STHITHIKA
COST-BASED QUERY DISTRIBUTION WITH QUERY RE-WRITING IN DISTRIBUTED COMPLEX EVENT PROCESSING SYSTEMS

Imiya Mohottige Thakshila Dilrukshi
(158211H)

Thesis submitted in partial fulfillment of the requirements for the degree Master of Science

Department of Computer Science & Engineering

University of Moratuwa
Sri Lanka

January 2019
DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: Date:

Name: I.M. Thakshila Dilrukshi

The above candidate has carried out research for the Masters of Science thesis under my supervision.

Signature of the supervisor: Date:

Name of the supervisor: Dr. Surangika Ranathunga
Abstract

Complex event processing (CEP) is very useful in analyzing event streams and identifying useful patterns from them. Due to the distributed nature of existing applications, high volume of event generation and complex queries, using a single node CEP became problematic. One way to overcome this problem is to introduce multiple complex event processing nodes and distribute the queries among them for load balancing. However, due to the stateful nature of events, distributing queries among CEP nodes is not an easy task. Query distribution across CEP nodes is an NP hard problem.

This research is focused on the problem of optimally processing a large number of different event streams using a large number of CEP queries in a distributed manner. Optimization of query processing and distribution is done in two aspects: optimizing the individual query by introducing query rewriting, and optimizing query distribution across multiple nodes by introducing new factors to the query distribution algorithm. Cost of individual queries, number of event streams common to queries, CPU and memory utilization of nodes that run CEP queries, type of queries, and the number of queries in each node are the factors considered for query distribution. Usability improvement is done in two ways: adding standard communication by introducing JSON messages for communication, and integrating firebase messaging service to standardize the event source.

Experiments show that with these optimizations, compared to existing systems, STHITHIKA is capable of providing a higher system throughput, without making an adverse impact on event duplication or process load variance across processing nodes. It has the ability to handle higher number of queries compared to existing system. It is also more robust to event bursts. Due to the changes in query distribution and re-writing, time taken for initial query distribution has increased. Usability improvement enabled the easy integration with other technology and decoupling event source from the system.
ACKNOWLEDGEMENT

I would like to express my sincere gratitude to Dr. Surangika Ranathunga, my research supervisor, all the lectures and MSc course assistants of Department of Computer Science and Engineering, University of Moratuwa for the continuous support given for the success of the research.

I would like to thank section head and the team members of web technologies team at Mubasher Technologies (Pvt) Ltd, for giving me laptops for testing and providing leaves when required.

Finally, I would like to thank my family and all the friends for being the motivation and encouraging me to complete the research.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Declaration</td>
<td>i</td>
</tr>
<tr>
<td>Abstract</td>
<td>ii</td>
</tr>
<tr>
<td>Acknowledgement</td>
<td>iii</td>
</tr>
<tr>
<td>List of Figures</td>
<td>vii</td>
</tr>
<tr>
<td>List of Abbreviations</td>
<td>viii</td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Research Problem</td>
<td>2</td>
</tr>
<tr>
<td>1.2 Research Objectives</td>
<td>4</td>
</tr>
<tr>
<td>1.3 Research Contributions</td>
<td>4</td>
</tr>
<tr>
<td>1.4 Structure of Thesis</td>
<td>5</td>
</tr>
<tr>
<td>2 LITERATURE REVIEW</td>
<td>6</td>
</tr>
<tr>
<td>2.1 Complex Event Processing</td>
<td>6</td>
</tr>
<tr>
<td>2.1.1 CEP Engines</td>
<td>8</td>
</tr>
<tr>
<td>2.2 Distributed Complex Event Processing</td>
<td>14</td>
</tr>
<tr>
<td>2.2.1 Need of distributed CEP</td>
<td>14</td>
</tr>
<tr>
<td>2.2.2 Problems with distributed CEP</td>
<td>15</td>
</tr>
<tr>
<td>2.2.3 Distributed CEP techniques</td>
<td>16</td>
</tr>
<tr>
<td>2.2.4 Query Cost Calculation</td>
<td>38</td>
</tr>
<tr>
<td>2.3) Query Optimization</td>
<td>39</td>
</tr>
<tr>
<td>2.3.1 Query re-writing</td>
<td>39</td>
</tr>
<tr>
<td>3 METHODOLOGY</td>
<td>42</td>
</tr>
<tr>
<td>3.1 Changes to the VISIRI system</td>
<td>43</td>
</tr>
<tr>
<td>3.2 Query Optimization</td>
<td>44</td>
</tr>
<tr>
<td>3.3 Query Distribution Algorithm Optimization</td>
<td>53</td>
</tr>
<tr>
<td>3.4 Standardized Event Source &amp; Communication</td>
<td>57</td>
</tr>
<tr>
<td>4 EVALUATION</td>
<td>59</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 2.1 - Complex event processing architecture [8] ........................................ 7
Figure 2.2 - Siddhi CEP architecture [10] .......................................................... 8
Figure 2.3 - Esper CEP architecture [11] ............................................................ 11
Figure 2.4 - Cayuga CEP architecture [12] ......................................................... 11
Figure 2.5 - S4 processing node architecture [13] .............................................. 13
Figure 2.6 - Load balancing strategies in CEP [3] ............................................. 17
Figure 2.7 - Wihidum setup [14] ....................................................................... 20
Figure 2.8 - Architecture of Next CEP system [24] .......................................... 21
Figure 2.9 - Borealis Architecture [20] ............................................................... 24
Figure 2.10 - System architecture of WSO2 CEP on Apache Storm [26] .......... 27
Figure 2.11 - ZStream tree representation [27] .................................................. 29
Figure 2.12 - SCTXPF architecture [3] ................................................................. 31
Figure 2.13 - High-level architecture of Visiri System [7] .................................. 33
Figure 2.14 - Low-level architecture of VISIRI system [7] .............................. 34
Figure 3.1 - Modifications to VISIRI Architecture .......................................... 43
Figure 3.2 - Modifications to VISIRI Processing Node ..................................... 44
Figure 3.3 - Query re-writing logic .................................................................... 49
Figure 3.4 - Sample query re-writing logic step 1 .......................................... 50
Figure 3.5 - Sample query re-writing logic step 2 .......................................... 50
Figure 3.6 - Extracted query from original query ............................................. 51
Figure 3.7 - Query after re-arrange ................................................................. 52
Figure 3.8 - Duplication removed query ........................................................... 52
Figure 3.9 - Firebase real-time database with stored events ......................... 58
Figure 3.10 - Firebase real-time database with stored events ....................... 58
Figure 4.1 - Comparison of Query distribution VISIRI vs STHITHIKA .......... 60
Figure 4.2 - Performance with increasing query count ................................... 61
Figure 4.3 - Performance evaluation in event bursts ................................. 62
Figure 4.4 - Analysis of time taken for query distribution ............................. 62
Figure 4.5 - Event duplication analysis ............................................................ 63
Figure 4.6 - Cost variance analysis ................................................................. 64
Figure 4.7 - Compare query re-writing ............................................................. 65
LIST OF ABBREVIATIONS

CEP - Complex Event Processing
CN - Client Notifier
CPU - Central Processing Unit
DISP - Dispatcher
EP - Event Processor
EP-CTL - Event Processing Controller
HA - High Availability
NFA - Non-deterministic Finite Automata
NP - Non-deterministic Polynomial
PE - Processing Element
PEC - Processing Element Container
QP - Query Processor
QT – Query Type
RTL - Register Transfer Level
S4 - Simple Scalable Streaming System
SCTXPT - Scalable Context Delivery Platform
SOA - Service Oriented Architecture
SQL - Structured Query Language