intensity, air quality, …)
  - Data collected in the Cloud infrastructure for value-added services (e.g, traffic or pollution forecast)
- Three layers:
  - Sensor layer of wireless sensors
  - Fog layer for preliminary data pre-processing (filtering, aggregation) or anomaly detection
  - Cloud layer as final data destination of refined data samples (analysis and storage)
- Mapping sensor data flows over the fog layer

Contributions

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Twofold contribution:

1) Optimization model for mapping incoming workload over fog nodes
   - Latency due to communication
   - Processing time due to local load

2) Heuristic to solve the optimization problem in a scalable way
   - Genetic Algorithms (GAs)

Realistic scenario

- Smart city environment

  Geographic testbed based on realistic scenario of Fog architecture in a small-sized city in Italy

Problem modeling

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- Set of *S* sensors
- Sensors produce data at a steady rate: frequency λ_i for sensor i
- Fog layer: *F* nodes
- One cloud data center
- Response time contributions:
  - Network-based latency $\delta_{i,j}$ of communication between sensor i and fog node j
  - Network-based latency δ_j of communication between fog node j and the cloud data center
  - Processing time on fog node: $1/\mu_j$ time to process a data packet on node j and the data rate λ_j arriving at fog node j

Goal: guarantee a fast response

Optimization model

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- Mapping incoming workload over fog nodes
- *Assumption*: all data of a sensor are sent to the same fog node
- Main decision variable: matrix **X** of boolean flags $\mathbf{x_{i,j}}$

$$x_{i,j} = \begin{cases} 1 & \text{if sensor i is sending data to fog node j} \\ 0 & \text{otherwise} \end{cases}$$

$$\min obj(X) = \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{F}} x_{i,j} \cdot \left(\frac{1}{\mu_j - \lambda_j} + \delta_{i,j} + \delta_j \right)$$

Processing time derived from Little's result applied to a M/G/1 model

subject to:

$$\lambda_j = \sum_{i \in \mathcal{S}} x_{i,j} \cdot \lambda_i \quad \forall j \in \mathcal{F},$$

(1) Arrival load on fog node j

$$\sum_{j \in \mathcal{F}} x_{i,j} = 1 \quad \forall i \in \mathcal{S},$$

(2) Mapping on one and only one fog node

$$\lambda_j < \mu_j \quad \forall j \in \mathcal{F},$$

(3) No overload conditions

$$x_{i,j} = \{0, 1\}, \quad \forall i \in \mathcal{S}, j \in \mathcal{F}.$$

(4) Boolean nature of decision variables

Heuristic algorithm

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- Solution based on Genetic Algorithms (GAs)
    - Viability evaluation
- Population of individuals
    - Each individual represents a candidate solution encoded in a chromosome
    - Chromosome composed by a fixed number of genes
    - Genes represent the single parameters characterizing a solution
- Population of individuals initialized randomly
- Fitness function applied to each individual
    - Describing the objective function of the optimization problem
- Evolution of population (set of generations) to improve the fitness of the population
- Three operators: mutation, crossover, selection

