Self-optimizing transactional data grids for elastic cloud environments

Paolo Romano
About me

• Master and PhD from “Sapienza” University of Rome

• Researcher at Distributed Systems Group, INESC-ID, Lisbon (since 2008)
  – Best INESC-ID Young Researcher 2011

• Invited professor at Instituto Superior Técnico, Lisbon (since 2011)

Some international projects in which I am currently involved:

• Coordinator of the FP7 Cloud-TM Project (Jun 2010-Jun 2012)
  – 4 international partners from industry and academy

• Coordinator of the Cost Action Euro-TM (fall 2010-fall 2013)
  – Pan-European Research network on Transactional Memories
  – 56 experts, 42 institutions, 12 countries

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Talk overview

• Cloud-TM Overview:
  – key goals
  – background on Transactional Memories
  – progresses so far

• Self-optimizing transactional data grids:
  – methodologies explored so far
  – case studies

• Open research questions & future work
# Cloud-TM at a glance

**Partners:**

<table>
<thead>
<tr>
<th>Logo</th>
<th>Name</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>🇵🇹</td>
<td>INESC ID (PT)</td>
<td>Portugal</td>
</tr>
<tr>
<td>✿</td>
<td>Algorithmica (IT)</td>
<td>Italy</td>
</tr>
<tr>
<td>🇮🇹</td>
<td>C.I.N.I. (IT)</td>
<td>Italy</td>
</tr>
<tr>
<td>🇮🇪</td>
<td>Red Hat (IE)</td>
<td>Ireland</td>
</tr>
</tbody>
</table>

**Project coordinator:**

Paolo Romano, INESC ID (PT)

**Duration:**

From June 2010 to May 2013

**Programme:**

FP7-ICT-2009-5 – Objective 1.2

**Further information:**

http://www.cloudtm.eu

---

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Key Goals

Develop a transactional data platform for the Cloud:

1. Providing a simple and intuitive programming model:
   - hide complexity of distribution, persistence, fault-tolerance

2. Minimizing administration and monitoring costs:
   - automate elastic resource provisioning based on applications QoS requirements

3. Minimize operational costs via self-tuning
   - maximize efficiency adapting consistency mechanisms upon changes of workload and allocated resources

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Background on the Cloud-TM Programming Paradigm....

TRANSACTIONAL MEMORIES

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Transactional Memories...

• Transactional Memories (TM):
  – replace locks with atomic transactions in the programming language
    – hide away synchronization issues from the programmer
      • avoid deadlocks, priority inversions, debugging nightmare
      • simpler to reason about, verify, compose
  – simplify development of parallel applications
• Distributed Transactional Memories (DTM):
  – extends TM abstraction over the boundaries of a single machine:
    • enhance scalability
    • durability via in-memory replication
  – minimize communication overhead via:
    • speculation
    • batching consistency actions at commit-time
...to Cloud-TM

Open-source DTM middleware providing:

• Language level support for:
  – object-oriented domain model
  – highly scalable abstractions

• Elastic scale-up and scale-down of the DTM platform:
  – automatic scaling based on user defined QoS & cost constraints

• Self-optimization as a pervasive feature:
  – pursue maximum efficiency via cross-layer self-tuning

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
PROGRESSES SO FAR
Main achievements

- Architecture specification
- Development of preliminary prototype
- Innovative transactional replication schemes
- Platform self-tuning
Preliminary prototype

• 1\textsuperscript{st} version of Data Platform already available:  
  \textbf{http://www.cloud-tm.eu}

• Integration/extension of mainstream open source projects:  
  – focus on innovation & avoid reinventing the wheel  
  – maximize project’s visibility & facilitate exploitation
Innovative transactional replication schemes

• Several approaches have been pursued:
  – overlap processing and communication via speculation
  – asynchronous leases to reduce communication overhead
    [Middleware2010]
  – weaker consistency models
    [PRDC2011]

• Different approaches with a same common goal:

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Data-grid self-optimization

- Self-tuning/performance forecasting of several platform layers
  - Software Transactional Memory layer
    [CMG10], [PEVA11]
  - Replication manager
    [Middleware2011]
  - Group communication system
    [SASO10], [Performance2011], [ICNC12]
Talk overview

• Cloud-TM Overview:
  – key goals
  – background on Transactional Memories
  – progresses so far

• Self-optimizing transactional data grids:
  – methodologies explored so far
  – case studies

• Open research questions & future work
Methodologies explored so far

• Analytical modeling:
  – queuing theory, markov processes
  – stochastic techniques

• Machine learning:
  – off-line techniques:
    • Decision Trees, Neural networks, Support Vector Machine
  – on-line techniques (reinforcement learning):
    • UCB algorithm
Analytical modeling

