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Energy Efficient Knowledge Distribution in Wireless Sensor Networks for Query Analytics

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A dissertation presented in part fulfilment of the requirements of the
Degree of Master of Science at The University of Glasgow

July 15, 2016

The research work disclosed in this publication may be partially funded by the Endeavour Scholarship Scheme (Malta). Scholarships may be considered for part-financing by the European Union - European Social Fund (ESF) - Operational Programme II – Cohesion Policy 2014-2020

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European Union - European Social Funds (ESF)
Co-financing rate: 80% EU Funds; 20% National Funds



Abstract

Systems using Wireless Sensor Networks (WSN) are shaped with the consideration of a great number of factors. These include power consumption, lifetime, network topology, responsiveness and transmission errors. Thus, several research challenges are introduced. We propose a system which lets each network node locally gather knowledge and distribute it amongst its peers. Then, based on this knowledge it evaluates the error and decides whether it should send the updated knowledge or not, minimizing power consumption. Using various techniques we will be querying the learnt shared knowledge and evaluating the accuracy of each to study what the effects of increasing the permissible error are.

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Acknowledgements

I wish to express my sincere gratitude to Dr. Christos Anagnostopoulos for his guidance and expert advice throughout all the various stages of this project. Apart from that I am also thankful to him for making me appreciate even more the subject of data science and machine learning.

Furthermore, I would like to thank my family for all their continuous support in this first year living abroad.

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Chapter 1

Introduction

The Internet of Things (IoT) is a rapidly growing area, with it more data is being stored and made accessible which previously has never even been thought possible. IoT is composed of billions of devices that can gather, share information and sometimes even capable of performing operations on this information. IoT devices are physical objects connected with the internet able to share information. This can include anything ranging from smartphones to Radio Frequency Identification (RFID) tags found in everyday products. As more data is made available for anything imaginable that affects our daily lives, opportunities arise for applications that extract this information and make use of it. EXAMPLE SMARTGRID AND REFERENCE. Making all this information useful is very challenging as it needs to be collected, transferred, stored and made accessible. [3]

Since these IoT devices are generally wireless, compact and have very limited resources they can be considered as WSNs. REFERENCE ? WSNs are made up of a large number of nodes, which are capable of wireless communication and minimal computation capabilities. [2] Each sensor node measures the temporal-spatial field of the area around it. These are called the contextual scalar parameters and can be of any form and value, example; humidity, temperature, acidity, etc.. This contextual information is relayed to a "sink", which can referred to as a central node.

In a naive system all these devices generate massive amounts of data which is periodically sent to central node with more computing resources. This in turn, might restructure the data more effectively to be sent to another node or make it available for querying. All this network transfer drains power and as the network size increases this effect is emphasized even more. This has created a need and opportunity for machine and statistical learning algorithms.[5] According to L.Bottou et al.[5] these technological improvements have outrun the exponential evolution of computing power. Thus, we must rely more on on-line learning algorithms to process these large amounts of data with comparatively less computing power.

The vision of IoT is to allow any device to be continuously connected sharing its knowledge about the surroundings. Machine learning then uses this stream of data to deduce results, infer new knowledge, reason about contextual events or make assumptions. The possibilities for such systems are endless, taking, for instance, the case of thermometers in rooms next to each other and based on previous information the temperature of various rooms can be predicted based on the temperature of adjacent ones.

1.1 Problem Synopsis

One of the factors in IoT systems is the collection of contextual information from certain sources in an IoT environment.[3] IoT devices communicate in an ad-hoc manner with the Central nodes, also known as collectors to send information. The objective of each collector is that it has the latest up-to-date information/context. This would allow the IoT system to further process the context and make use of it, example environmental monitoring.

In this IoT environment the IoT devices are not able to communicate directly together due to the limited resources, so instead they communicate with the collectors. Even if each device has an infinite power supply, a naive system which periodically transmits the context is not feasible especially as the network grows in size. Collectors would become overloaded with messages from all devices and incur a performance degradation as network size increases. Transmitting wireless messages is very costly and in most cases IoT devices run on limited battery power. These devices need to make intelligent decisions whether to send data or not to conserve battery power and increase their lifetime. In this naive system there is no concept of knowledge, thus withholding data would result in the collectors having gaps of knowledge.