Mutation and Crossover

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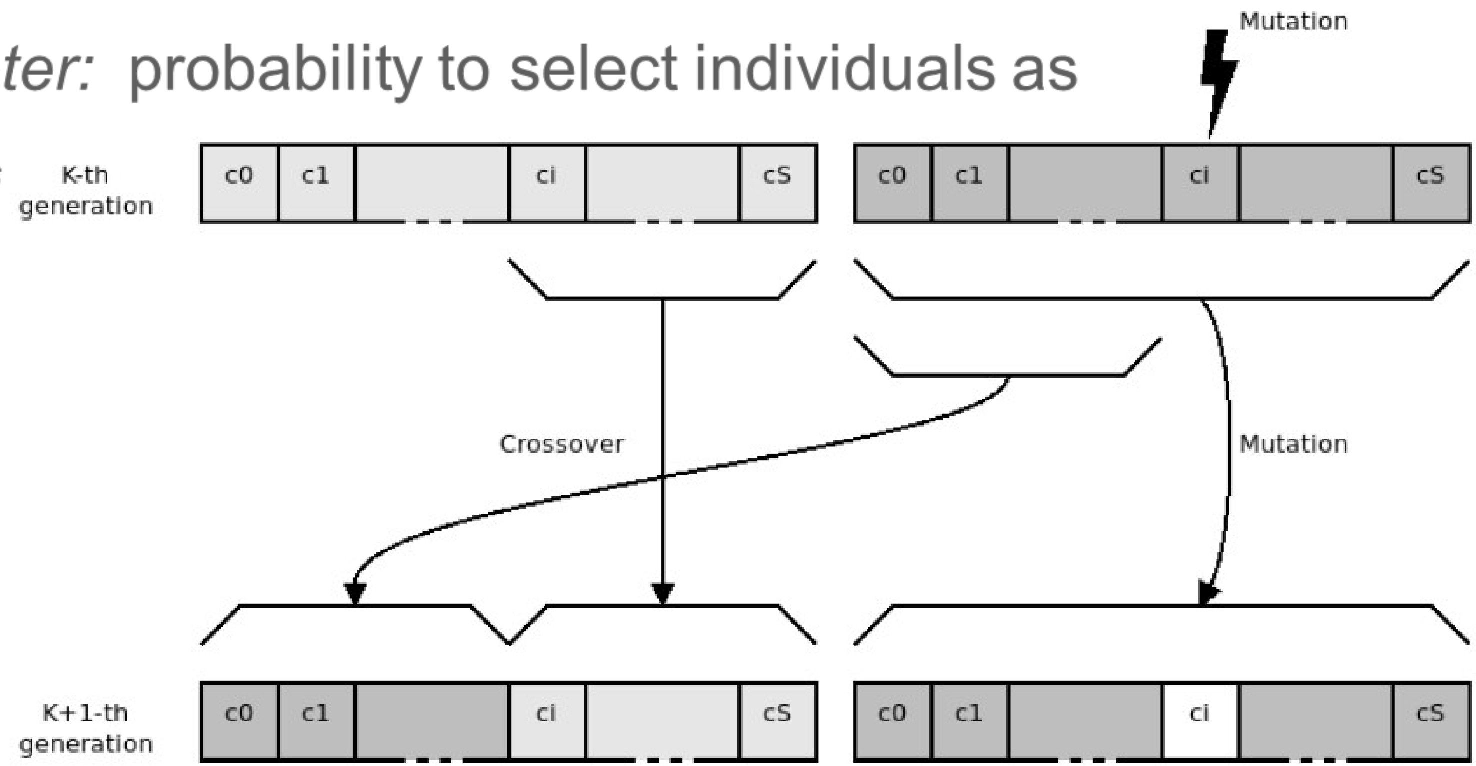
- Mutation: change of single or group of genes in a chromosome
  - *Main parameter*: probability to select an individual to perform mutation on one of its genes P_{mut}
- Crossover: merge of two individuals by exchanging part of their chromosome
  - *Main parameter:* probability to select individuals as parents P_{cross}



Selection

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- Selection: selection of individuals passing to the next generation
  - Stable population size over generations
- Approach:
  - Fitness function applied to each individual (including new ones)
  - Probability of being selected for the next generation proportional to fitness value

Solution encoding

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- A solutions encoded as a chromosome
- Chromosome: a set of *S* genes, with *S* number of sensors
- Gene: an integer number from 1 to *F*, with *F* number of fog nodes
- The i-th gene in a chromosome: $c_i = \{j : x_{i,j} = 1\}$
- Objective function used as basis
- Direct mapping between chromosomes and solutions of optimization problems - constraint (2)
- Constraints satisfied by the encoding except (3) on fog nodes overload
  - Embedded in the fitness function through penalty on overloading individuals

