Making in-network data processing decisions based on pragmatic value of information

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June 11, 2012
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Conclusions
Sensor networks

- Sensor networks:
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  - distributed systems
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  - nodes embedded in an environment
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- Overall objective
  - Minimize consumption of a set of scarce resources
  - Maximize some metric of sensing quality
Scarce resources

- Energy
- Network bandwidth
  - For real time communication
- Data muling delay
  - How soon will the data mule come by?
- Human resources
  - Attention span and cognitive load of the customer
Some thoughts about the balance between networking and sensing

- For some sensor types, the amount of data collected is trivially small
  - Eg. most types of thermometers
- For others, it can be huge
  - Eg. imaging
When real time networking fails

- A 100 euro video camera can generate 28Mbps (1080p/60)
  - 100 such cameras exceed just about any networking technology, except dedicated optical fiber to every camera.
- What to do?
- **Data muling**: put a 64GB SD card in each sensor
  - physically collect it every 5hrs (about 60GB will be filled)
  - long delay in obtaining the data
- **Local rating**
  - allow the local not do decide whether the data is important or not
  - prioritize high-value data (either on fast networking, or by bringing over the data mule)
  - must put processing intelligence in the local node
- **Local summarization**
  - Create summaries / digests in the local node
  - Prioritize the transmission of digests
  - Still requires local intelligence
  - The value of the data can be determined in collaboration
Measuring sensing quality: quantity, accuracy, pragmatics

- Information theoretic metrics of information
  - measure the **quantity** of information, without regards to its meaning
  - a report take the same amount of bits whether correct and incorrect
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- Pragmatic metrics
  - measure the utility of the information to the customer - thus it depends on the **actions** taken by the customer
  - accuracy of information is an upper limit on pragmatic utility
Pragmatic value of information

- Probably useful to express it in form of **money**
- Must consider
  - Content - what aspect of reality the information refers to
  - Accuracy - correspondence between reality and information
  - Latency - time between evaluation and the events the information refers to
  - Novelty - did I know this before?
Decisions of the customer

- Pragmatic value depends on the decisions of the customer
- **Disruptive decisions**
  - change the algorithm for calculating the pragmatic value of information.
  - usually: commitment to a new plan - e.g. raising an alarm.
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- **Disruptive decisions**
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- **Incremental decisions**
  - do not change the algorithm for calculating the pragmatic value of information
Why considering pragmatic value is useful

- Prioritize information which is acted on in real time
- Buffer information which will not be acted on real time
- Discard worthless information
- Target the amount of information to the action being taken
Why considering pragmatic value is challenging

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  - thus it must be aware of the impact of various pieces of information on the decisions.
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- The system must support recovery from erroneous costumer decisions.
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Customers building a model of the world

- Customer $C$ at time $t$
- Collection of raw data $D = \{d_1, d_2, \ldots d_k\}$
- Build a model of the world $M = f_M(D, t)$
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Nature of the model

We will treat the model as a black box. The actual data structure can range from a single scalar to lists of values, raster-based environmental models, linear or non-linear predictors, confidence ranges and other models of arbitrary complexity. The modeling function can use a combination of techniques such as filtering, interpolating, extrapolating, system identification and others.
The value of the model

- The value of the model is a scalar:
  \[ V = f_V(M) = f_V(f_M(D, t)) \in \mathbb{R} \]

- Scores the detail, accuracy and timeliness of the model, weighted by the interests of the customer.
The value of an information chunk $d$

- sensor node has a chunk of data $d$
- if sent to customer, added to raw data $D' = D \cup d$
- updated model $M' = f_M(D', t)$
- value of data chunk $V(d, t) = f_V(M') - f_V(M) \geq 0$
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Worthless data

If $V(d, t) = 0$, the data was worthless for the customer. This can happen if:

- the data was already received from other sources
- the data is of no interest to the customer
How to build a value function?

- **Common sense:**
  - more accurate models are better
  - if an information chunk does not change the model, its value is zero.
- Many functions conform to this!
- Systematic approach in terms of **pragmatics**
Let us denote with $f_V(M, A)$ the pragmatic value of a model of the world $M$ for an agent $A$. We define this value to be the cumulative value of the actions which had been taken while using the model as source of information.

Are we just pushing the problem of defining value further?
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It is easier to define values in the application domain!
Pragmatic value of information

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- Many terminal states have natural values
- Contrast this with trying to assign a value to 100kB of data!
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The sources of decisions

- The main sources of decisions is (surprise!) the sensor readings themselves

- The local node:
  - Has access to the full local data in real time
  - Limited processing power

- The central node:
  - Has access to the global picture
  - More processing power
  - Human decision makers might be present
  - Delayed or incomplete access to the local data
The problem of being wrong

- Sensors are noisy, processing algorithms imperfect, humans inattentive:
  - Errors happen!
- The judgements will be inevitably fuzzy/probabilistic/degree based.
  - But decisions are usually binary: transmit / not transmit, send the DM or not.
- Underestimating and overestimating the value of information can both be wrong
  - Having a fixed safety margin doesn’t buy us anything when we are resource constrained - it won’t change the resource allocation
- One solution: estimate uncertainty in judgement
Dempster-Shafer theory of evidence

- Dempster-Shafer mathematical theory of evidence
  - find a belief function which combines evidence from various sources
  - can be seen as a generalization of probability
- Uses two values: **belief** and **plausibility**
  - ... instead of a single probability value
  - belief < plausibility
  - mass function: assigns weights to the powerset of possible outcomes
  - belief = mass of evidence for
  - plausibility = 1 - mass of evidence against
The **belief** is used as an input to the operator in order to support a disruptive decision.

- a belief $> 0.5$ leads to a classification decision.
- A human operator can override this value.

The **plausibility** used to assess the likelihood of being wrong

- eg. what I see is probably just a scratch, but it is still plausible that it is a crack.
- the system must prepare for the possibility of the customer changing his mind about the classification.
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The ultimate use to which the data can be put (the pragmatic value) is a natural basis to answer such questions.

Value of information resides in:
- deciding what actions to take
- providing data for successful completion of the actions
- providing support for correcting bad decisions

All these are application dependent, but it is possible to establish a general purpose theoretical framework.
Conclusions - the big picture

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... there is much left to do.
Questions?