• white box approach:
  – requires detailed knowledge of internal dynamics

• good extrapolation power:
  – allow forecasting system behavior in unexplored regions of its parameters’ space 😊

• minimal learning time:
  – basically parameters instantiation 😊

• complex and expensive to design/validate 😞

• subject to unavoidable approximation errors 😞
Machine learning

- black box approach:
  - observe inputs, context and outputs of a system
  - use statistical methods to identify patterns/rules
- good accuracy in already explored regions of the parameters’ space 😊
- ...but poor extrapolation power 😞
- learning time grows exponentially with number of features:
  - but eventually outperforms analytical models (typically!)

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Hybrid techniques

IDEA: get the best of the two worlds

Two alternative approaches so far:

1. Divide-and-conquer:
   • AM for well-specified sub-components
   • ML for sub-components that are:
     – too complex to model explicitly, or
     – whose internal dynamics are only partially specified

2. Use AM to initialize ML knowledge:
   • reduce learning time of ML techniques
   • correct AM using feedback from operational system

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Case studies

• Dynamic selection and switching of data replication protocols:
  – total order based replication protocols (Case study 1):
    • purely based on Machine Learning techniques
  – single-master vs multi-master (Case study 2):
    • hybrid ML-AM solution – divide-et-impera

• Group Communication System self-optimization:
  – batching in total order protocols (Case study 3)
    • hybrid ML-AM – ML bootstrapped with AM knowledge
SELF-OPTIMIZING DATA CONSISTENCY PROTOCOLS
The search for the holy grail

transactional data
consistency protocols

Single master (primary-backup)
Multi master
Total order-based
2PC-based

Certification
Non-voting
BFC

Voting
State machine replication

NO ONE SIZE FITS ALL SOLUTION

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
The Cloud-TM vision

- **Low traffic**
  - Read-dominated
  - Low conflict

- **Hi traffic**
  - Write-dominated

- **Low traffic**
  - Minimum costs
  - Primary-backup: low % write; low load on primary

- **Hi % write**
  - Primary overwhelmed
  - Multi-master: higher scalability

- **Auto-scale up**
  - New nodes hired for read-only requests

- **Auto-scale down**
  - Minimum costs
  - Switch back to primary-backup

Legend:
- Node processing read-only requests
- Node processing read&write requests

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Self-optimizing data replication: key challenges

1. allow efficient switch among multiple replication protocols:
   – avoid blocking transaction processing during transitions

2. determine the optimal replication strategy given the current workload characteristics:
   – machine learning methods (black box)
   – analytical models (white box)
   – hybrid analytical/statistical approaches (gray box)

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Case studies

• Dynamic selection and switching between replication protocols:
  – total order based replication protocols (Case study 1):
    • purely based on Machine Learning techniques
  – Two phase commit vs primary backup (Case study 2):
    • hybrid ML-AM solution – divide-et-impera

• Group Communication System self-optimization:
  – batching in total order protocols (Case study 3)
    • hybrid ML-AM – ML bootstrapped with AM knowledge

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
POLYCERT: POLYMORPHIC SELF-OPTIMIZING REPLICATION FOR IN-MEMORY TRANSACTIONAL GRIDS

Maria Couceiro, Paolo Romano, Luis Rodrigues
ACM/IFIP/USENIX 12th International Middleware Conference (Middleware 2011)

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Where they fit in the picture

Single master (primary-backup)

Multi master

Total order-based

2PC-based

Certification

Non-voting

Voting

BFC

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Certification
(a.k.a. deferred update)

• A transaction is executed independently at a single replica until its commit phase:
  – minimize network traffic

• Distributed certification is run to detect conflicts with transactions executed concurrently at different replicas

• Certification is typically much more lightweight than full transaction execution
  – good scalability also in write intensive workloads
Certification

• Three different approaches in literature:
  – Non-voting algorithm
  – Voting algorithm
  – BFC

• One key commonality:
  – reliance on Total Order Broadcast to avoid distributed deadlocks
  – TOB ensures agreement on delivery order of broadcast messages in a non-blocking fashion
Classic Replication Protocols

- Focus on full replication protocols

- Single master (primary-backup)
- Multi master
  - AB-based
  - 2PC-based
  - Certification
    - Non-voting
    - Voting
    - BFC
  - State machine replication

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Non-voting

execution of T1’s read & writeset

TOB of T2’s read & writeset

R1

Execution Transaction T1

Validation & Commit T1

Validation & Abort T2

R2

Execution Transaction T2

Validation & Commit T1

Validation & Abort T2

R3

+ only validation executed at all replicas:

  high scalability with write intensive workloads

- need to send also readset: often very large!