Experimental testbed

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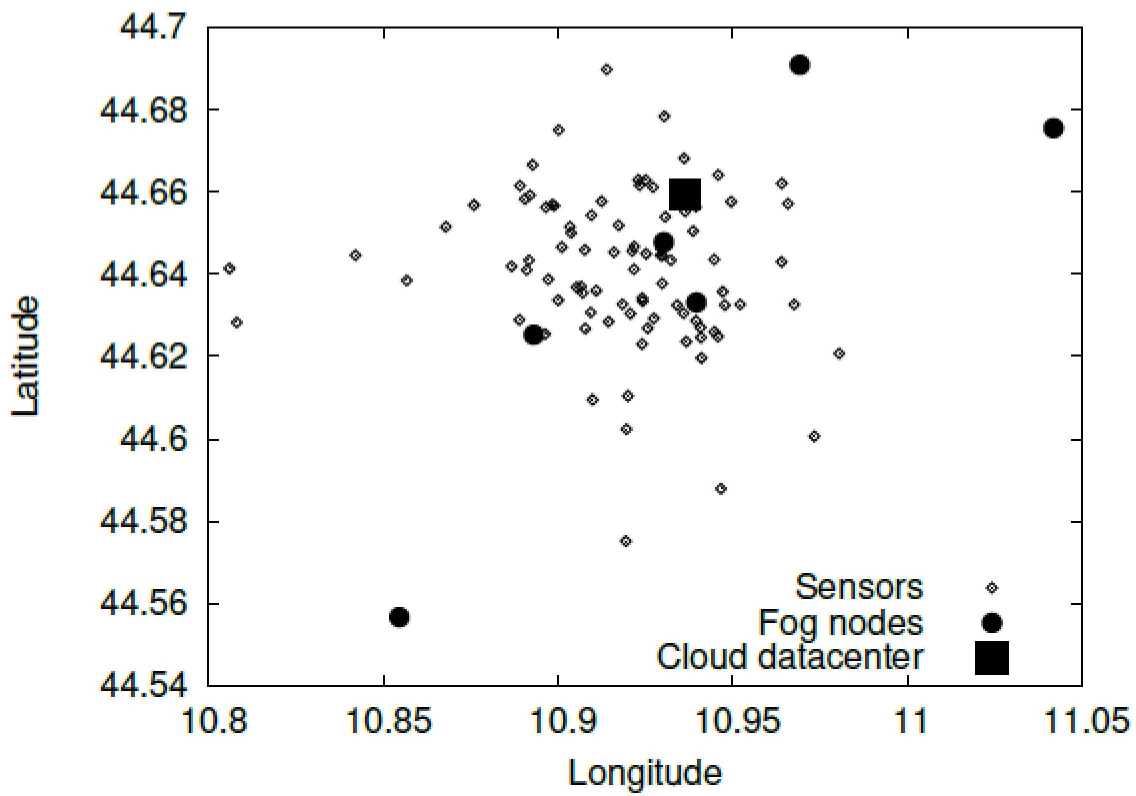
- Realistic based on the small city of Modena - Italy (180.000 inhabitants)
- Assumption: support for traffic monitoring application
- Sensors: on main streets, collecting data on traffic measures (90)
- Fog nodes: buildings hosting municipality offices (5)
- Municipality data center (1)
- Euclidean distance to model communication latency

