10-7-2014

Strategies for Sensor Data Aggregation in Support of Emergency Response

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MILCOM 2014
Affordable Mission Success: Meeting the Challenge

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October 7, 2014

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Key Problem in Emergency Response

In emergency situations such as fire,

how to aggregate the information collected by sets of sensors in a timely and efficient manner?

Challenges in Emergency Response

- The perceived value of the data collected by the sensors decays often quite rapidly;
- Aggregation takes time and the longer they wait, the lower the value of the aggregated information;
- A determination needs to be made in a timely manner;
- A false alarm is prohibitively expensive and involves huge overheads.

Our Solution

- Aggregation usually increases the value of information;
- We provide a formal look at various novel aggregation strategies;
- Our model suggests natural thresholding strategies for aggregating the information collected by sets of sensors;
- Extensive simulations have confirmed the theoretical predictions of our model.

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Information Value Discounting

- Information is a good that has value;
- The value of information is hard to assess;
- Measuring the value of the aggregated information remains challenging;
- The value of information is subject to rapid deterioration over time.

General Time-discounted Functions

Assumptions:

- The phenomena we discuss occur in continuous time;
- The value of information is taken to be a real in $[0, \infty)$;
- The value of information decreases with time;

Mathematical Description:

$$\begin{cases} X(t) \geq 0 & t \geq 0 \\ X(t) = X(r)g(t,r) & 0 \leq r \leq t \\ X(t) \leq X(r) & 0 \leq r \leq t \end{cases}$$

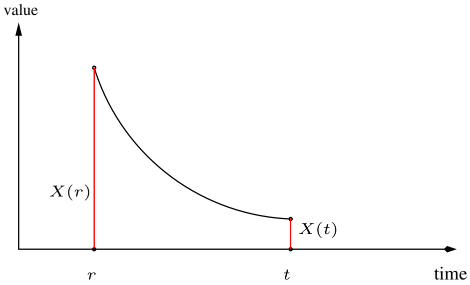
where
$g : \mathbb{R}^+ \cup \{0\} \times \mathbb{R}^+ \cup \{0\} \to [0,1]$ is referred to as a discount function.

A Special Class of Time-discounted Functions

- This discount function depends on the difference $t - r$ only;
- The value of information vanishes after a very long time;

Mathematical Description:

$$\begin{cases} X(t) = X(r)\delta(t - r), \; 0 \leq r \leq t \\ \delta : \mathbb{R}^{+} \cup \{0\} \longrightarrow [0, 1] \end{cases}$$



Exponential Time-discounted Funtions

- No discount at the beginning: $X(r) = X(r)\delta(0)$ implies $\delta(0) = 1$
- **Functional equation:**

$$\delta(t-r) = \delta(t-s)\delta(s-r), \quad \forall\, 0 \le r \le s \le t$$

- **Exponential discount function:**

$$\delta(t-r) = e^{-\mu(t-r)} \quad \forall\, 0 \le r \le t$$

where

$$\mu = -\ln \delta(1) > 0$$

- **Exponentially discounted value of information:**

$$X(t) = X(r)e^{-\mu(t-r)}, \quad \forall\, 0 \le r \le t$$

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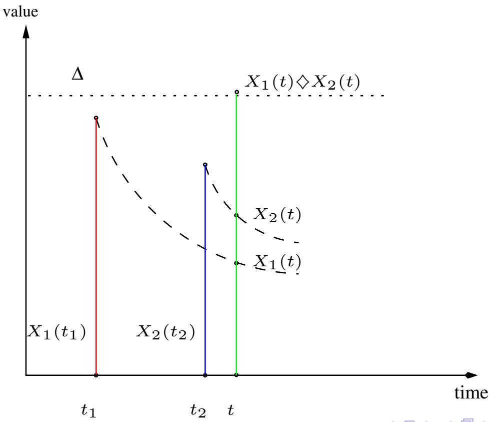
Expected Effect of Aggregation



Algebra of Aggregation

Aggregation operator $\diamondsuit$ integrates values of sensor data such as X and Y to get an aggregated value $X \diamondsuit Y$.