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Classic Replication Protocols

- Focus on full replication protocols

  - Single master (primary-backup)
  - Multi master
    - AB-based
    - 2PC-based
      - Certification
        - Non-voting
        - BFC
      - State machine replication
        - Voting

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Voting

- sends only write-set (much smaller than read-sets normally)
- Additional communication phase to disseminate decision (vote)

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Classic Replication Protocols

• Focus on full replication protocols

Single master
(primary-backup)

Multi master

AB-based

2PC-based

Certification

Non-voting

Voting

BFC

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Bloom Filter Certification (BFC)

• Use a single TOB as in non-voting, but encode readset in a Bloom filter
  – Bloom filters:
    • space-efficient, probabilistic data structure for test membership
    • compression is a function of a (tunable) false positive rate

• A transaction T is certified successfully only if:
  – none of the items written by concurrent transactions is present in the BF used to encode T’s readset
  – strongly reduce network traffic at the cost of negligible abort increase
    • 1% false positive yields up to 30x compression

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
The system architecture is depicted in the diagram shown in Figure 2. At the topmost layer, it exposes the API of an object-oriented STM, which is however fully replicated across a number of distributed nodes. The API provided to applications is a transparent extension of JVSTM's API, a state-of-the-art STM relying on an efficient Multi-Version Concurrency Control (MVCC) algorithm. A strong advantage of JVSTM is that read-only transactions are never required to block. The JVSTM programming paradigm requires that the programmer encapsulates any shared mutable state within VBoxes, which are then managed by JVSTM's MVCC to ensure transactional atomicity and isolation. This allows separating the transactional and non-transactional state of the application, ensuring strong atomicity at no additional costs. We modularly extended JVSTM by augmenting it with what we have named a Polymorphic Replication Manager (PRM). The PRM is in charge of triggering the execution of a certification protocol for each of the locally executed transactions and to participate in the certification of transactions that have been executed at remote nodes. A unique feature of PRM with regard to existing replication managers is that it is able to determine, for each locally executing transaction, which certification algorithm is more appropriate, given the characterization of the transaction. The logic for determining the certification scheme is encapsulated by the abstraction of a Replication Protocol Selector Oracle (RPSO), whose interface exports two main functionalities:

– Given a local transaction, it selects the most appropriate certification protocol to be executed by the PRM. In Section 3, we will present and evaluate two performance forecasting methods which are based on alternative machine learning techniques.
Self-optimizing data replication: key challenges

1. allow efficient switch among multiple replication protocols:
   – **coexistence** of multiple certification schemes via the Polymorphic Certification (PolyCert) protocol

2. determine the optimal replication strategy given the current workload characteristics:
   – entirely based on **machine learning** techniques
     • off-line: decision-trees, neural network, SVM
     • on-line: reinforcement learning (UCB)

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
PolyCert

• Polymorphic Self-Optimizing Certification

• Co-existence of the 3 certification schemes:
  – exploit common reliance on total order broadcast

• Machine-learning techniques to determine the optimal certification strategy per transaction

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
• Two implementations:

  – Off-line Machine Learning Techniques

  – On-line Reinforcement Learning
Off-line Machine Learning Techniques

• For each transaction:
  – Determine size of exchanged messages for each certification scheme
  – Forecast AB latency for each message size. We evaluated several ML approaches:
    • Regression decision trees (best results)
    • Neural networks
    • Support vector machine
Off-line Machine Learning Techniques

- Uses up to 53 monitored system attributes:
  - CPU
  - Memory
  - Network
  - Time-series

- Requires computational intensive feature selection and training phase

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
On-line Reinforcement Learning

• Each replica builds on-line expectations on the rewards of each protocol:
  – no assumption on rewards’ distributions

• Upper Confidence Bound (UCB) algorithm:
  – lightweight and provably optimal solution to the exploration-exploitation dilemma:
    • did I test this option sufficiently in this scenario?
On-line Reinforcement Learning

• Distinguishes workload scenario solely based on read-set’s size
  – exponential discretization intervals to minimize training time

• Replicas exchange statistical information periodically to boost learning
Fig. 5. Normalized throughput of the adaptive and non-adaptive protocols on Bank benchmark, thus allowing us to focus on the performance of the transactions that require the activation of a commit-time certification phase. As shown in Figure 5 around 1/3 of transactions, namely the so-called long traversal transactions in this benchmark, have read-set sizes larger than 100K items. As a consequence, when using either NVC or BFC, this benchmark generates an extremely high traffic volume that, in all our runs, eventually determined the saturation and the collapse of the GCS. This is the reason why in Figure 8, we only report the throughput of VC, DT, UCB and DistUCB normalized with respect to the throughput of the optimal non-adaptive protocol, namely VC. In this scenario, the adaptive protocols clearly outperform the non-adaptive VC scheme, thanks to their ability to use the more efficient NVC and BFC protocols to handle transactions with smaller read-set's size. The speedup of PolyCert when using the three alternative oracles range from 2 to 4, with the best performance also in this case achieved by DistUCB.