$\lambda_i = 1, \forall i \in S$

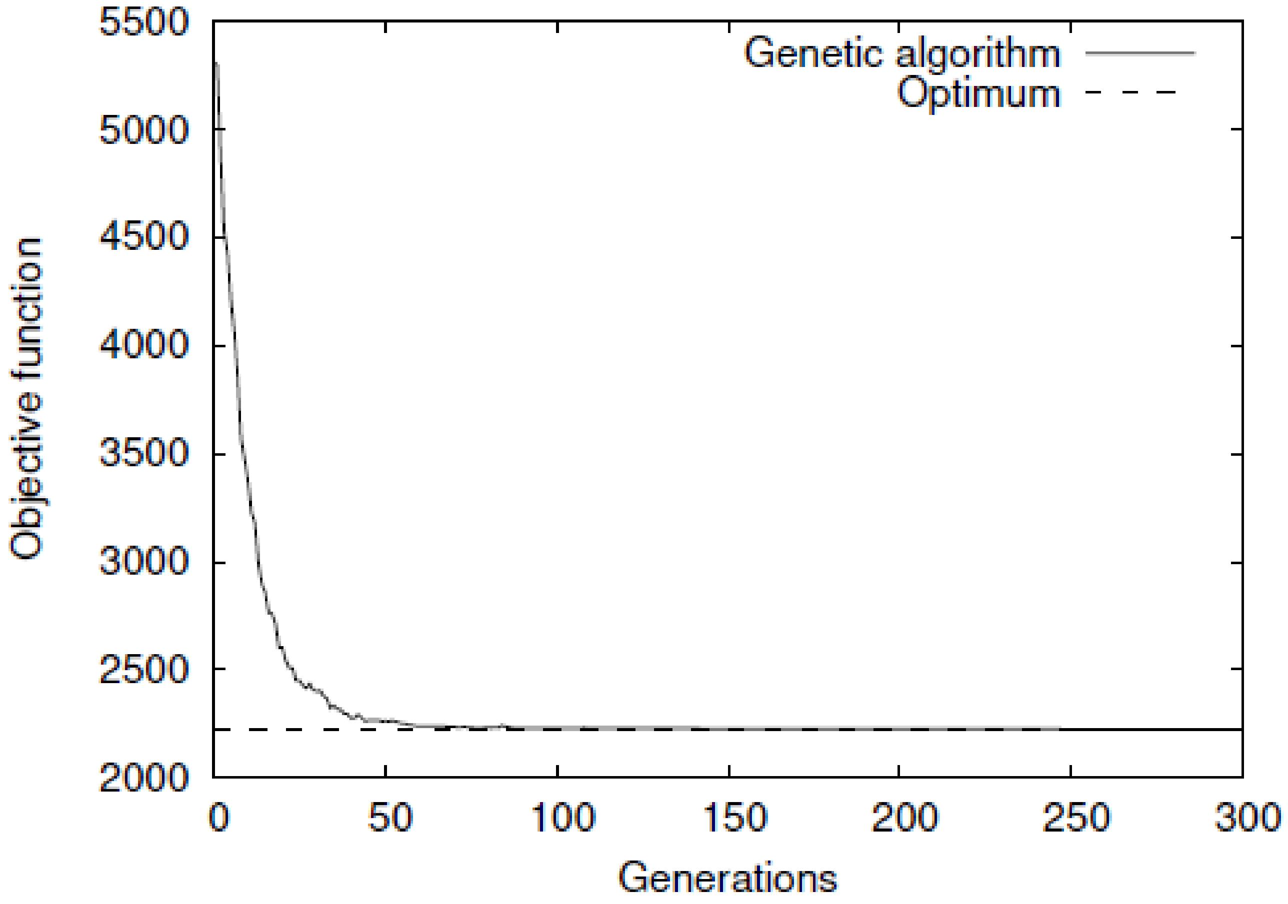
$\mu_j = 100, \forall j \in F$

- Optimization problem: AMPL / CPLEX
- GA: Distributed Evolutionary Algorithms in Python



Genetic algorithm performance

- Fast Convergence (<1% between fitness and optimal values)
- Execution time: one order of magnitude lower for convergence



Sensitivity Analysis

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Evaluating stability of the results against main parameters variance

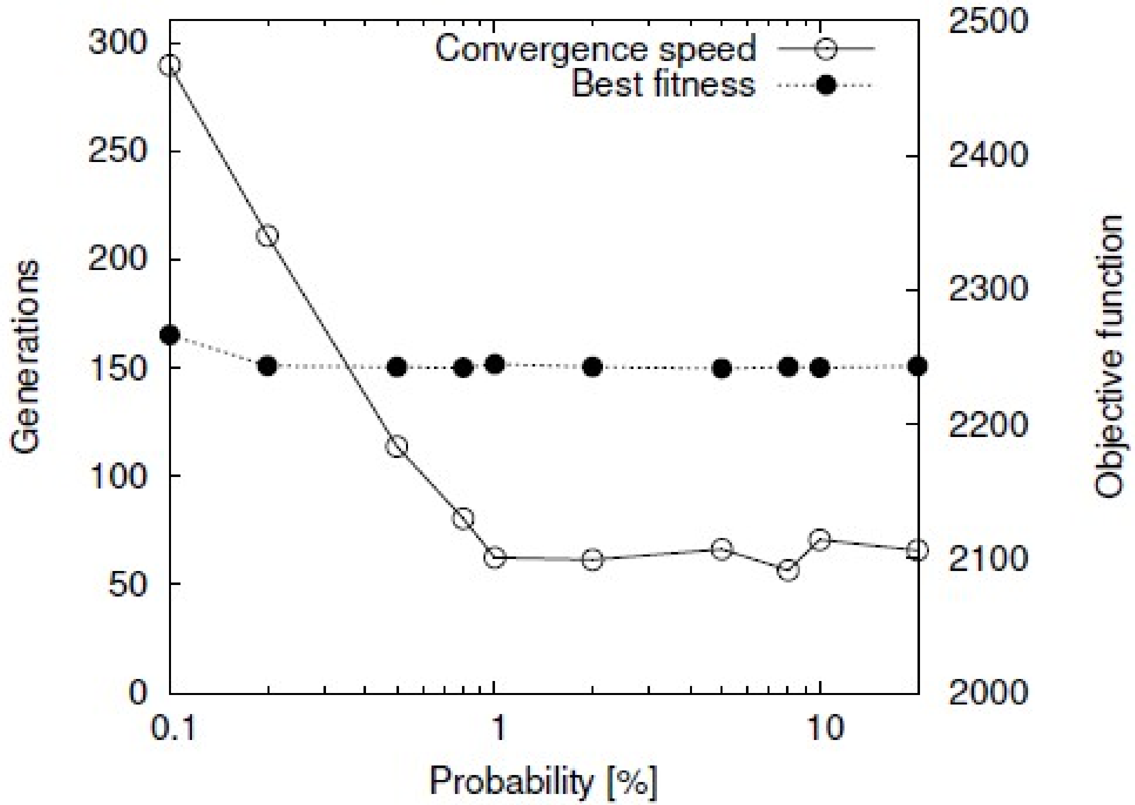
1) Probability of selecting an individual for a crossover operation P_{cross} [0.1%, 20%]

