Accuracy Analysis of Data Aggregation for Network Monitoring

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Abstract— The quality of computing certain aggregation functions based on incomplete measurements for the purpose of distributed network monitoring is considered. Network monitoring plays a fundamental role in network management systems by providing timely information on the network status, which is crucial for network administration purposes. To reduce network overhead and for easier assimilation, this information is usually presented by calculating a few key aggregate metrics. The aggregates are periodically computed from a large number of detailed events collected continuously during the course of the network operations. Under errors induced by network delays, the accuracy of typical aggregation functions used in network management systems (e.g., sum, average, maximum) is evaluated both analytically and by simulations. The results provide a quantifiable trade-off between accuracy and timeliness of the information acquired, which can then be used to design and optimize network management systems.

I. INTRODUCTION

Network monitoring is a critical function, through which timely information on the status of network elements and communication links is provided to network administrators. Network monitoring systems continuously collect numerous measurements of key performance indicators and events such as bandwidth utilization and link status and process them into more meaningful, aggregate metrics such as average delay and network availability.

The accuracy of computed aggregates is affected by errors introduced by the measurement process as well as the transmission of the collected data to the processing station. The latter case occurs when monitoring of the network is distributed to several monitoring agents and processing of the measured data takes place in a remote network management center. Such deployment can cause transmission delays and packet loss of sampled data, which skew the results of the periodic calculation of aggregate metrics.

Recent work on computing in-network aggregates in the field of sensor networks primarily focuses on the trade-off between accuracy and energy consumption for extending the lifetime of the network. Other studies explore the trade-off between communication overhead and accuracy of aggregation. This work provides an analysis of the error that is induced in the calculation of the typical aggregation functions used for network monitoring, when the measurement samples are delayed or missing, independent of the particular topology used for delivering the results, or the communication costs for transmitting the underlying measurements. As such, it provides a characterization of the quality of aggregation irrespective of the underlying architecture, which extends the concept of Quality of Management (QoM) introduced in [1].

II. SYSTEM MODEL

There are \( N \) managed network elements in the network, represented by a set \( \{1, 2, \ldots, N\} \), and each such network element collects information by means of a monitoring agent. The events captured at the monitor \( i \) occur according to a homogeneous Poisson process with arrival rate \( \lambda_i \). Each event is associated with a value, the event’s intensity. The intensity of an event \( x(j) \) at a monitor \( i \) is drawn from a random variable \( X_i \). We assume \( \{X_i\}, i=1, \ldots, N \), are i.i.d. random variables, for which \( E[X] = m_X \) and \( \text{Var}(X) = \sigma_X^2 \).

Whenever a monitoring agent captures such an event, it sends it to the next level for aggregation. The network delay is assumed to be a random variable, \( D_i \), exponentially distributed with mean \( 1/\mu_i \). The network management center aggregates the events that it has received periodically, with a period \( T \). The aggregation takes place at time \( t_{agg}=kT+h \) for all the events that have occurred within the interval \( [(k-1)T, kT) \). Even though the additional time \( h \) facilitates for the delay induced in the network, there can still exist some events that miss this deadline. This results in some data missing at the time when the aggregation occurs, introducing an error on these calculations. We assume that events are time stamped, so that those received after the according time interval are dropped and do not interfere with later calculations.

III. QUALITY OF AGGREGATION

We focus our study on accuracy as the property that primarily characterizes the quality of aggregation. The accuracy of a particular aggregation function is captured by looking at the difference between the output of the aggregation function applied to the (ground-truth) set of all the events \( S \), and that applied to the set of events that reached the aggregation point in time, \( L \). Formally, if \( F \) is an aggregation function, then the quality of \( F \) under our event model is measured by the absolute error:

\[
ERR_F = |F(S) - F(L)|
\]
We hereby give some main results within the framework that has been defined so far. The analysis from which these are derived, together with more results, can be found in [2].