Overall, our experimental data demonstrated the effectiveness and viability of the proposed self-tuning polymorphic replication technique, highlighting in particular the efficiency of the DistUCB oracle, which, not needing any time-consuming offline training phases, and being totally parameter-free, results extremely convenient for deployment in real-life practical scenarios. Interestingly, PolyCert does not only provide benefits in terms of performance, but also in terms of robustness, avoiding to saturate the GCS in presence of transactions with extremely large read-sets, a main source of instability for BFC and, in particular, NVC.

Related Work

Our work is clearly related to the vast literature on replication of transactional systems and in particular to the more recent works relying on AB to achieve a replica-wide...
...and beating it!

![Normalized throughput chart](chart.png)

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Case studies

• Dynamic selection and switching between replication protocols:
  – total order based replication protocols (Case study 1):
    • purely based on Machine Learning techniques
  – single-master vs multi-master (Case study 2):
    • hybrid ML-AM solution – divide-and-conquer

• Group Communication System self-optimization:
  – batching in total order protocols (Case study 3)
    • hybrid ML-AM – ML bootstrapped with AM knowledge

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Diego Didona, Sebastiano Peluso, Paolo Romano and Francesco Quaglia,
Self-tuning replication of elastic in-memory transactional data platforms,

SINGLE VS MULTI-MASTER

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Classic Replication Protocols

- Focus on full replication protocols

- Single master (primary-backup)

- Multi master
  - Total order based
    - Certification non-voting
    - Voting
  - 2PC-based
    - State machine replication
Single Master

• Write transactions are executed entirely in a single replica (the primary)

• If a write transaction is ready to commit, coordination is required to update all the other replicas (backups).

• Read transactions can be executed on backup replicas.

• No distributed deadlocks
• No distributed coordination during commit

• **Throughput of write txs doesn’t scale up with number of nodes**

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
• Focus on full replication protocols

- Single master (primary-backup)
- Multi master
  - Total order based
  - 2PC-based
    - Certification
      - Non-voting
      - Voting
    - State machine replication

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
2PC-based replication

- Transactions executed at all nodes w/o coordination till commit time
- Acquire atomically locks at all nodes using two phase commit (2PC):
  - 2PC materializes conflicts among concurrent remote transactions generating:

  DISTRIBUTED DEADLOCKS

+ good scalability at low conflict
- thrashes at high conflict
Goals

• Autonomically select the best suited protocol that
  – Minimizes transactions' service time
  – Maximizes achievable throughput

• Automate elastic scaling
  – Scale up if the system needs more computational power
  – Scale down if the system is oversized
Self-optimizing data replication: key challenges

1. allow efficient switch among multiple replication protocols:
   – here coexistence of the 2 schemes is impossible:
     • design of an non-blocking protocol switching strategy

2. determine the optimal replication strategy given the current workload characteristics:
   – analytical models of effects of data contention
   – machine learning methods to predict hw-dependant latencies
     • CPU execution time, network RTT

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Key Technical Problem

• How to forecast:
  – Performances of protocol B while running protocol A?
  – Performances with X nodes while running on Y nodes?

given that replication protocol/scale changes affect:
  – The transaction conflict probability
  – The transport layer latency
Methodology

Joint usage of analytical modeling and machine learning techniques:

– analytical model of replication algorithm dynamics:
  • lock contention, distributed deadlock probability
  • message exchange pattern

– machine learning to forecast performance of group communication layer:
  • RTT as a function of msg size, throughput, #nodes
Analytical Model

• Distributed lock contention dynamics captured via an analytical model:
  – the replication algorithms' behavior is fully specified
  – it is possible to mathematically model them
    (...although not easily, but that’s another story!)

• Key methodologies:
  – Mean value analysis & Queuing theory

• Rely on Machine Learning to forecast hardware dependent metrics, in particular network latencies...