Number of generations

- Non-negligible dependence
- Stability for P_{cross} > *1%*

Best fitness value

- *Stable*



Sensitivity Analysis

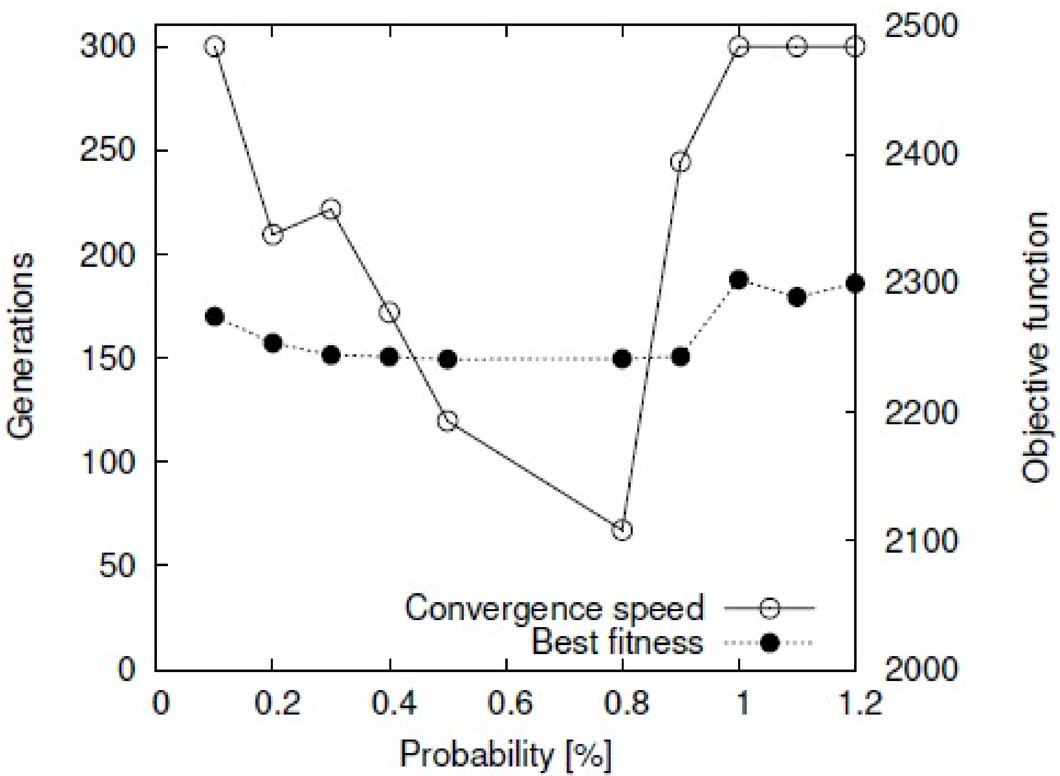
2) Probability of selecting an individual for a mutation operation P_{mut} [0.1%, 1.2%]

No converge within the threshold (300 generations) for very low (0.1%) and high values (>1%) of P_{mut}

V-shaped curve with point of fast convergence close to 0.8%

Low P_{mut} : low possibility to explore solution space

Hit P_{mut} : late convergence due to fast changes in population



Concluding remarks

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- Scenario: Fog Computing for smart city applications
- Challenge: mapping sensors data flows over fog nodes
- Contributions: optimization model and GA-based heuristic
- Results:
  - GA-based heuristic is a viable solution

    Reach optimal solution in presence of a complex problem with integer programming and non-linear objective function
  - Sensitivity analyis on main parameters
- Future directions:
  - More complex scenarios involving dynamic changes in workload
    - Sensors mobility
    - Adaptive sampling techniques at the sensor level

Thanks for your attention!