Once the collectors have access to the context of the connected devices, they need to make it available for querying. A naive system stores all the data items inside the context for each device. This would result in a very resource hungry collector due to the huge amount of processing and storage capabilities it would need to support. C.Anagnostopoulos [3] states that the contextual sensor data exhibits high complexity, dynamism, accuracy, precision and timeliness. This is due to the huge volumes, interdependency relationships between devices and continuous updates performed in real-time. From this statement he then argues that "an IoT system should not concern itself with the individual pieces of contextual sensor data: rather, context should be intelligently collected and interpreted into a higher, domain relevant concept." [3]

Using this concept, instead of having access to all the raw data, collectors would contain multiple intelligent contexts. This raises the challenge on whether for each query there exists an optimal set of intelligent contexts that increase the accuracy. In other words it opens the opportunity for ensemble learning [7]. This means that we cannot guarantee to find the best hypothesis (intelligent context) that gives the best accuracy from all contexts. Ensemble learning tries to intelligently choose contexts and assign weight depending on their likelihood of providing the best result. Hence, it aims at reducing the bias and variance of the learning algorithms used to construct the context.[7]

The research challenge we will be looking at is the building of an energy efficient network which minimises power consumption while simultaneously minimising transmission error. Furthermore, we will investigate the use of ensemble learning on the local contexts to achieve more accurate queries. This system must make use of very little computing resources to maximise its lifetimes while at the same time support scalability and real-time querying for environment monitoring.

1.2 Project Aims

We argue that instead of directly sending the contextual information, devices should locally learn their context using machine learning algorithms and then transmit this knowledge. If we transmit the local model to the central node each time it is updated then we would not save any power

consumption. Thus, we go a step further and set up the notion of a permissible error, which allows the local and central models to have a limited amount of discrepancy. This allows us to avoid unnecessary transmissions which do not "teach" the collector any valuable knowledge, and in turn reduce the power consumption. Altering the permissible error should determine the percentage of messages being sent, thus directly affecting power consumption.

We will be using on-line linear regression to learn the context of each device with real-time constraints. Primarily we will be investigating how the error discrepancy between devices and collectors affect battery consumption and network lifetime. Secondly we will study how altering this error discrepancy has an effect on the querying accuracy of the collectors.

The primary objectives for this project may be defined as follows:

- Obtain a clear understanding on how IoT systems operate and what they try to achieve.
- Implement On-line machine learning and clustering algorithms. In particular, we will be focusing on a 3-dimensional implementation.
- Build a system capable of simulating a real-life IoT system containing collectors and devices. We will be using the U-Air [10] dataset, which contains air quality data from real-life stations in Beijing and Shanghai.
- Integrate the capability of transmitting both raw context and knowledge (with a flexible degree of error) to investigate energy efficiency of our implementation.
- Evaluate the query accuracy performance of both naive system and our implementation.

1.3 Document Outline

The content of this report is organized into the following chapters:

- **Chapter 2** provides the reader with the background knowledge required for understanding the basic principles and algorithms behind this work. In particular, we introduce the general theory behind on-line algorithms, linear regression and normalization.
- Afterwards, in **Chapter 3** we analyse the related work in this field to provide us with the required knowledge to improve upon what there already is.
- **Chapter 4** describes our major contributions to the research challenges, namely network efficiency and ensemble learning.
- In **Chapter 5** we describe the major design and implementation decisions of our contributions and simulation system.
- **Chapter 6** contains the evaluation and performance analysis of our work.
- Lastly in **Chapter 7** we identify possible future extensions, and conclude the presented work.

Chapter 2

Preliminaries

In this chapter, we present an overview of the concepts and base principles we mention and make use of in our work. We develop a system which deals with a continuous data stream and thus, has to use specialized algorithms which treat each data item individually without storing past data items. Various algorithms are used which extract knowledge from each individual sensor by minimizing loss and then quantize the input.

2.1 On-line Algorithms

According to M.Karp [9] an on-line algorithms is one which receives a sequence of requests and performs an immediate action to each request. These are useful in situations where decisions must be made without any future knowledge. Their effectiveness is measured by the comparing them with their off-line (batch) counterparts. In this dissertation we make use of well known common techniques already proven to work.