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Machine learning techniques

• Resource virtualization makes mathematical modeling unfeasible:
  – No knowledge of actual load
  – No knowledge of actual physical resources

• Transport layer latency (RTT) of the two protocols predicted via decision tree regressors
Inputs for the ML

- Number of nodes
- RTT in the current configuration
- Size of exchanged messages
- Throughput of the current configuration
  - Unknown!!!
  - Guessed using the analytical model (more next)
Statistical Model Accuracy

- Correlation between 0.96 and 0.98
- Relative error between 0.19 and 0.22

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Models Coupling

Analytical model forecasts the data grid throughput taking as input the RTT in the target configuration.

Machine learning forecasts the RTT taking as input the data grid throughput in the target configuration

Fixed point solution found using recursion
Global Model Accuracy

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
...and now in action!

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Case studies

• Dynamic selection and switching between replication protocols:
  – total order based replication protocols (Case study 1):
    • purely based on Machine Learning techniques
  – single-master vs multi-master (Case study 2):
    • hybrid ML-AM solution – divide-and-conquer

• Group Communication System self-optimization:
  – batching in total order protocols (Case study 3)
    • hybrid ML-AM – ML bootstrapped with AM knowledge

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Paolo Romano and Matteo Leonetti

Self-tuning Batching in Total Order Broadcast Protocols via Analytical Modelling and Reinforcement Learning


BATCHING IN TOTAL ORDER BROADCAST PROTOCOLS

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Sequencer based TOB (STOB)

- Total order broadcast (TOB) algorithms rely on a special process to ensure total order:

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Batching in STOB protocols

• STOB have theoretically optimal latency:
  – 2 comm. steps, independently of the number of processes
• ...but sequencer becomes the bottleneck at high throughput

• Batching at the sequencer process:
  – wait for several msgs and order them altogether:
    • amortize sequencing cost across multiple messages
  – optimal waiting time depends on message arrival rate:
    • very effective at high throughput...
    • very bad at low throughput!

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
• Using queuing theory arguments we can determine the optimal batching time, $b^*$, as a function of the current load, $m$: 

$$b^*(m) = \begin{cases} 
1, & \text{if } m < \frac{T_{add}\sigma^2}{2} + \frac{1}{2} \sqrt{\frac{4\sigma^2 + 2T_{add}^2\sigma^4}{2}} \\
\frac{2m - \sigma - 2mT_{add}\sigma}{\sigma - 2mT_{add}\sigma + \sqrt{\frac{2(\sigma + 2m(T_{add}\sigma - 1))^2}{(2\sigma T_{add} - 1)^2(1 + 2\sigma T_{add})\sigma^2}}}}, & \text{if } \frac{T_{add}\sigma^2}{2} + \frac{1}{2} \sqrt{\frac{4\sigma^2 + 2T_{add}^2\sigma^4}{2}} < m < m^* 
\end{cases}$$
Model Accuracy

Model underestimates optimal batching value at “medium” load...

Problem:

batching underestimation causes system instability!
Peak period analysis

Ramp-up & ramp-down transition through the “problematic” areas:
- ramp-up is sufficiently short:
  ⇒ system “struggles”, but recovers
- ramp-down is longer:
  ⇒

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
What about a pure ML approach?

- Problem:
  - ML techniques need to explore different solutions (batching values) to identify optimal one:
    - low load: useless additional latency

  **INITIALLY INEFFICIENT**

  - medium-high load: insufficient batching values lead very rapidly to instability and thrashing

**UNFEASIBLE**

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Combining the two approaches

1. Initialize ML’s knowledge with the predictions of the analytical model:
   – reduce frequency of obviously wrong explorations

2. Let ML update the initial reward values:
   – correct model’s prediction errors exploiting feedback from the system
Combining the two approaches

![Graph showing latency and messages per second over time](image)

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Talk structure

• Cloud-TM Overview:
  – key goals
  – background on Transactional Memories
  – progresses so far

• Self-optimizing transactional data grids:
  – self-optimizing methodologies explored so far
  – case studies

• Open research questions & future work
Open research issues

• Holistic approaches to self-optimization:
  – understand effects of self-optimizing multiple, mutually dependent layers

• QoS-aware programming paradigms:
  – methodologies and tools to allow providers to assess feasibility of fulfilling SLAs

• Highly scalable data consistency models:
  – beyond eventual consistency

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
Future work

• Focus on elastic-scaling, keeping into account data grids dynamics:
  – consistency costs, transaction conflicts

• Study effects of self-tuning multiple, mutually dependent layers of the data grid

• Highly scalable quasi-serializable protocols
THANKS FOR THE ATTENTION

Cloudviews 2011, Porto, Portugal, Nov. 4 2011
References (I)


Cloudviews 2011, Porto, Portugal, Nov. 4 2011
References (II)


Cloudviews 2011, Porto, Portugal, Nov. 4 2011