A. The COUNT function

\[
E[ERR_{CNT}] = Var(ERM_{CNT}) = \sum_{i=1}^{N} \lambda_i e^{-\mu_i h} \frac{(1-e^{-\mu_i T})}{\mu_i} \tag{2}
\]

B. The SUM function

\[
E[ERR_{SUM}] = m_X \sum_{i=1}^{N} \lambda_i e^{-\mu_i h} \frac{(1-e^{-\mu_i T})}{\mu_i} \tag{3}
\]

\[
Var(ERM_{SUM}) = (\sigma_X^2 + m_X^2) \sum_{i=1}^{N} \lambda_i e^{-\mu_i h} \frac{(1-e^{-\mu_i T})}{\mu_i}
\]

C. The AVERAGE function

Assuming homogeneous transmission delay and events’ generation rates, we obtain the following bounds:

\[
E[ERR_{AVG}] \leq 2m_X e^{-\mu h} \frac{(1-e^{-\mu T})}{\mu T}
\]

\[
\max \left( 0, \sigma_X^2 \left( \frac{p}{1-p} \left( 1-e^{-\mu T} \frac{1}{\lambda T} \right) - 4m_X^2 \frac{p^2}{\lambda T} \right) \right) \leq Var(ERM_{AVG}) \tag{4}
\]

\[
\leq \sigma_X^2 \left( 1 - e^{-\mu T} \frac{1}{\lambda T} \right)
\]

D. The MAX function

The absolute error for the MAX function depends on the distribution of the intensity of the events, and no general closed-form solution exists. The expected value of the absolute error when the underlying values are uniformly distributed in \([0,a]\) is given by:

\[
E[ERR_{MAX}] = a \left[ 1 - \exp \left( \frac{\lambda T - e^{-\mu h}(1-e^{-\mu T})}{\mu} \right) \right] \frac{a}{\lambda T - e^{-\mu h}(1-e^{-\mu T})} \tag{5}
\]

We can also turn to a simpler error measure : the indicator error, giving the probability of getting a wrong estimate. The probability of missing the event of maximum value equals the marginal probability of missing any event: 

\[
e^{-\mu h} (1 - e^{-\mu T}) / \mu T\]

E. Simulation Results

We evaluate the quality of aggregation using the normalized mean absolute error, defined as the ratio of mean absolute error and expected true value. To evaluate the influence of event intensity, we simulate two intensities—uniform and lognormal—with the same mean and variance. The simulations are consistent with the analytical results.

In Fig. 1, we plot the error versus mean latency, to evaluate the trade-off between accuracy and timeliness. Mean latency is defined as the expected value of the time between the generation of an event and the time when it is included in the aggregation, given by \(t=T/2+h\). We can adjust the mean latency by either varying \(T\) or varying \(h\). As expected, all the errors decay as latency increases. However, there exists a threshold latency, below which varying \(T\) gives better tradeoff and the opposite holds otherwise. This is because the latency increases twice slower with \(T\), but the error decays much faster with \(h\). From a design perspective, this means that given overall latency constraint, there is an optimal pair of aggregation period and waiting time that minimizes the error.

V. CONCLUSION

Data aggregation of network measurements is an important function of network monitoring systems, as it summarizes performance indicators of the network into metrics that are easily assimilated by network administrators and are further used as a basis for SLAs with customers. This paper provides the results of an analytical study of the error that is introduced into the calculation of typical aggregation functions. Simulation results verify our analysis and provide further insights on the accuracy-timeliness tradeoff.

ACKNOWLEDGMENT

Research was sponsored by the U.S. Army Research Laboratory and the U.K. Ministry of Defence and was accomplished under Agreement Number W911NF-06-3-0001. The views and conclusions contained in this document are those of the author(s) and should not be interpreted as representing the official policies, either expressed or implied, of the U.S. Army Research Laboratory, the U.S. Government, the U.K. Ministry of Defence or the U.K. Government. The U.S. and U.K. Governments are authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation hereon.

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