2.1.1 K-Means

The K-means algorithm attempts to find K representatives (centroids) of a data set in such a way as to best represent the data. [4] Although it is algorithmically simple, it still manages to be relatively robust and give close to optimal results on a wide range of data sets. Its disadvantage is that one has to predefine K. Furthermore, the initial K centroids chosen have a drastic effect upon the clusters chosen. The first k inputs initialize the codebook vectors (centroids) $m_j, j = 1, \dots, k$. The rest of the inputs $x^t \in X$ are used for the update function.

$$i \leftarrow \operatorname{argmin}_j \|x^t - m_j\| \quad (2.1)$$

$$m_i \leftarrow m_i + \eta(x^t - m_i) \quad (2.2)$$

Equation 2.1 finds the closest centroid to the input. Then the closest centroid is updated as shown in equation 2.2 depending on the learning rate defined by η . A large η enhances accuracy but makes m_i oscillate. Therefore to reach convergence one needs to use a small or decaying η .

2.1.2 Adaptive Resonance Theory (ART)

ART[6] is another unsupervised learning algorithm similar to k-means. It does not require the number of clusters to be predefined before hand. Instead one has to define *vigilance* which represents the degree of similarity between points. An data item $x^t \in X$ is a member of a cluster m_j only if the distance between them is less than vigilance. Similar to the K-means procedure, once m_j is chosen, equation eq:updateCluster is used to update the centroid. If no centroid satisfies this constraint, then a new cluster is created. This allows a better flexibility but has the disadvantage of creating an infeasible and unpredictable amount of clusters in certain situations.

2.1.3 Linear Regression

Once it is proven that there is a statistically significant correlation between two variables, linear regression allows us to make predictions about one variable based only on the other variable. The relationship between these two values must be linear, else this technique would not be able to model the data accurately.

To perform this supervised learning we must first start by defining the hypothesis example the linear function 2.3.

$$h_{\theta}(x) = \theta_0 + \theta_1 x_1 + \theta_2 x_2 \quad (2.3)$$

The θ_i 's represent the weights of the linear function, thus, determining the mapping between X and Y. Let $x_0 = 1$, we then rewrite equation 2.3 to a more compact form represented by equation 2.4.

$$h(x) = \sum_{i=0}^n \theta_i x_i = \theta^T x \quad (2.4)$$

For this hypothesis to be useful, the θ parameters need to be trained to fit a particular dataset. Conceptually the closest $h(x)$ is to Y, the better we are at representing the data. Thus, we define the cost function equation 2.5 which measures the total discrepancy for each input $x^{(i)}$ with output $y^{(i)}$.

$$J(\theta) = \frac{1}{2} \sum_{i=1}^m (h_{\theta}(x^{(i)}) - y^{(i)})^2 \quad (2.5)$$

Naturally, we would like to choose a theta which minimizes the error. One such technique which does this is the gradient descent rule. It calculates the gradient of the error and takes a step proportional to the negative gradient. To achieve this we need to use the partial derivative of equation 2.5. For all θ the update rule then becomes equation 2.6. This update rule is called least mean squares (LMS) and it has a very interesting property. The magnitude of the update is proportional the the error. This means that the greater the error, the steeper the descent towards the minima. After completing the derivative we are left with the complete equation 2.7. This has to be repeated for each θ until convergence. Meaning until we reach the best possible theta values.

$$\theta_j := \theta_j - \alpha \frac{\partial}{\partial \theta_j} J(\theta) \quad (2.6)$$

$$\text{Repeat until convergence: (For each j) } \theta_j := \theta_j - \alpha \sum_{i=1}^m (y^{(i)} - h_{\theta}(x^{(i)})) x_j^{(i)} \quad (2.7)$$

One might argue that with this iterative approach we might get stuck at a local minima instead of finding the optimal minima. In this particular scenario J is a convex quadratic function, meaning it has only one minima. Thus, gradient descent will always converge at the global minima assuming α is not too large.