- $\diamondsuit$ is an application-dependent operator;
- $\diamondsuit$ can be extended to an arbitrary number of operands: $\diamondsuit_{i=1}^{n} X_i \equiv X_1 \diamondsuit X_2 \diamondsuit \cdots \diamondsuit X_n$;
- $\diamondsuit$ is assumed to have the following fundamental properties:
  - **Commutativity:** $X \diamondsuit Y = Y \diamondsuit X, \ \forall X, \ Y$;
  - **Associativity:** $[X \diamondsuit Y] \diamondsuit Z = X \diamondsuit [Y \diamondsuit Z], \ \forall X, \ Y, \ Z$;
  - **Idempotency:** If $Y = 0$ then $X \diamondsuit Y = X$.

The Interaction between Aggregation and Discounting

The aggregated value of $X(r)$ and $Y(s)$ at time τ, with $0 \leq r \leq t \leq \tau$ and $0 \leq s \leq t \leq \tau$, is $X(\tau)\diamondsuit Y(\tau)$:

$$\begin{aligned} X(\tau)\diamondsuit Y(\tau) &= [X(r)\delta(\tau - r)] \diamondsuit [Y(s)\delta(\tau - s)] \\ &= [X(t)\delta(\tau - t)] \diamondsuit [Y(t)\delta(\tau - t)] \end{aligned}$$

The discounted value of the aggregated value $X(t)\diamondsuit Y(t)$ at time τ is:

$$(X(t)\diamondsuit Y(t))\,\delta(\tau - t)$$

A Taxonomy of Aggregation Operators

Three distinct types of the aggregation operator $\diamondsuit$ $(0 \leq t \leq \tau)$:

Type 1: if
$$[X(t) \diamondsuit Y(t)]\,\delta(\tau - t) < [X(t)\delta(\tau - t)] \diamondsuit [Y(t)\delta(\tau - t)]\,;$$

Type 2: if
$$[X(t) \diamondsuit Y(t)]\,\delta(\tau - t) = [X(t)\delta(\tau - t)] \diamondsuit [Y(t)\delta(\tau - t)]\,;$$

Type 3: if
$$[X(t) \diamondsuit Y(t)]\,\delta(\tau - t) > [X(t)\delta(\tau - t)] \diamondsuit [Y(t)\delta(\tau - t)]\,.$$

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General Properties of Type 1 Operators

Lemma

Assume an associative Type 1 operator $\diamondsuit$*. For all* t, τ *with* $\max_{1 \leq i \leq n}\{t_i\} \leq t \leq \tau$ *we have*

$$[\diamondsuit_{i=1}^{n} X_i(t)]\,\delta(\tau - t) < \diamondsuit_{i=1}^{n} X_i(\tau).$$

Theorem

Assuming that the Type 1 aggregation operator $\diamondsuit$ *is associative and commutative, the discounted value of the aggregated information at time* t *is upper-bounded by* $\diamondsuit_{i=1}^{n} X_i(t)$*, regardless of the order in which the values were aggregated.*

A Special Type 1 Operator

Definition

$X \diamondsuit Y = X + Y - XY; \quad X, Y \in [0,1]$

This operator satisfies the associativity, commutativity and idempotency properties and is a Type 1 operator.

Lemma

Consider values $X_1, X_2, \cdots, X_n$ in the range $[0,1]$ acted upon by the operator defined above. Then the aggregated value $\diamondsuit_{i=1}^{n} X_i$ has the close algebraic form:

$$\diamondsuit_{i=1}^{n} X_i = 1 - \Pi_{i=1}^{n}(1 - X_i)$$

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Aggregation Strategies for Type 1 Operators

Scenario: In an emergency n ($n \geq 2$) sensors have collected data about an event at times $t_1, t_2, \cdots, t_n$ and let $t = \max\{t_1, t_2, \cdots, t_n\}$. Further, let $X_1(t_1), X_2(t_2), \cdots, X_n(t_n)$ be the values of the data collected by the sensors.

Problem: How to aggregate these values at current time τ ($\tau \geq t$) and trigger an alarm?

Solution: **THRESHOLDING**

Two Classes of Aggregation Strategies:

- Aggregation strategy with fixed threshold;
- Aggregation strategy with adaptive threshold;

Fixed Thresholding

- **Fixed Thresholding Criterion:**

$$\left[\Diamond_{i=1}^{n} X_i(t)\right] \delta(\tau - t) > \Delta$$

- **Latest Aggregation Time:**

$$\tau < t + \frac{1}{\mu} \ln \frac{\Diamond_{i=1}^{n} X_i(t)}{\Delta}$$

- **Time Window for Aggregation:**

$$\left[t, t + \frac{1}{\mu} \ln \frac{\Diamond_{i=1}^{n} X_i(t)}{\Delta}\right]$$

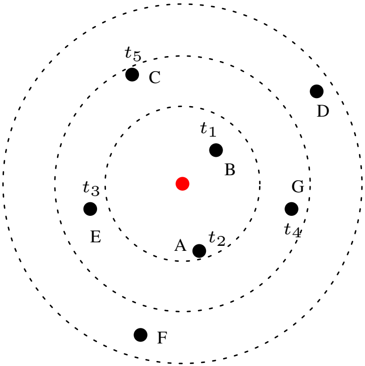
Motivation for Adaptive Thresholding

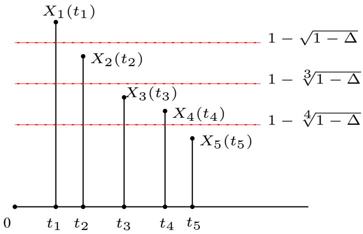
Assume sensor readings about an event were collected and the resulting values $X_1, X_2, \cdots$ are reals in $[0, 1]$ and one of the network actors (e.g., a sensor) is in charge of the aggregation process and an aggregation operator $\diamondsuit$ is employed in conjunction with a threshold $\Delta > 0$.

Theorem

If $X_{i_1}, X_{i_2}, \cdots, X_{i_m}$, $m > 1$, satisfy $X_{i_j} > 1 - \sqrt[m]{1 - \Delta}$, $\quad j = 1, 2, \cdots, m$, then $\diamondsuit_{j=1}^{m} X_{i_j} > \Delta$.

Illustration of Our Adaptive Aggregation Strategy





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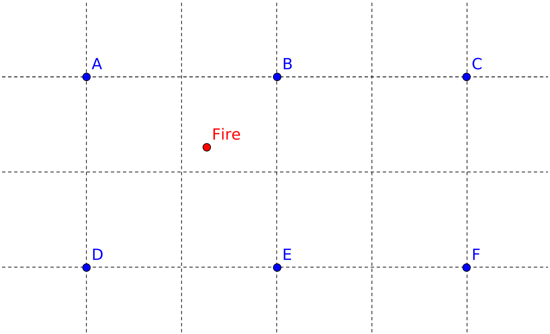
Emergency Scenario

A fire just broke out on a ship instrumented by a set of relevant sensors.



Emergency Model

- Temperature distribution: linear model with a plateau temperature of 1000°C and an ambient temperature of 20°C;
- Fire propagation: dot source model with an isotropic spreading speed of $1m/s$;
- The fire source location is randomly generated.

Sensor Network Configuration

- The temperature sensors are deployed in a rectangular lattice of size 3×2 in a plane with every side of $3m$;
- The sensors are asynchronous;
- Sensor sampling period: $2s$;
- Threshold to trigger an alarm: 0.99.

Application-dependent Aggregation Operator

- **Value of Information:**

$$X_i = \Pr[T_i \in K | F] = \begin{cases} 0.9 & T_i \in K \\ 0 & T_i \notin K \end{cases}$$

$K = [100℃, 1000℃]$ is the critical temperature range.

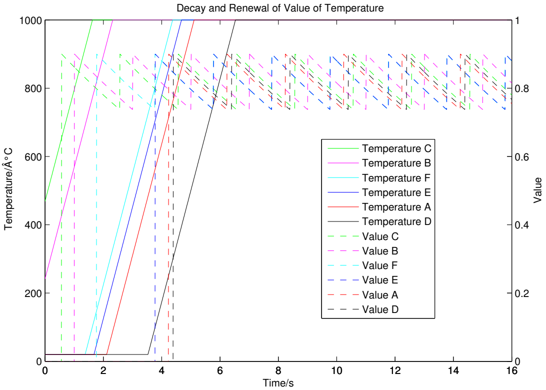
- **Exponential Discount Rate:** Value discount constant