Multivariate Stochastic Gradient Descent

The previous algorithm is called batch gradient descent as for each update step it uses all the training set. This would not be feasible to compute especially as the dataset size increases. Another issue would be that previous data items have to be stored, and this is not always possible. In fact we will be using the more lightweight and on-line version called stochastic gradient descent. In batch gradient descent we go through all the data set for a single update step while when using equation 2.8 we start making progress right away. We use this update rule for each new training item we encounter. This in fact has the tendency of getting close to θ much faster than batch gradient descent, however it may never converge and instead keep oscillating around the minimum. The reason it is called multivariate is that we will be using multiple inputs (more than one x) to get y .

$$(\text{For each } j) \theta_j := \theta_j + \alpha(y^{(i)} - h_{\theta}(x^{(i)}))x_j^{(i)} \quad (2.8)$$

2.1.4 Mean and Variance

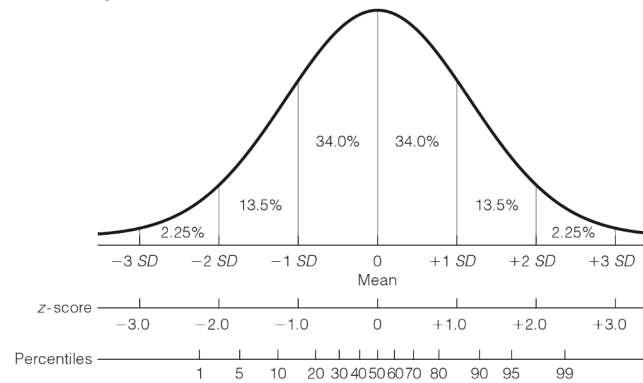
2.2 Probability Distribution Function

2.3 Normalization

We use the standard score [8] to normalize the dataset. This is done by subtracting each item x by the mean and then dividing it by the standard deviation of the dataset as shown in equation 2.9. Performing this normalization allows us to better understand the results as it gives a meaning to a raw value. Figure 2.1 demonstrates the distribution of z , a negative value means that x was less than the mean. Furthermore, the magnitude of this value represents the distance from the mean in terms of standard deviation.

$$z = \frac{x - \mu}{\sigma} \quad (2.9)$$

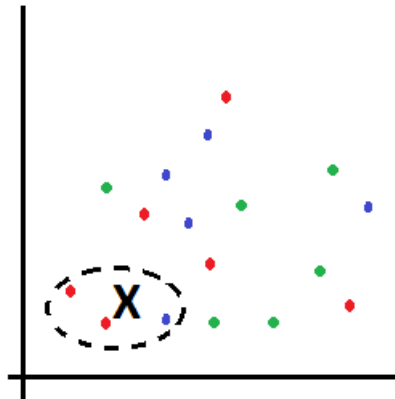
Figure 2.1: Standard score normalization [8]



2.4 K Nearest Neighbours (KNN)

KNN [1] is a straightforward classification technique, in which given an input it is able to classify it to certain class. As the name implies it takes the closest K neighbours and depending on the majority of their classes it determines the class of the input. Figure 2.2 demonstrates KNN ($K = 3$) while classifying X using a data set containing 3 different classes. In this case input X is classified as Red due to the fact that the majority of its 3 closest neighbours are Red.

Figure 2.2: At KNN=3, Input X is classified as Red



Chapter 3

Literature Review

Chapter 4

Contributions

In this chapter we discuss our major contributions with the aim of improving WSNs. More specifically how we can increase network efficiency, which extends the devices' life time. We shall delineate a strategy for creating knowledge from the raw context, by locally learning the context in real-time using on-line stochastic gradient descent. Based on this knowledge, we then decide whether it is worth it to transmit data or not. Additionally we look into how we can minimize the error when querying the knowledge found inside the collectors.

4.1 Network Efficiency

4.2 Ensemble Learning

4.3 Optimal Stopping

Chapter 5

Design and Implementation

5.1 Network Architecture

5.2 Query Analytics

Chapter 6

Evaluation and Case Study

6.1 Data Set

6.2 Error Allowance vs Messages Sent

6.3 Probability Distribution Functions

6.4 Query Validation

Chapter 7

Conclusion

7.1 Achievements

7.2 Future Work

7.3 Final Remarks

Appendix A

First appendix

A.1 Section of first appendix

Appendix B

Second appendix

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