$$\mu = 1.25 \times 10^{-3} s^{-1}$$

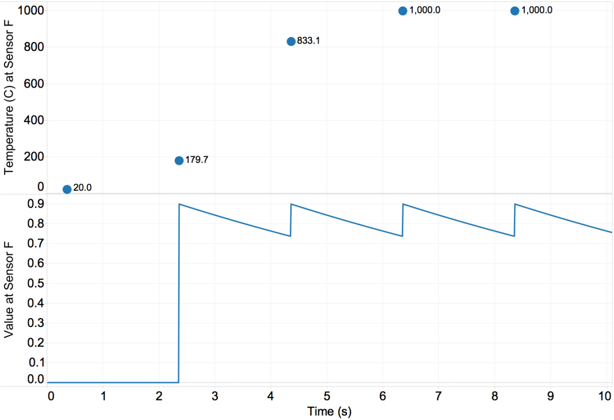
- **Aggregation Operator:**

$$\begin{aligned} X_i \diamondsuit X_j &= \Pr[\{T_i \in K\} \cup \{T_j \in K\} | F] \\ &= X_i + X_j - X_i X_j \end{aligned}$$

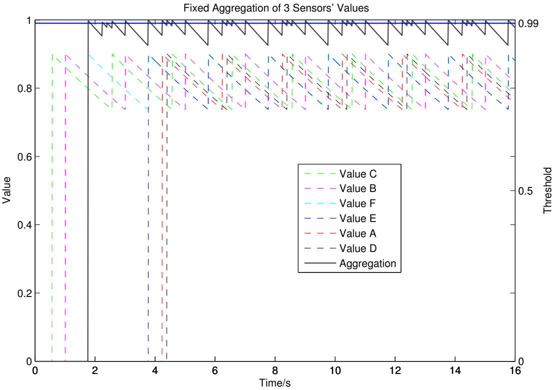
Renewal and Decay of Value of Temperature — 6 Sensors



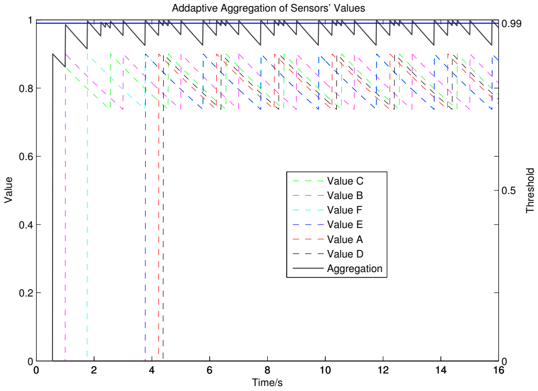
Renewal and Decay of Value of Temperature — 1 Sensor



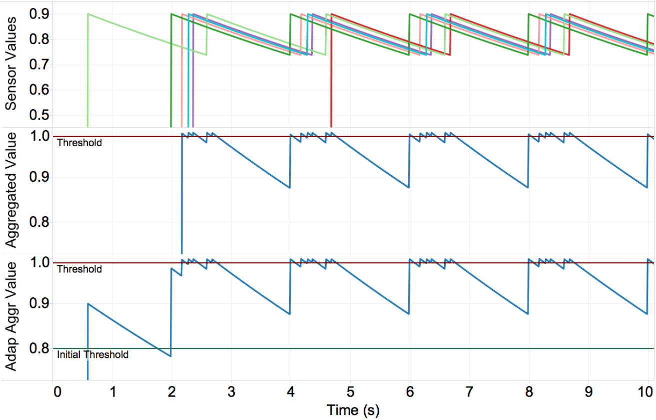
Result for Fixed Thresholding



Result for Adaptive Thresholding



Comparison of Two Strategies



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Conclusions

- Offered a formal model for the valuation of time-discounted information;
- Provided a formal way of looking at aggregation of information;
- Found that the aggregated value does not depend on the order in which aggregation of individual values take place;
- Suggested natural thresholding strategies for the aggregation of the information in support of emergency response.

Future Works

- How to aggregate data across various types of sensors in a cooperative fashion?
- How about discounting regimens other than exponential discounting?
  - Step function?
  - Linear function?
  - Polynomial function?
- How to retask the sensors as the mission dynamics evolve?

THANK YOU

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IDEA FUSION

Work supported by NSF grant CNS-1116238

Questions?